Coolant Refill of the Photovoltaic Thermal Control System (PVTCS) on the International Space Station (ISS)

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Presented By
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THERMAL & FLUIDS ANALYSIS WORKSHOP

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Overview

- Background
- ISS Physical Overview
- PVTCS Configurations
- Coolant Refill Operations Overview
- Analysis Methods, Constraints, Assumptions & Results
- Comparison to On-orbit Operation
- Summary
- Backup
  - Acknowledgments

Background

- The Photovoltaic Thermal Control System (PVTCS) on the International Space Station (ISS) provides active cooling to the ISS electric power production and storage equipment
- The coolant inventory in ISS PVTCS Port 6 (P6) Channel 2B decayed to levels threatening sustainability, due to a long-term leak episode involving extensive troubleshooting, system reconfiguration, and component change-out
- On November 6, 2015, a spacewalk, or Extravehicular Activity (EVA), was performed to refill the PVTCS P6 Channel 2B to satisfactory levels
- The refill involved coordinated EVA and ground operations to transport coolant from the reservoir stored in the External Active Thermal Control System (ETCS) Port Ammonia Tank Assembly (ATA) to the PVTCS P6 Channel 2B by means of commanded pressure adjustments
- To safely perform the mission, analysis was needed to define the necessary command inputs, monitor the resulting mass transfer in real time in order to confirm an acceptable amount of mass transfer, and to protect intermediate fluid volumes from being overfilled
- Major analysis campaign – included integrated active/passive thermal, two-phase thermodynamics, real time data acquisition & reduction, and compressible gas equilibrium analysis

Background

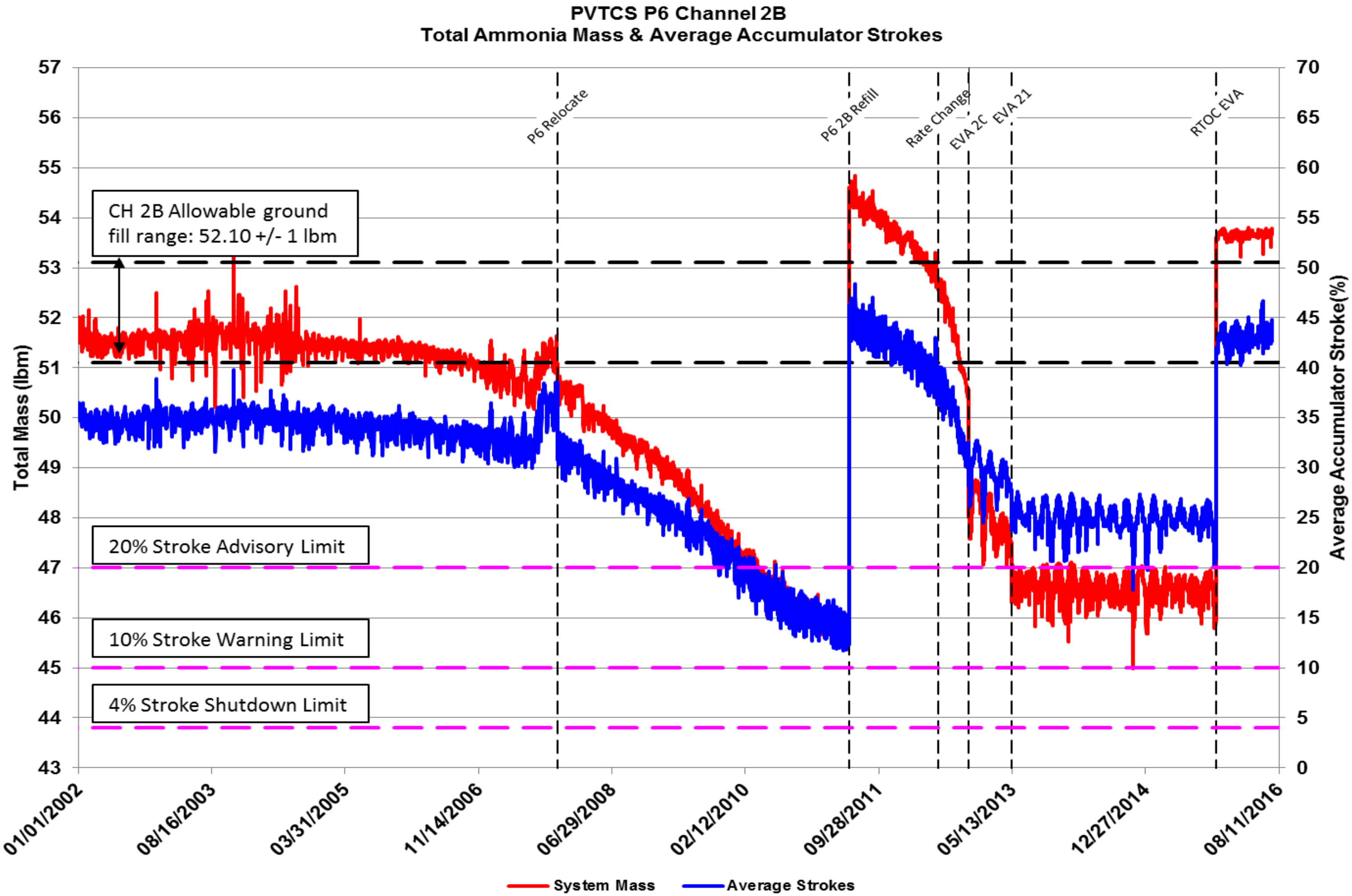


Figure 1: PVTCS P6 Channel 2B Mass and Accumulator Strokes

ISS Physical Overview

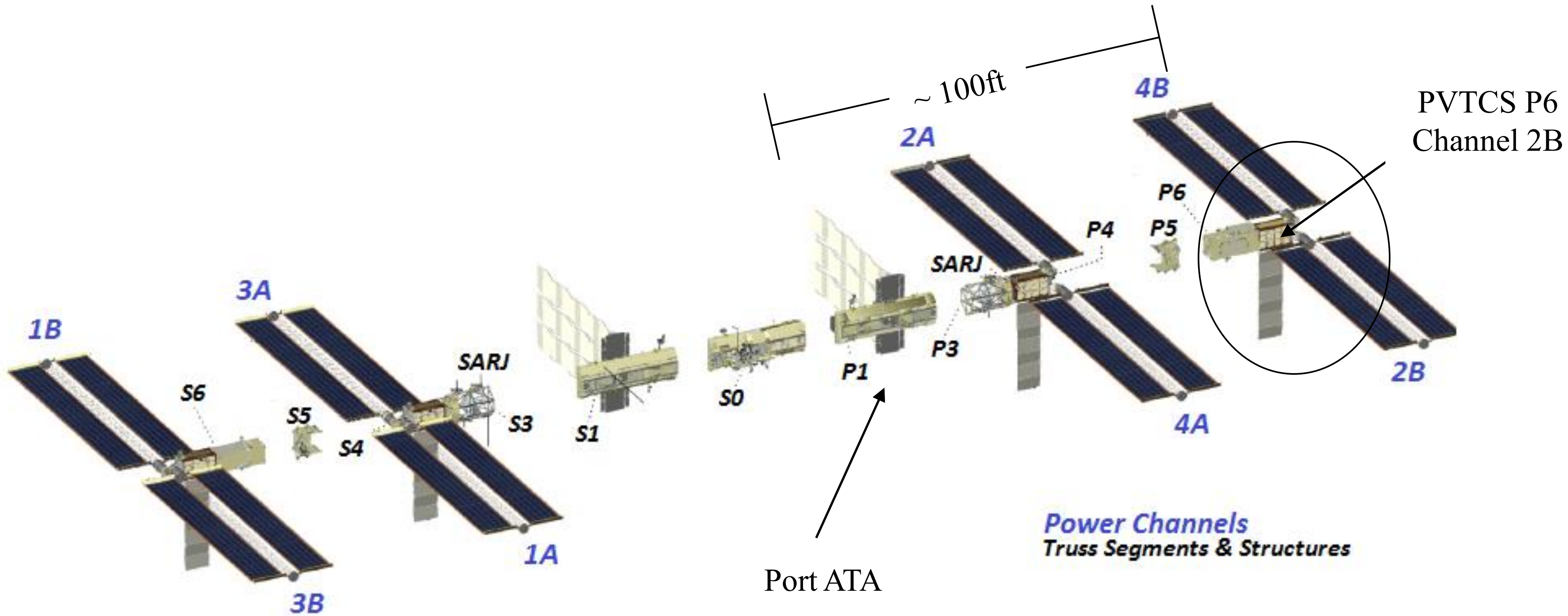


Figure 2: ISS Truss Segments

PVTCS Configurations

- Nominal configuration of the PVTCS P6 Channel 2B is an active pump providing cooling to electronic hardware, and rejecting heat to a deployable radiator

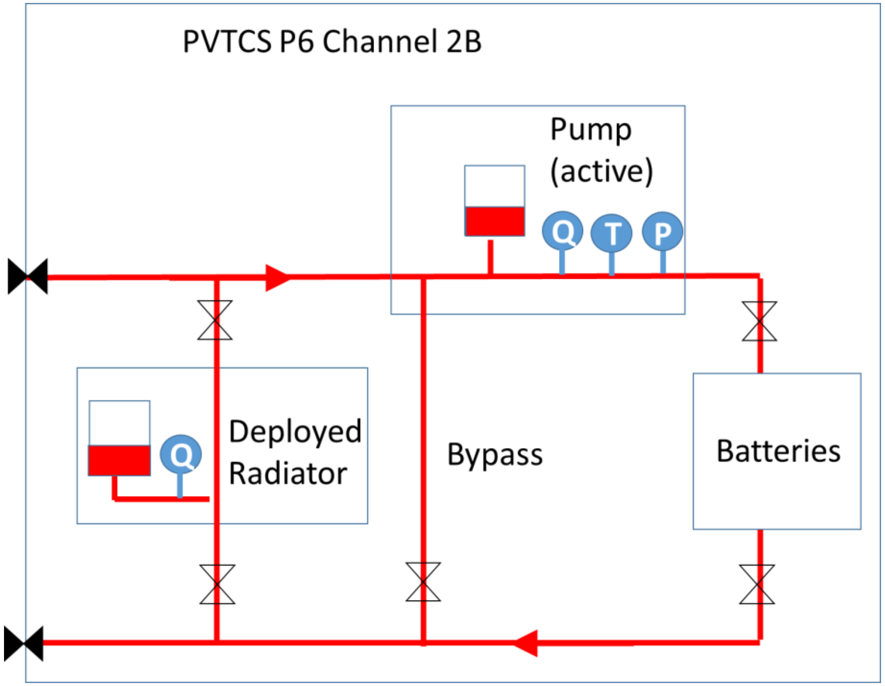
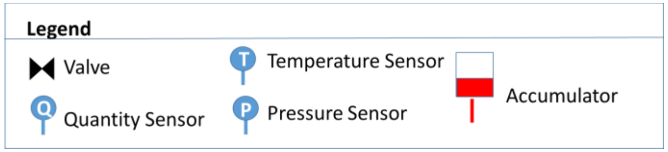


Figure 3: PVTCS P6 Channel 2B Simplified Schematic



PVTCS Configurations

- Upon discovery of a PVTCS P6 Channel 2B leak, the PVTCS P6 Channel 2B deployed radiator was isolated, and the rest of the system was integrated with the dormant (nominally stagnant) Early External Active Thermal Control System (EETCS) Loop A
  - EETCS Loop A was used to provide cooling during the early stages of the ISS, but was decommissioned in 2007, and its TCS hardware allocated as spares
  - Both radiators are nominally stowed, but one was deployed to support PVTCS P6 Channel 2B in lieu of the isolated radiator
- The integrated PVTCS P6 Channel 2B and EETCS Loop A systems continued to lose coolant slowly until the leak was ultimately located at the PVTCS P6 Channel 2B pump package, and successfully repaired

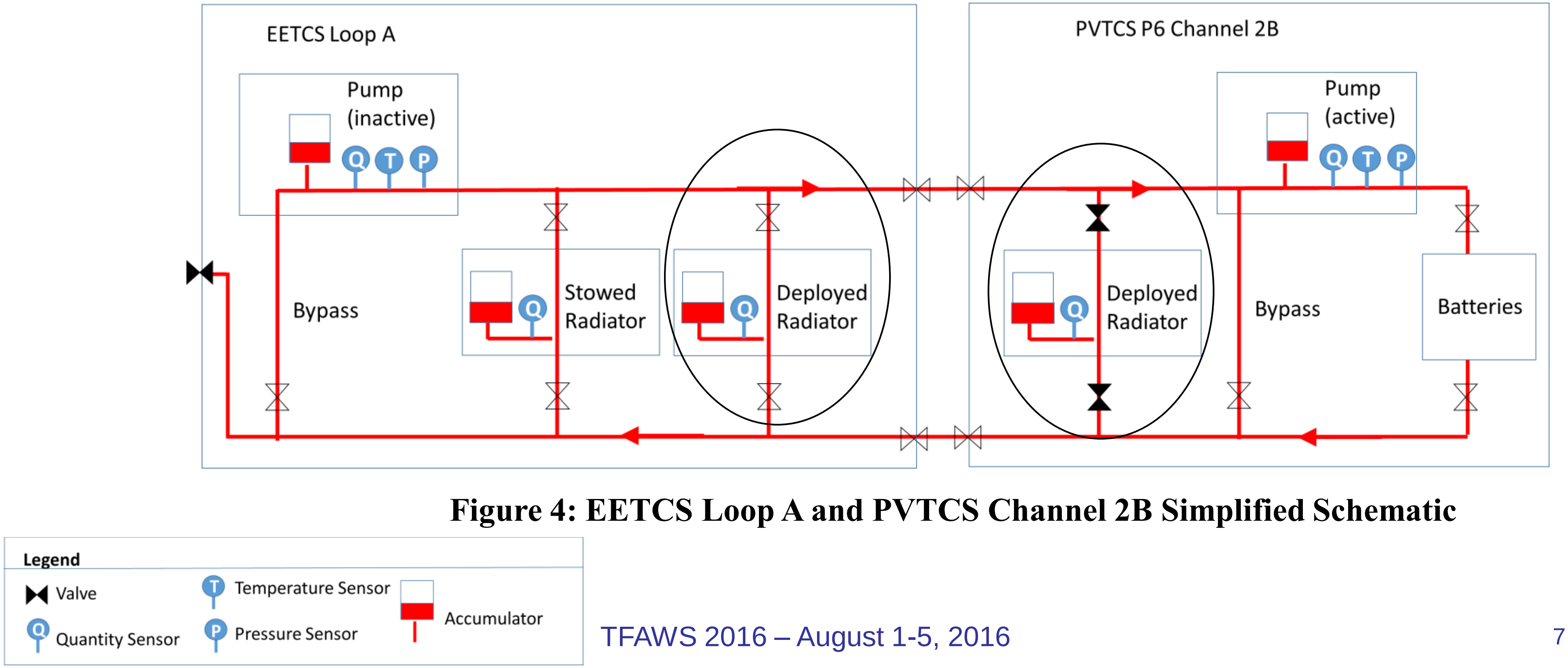


Figure 4: EETCS Loop A and PVTCS Channel 2B Simplified Schematic

PVTCS Configurations

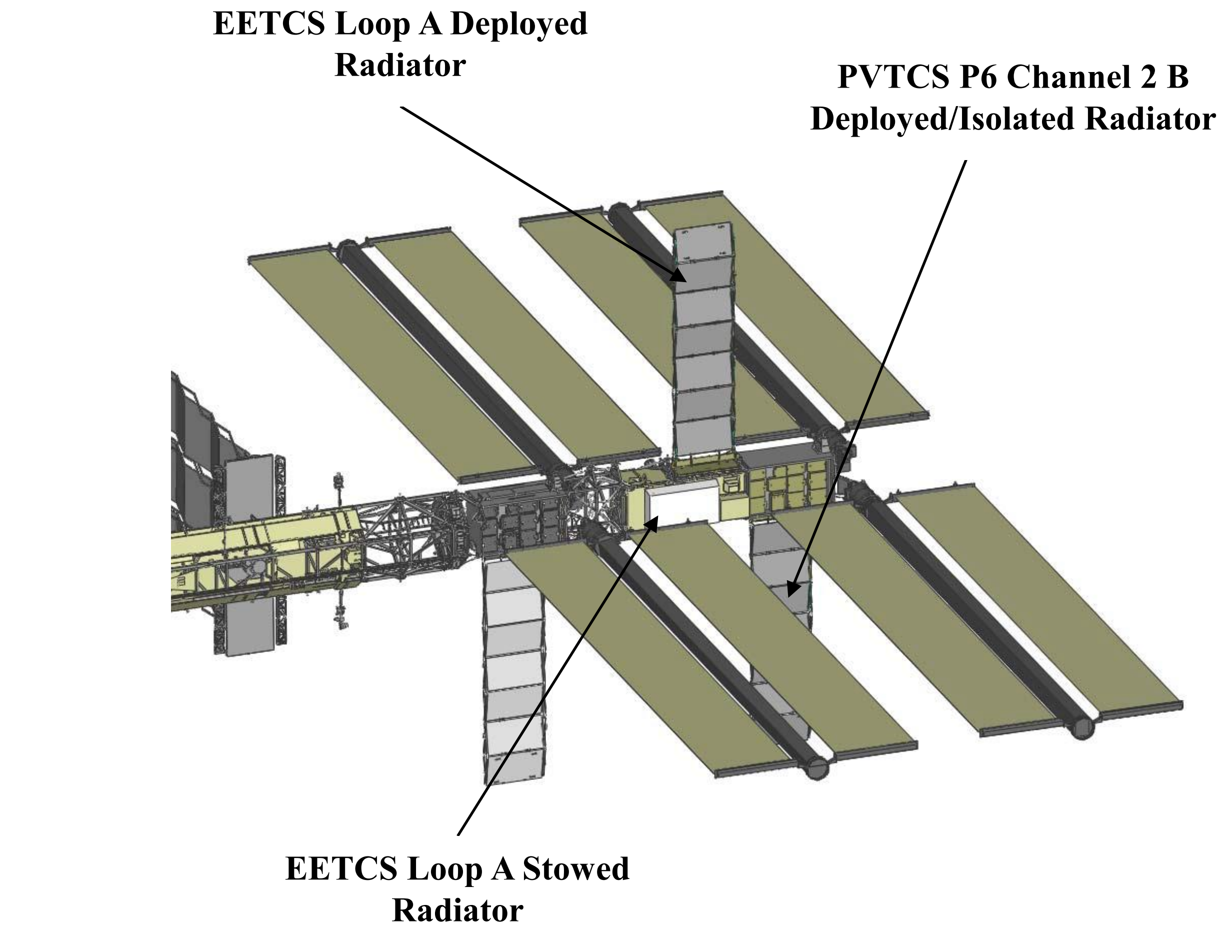


Figure 5: ISS P6 Truss

Coolant Refill Operations Overview

- Refill operations involved the following:
  - Connecting the PVTCS P6 Channel 2B and EETCS Loop A to the Port ATA through the Port 3 (P3) and Port 5 (P5) Truss segment
  - Driving ammonia from the Port ATA to the PVTCS P6 Channel 2B by means of commanded pressure adjustments
  - To ensure a proper refill and optimize EVA time, the EETCS Loop A and PVTCS P6 Channel 2B was overfilled and then backed down to the desired inventory levels

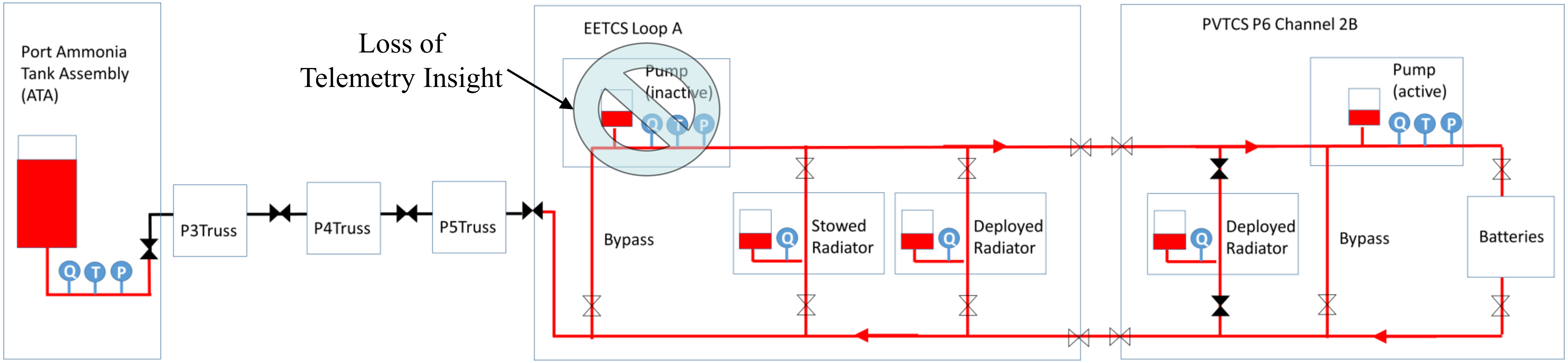
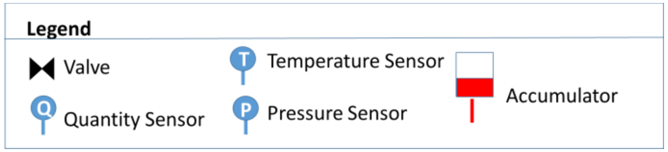


Figure 6: Refill Path and Configuration Prior to Refill



Coolant Refill Operations Overview

- Refill operations involved the following
  1. **Re-integrating the PVTCS P6 Channel 2B deployed radiator**

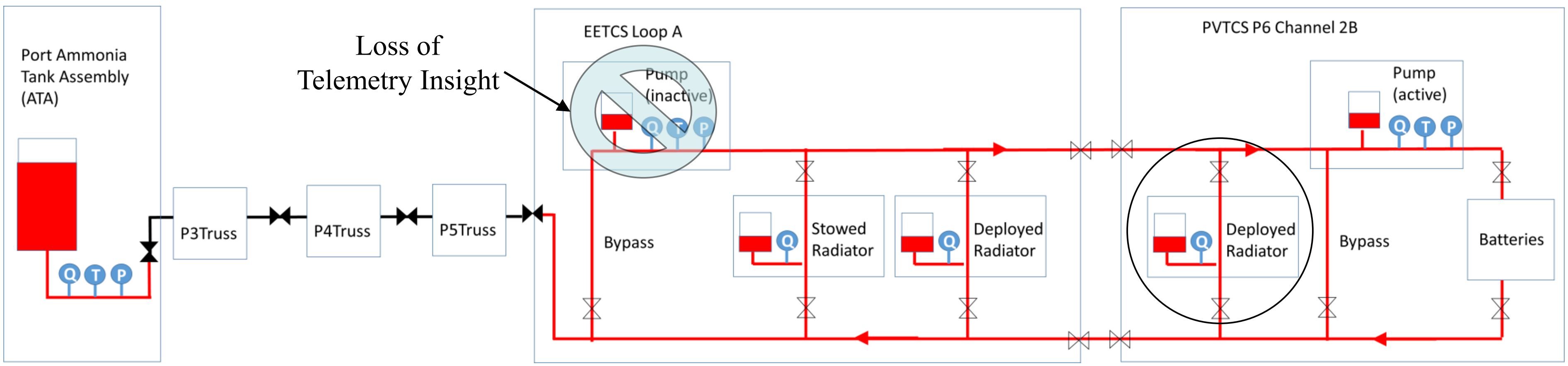
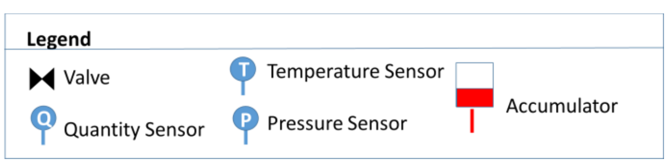


Figure 7: Integrating the Isolated PVTCS Radiator



- Refill operations involved the following
  1. Re-integrating the PVTCS P6 Channel 2B deployed radiator
  2. **Isolating EETCS Loop A from PVTCS P6 Channel 2B**

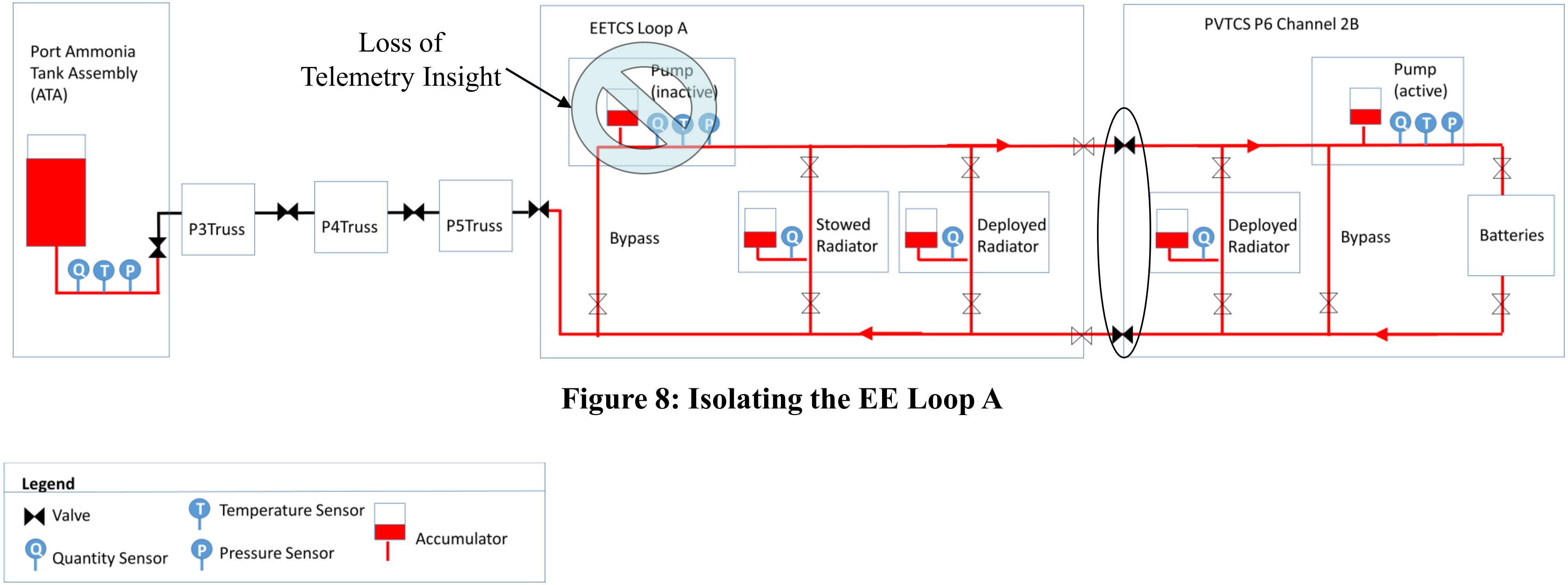


Figure 8: Isolating the EE Loop A

Coolant Refill Operations Overview

- Refill operations involved the following
  1. Re-integrating the PVTCS P6 Channel 2B deployed radiator
  2. Isolating EETCS Loop A from PVTCS P6 Channel 2B
  3. **Filling the plumbing through P1-P5 from the Port ATA**

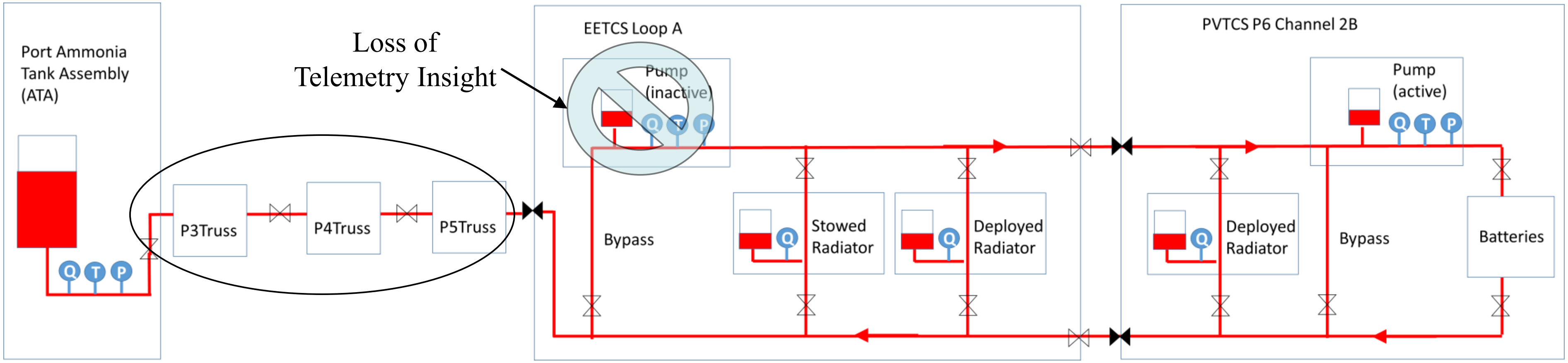
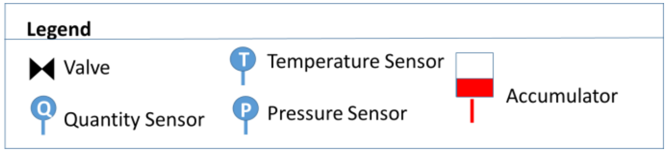


Figure 9: Filling P1-P5 plumbing



Coolant Refill Operations Overview

- Refill operations involved the following
  1. Re-integrating the PVTCS P6 Channel 2B deployed radiator
  2. Isolating EETCS Loop A from PVTCS P6 Channel 2B Filling the plumbing through P1-P5 from the Port ATA
  3. Filling the plumbing through P1-P5 from the Port ATA
  4. **Filling EETCS Loop A**

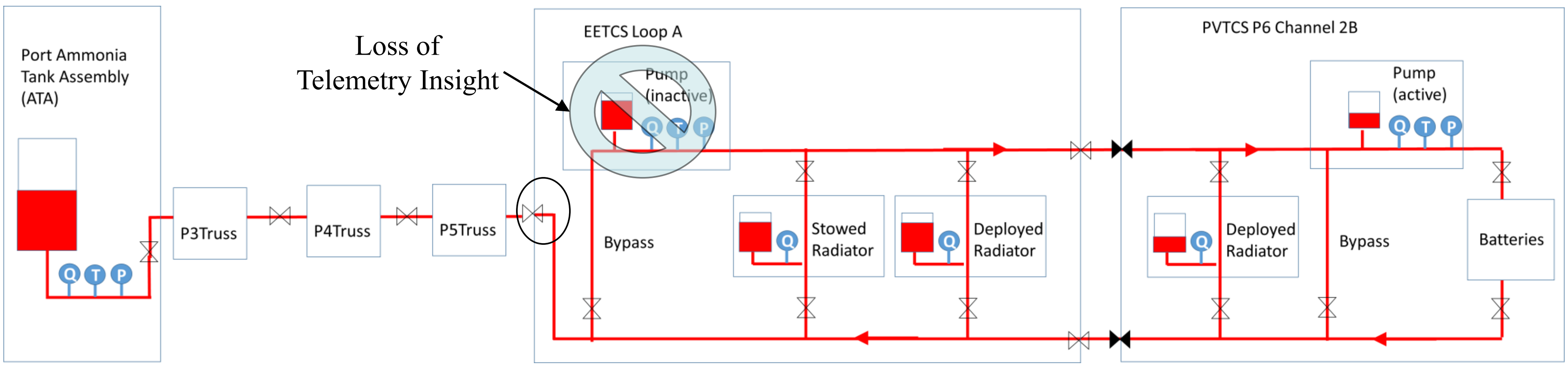
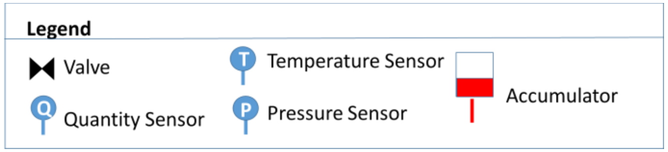


Figure 10: Filling EETCS Loop A



Coolant Refill Operations Overview

- Refill operations involved the following
  1. Re-integrating the PVTCS P6 Channel 2B deployed radiator
  2. Isolating EETCS Loop A from PVTCS P6 Channel 2B Filling the plumbing through P1-P5 from the Port ATA
  3. Filling the plumbing through P1-P5 from the Port ATA
  4. Filling EETCS Loop A
  5. **Initially overfilling the PVTCS P6 Channel 2B**

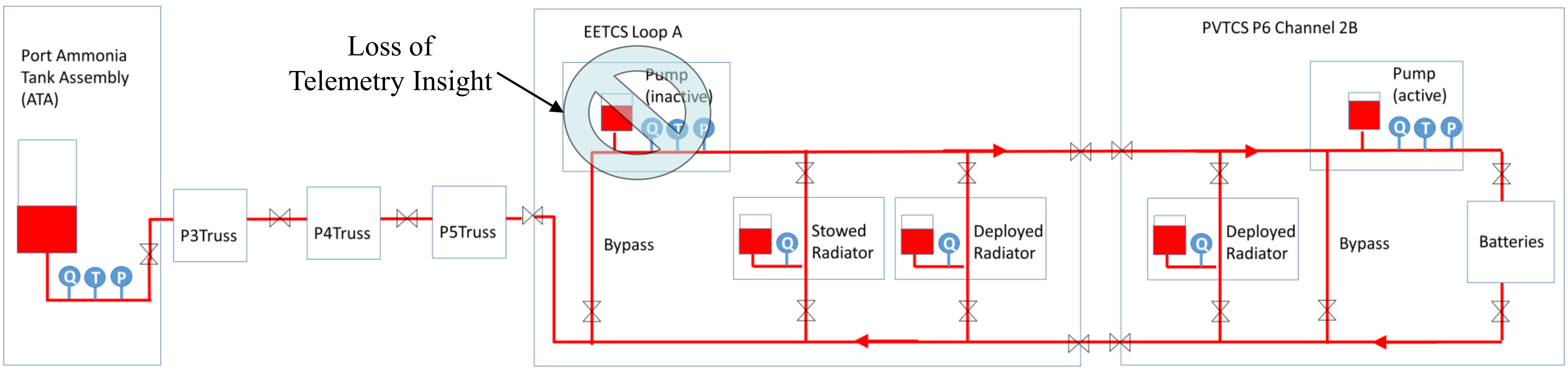
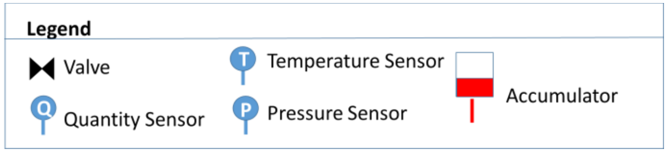


Figure 11: Initial PVTCS fill



Coolant Refill Operations Overview

- Refill operations involved the following
  1. Re-integrating the PVTCS P6 Channel 2B deployed radiator
  2. Isolating EETCS Loop A from PVTCS P6 Channel 2B
  3. Filling the plumbing through P1-P5 from the Port ATA
  4. Filling EETCS Loop A
  5. Initial overfill of the PVTCS P6 Channel 2B
  6. **Backing down the PVTCS P6 Channel 2B to desired inventory levels**

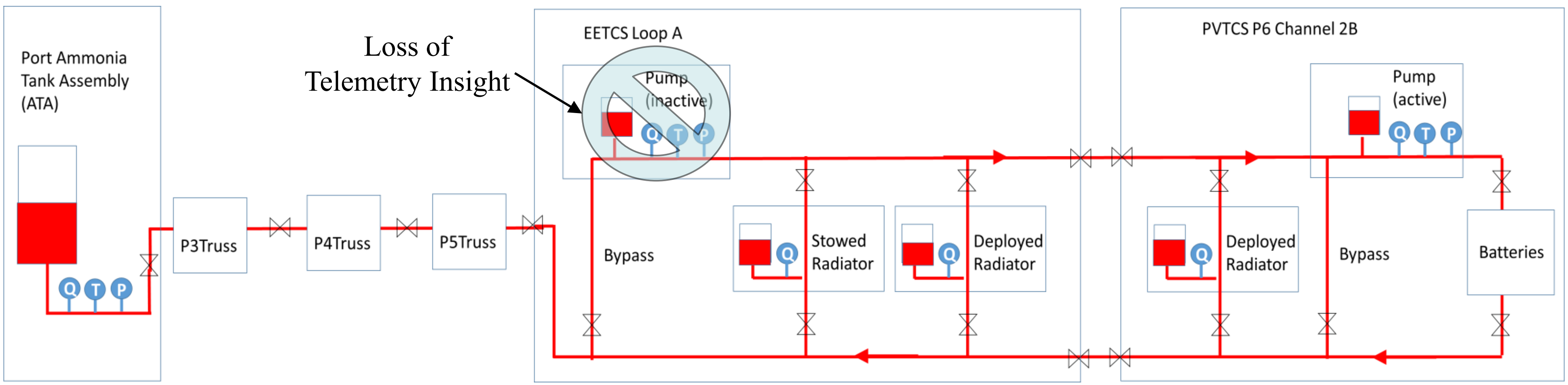
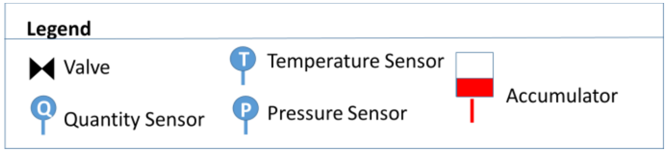


Figure 12: Backing Down inventory of the PVTCS



Coolant Refill Operations Overview

- Refill operations involved the following
  1. Re-integrating the PVTCS P6 Channel 2B deployed radiator
  2. Isolating EETCS Loop A from PVTCS P6 Channel 2B
  3. Filling the plumbing through P1-P5 from the Port ATA
  4. Filling EETCS Loop A
  5. Initial overfill of the PVTCS P6 Channel 2B
  6. Backing down the PVTCS P6 Channel 2B to desired inventory levels
  7. **Backing down the EETCS, if necessary**

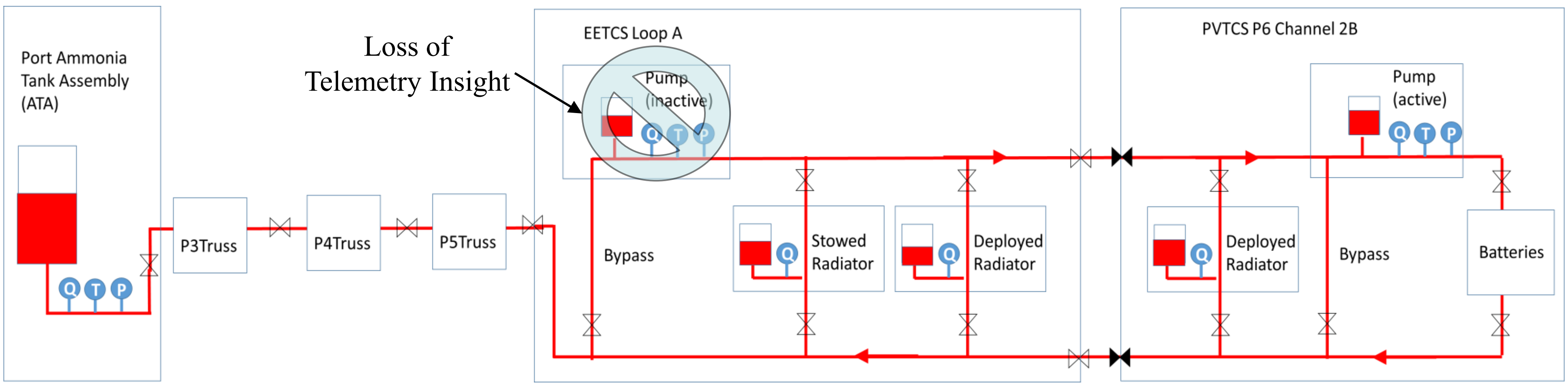
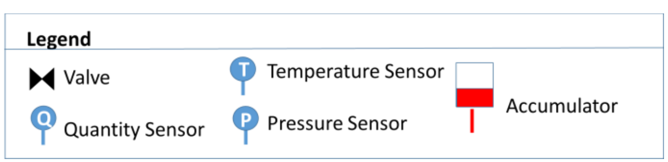


Figure 12: Backing Down inventory of the PVTCS



Coolant Refill Operations Overview

- Refill operations involved the following
  1. Re-integrating the PVTCS P6 Channel 2B deployed radiator
  2. Isolating EETCS Loop A from PVTCS P6 Channel 2B
  3. Filling the plumbing through P1-P5 from the Port ATA
  4. Filling EETCS Loop A
  5. Initial overfill of the PVTCS P6 Channel 2B
  6. Backing down the PVTCS P6 Channel 2B to desired inventory levels
  7. Backing down the EETCS
  8. **Venting the P1-P5 plumbing, Retracting EETCS Loop A Deployed Radiator (not completed) and isolating each system**

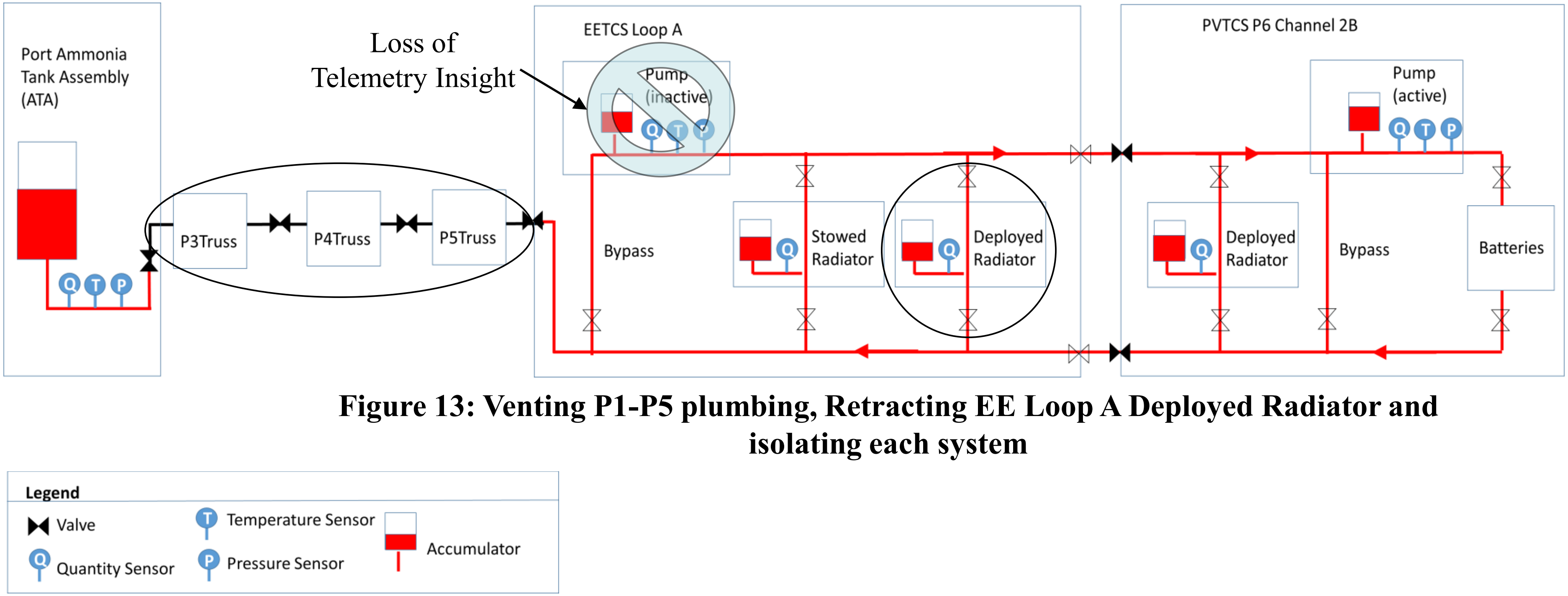


Figure 13: Venting P1-P5 plumbing, Retracting EE Loop A Deployed Radiator and isolating each system

Analysis Methods, Constraints, Assumptions & Results

- Analysis
  1. Determined the initial Port ATA pressure to fill the P1-P5 plumbing, EETCS Loop A and overfilling PVTCS P6 Channel 2B
     - Final Port ATA pressure to back down the PVTCS P6 Channel 2B to desired inventory levels was determined using a real-time tool
  2. Determined ammonia vent times and thrust of the P1-P5 plumbing after the refill is complete

- Constraints
  - Cannot overfill EETCS Loop A or PVTCS P6 Channel 2B system after the refill operations is complete to protect for over-pressurization
    - No pressure relief capability for either system
    - PVTCS Maximum Operating Pressure (MOP) = 240 psia (1655 kPa)
    - EETCS Maximum Design Pressure (MDP) = 586 psia (4061 kPa)
  - An underfill will result in reduced margin and may drive a future refill if a new leak is determined

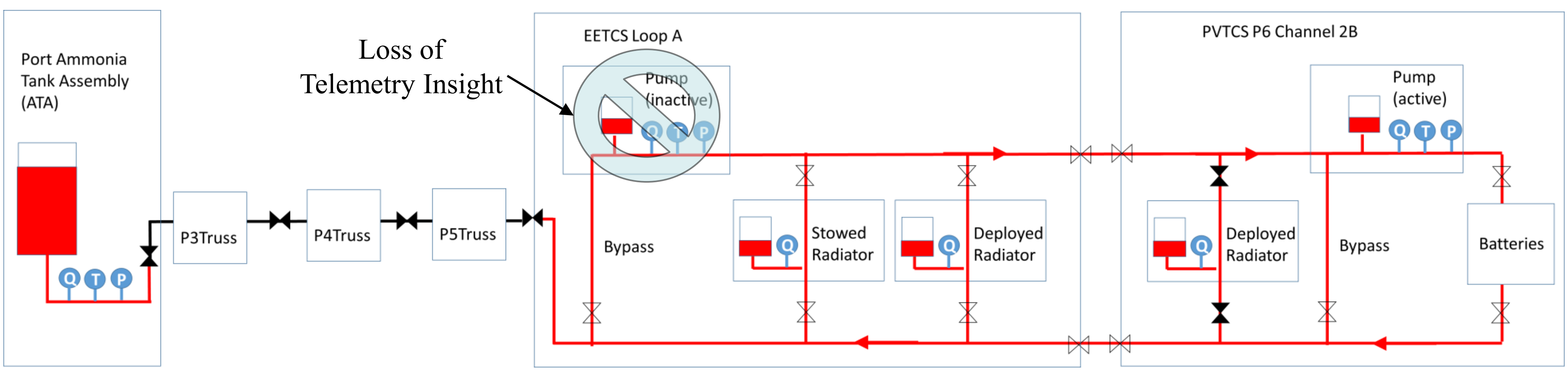
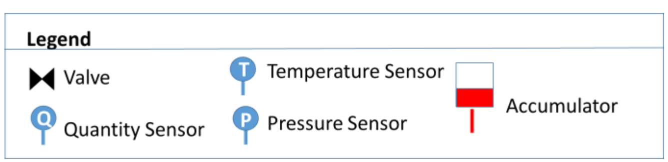


Figure 14: Configuration Prior to Refill



Analysis Methods, Constraints, Assumptions & Results

- Determined the initial Port ATA pressure to fill the P1-P5 plumbing, EETCS Loop A and overfilling PVTCS P6 Channel 2B
    1. Calculated the initial conditions (temperature, pressure and mass) due to the various configuration changes (i.e. re-integrating the PVTCS P6 Channel 2B Deployable Radiator) and orbital cycles

- Modeling
    - Sinda/Trasys to predict worst case initial temperatures
    - Sinda/Fluint to predict mass and pressure swings

- Assumptions
    - Single phase, incompressible liquid ammonia
    - No ammonia leaks
    - EETCS Loop A is isobaric while stagnant

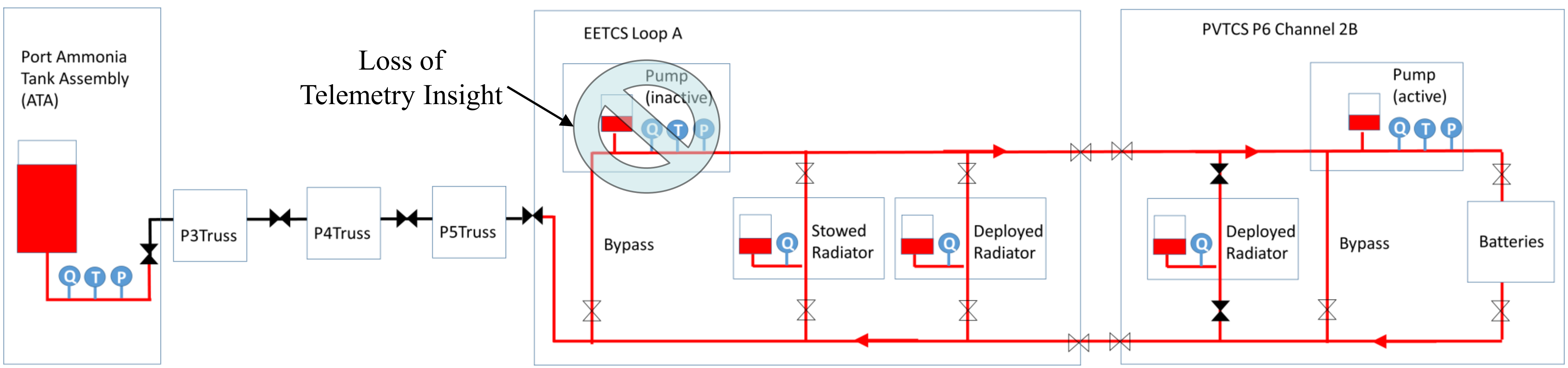
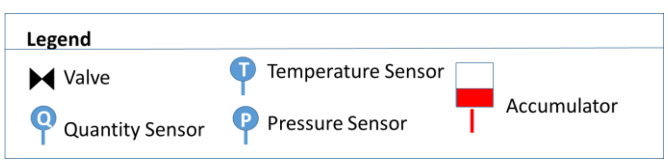


Figure 15: Configuration Prior to Refill



Analysis Methods, Constraints, Assumptions & Results

- Determined the initial Port ATA pressure to fill the P1-P5 plumbing, EETCS Loop A and overfilling PVTCS P6 Channel 2B
  1. Calculated the initial conditions (temperature, pressure and mass) due to the various configuration changes (i.e. re-integrating the PVTCS P6 Channel 2B Deployable Radiator) and orbital cycles
  2. **Calculated the final pressure to overfill the PVTCS P6 Channel 2B system**

- Modeling
  - Input initial conditions into a PVTCS thermal/hydraulic model to calculate the final system pressure

- Assumptions
  - Single phase, incompressible liquid ammonia
  - No ammonia leaks

- Results
  - Final pressure of the PVTCS P6 Channel 2B = 165 psia (1140 kPa)

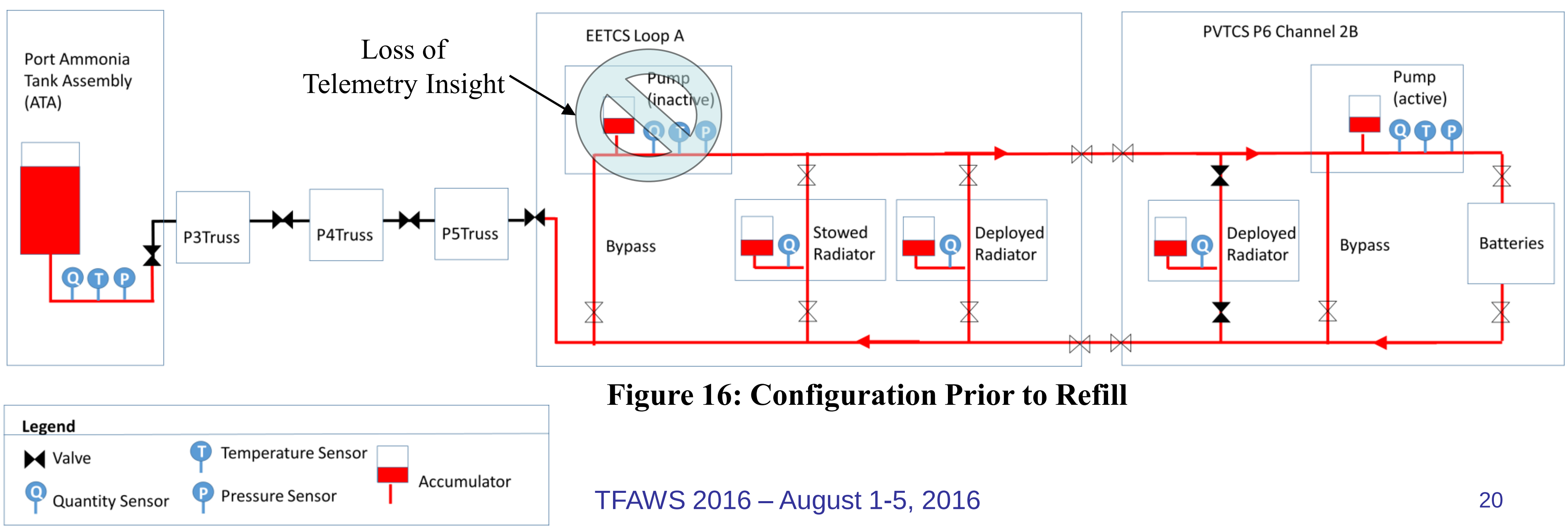


Figure 16: Configuration Prior to Refill

Analysis Methods, Constraints, Assumptions & Results

- Determined the initial Port ATA pressure to fill the P1-P5 plumbing, EETCS Loop A and overfill PVTCS P6 Channel 2B
  1. Calculated the initial conditions (temperature, pressure and mass) due to the various configuration changes (i.e. re-integrating the PVTCS P6 Channel 2B Deployable Radiator) and orbital cycles
  2. Calculated the final pressure to overfill the PVTCS P6 Channel 2B system
  3. **Calculated the initial Port ATA pressure**
- Modeling
  - Thermal/hydraulic to predict the total NH3 mass transferred needed during the fill
  - Port ATA initial conditions determined from historical telemetry
  - The initial Port ATA pressure can be determined using Ideal Gas Law relations
- Assumptions
  - Single phase, incompressible liquid ammonia
  - No ammonia leaks
  - Mass in the EETCS Loop A Pump is approximated based on historical telemetry (lost telemetry insight on 5/26/2014)
  - EETCS Loop A is isobaric while stagnant
- Results
  - Initial Port ATA pressure = 197 psia (1358 kPa)

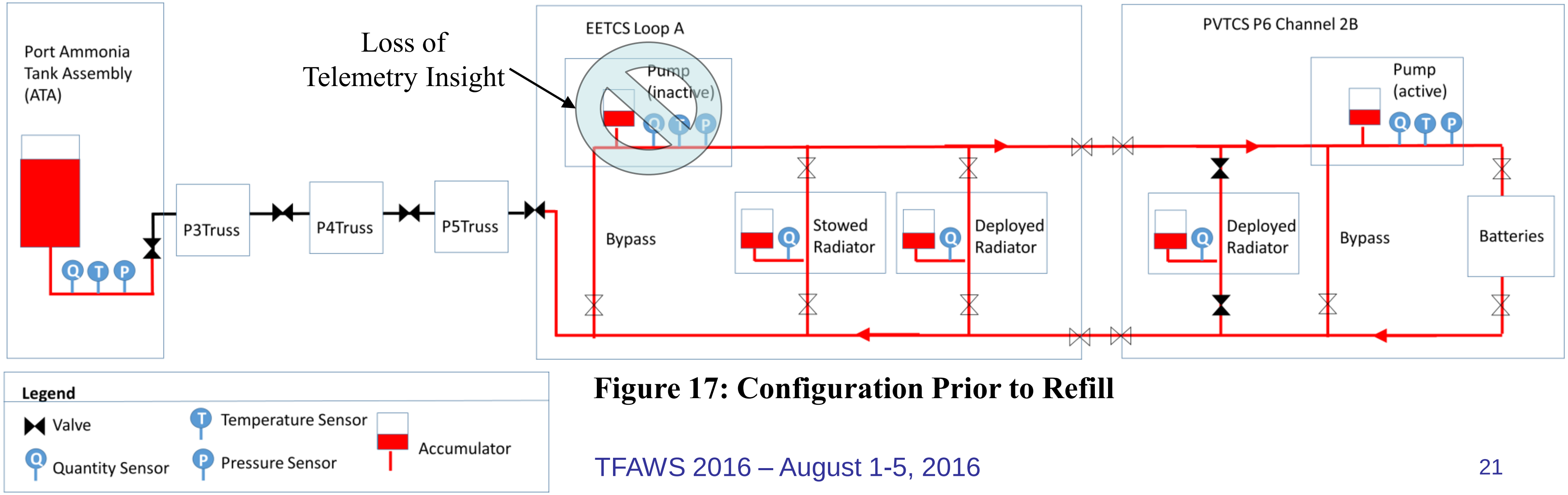


Figure 17: Configuration Prior to Refill

Analysis Methods, Constraints, Assumptions & Results

- Determined ammonia vent times and thrust for venting the P1-P5 plumbing post refill
- Modeling
  - Sinda/Trasys to predict worst case temperatures post the refill (no telemetry insight of P1-P5 plumbing)
  - P1-P5 plumbing was modeled as a single lumped reservoir using a thermal/hydraulic model
- Assumptions
  - Reservoir is isentropic
    - No heat transfer so as the pressure decreases the temperature decreases to maintain constant entropy
  - Ammonia vents through a pipe without heat transfer or friction directly to space
    - Liquid/vapor interface at the exit of the vent tool
    - Pressure of the liquid decreases as the ammonia is exhausted (vented)
      - Once the reservoir reaches saturation, the vent continues as a gaseous fluid
  - Flow is choked at the exit
- Results
  - Ammonia vent times and thrust is ~17 min and 25 lbf (112 N), respectively

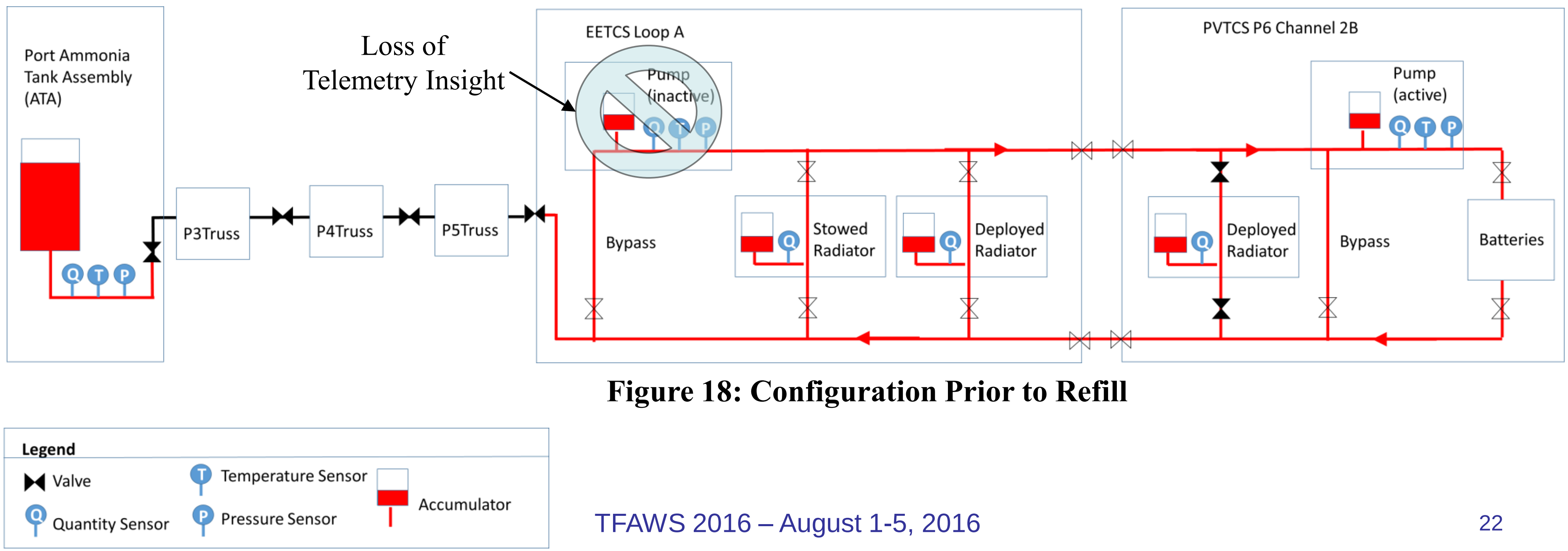


Figure 18: Configuration Prior to Refill

- Constraints
  - It was determined that the maximum allowable PVTCS P6 Channel 2B system mass without over-pressurizing the loop post refill was ~56 lbm (25 kg)
    - Based on a maximum allowable operating pressure (MOP) of 240 psia (1655 kPa) and 93.4 % accumulator stroke upper limit
  - Therefore, ~54 lbm (25 kg) was the desired mass post refill to account for uncertainty
- Modeling
  - Sinda/Trasys to predict worst case temperatures post the refill
  - Thermal/hydraulic model to determine if worst case temperatures could result in the system exceeding ~54 lbm (25 kg)
- Assumptions
  - Single phase, incompressible liquid ammonia
  - No ammonia leaks
- Results
  - Results indicated system would not exceed ~54 lbm (25 kg)

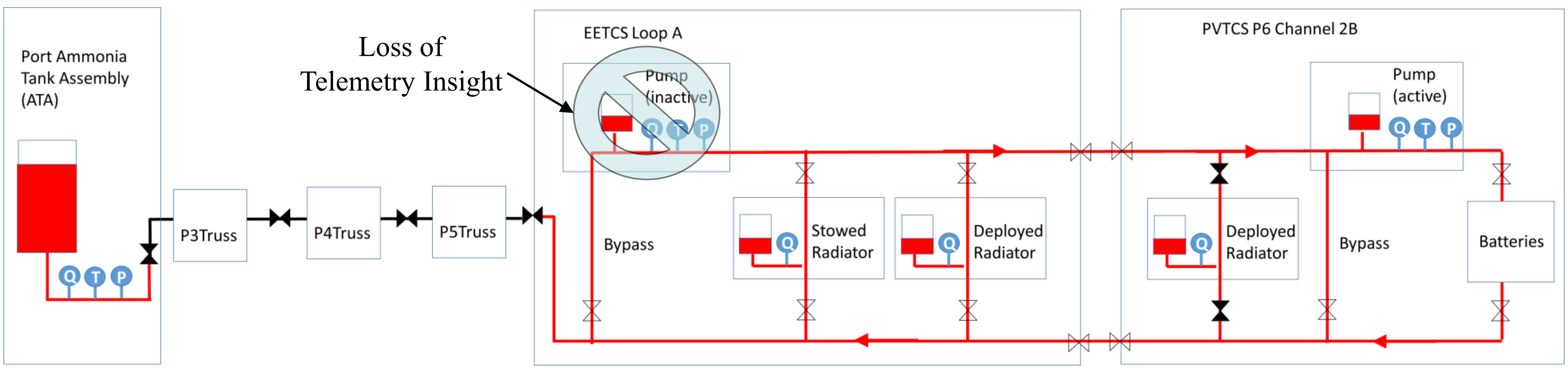
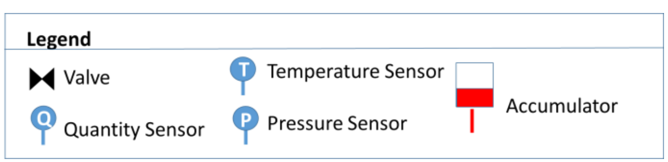


Figure 19: Configuration Prior to Refill



- Constraints
  - It was determined that the maximum allowable EETCS Loop A system mass without over-pressurizing the loop post refill was ~90 lbm (41 kg)
    - Based on a maximum design pressure (MDP) of 589 psia (4061 kPa), 93.4 % accumulator stroke upper limit
- Modeling
  - Sinda/Trasys to predict worst case temperatures during the refill
  - Two-phase thermodynamic model to determine if worst case temperatures could result in the system exceeding ~ 90 lbm (41 kg
    - Model to calculate partial pressure, two-phase vapor formation and final pressures after a bellows tear
- Assumptions
  - Single phase, incompressible liquid ammonia
  - No ammonia leaks
  - EETCS Loop A is isobaric while stagnant
- Results
  - Conditions during the day of the refill could result in EETCS Loop A mass exceeding ~90 lbm (41 kg) limit
  - Operations and procedures were put in place in case we needed to back down the EETCS Loop A mass at the end of the refill

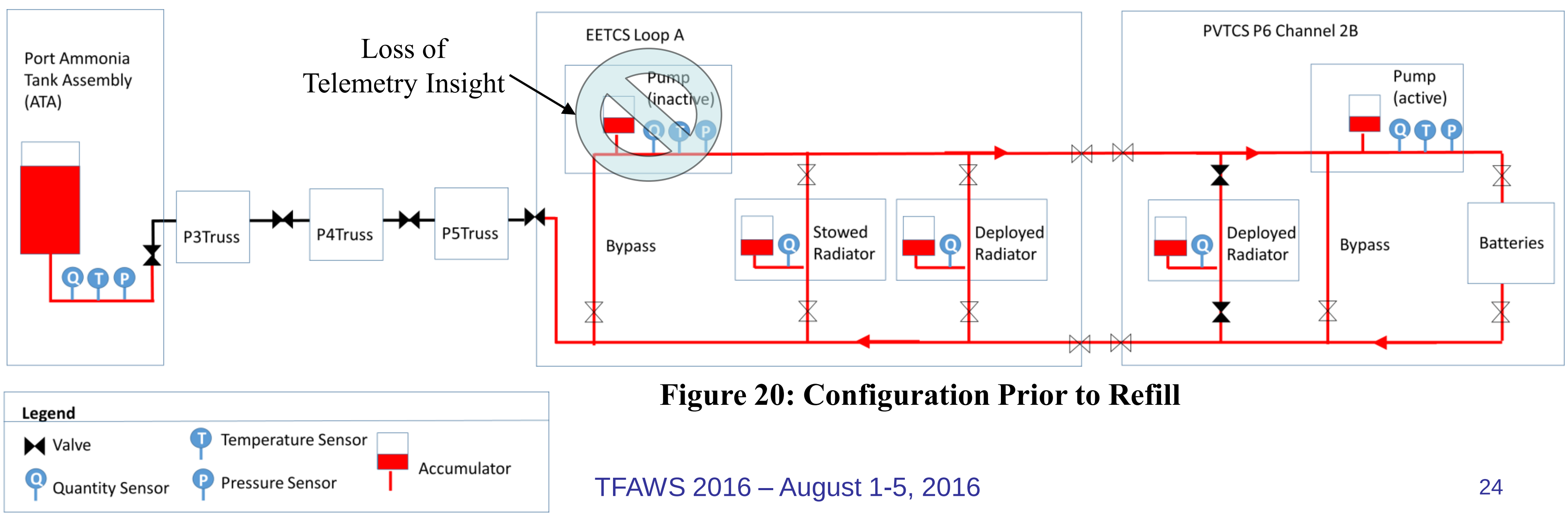
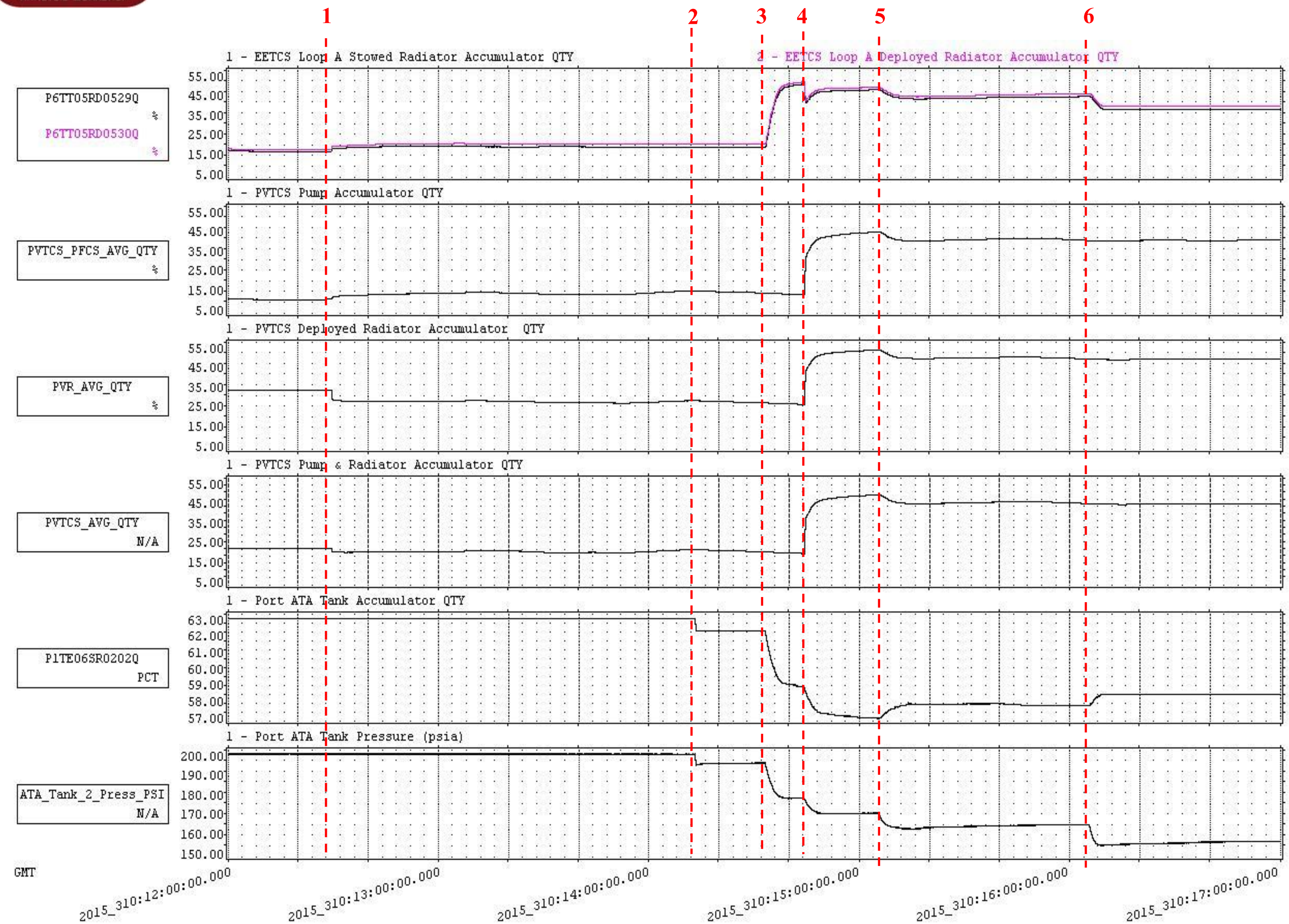


Figure 20: Configuration Prior to Refill

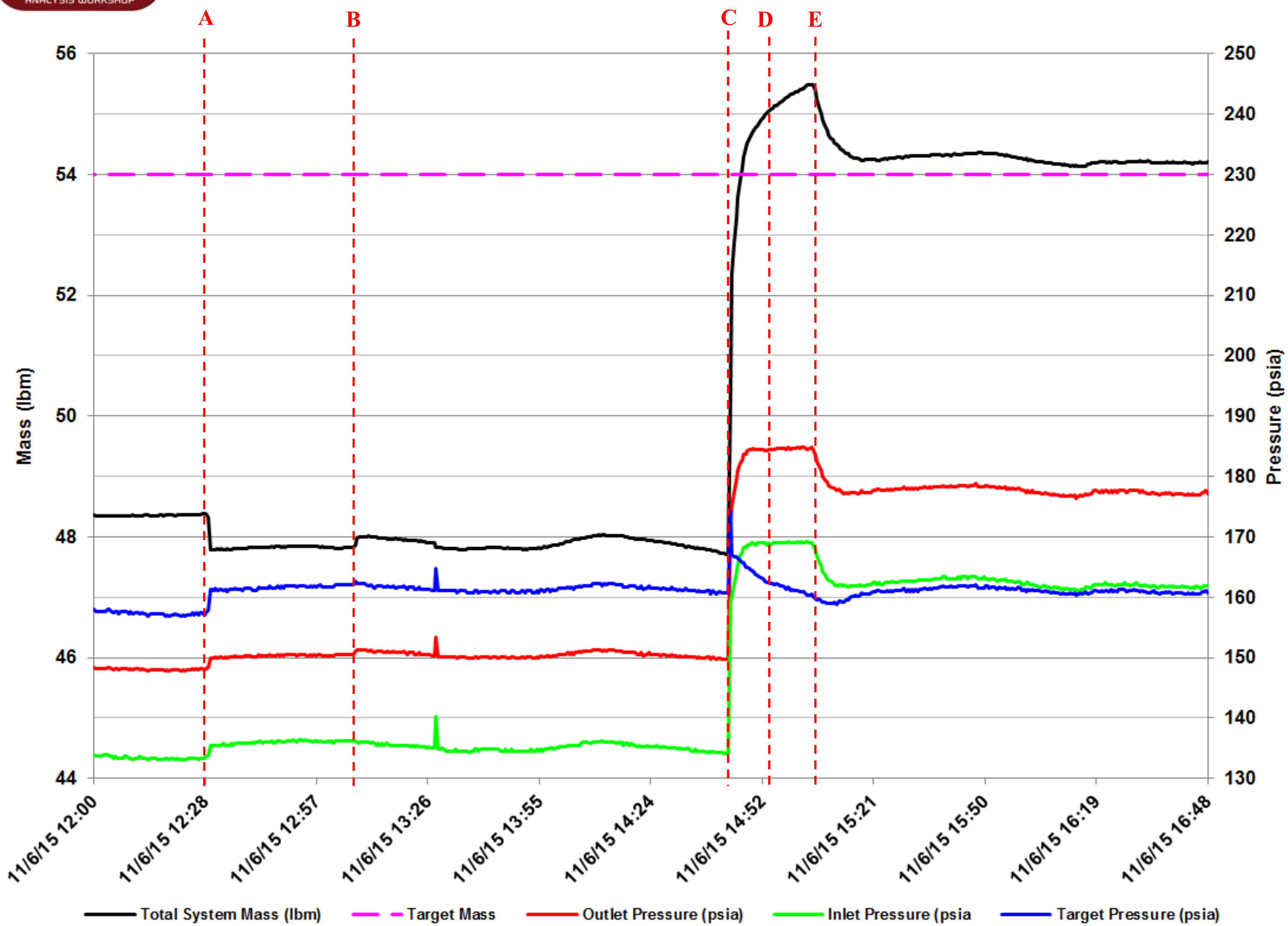
Comparison to On-Orbit Operations



1. **Re-integrating the PVTCS P6 Channel 2B deployed radiator (minimum swing as predicted)**
2. **P1-P5 Fill**
3. **EETCS LpA Fill – Exceeded 90 lbm (41 kg) limit**
4. **Initial PVTCS P6 Channel 2B overfill**
5. **PVTCS P6 Channel 2B backed down to 54 lbm (25kg)**
6. **EETCS LpA backed down below 90 lbm (41 kg)**

Figure 21: Accumulator Quantities and Pressures during the Refill

Comparison to On-Orbit Operations



A. Re-integrating the PVTCS P6 Channel 2B deployed radiator (minimum swing as predicted)

B. PVTCS P6 Channel 2B Isolation

C. Initial PVTCS P6 Channel 2B overfill

D. Real-time calculation determined pressure to back down the system mass to 54 lbm (25 kPa) (pressure close to predictions)

E. PVTCS P6 Channel 2B mass decreased 54 lbm (25 kPa)

Figure 22: PVTCS Mass during the Refill

Summary

- The ISS PVTCS P6 Channel 2B experienced a series of leaks that reduced the coolant (liquid ammonia, NH_3) inventory to below desired levels before the leak could be contained
- On November 6, 2015, a spacewalk, or Extravehicular Activity (EVA), was performed that refilled PVTCS P6 Channel 2B to satisfactory levels
  - Temperature, pressures and masses predictions resulted in a successful refill
- PVTCS P6 Channel 2B is in its original configuration with sufficient coolant (ammonia) inventory
- During the refill, real time data reduction and analysis tools were in place, and used, to detect over-limit mass in EETCS Loop A, and to determine necessary command input to reduce mass to within limits
- The EETCS Loop A deployed radiator was retracted, but due to EVA consumables and time, it was re-deployed, and to be retracted in a future EVA
- P1-P5 plumbing was successfully vented post refill

Backup

Acknowledgments

- Would like to acknowledge the outstanding work of the Flight Operations Directorate (FOD) and Mission Evaluation Room (MER) engineering teams whom's hard work made this EVA and refill successful
  - Particularly the following:
    - The Boeing Company - Houston Active Thermal Control (ATCS) and Passive Thermal Control Systems (PTCS) team
    - FOD - Station Power, Articulation, Thermal, and Analysis (SPARTAN) group
    - NASA - JSC Active Thermal Control System (ATCS) team