
# Liquid Nitrogen Testing of an Integrated Reaction Control System

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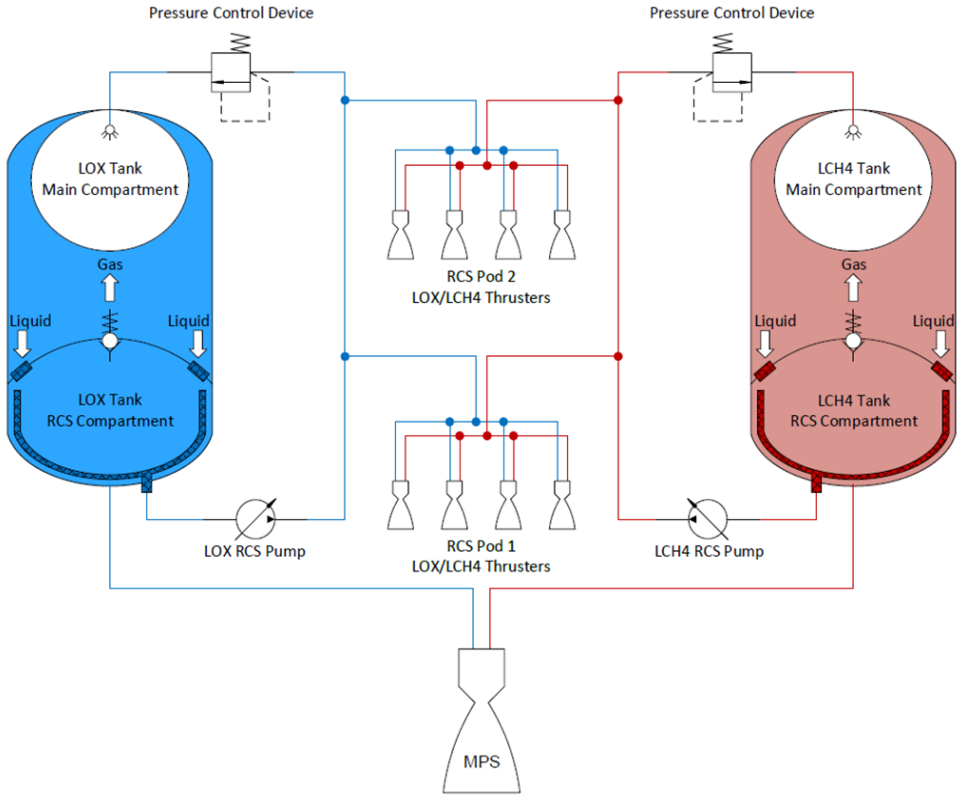
# iRCS Background

- **Integrated Reaction Control System (iRCS) is an innovative concept to utilize MPS propellant for RCS thrusters**
- **Intended to reduce system complexity and potentially reduce attitude control system mass**



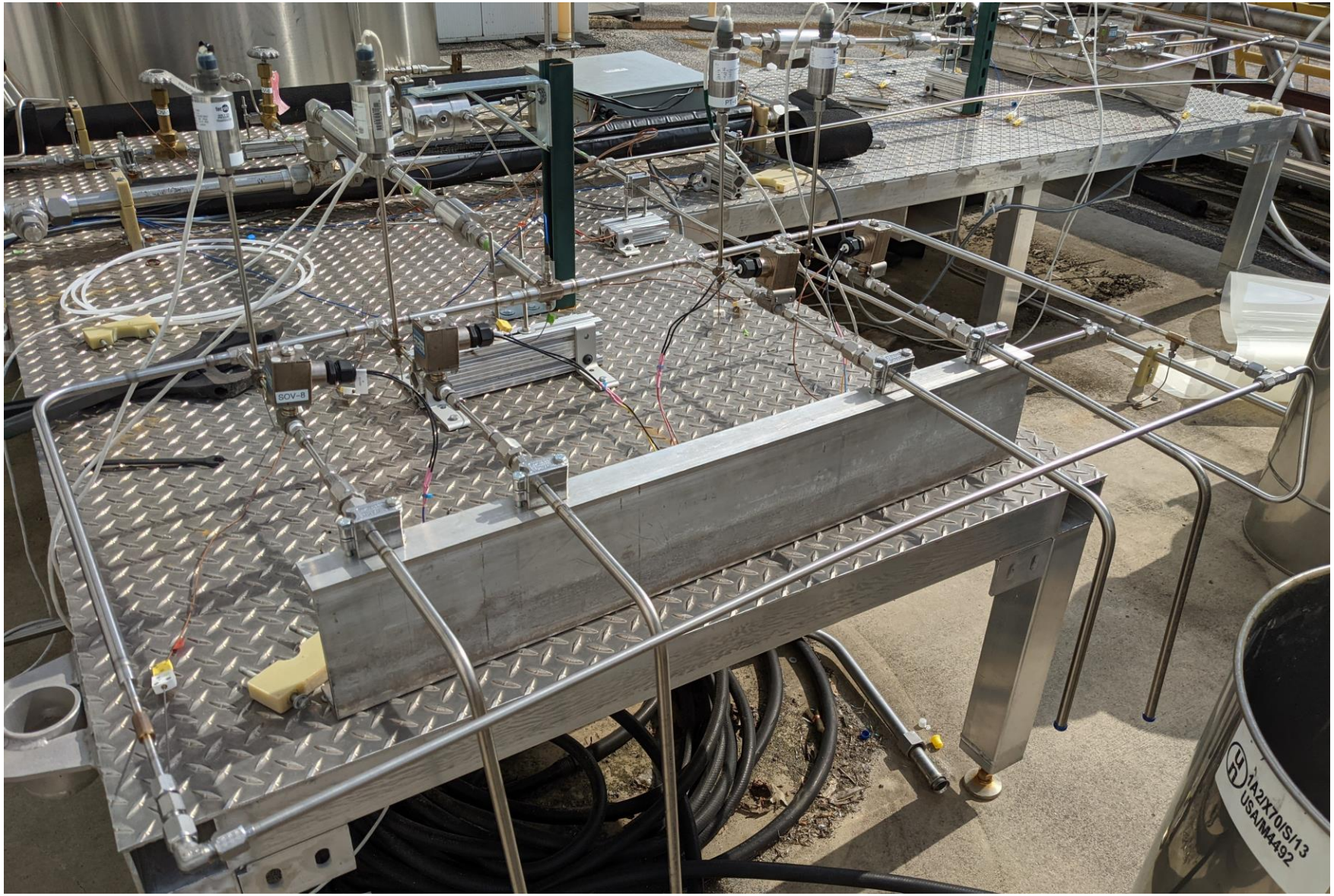
# iRCS Challenges

- **Storage: MPS propellants are stored at pressures well below typical RCS chamber pressure**
- **CFM: additional heat leak during RCS operation into MPS tank**
- **Operational: Cryogenic RCS is not as on-demand as traditional RCS**
  - Requires chilldown of RCS hardware prior to operation

# LN2 Testing

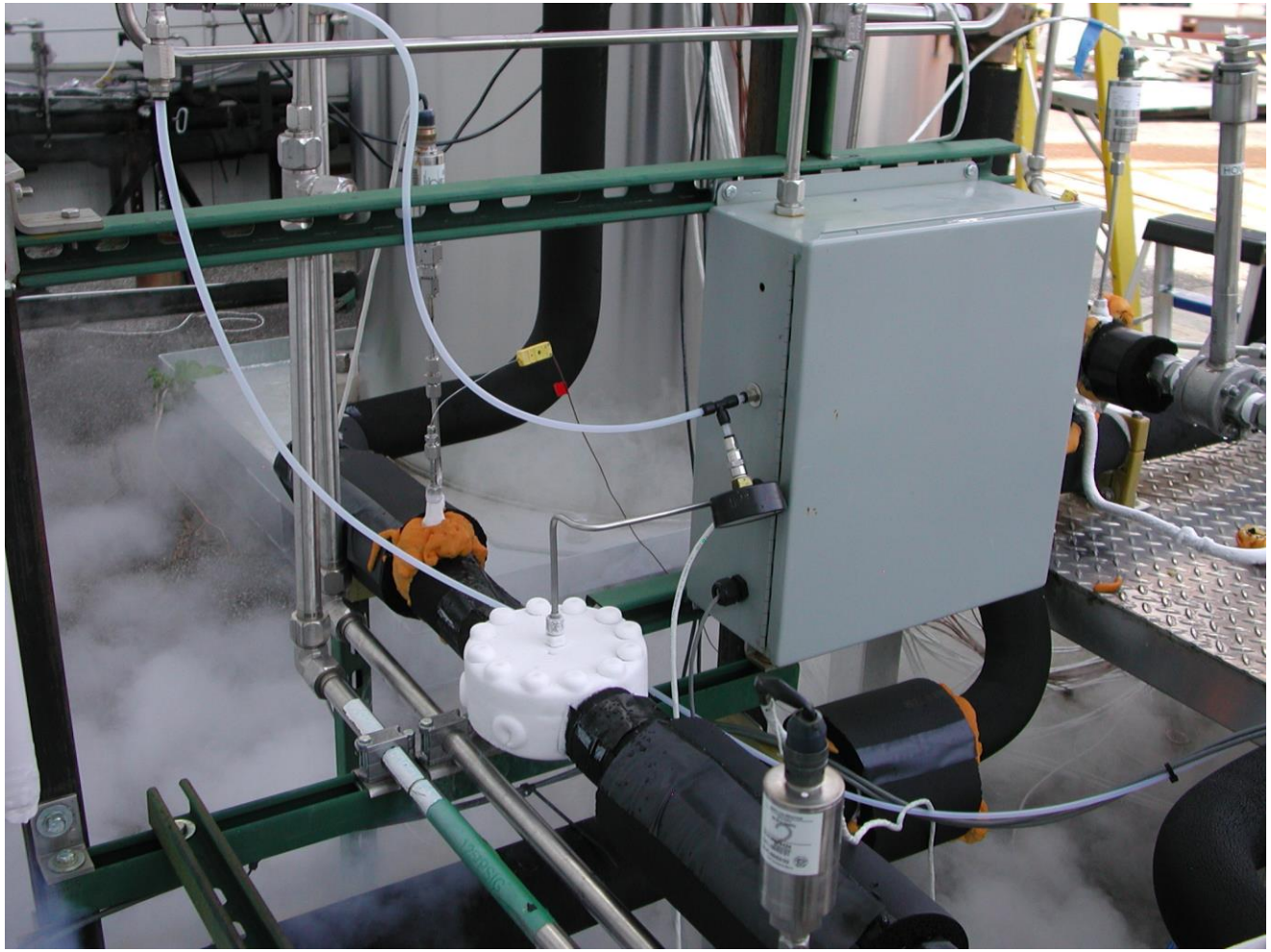
- **iRCS Liquid Nitrogen testbed buildup began in late 2019 in the Propulsion Research Lab in lab 108**
- **CTB2 Tank used as main LN2 supply inside 108**
- **Recirculation loop with “thruster pods” set up outside 108**
- **Buildup on hold due to COVID-19, resumed in January 2021**
- **Test series completed in late August 2021**

# Thruster Pod Before Insulating

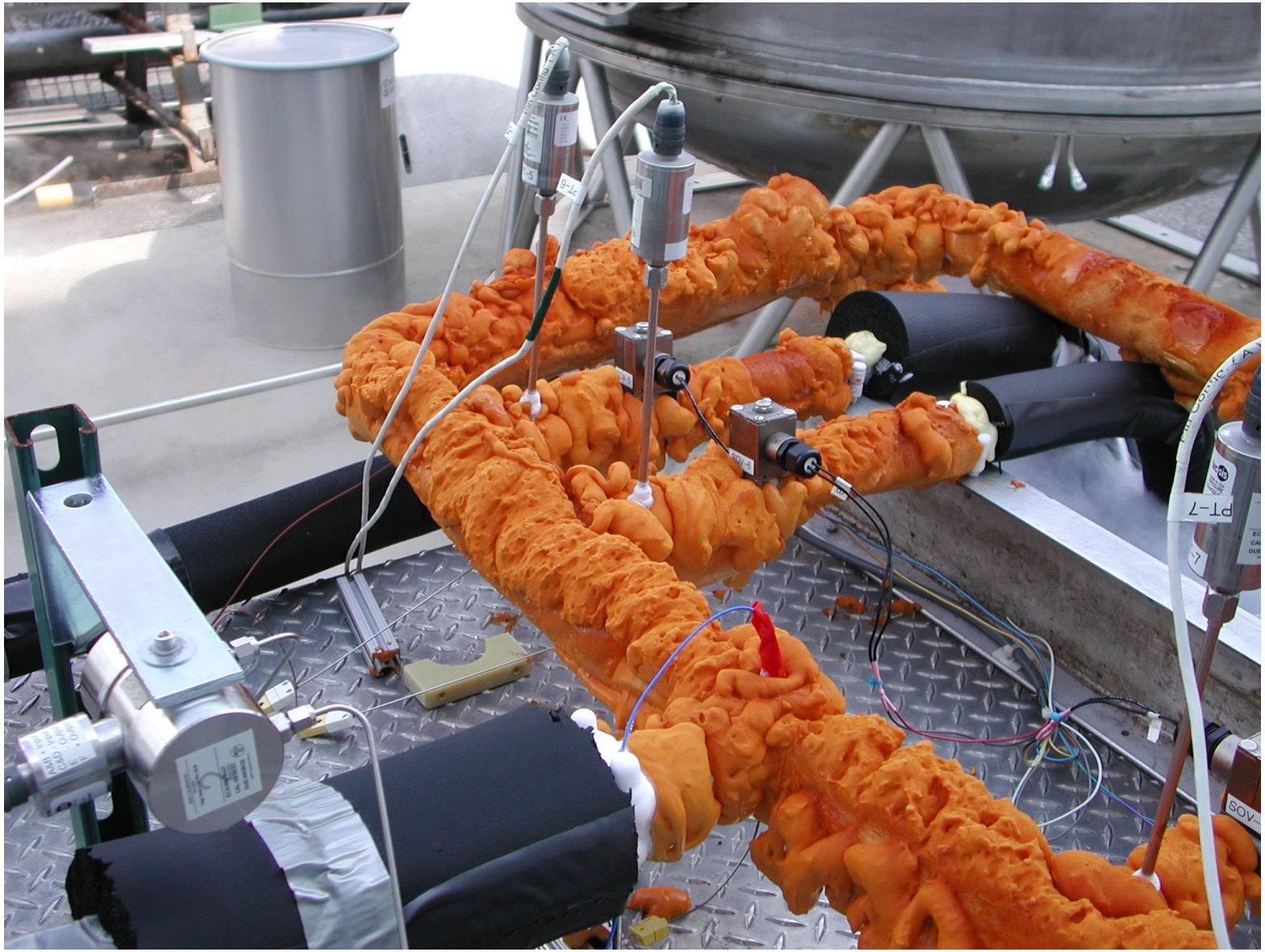


# Test Article Pictures

# Back Pressure Regulator

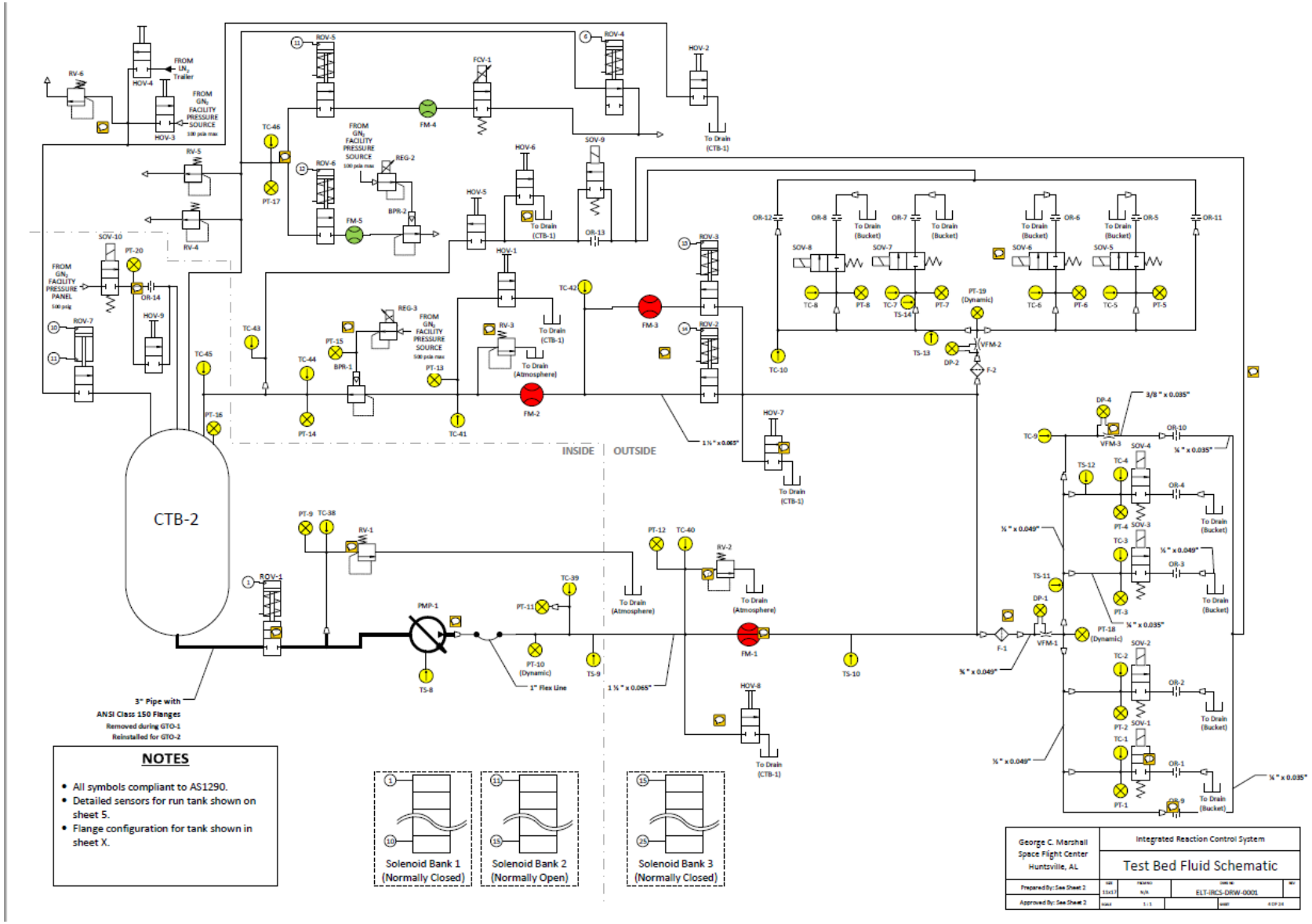


# Thruster Pod Detail



# System During Testing

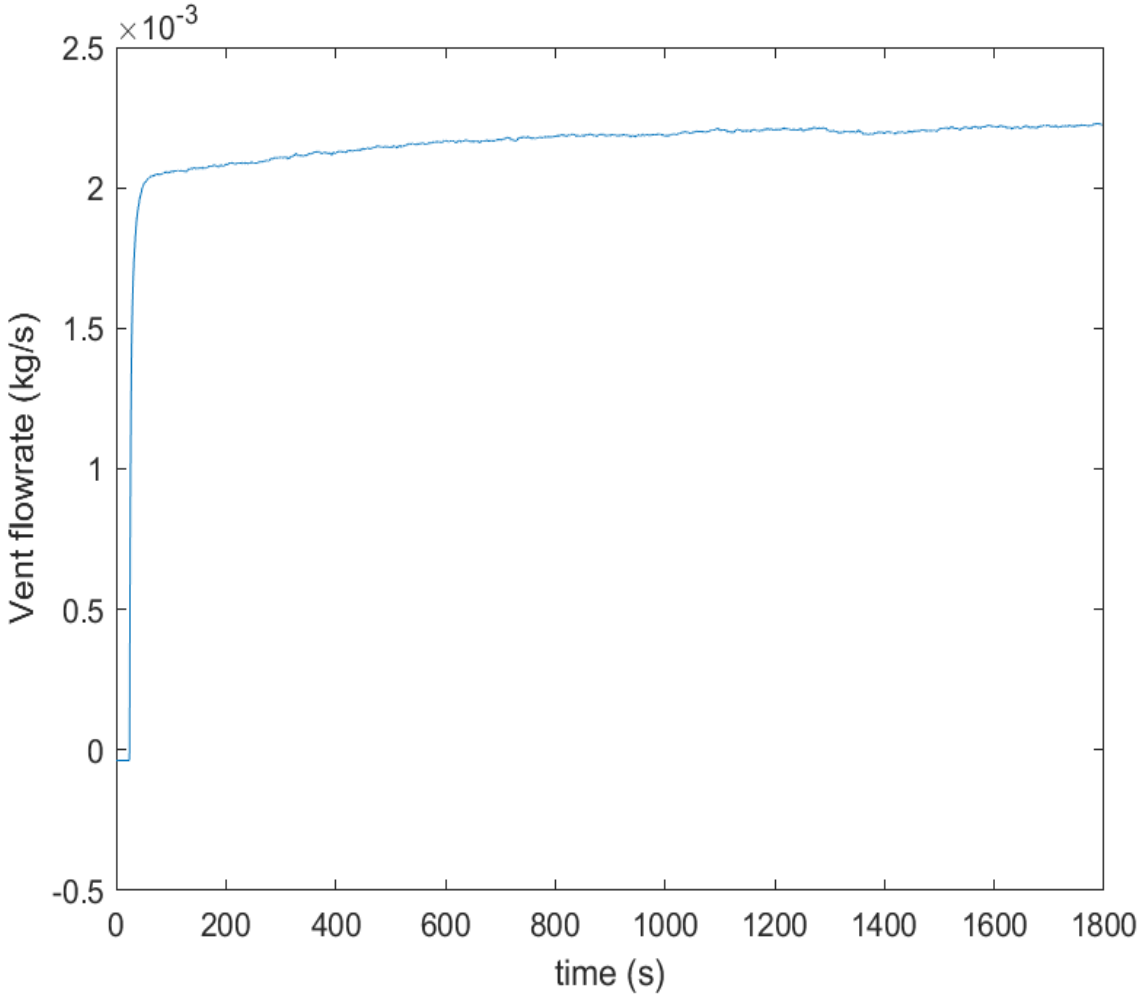
# System Schematic

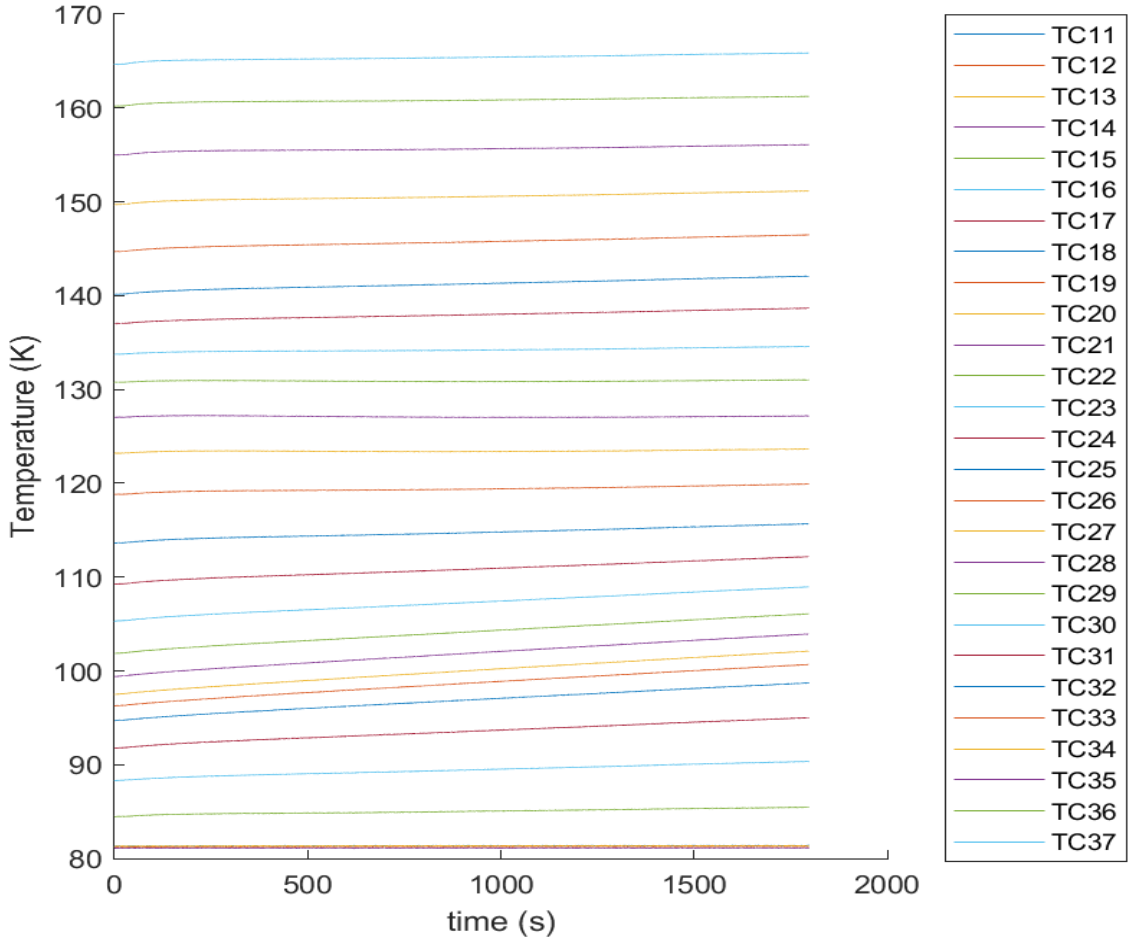


# Test Objectives

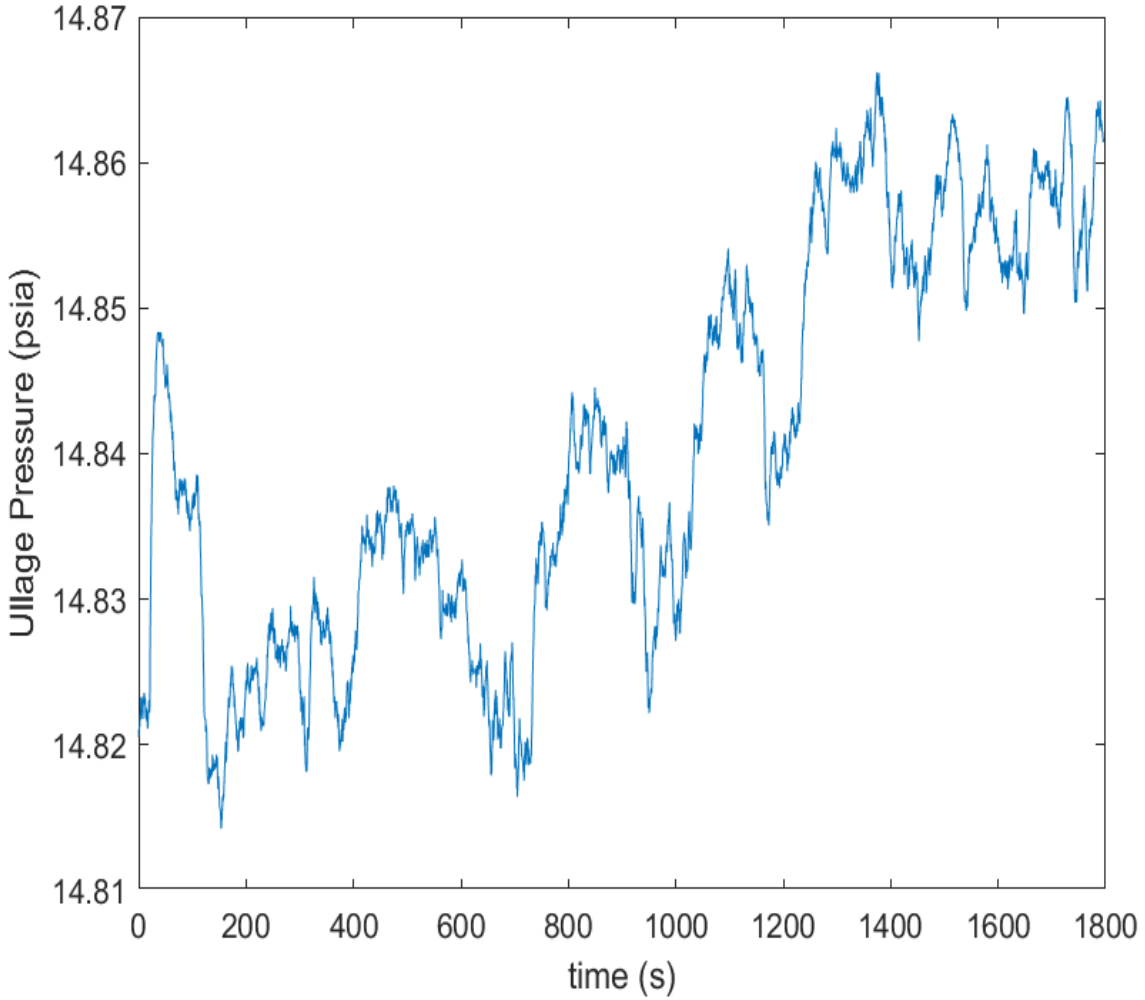
- **GTO-1 Tests: Ambient Heat Load on the Storage Tank**
  - Quantify the ambient heat load on the test bed's storage tank. This will help the analysis separate confounding sources of heat to the propellant.
- **GTO-2.1 Tests: IRCS Standby Mode**
  - Determine the performance of the IRCS in Standby Mode. To accomplish this, the following sub-objectives are to be met:
  - Determine additional heat input to the cryogenic propellant as a result of recirculation
  - Ability of the system to maintain quality while flowing minimal propellant through the recirculation loop
- **GTO-2.2 and GTO-2.3 Tests: IRCS Active Mode**
  - Determine the Steady State and Pulsing performance of the IRCS in Active Mode. To accomplish this, the following sub-objectives are to be met:
    - Determine additional heat input to the cryogenic propellant as a result of recirculation
    - Investigate ability of the system to maintain thruster inlet pressure, flow rate, and quality during steady state and pulsing operations
    - Investigate water hammer magnitude and how it propagates through the system

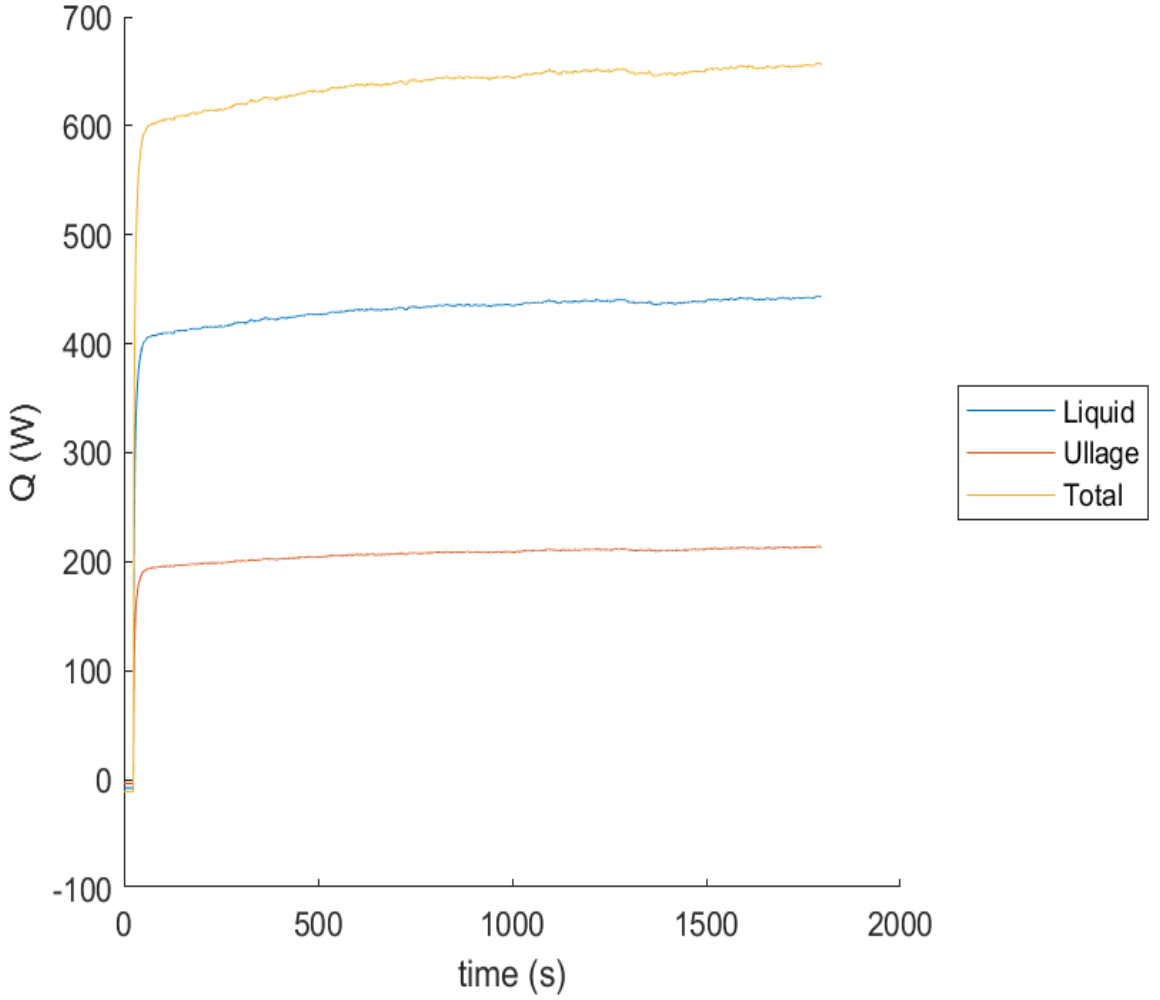
# GTO-1: Amb. Heat Load Characterization 10% Fill Level



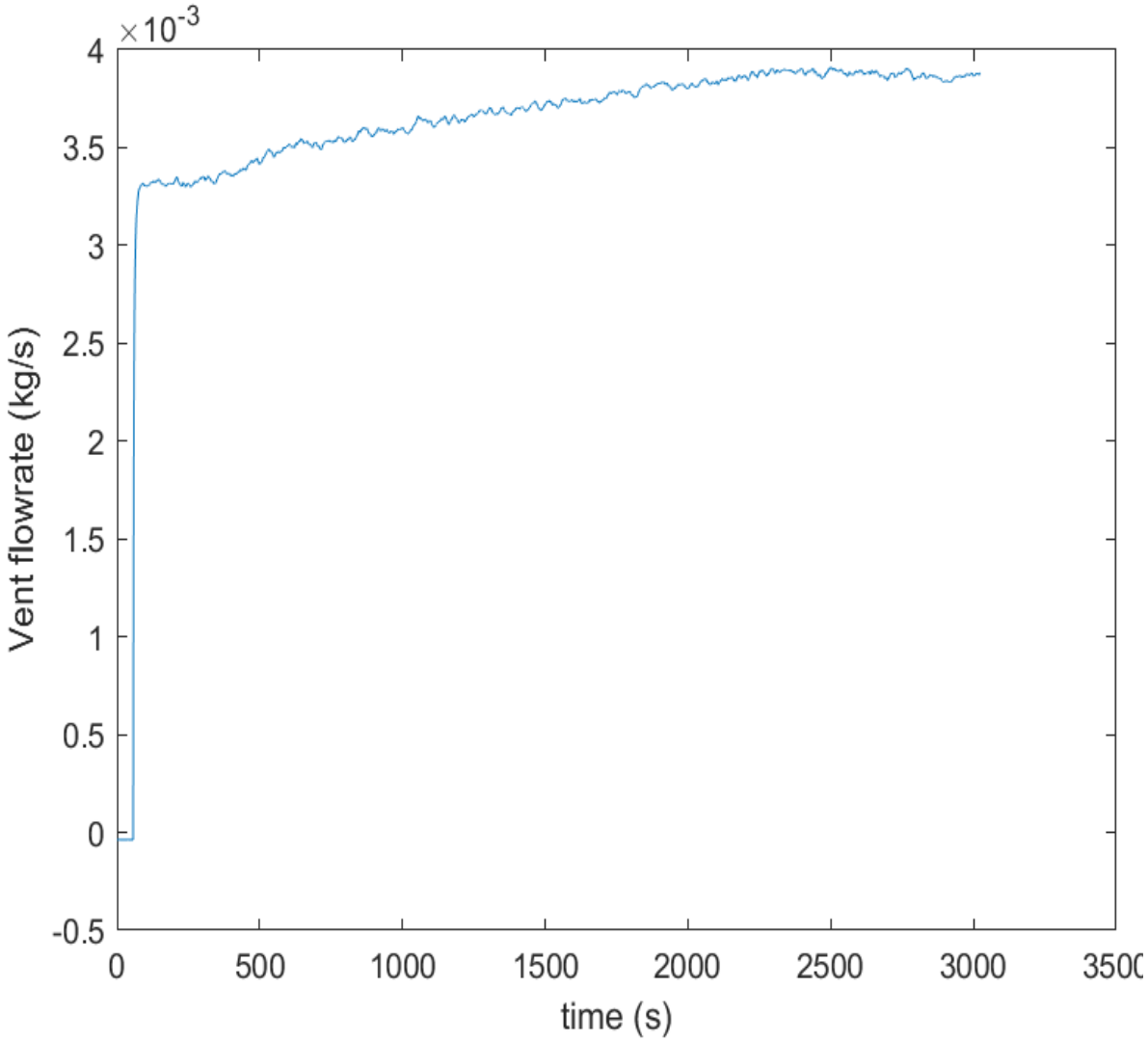



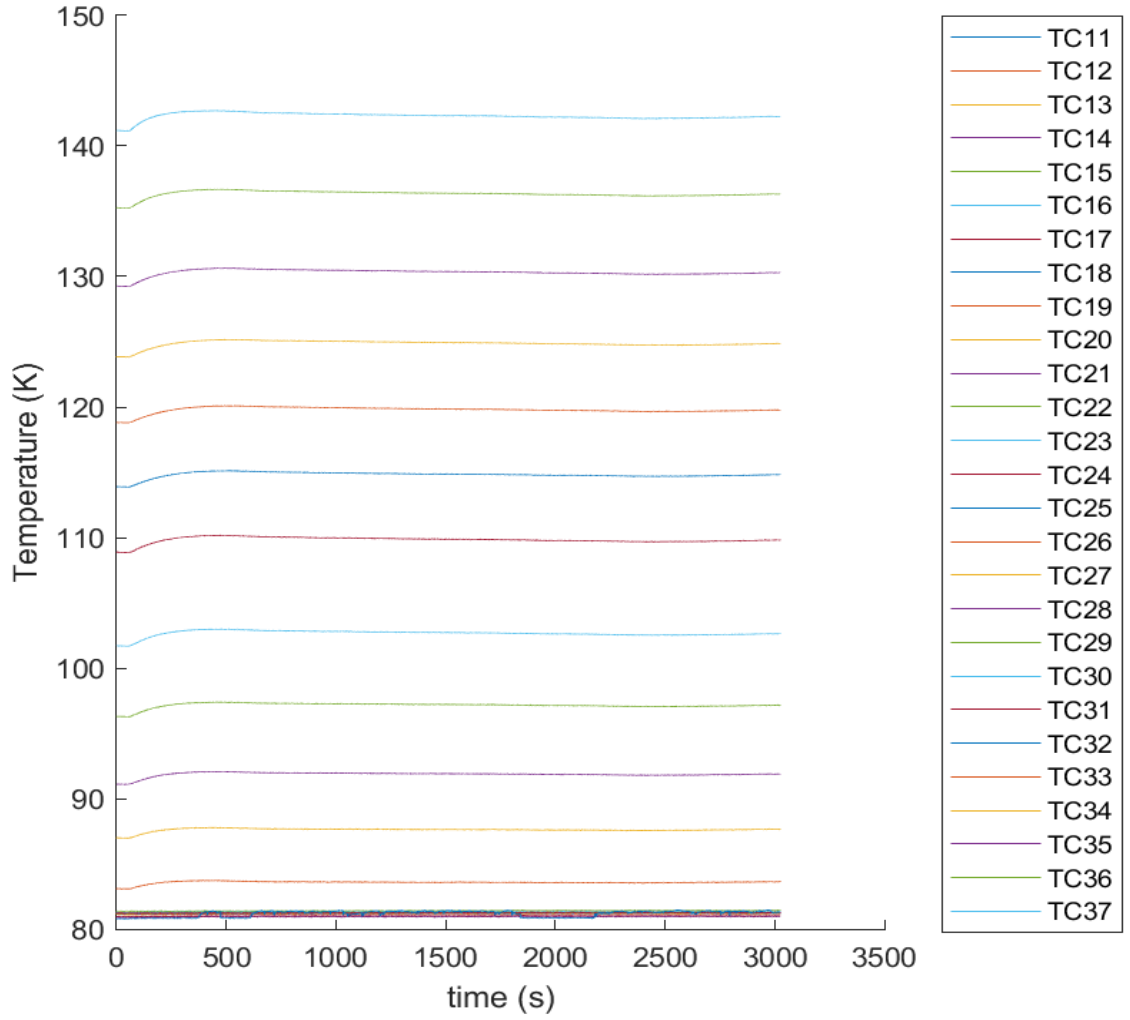
# GTO-1: 10% Fill Ctd.



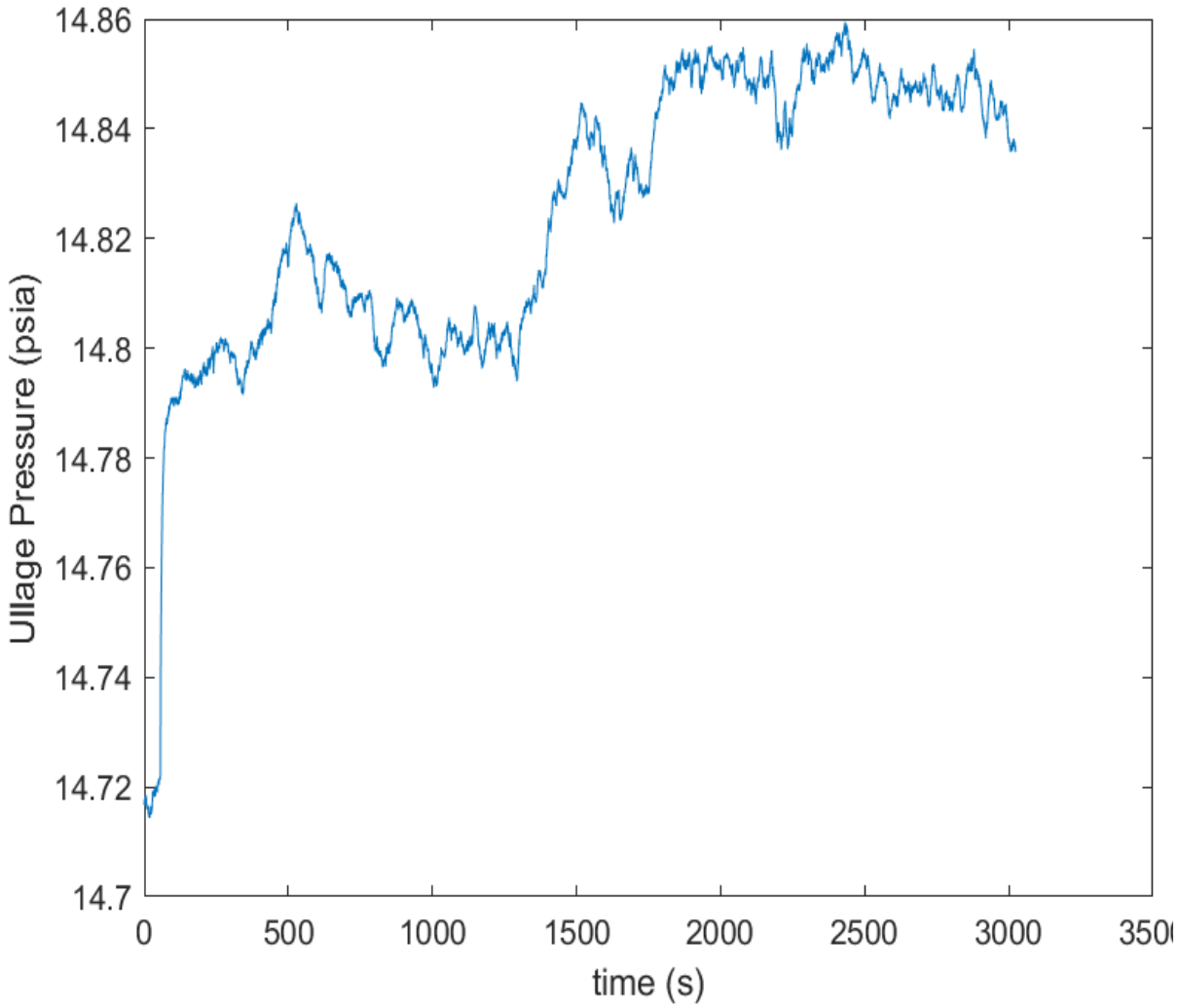



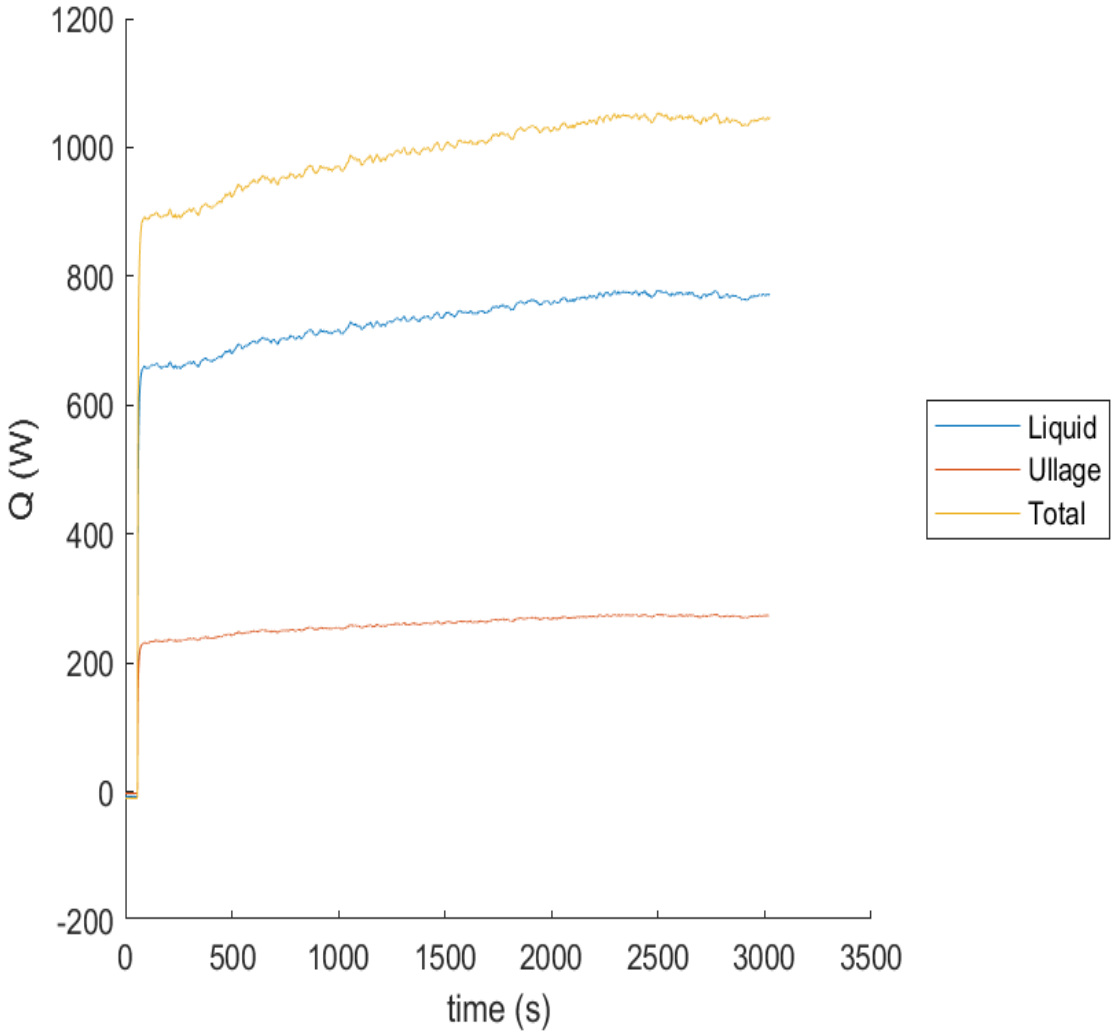
# GTO-1 52% Fill



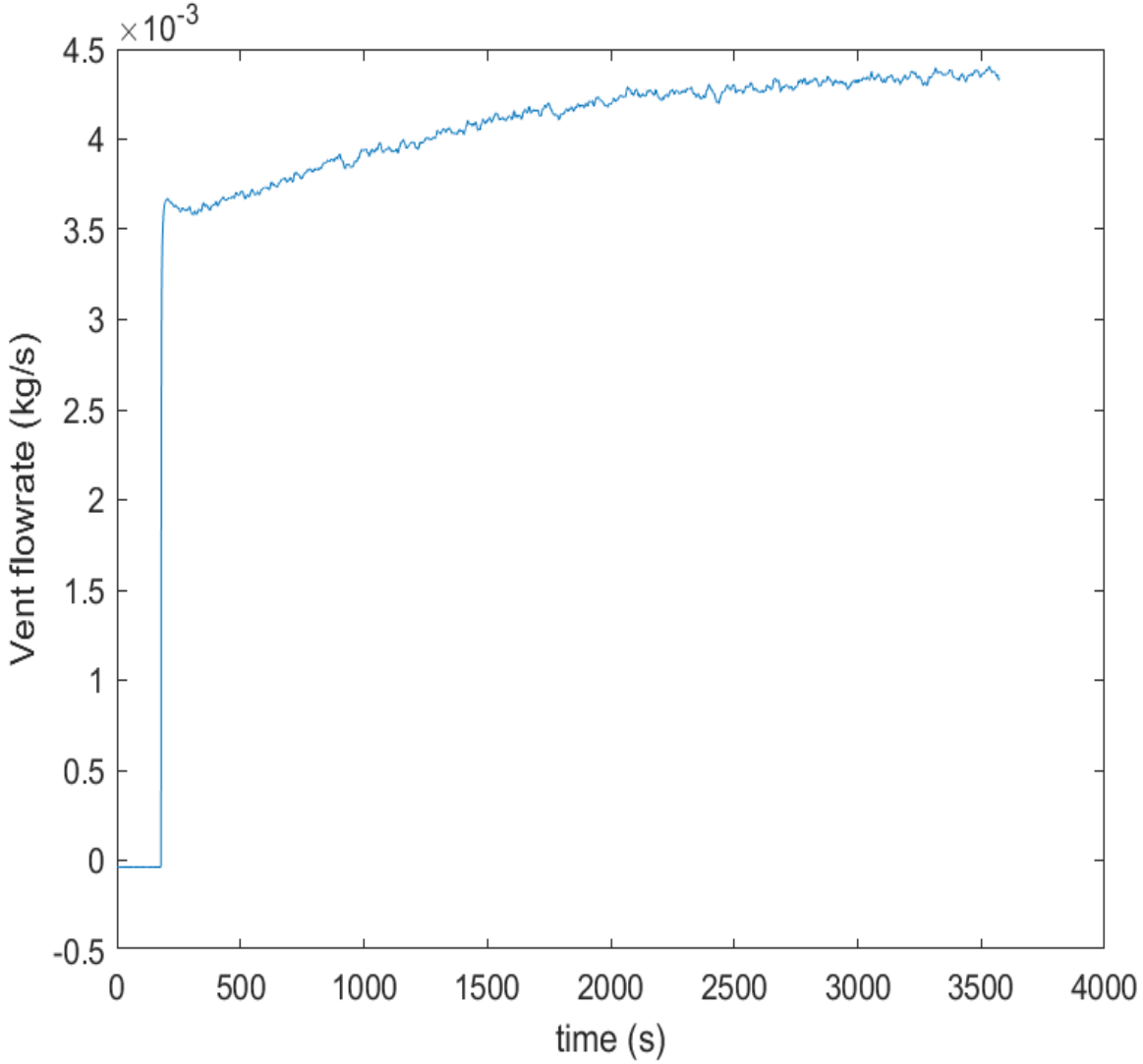



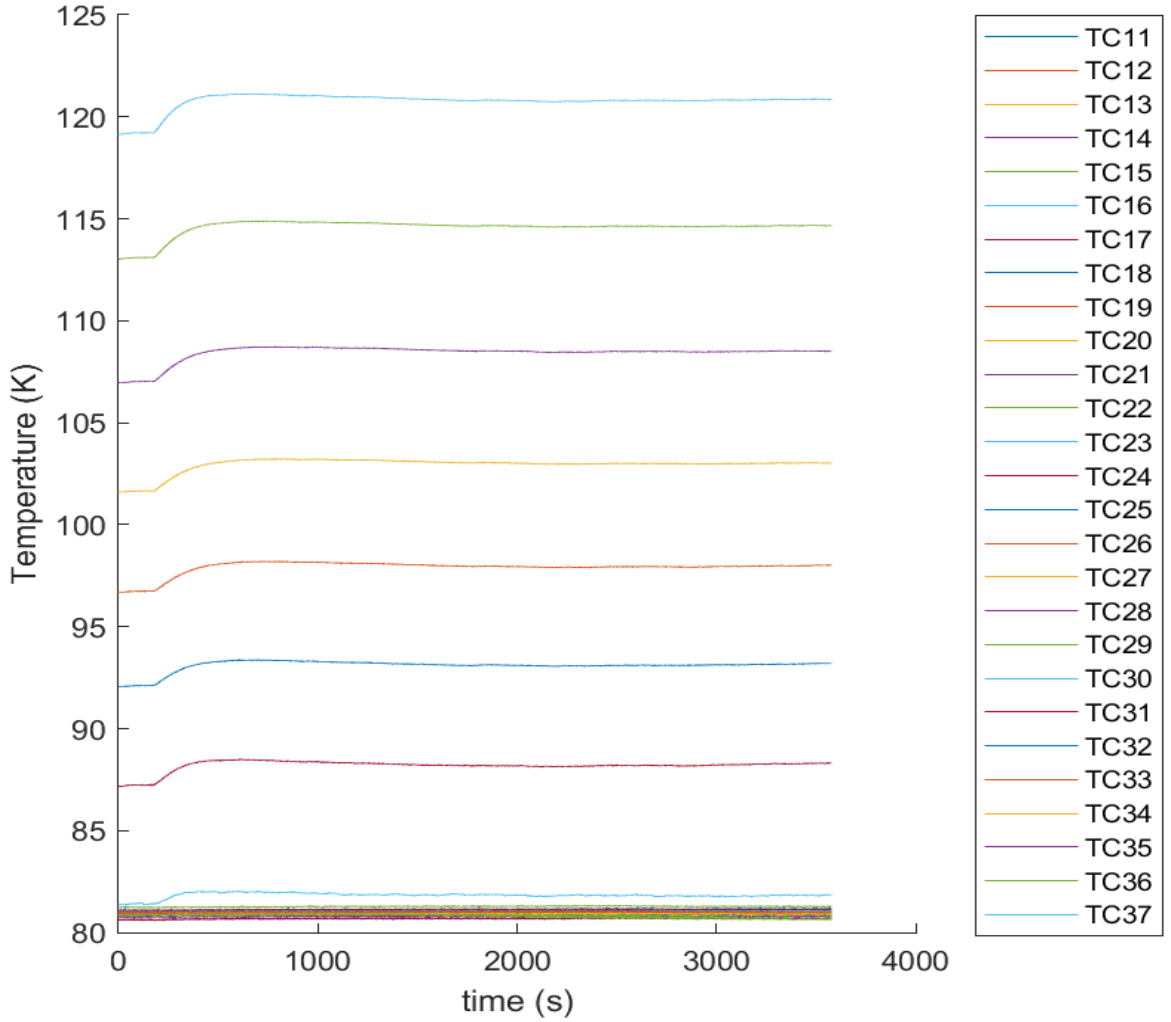
# GTO-1 52% Fill ctd



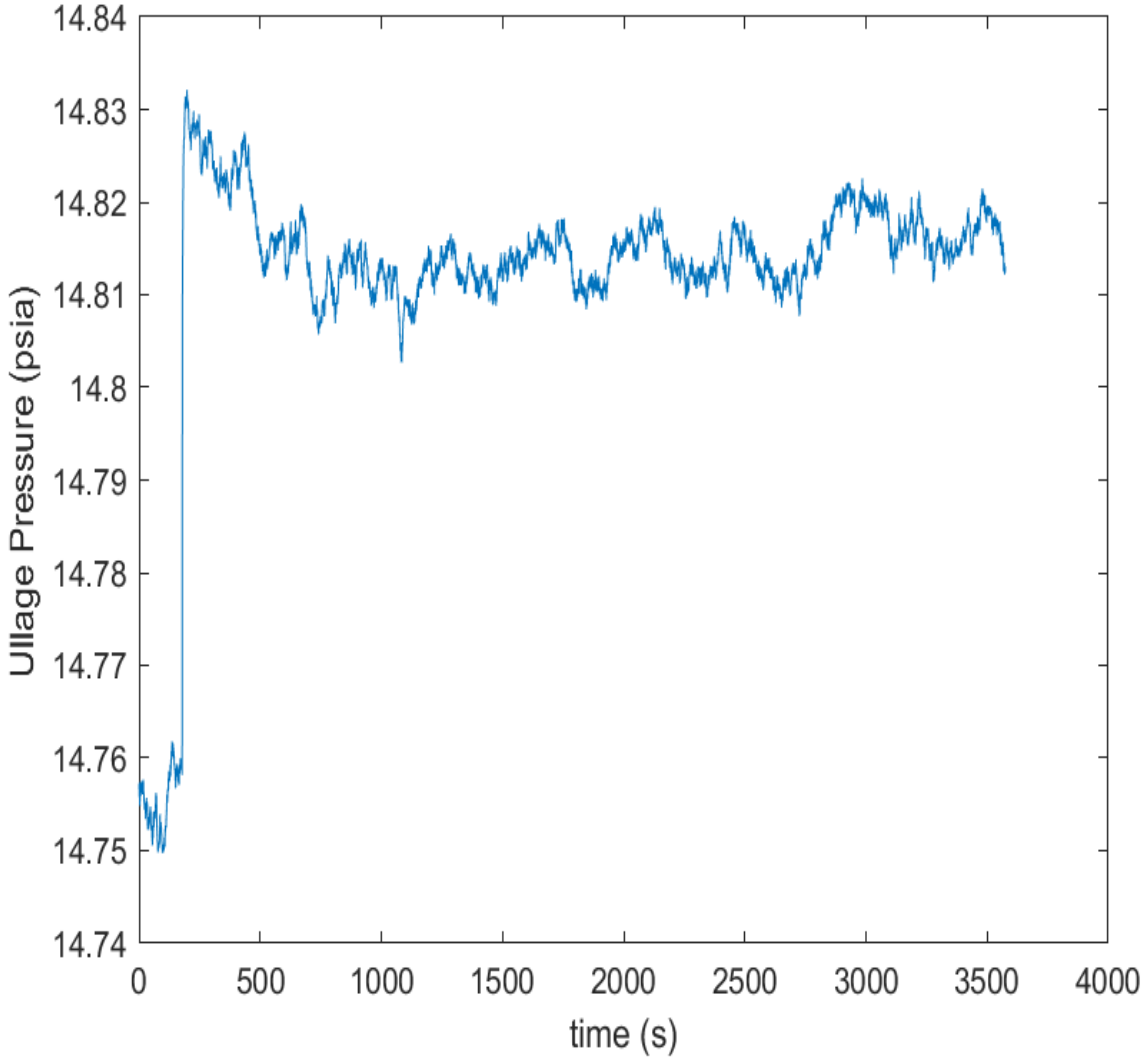



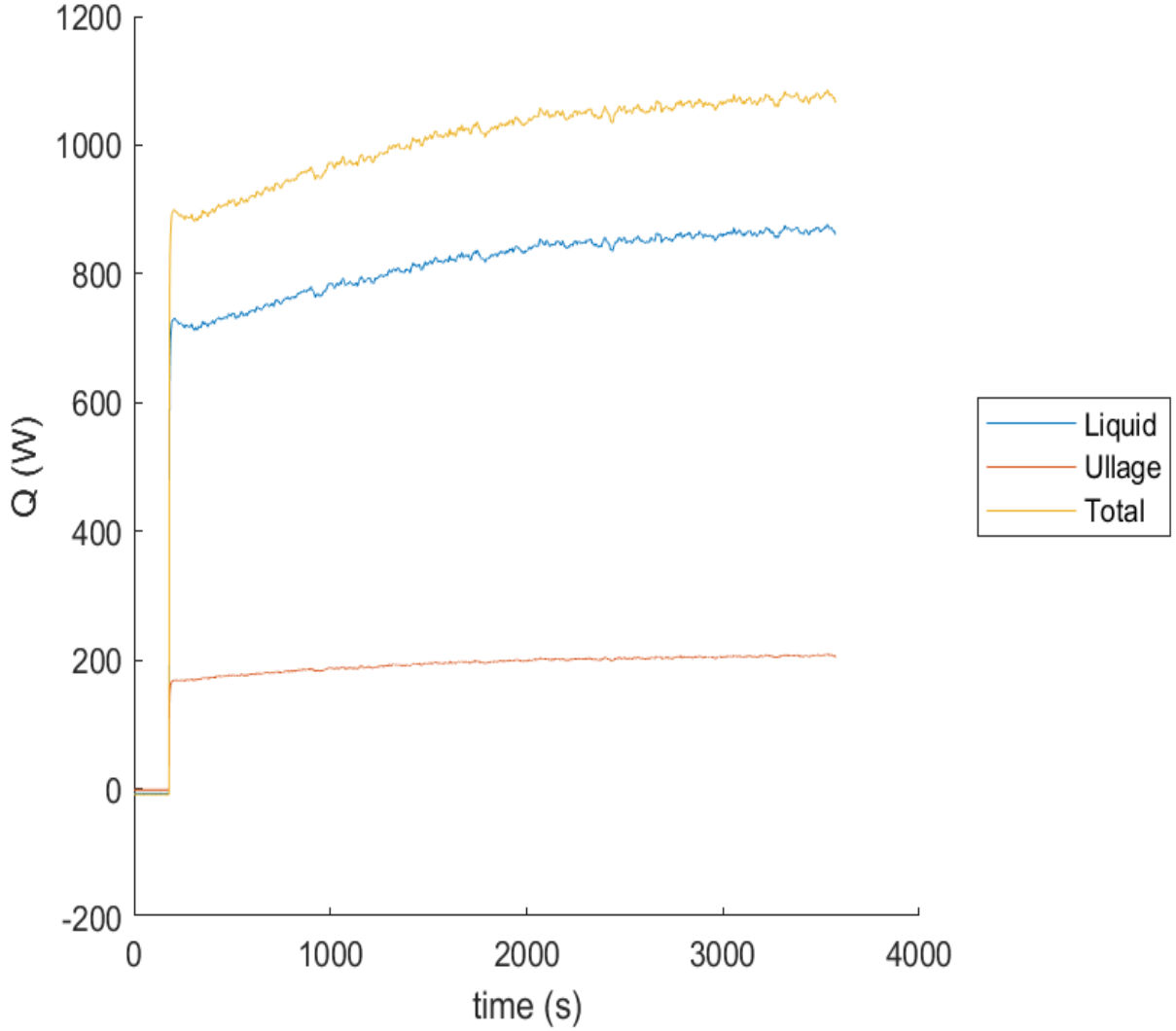
# GTO-1 72% Fill



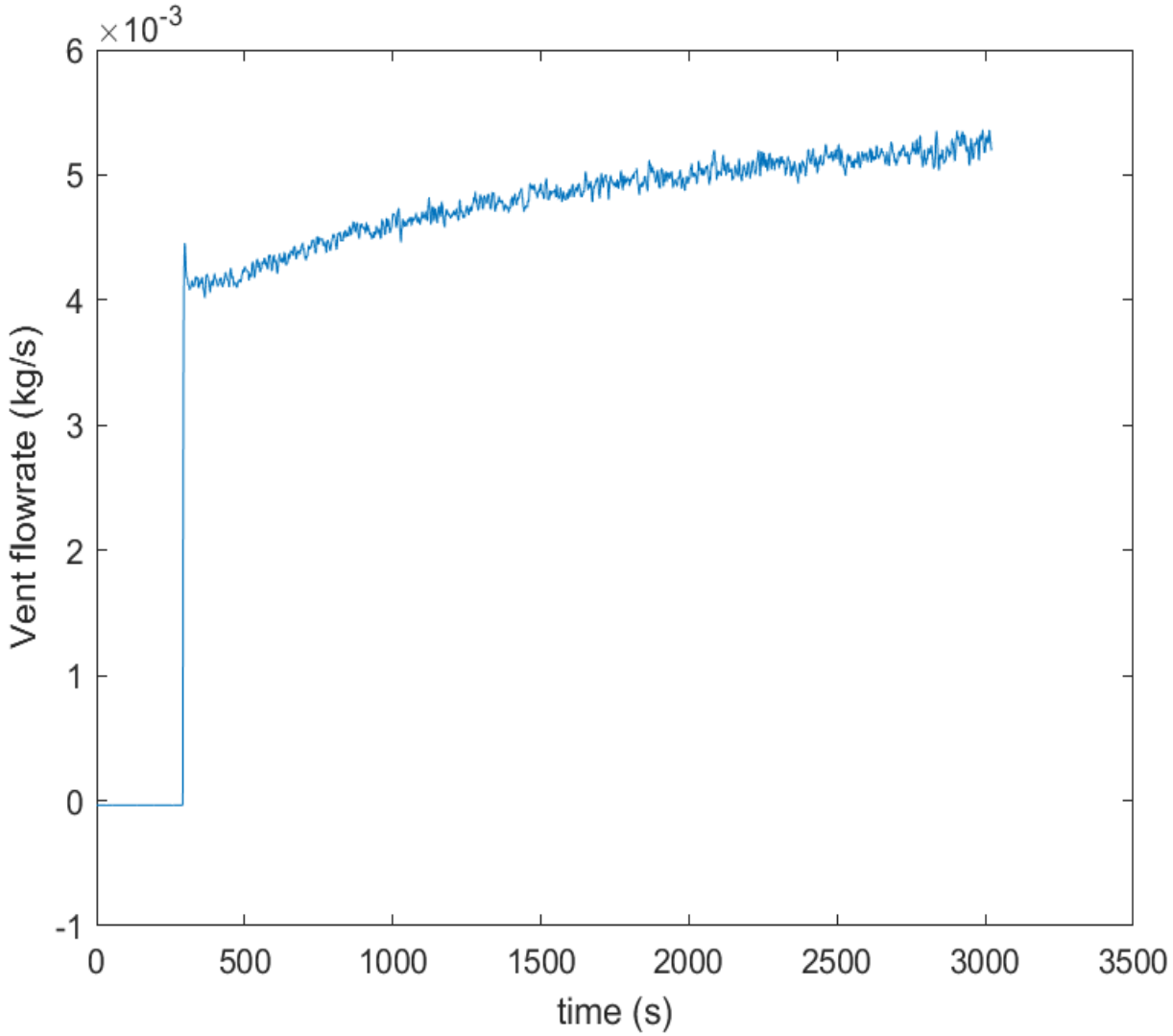



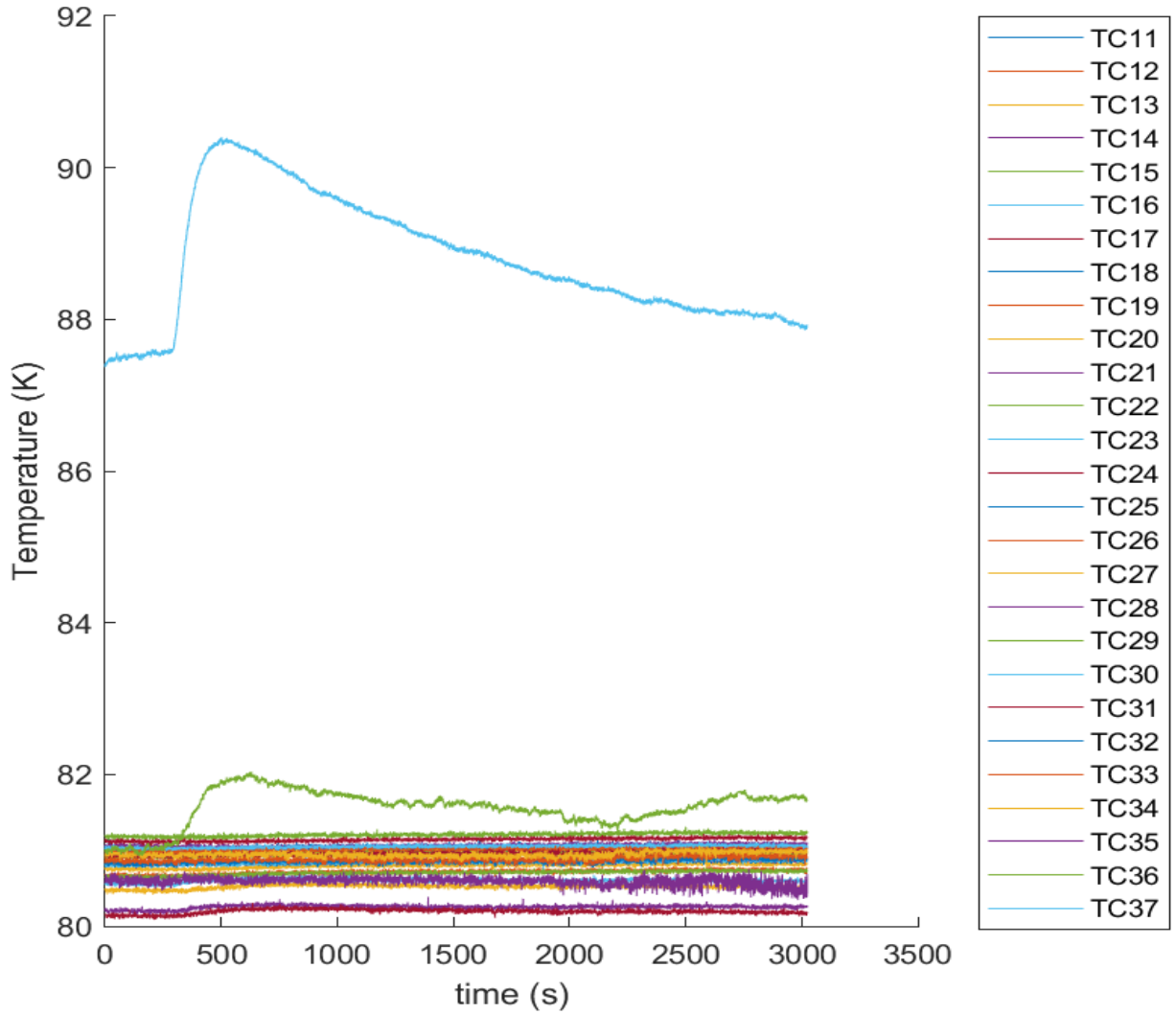
# GTO-1 72% Fill ctd



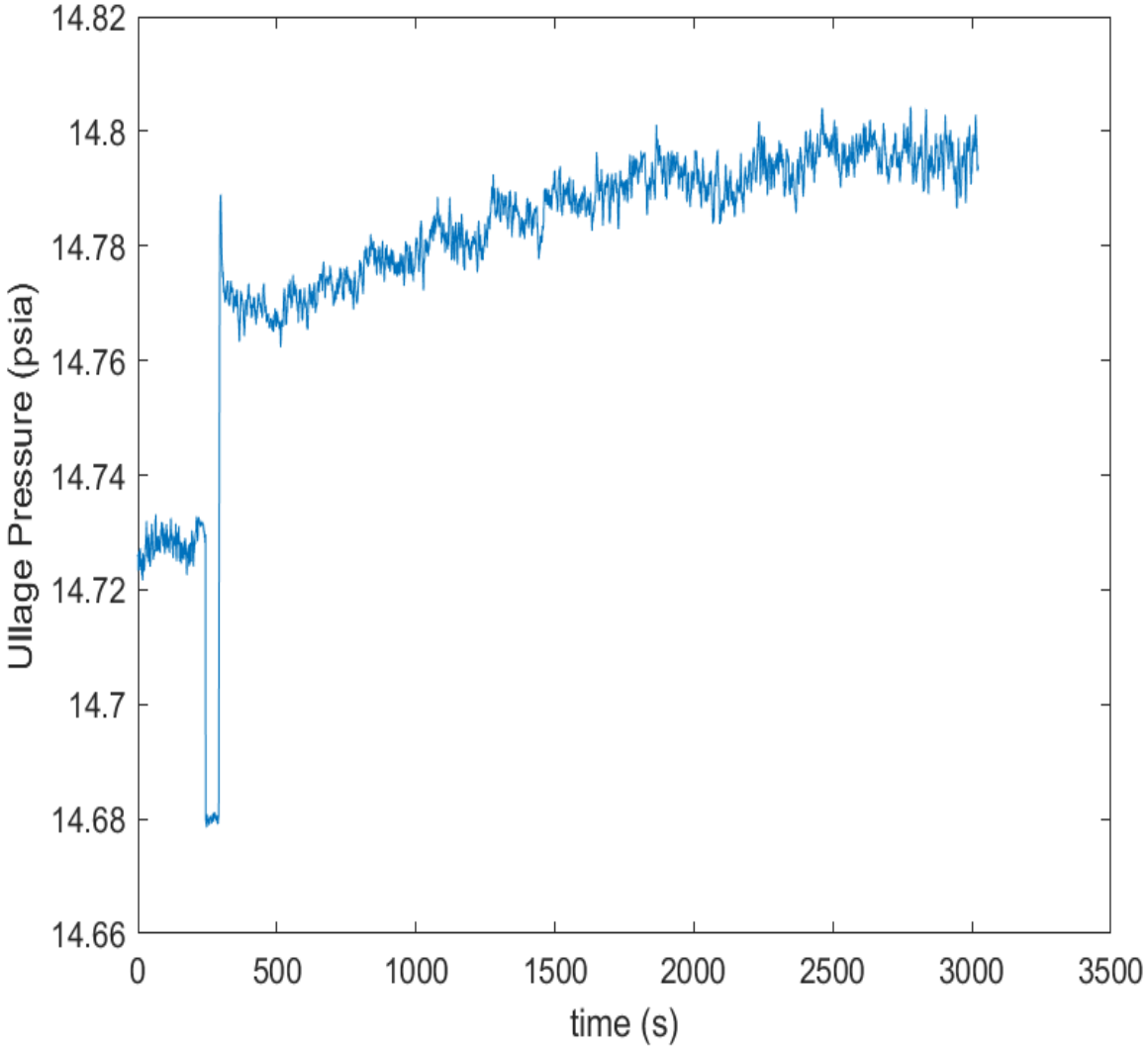



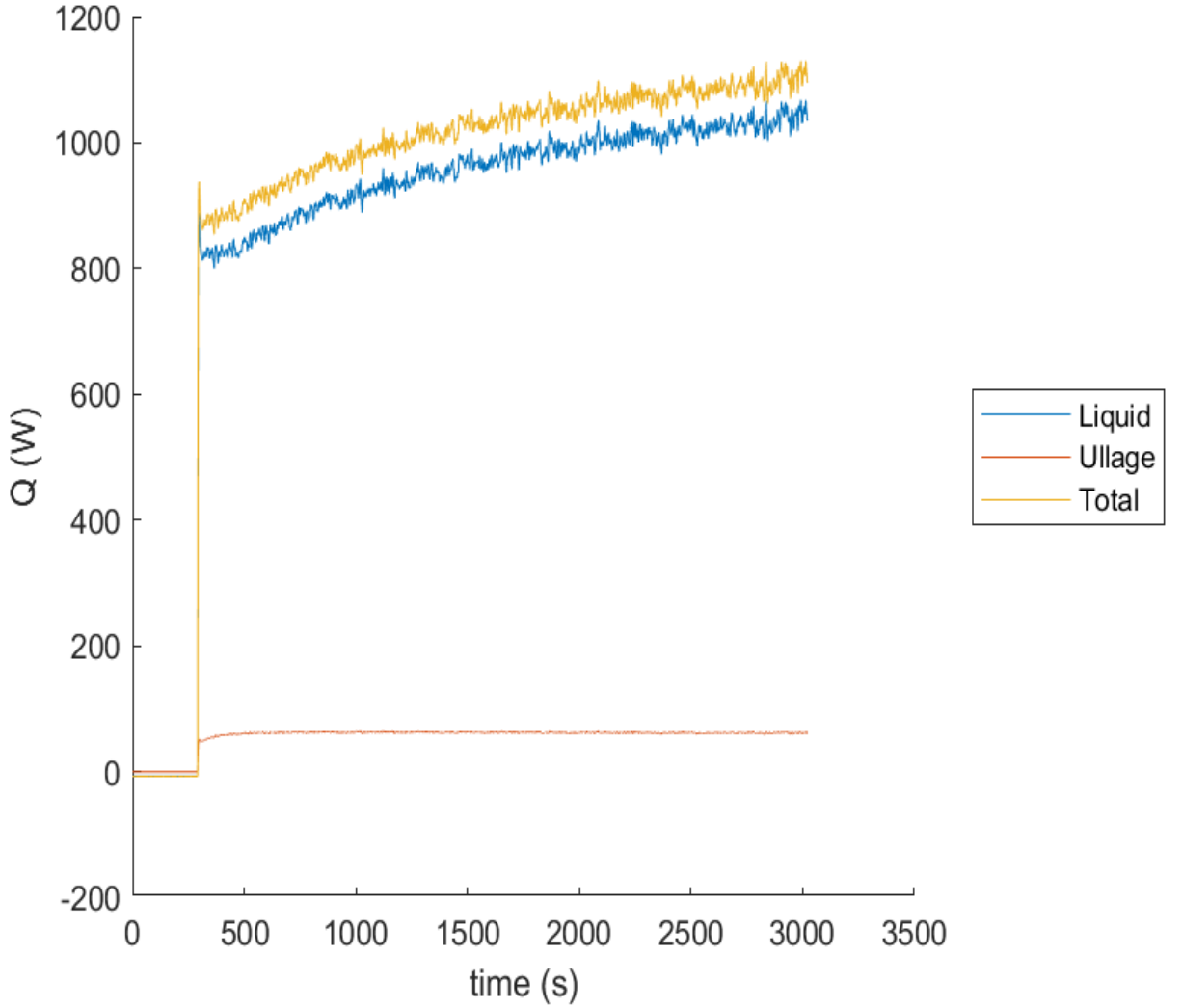
# GTO-1 90% Fill



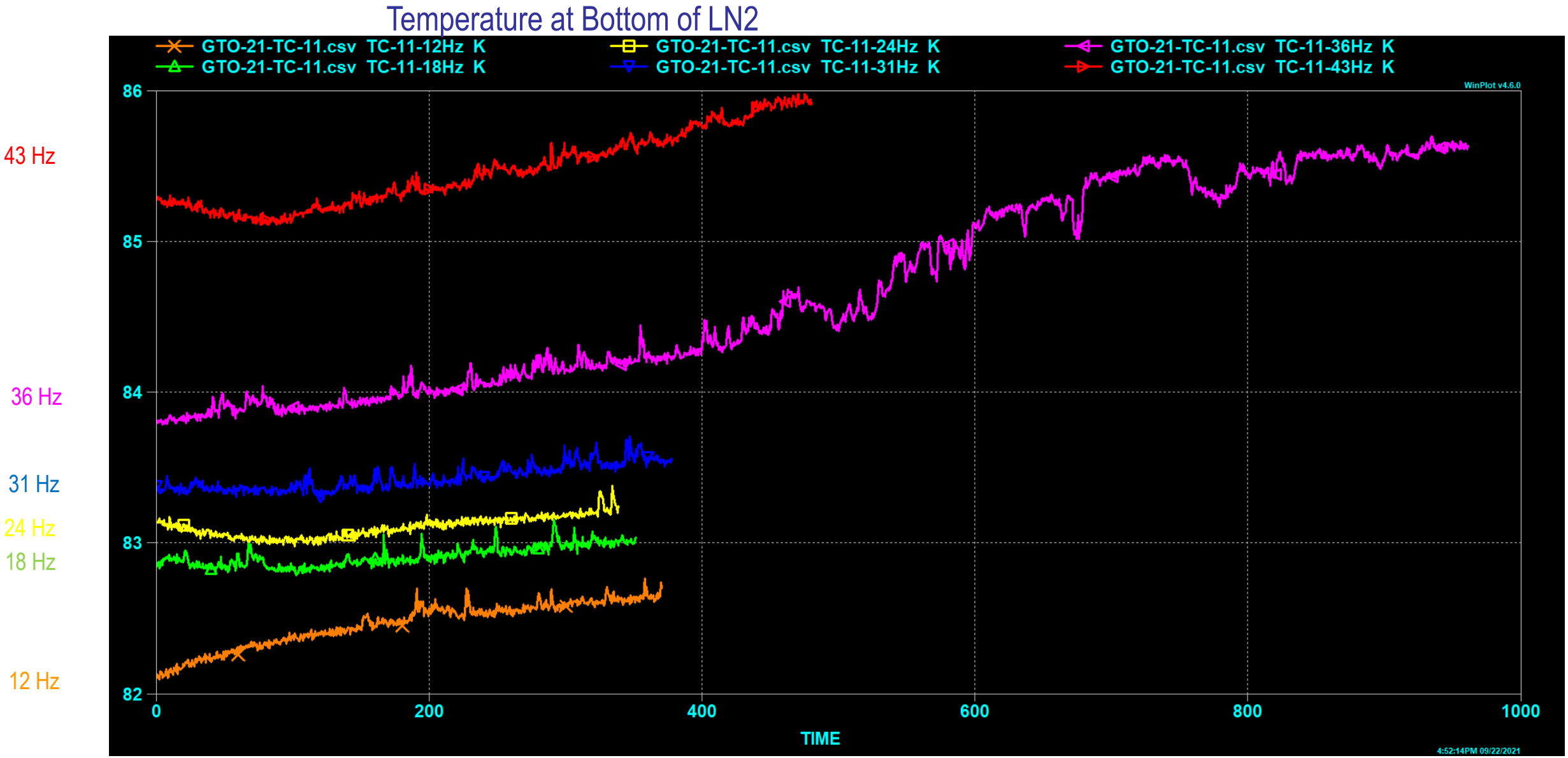



# GTO-1 90% Fill ctd.



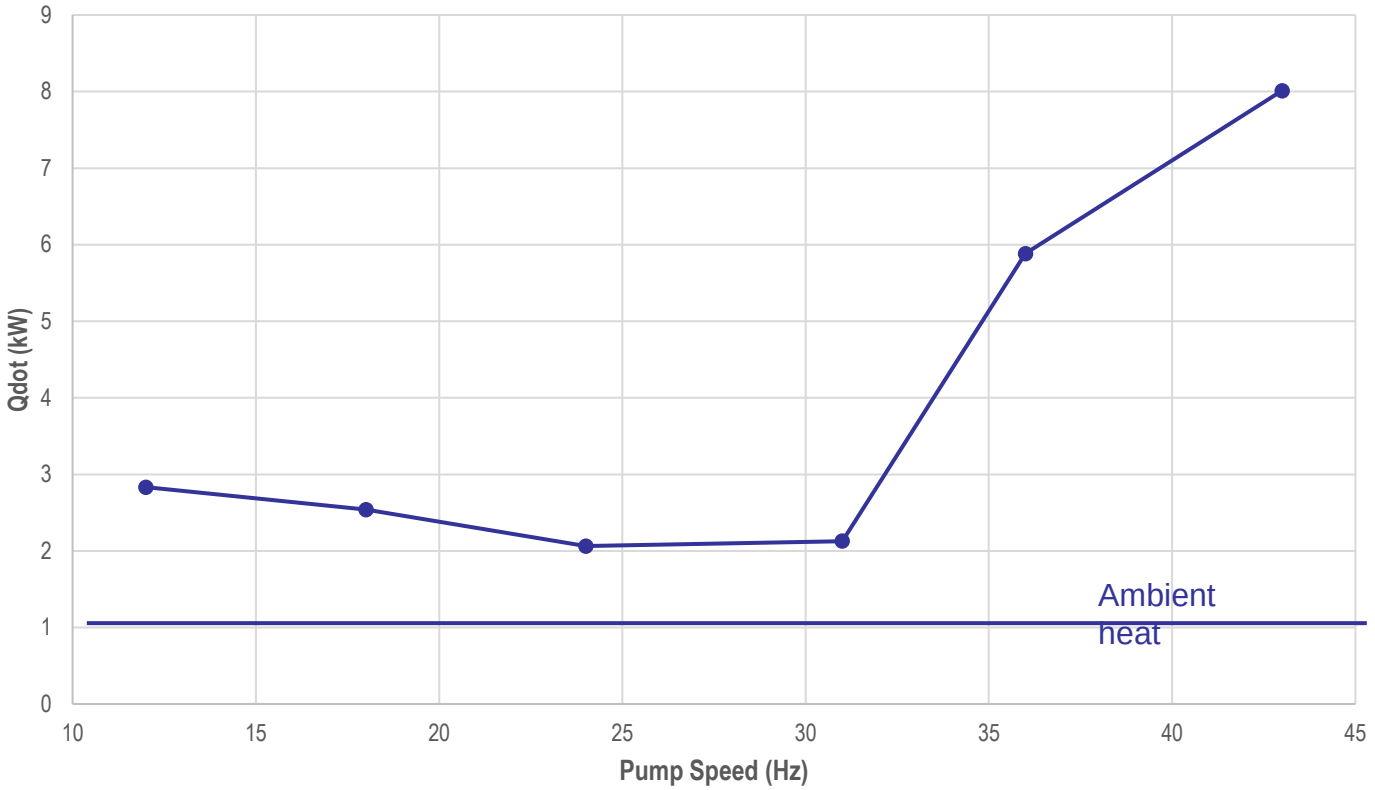



# Additional Heating from Pump



# Additional Heating from Pump

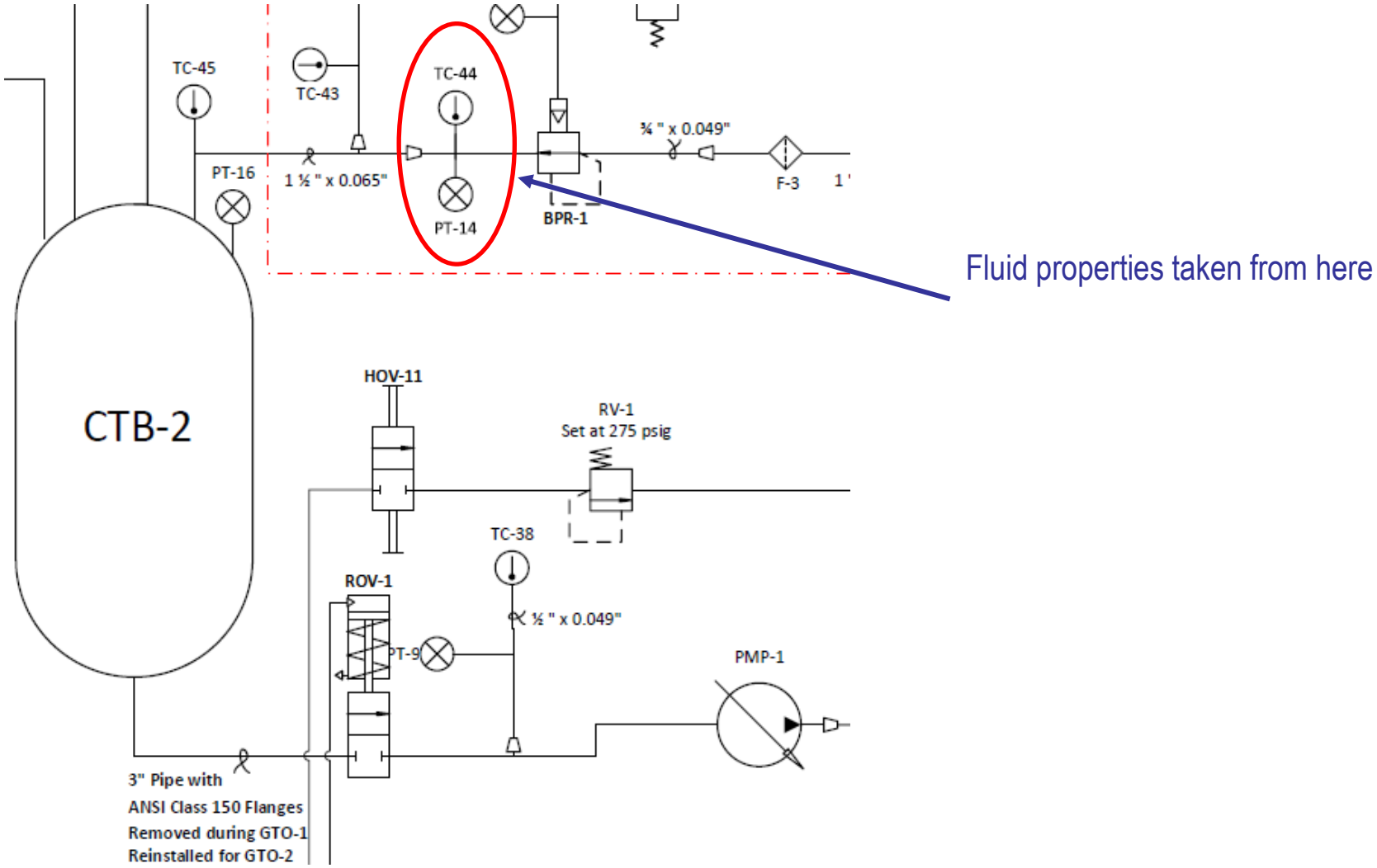
- **The pump is a significant source of heat addition**
- **This pump is over-sized for a lunar mission**
  - Acquired when the driving operational scenario was a manned Mars landing, which called for 1000-lbf thrusters



# GTO 2.2

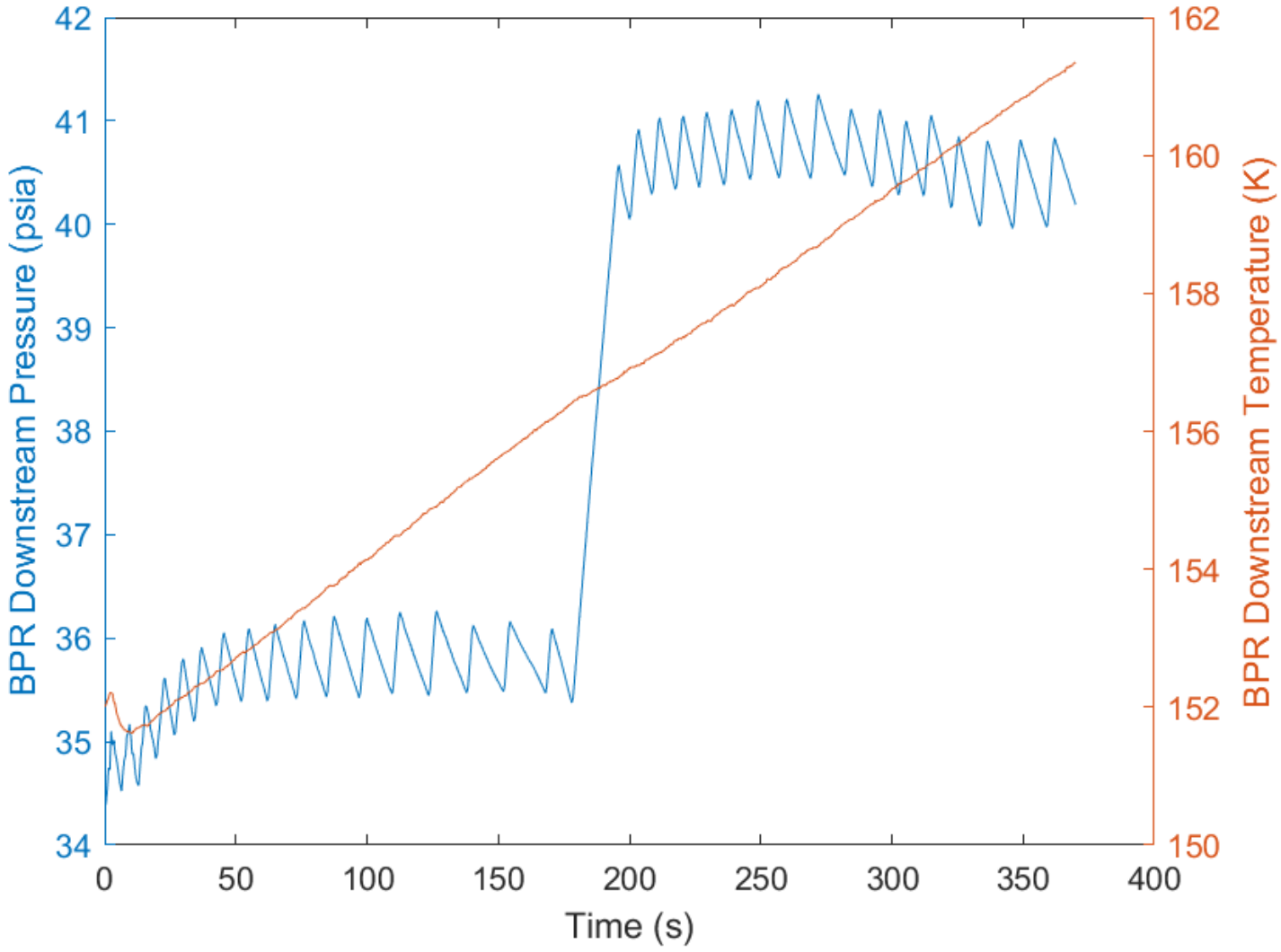
- **DESCRIPTION OF 2.2 TK**
- **Piece that was added back to allow for recirculation of LN2 thru system**
- **Steady state standby mode**

# Return Flow Measurement Location during GTO-2.2

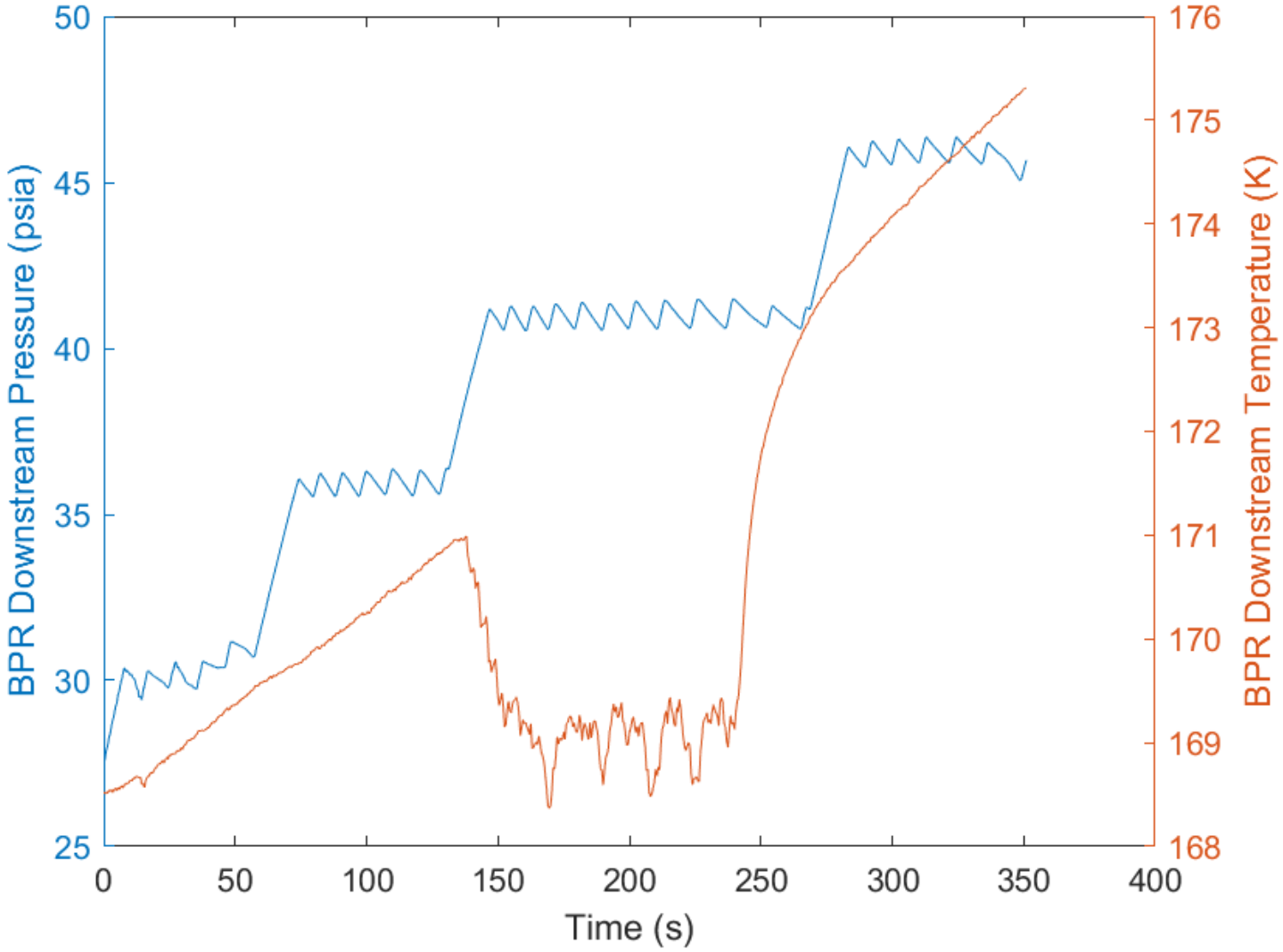


# GTO-2.2: Return Flow Conditions, 12 Hz

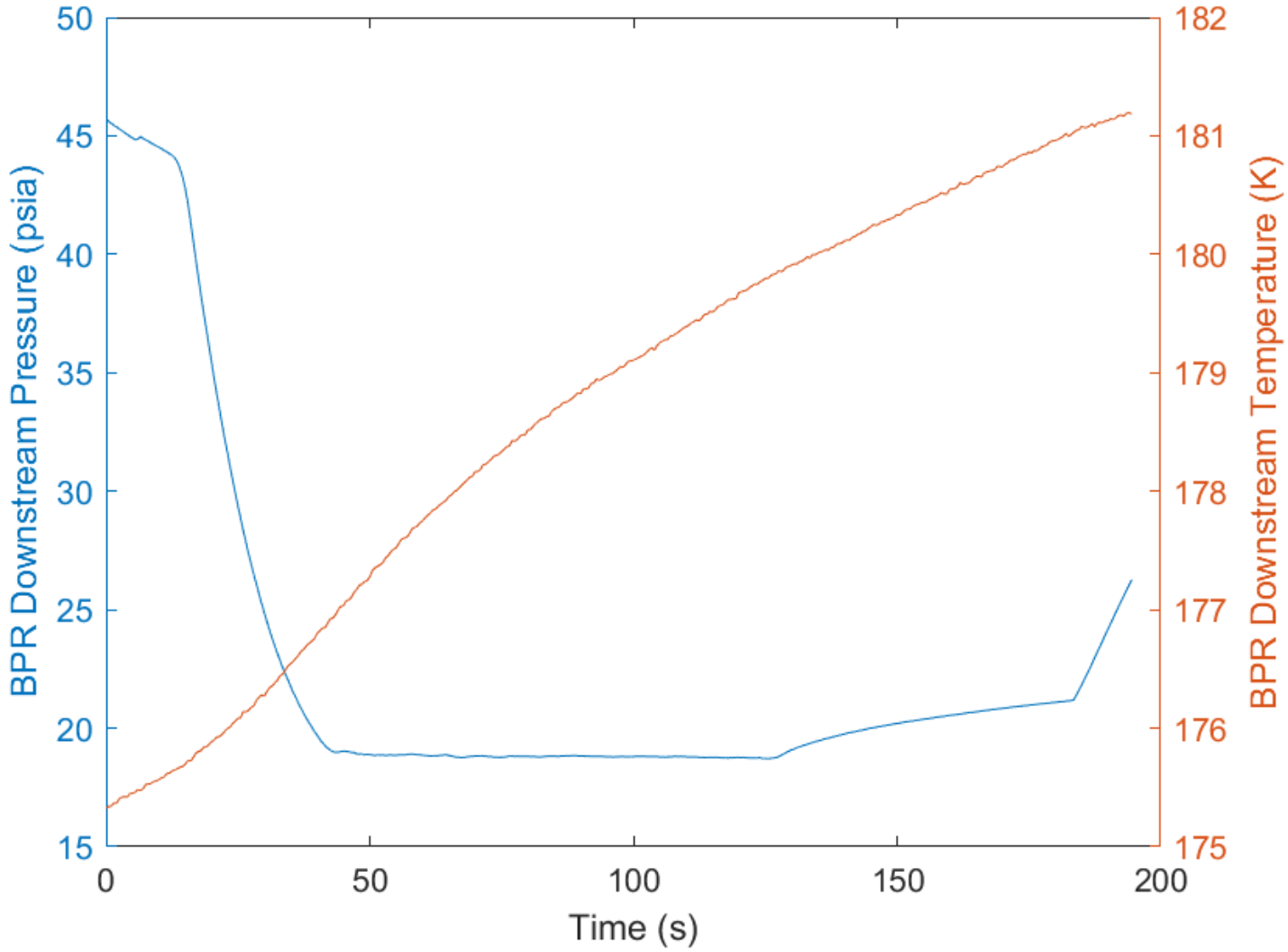
TK
Should we describe anything on these?



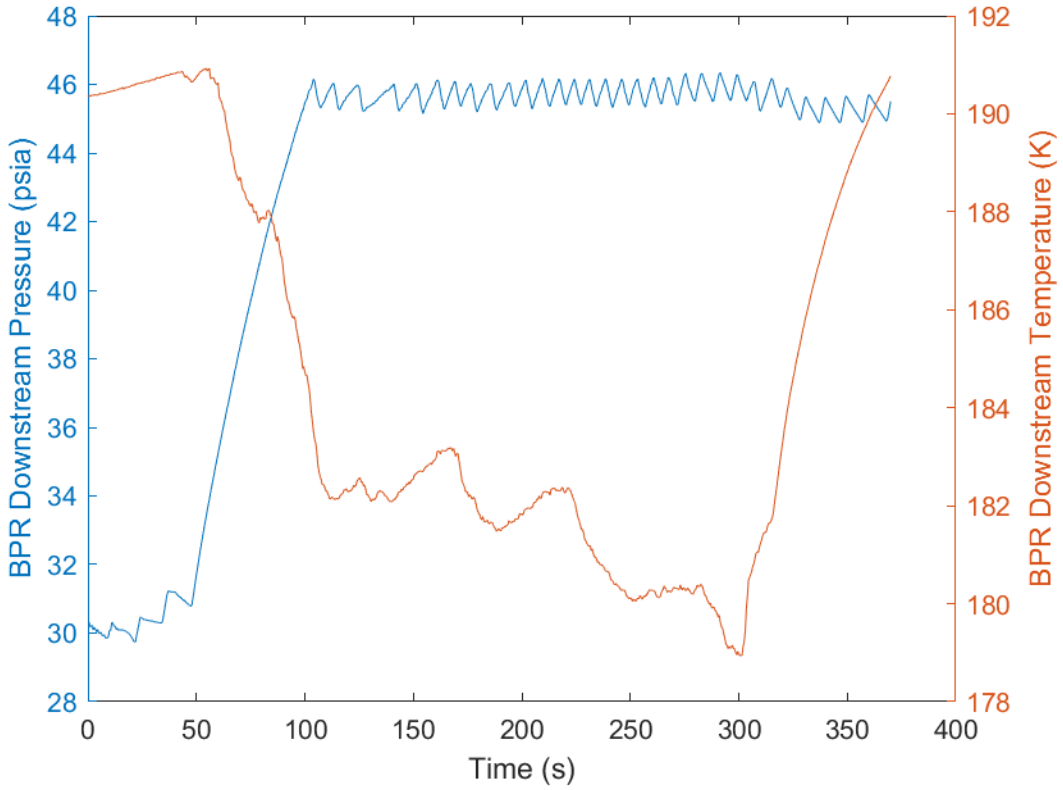
# GTO-2.2: Return Flow Conditions, 18 Hz



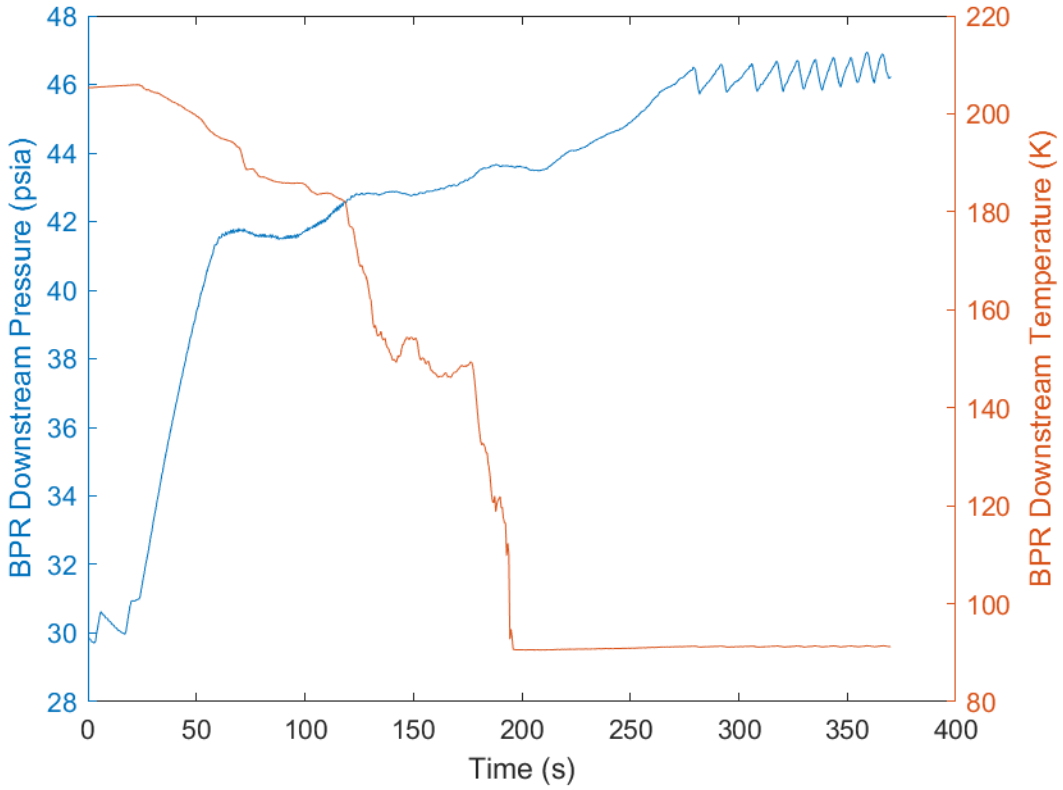
# GTO-2.2: Return Flow Conditions, 24 Hz



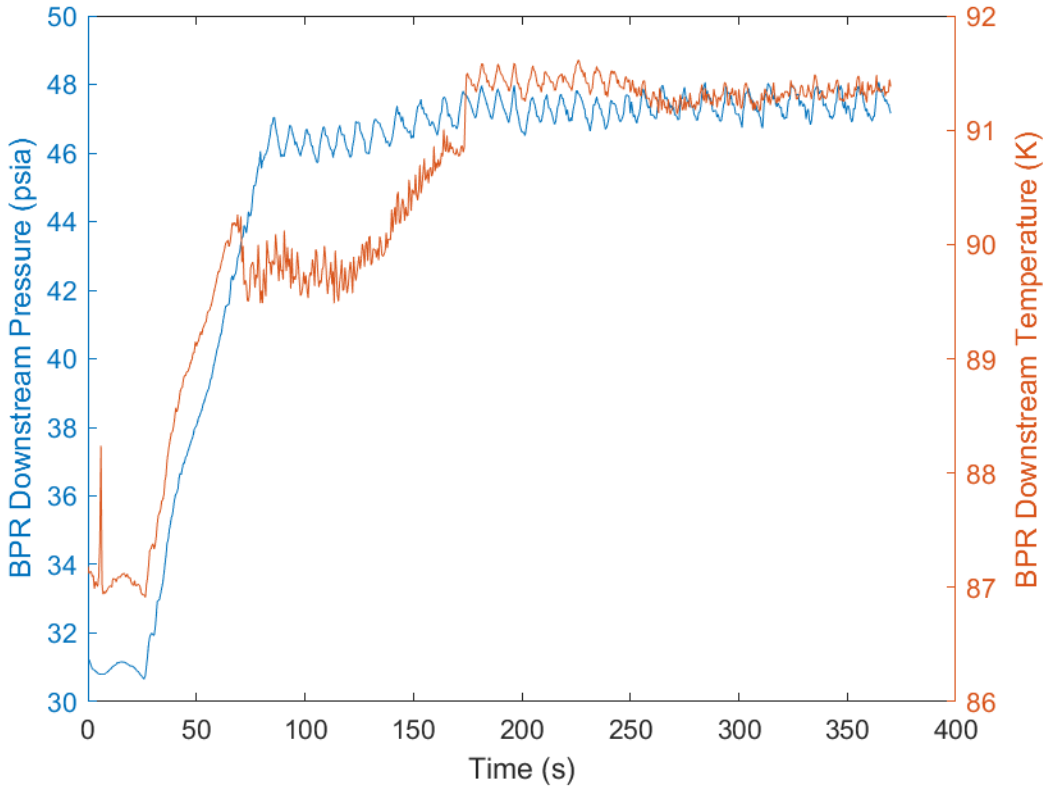
# GTO-2.2: Return Flow Conditions, 31 Hz



# GTO-2.2: Return Flow Conditions, 36 Hz



# GTO-2.2: Return Flow Conditions, 43 Hz

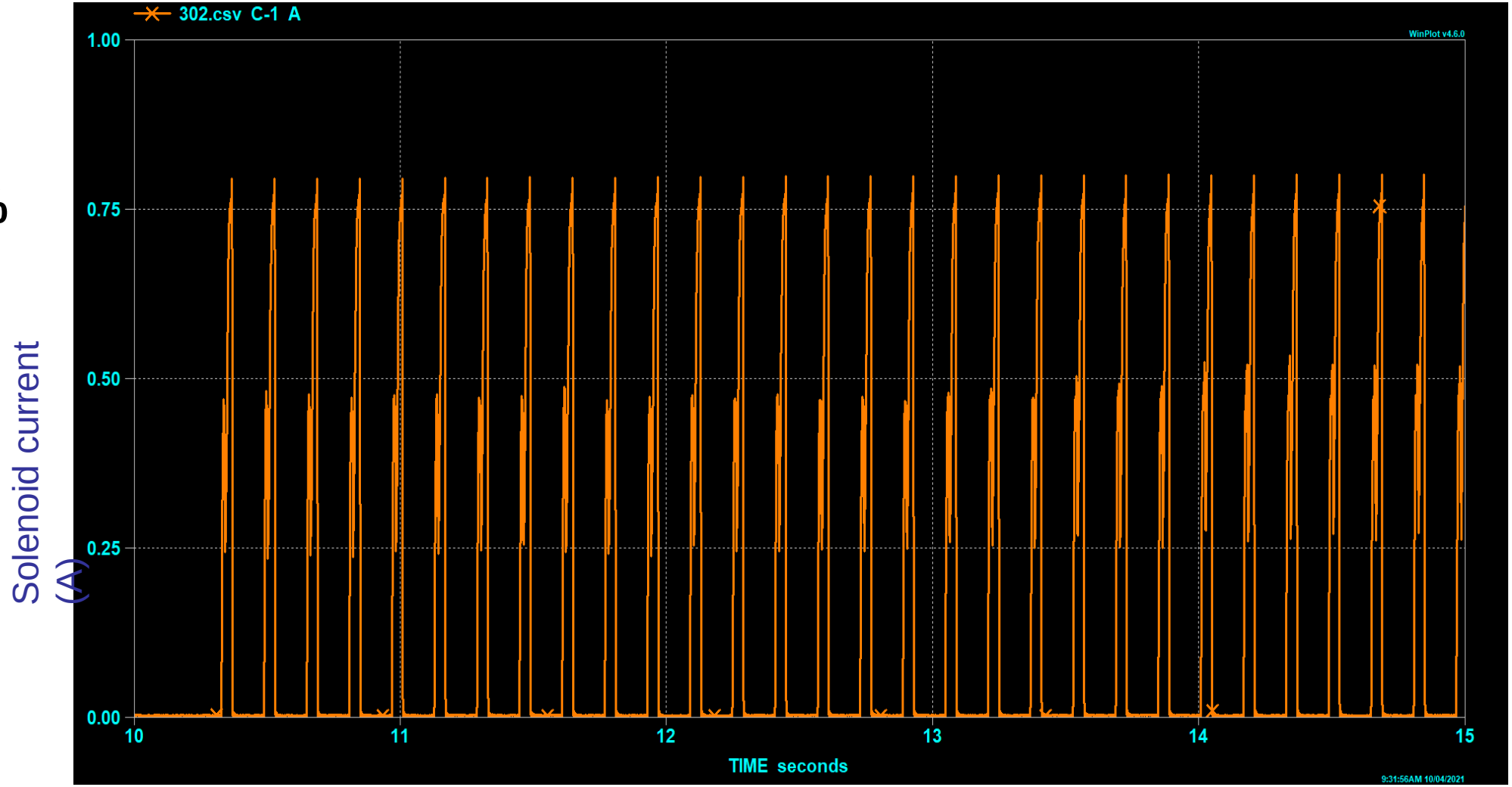


# GTO-2.3: Pulsing Mode

- **Ran 16 different pulse profiles**
  - Varied number of active thrusters, duty cycle, pulse width, and number of pulses
  - Constant pump speed and tank pressures
  - Intent was to cover a wide range of potential operational scenarios

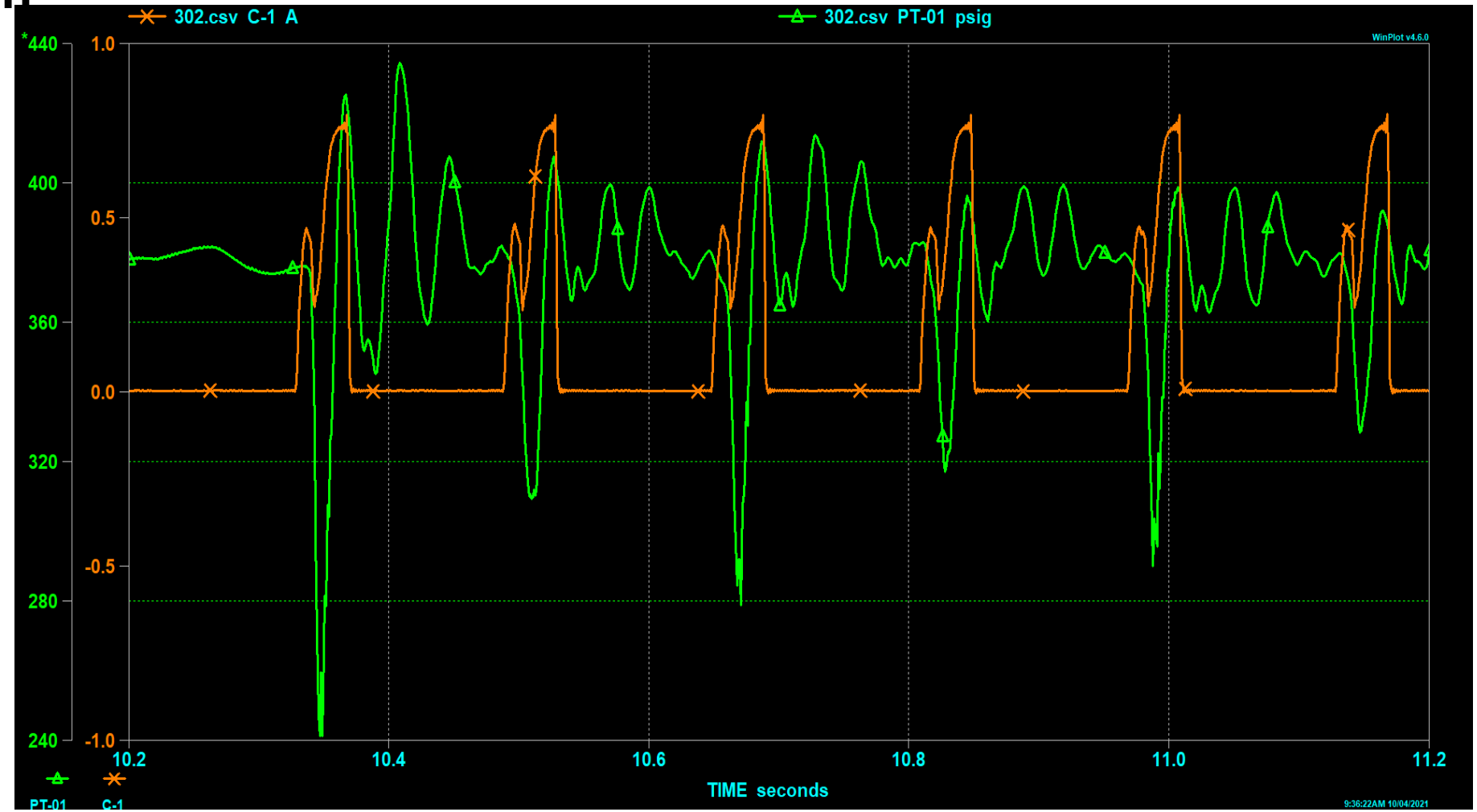
# GTO-2.3: Test #302: Rapid Pulses

- **2 thrusters, 40 msec pulses, 5% duty cycle**



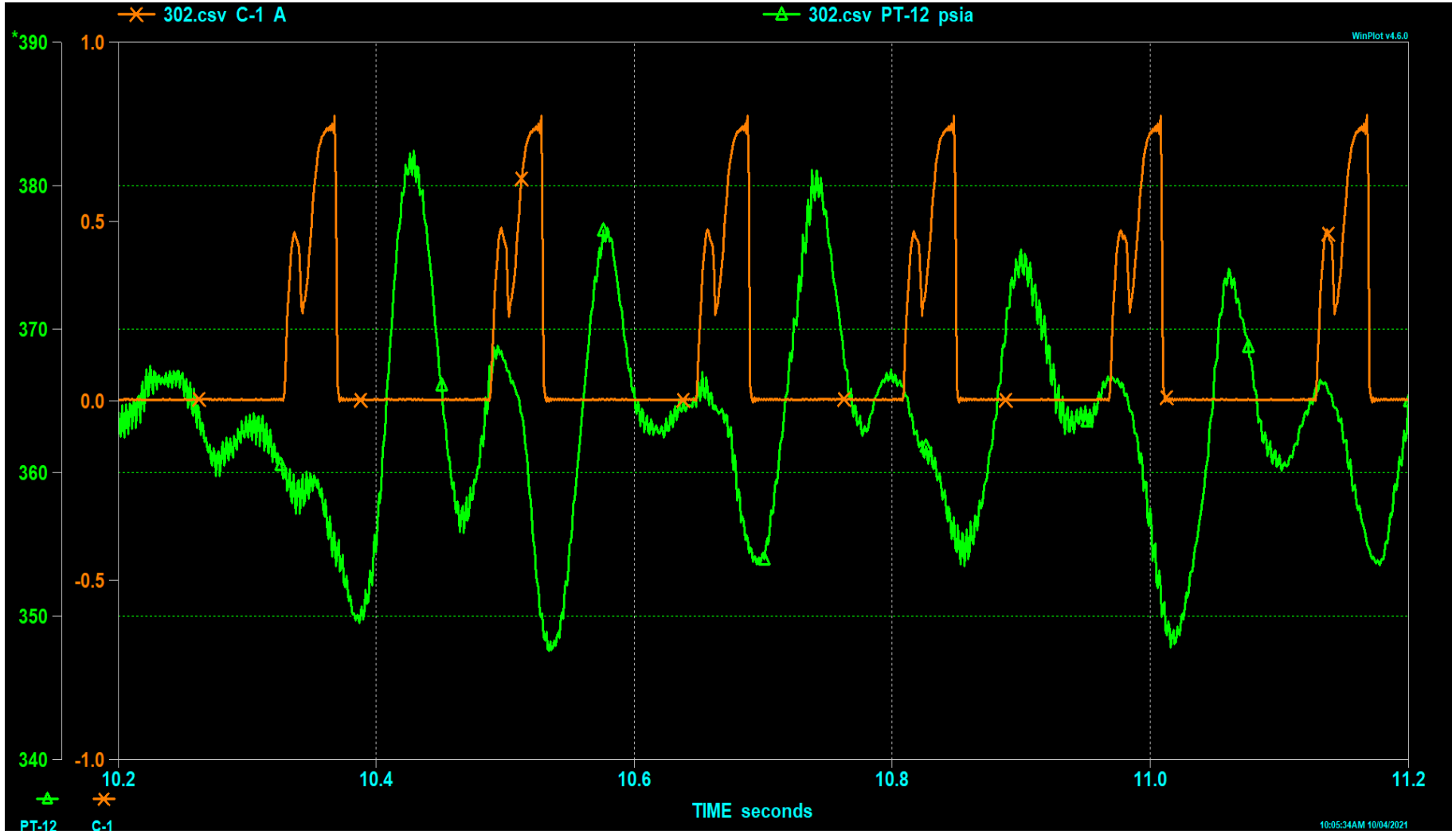
# GTO-2.3: Test #302: Thruster Inlet Pressure Response

- **135 psi slump on opening**
- **60 psi spike on closing**

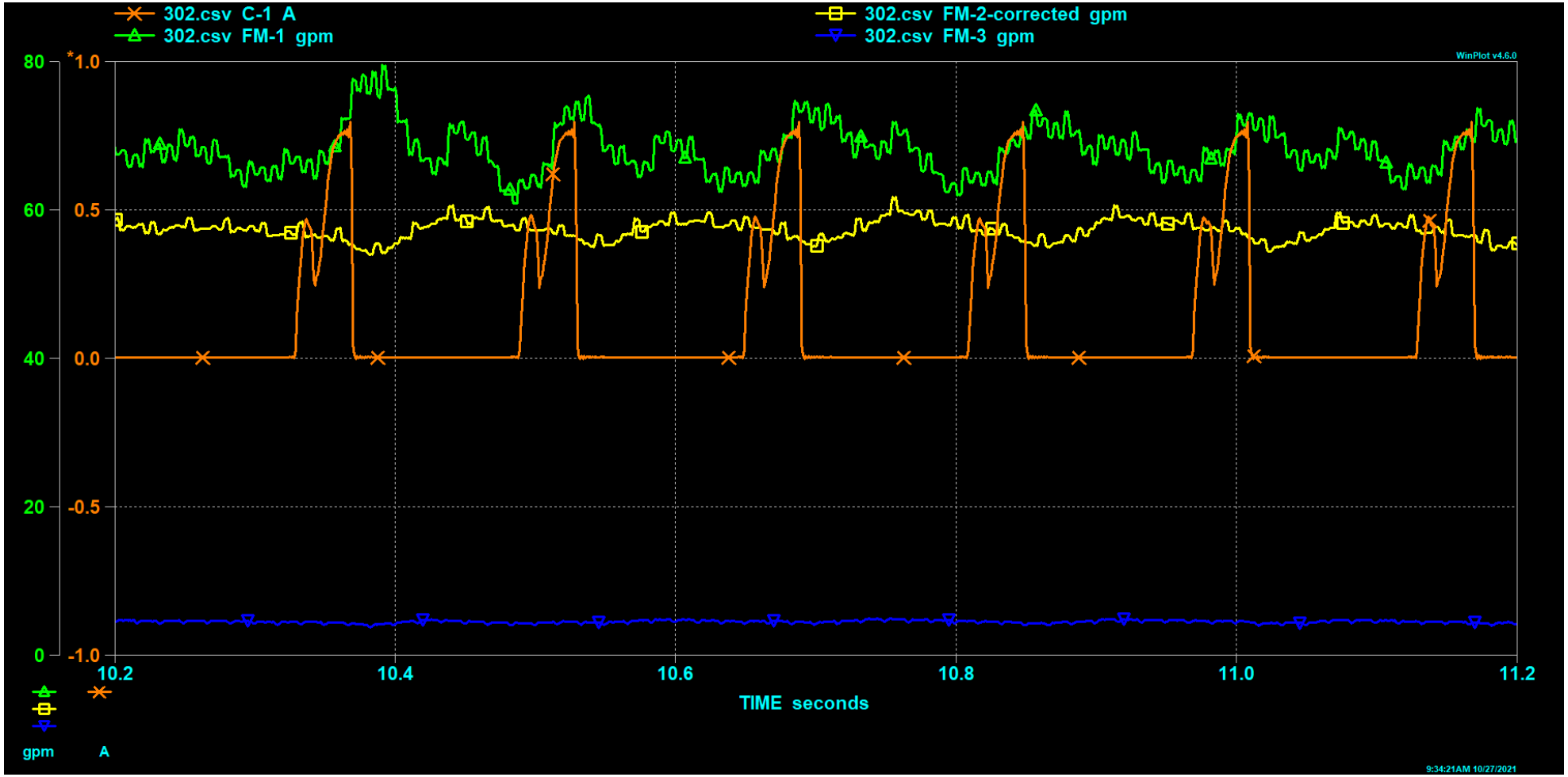


# GTO-2.3: Test #302: BPR Inlet Pressure

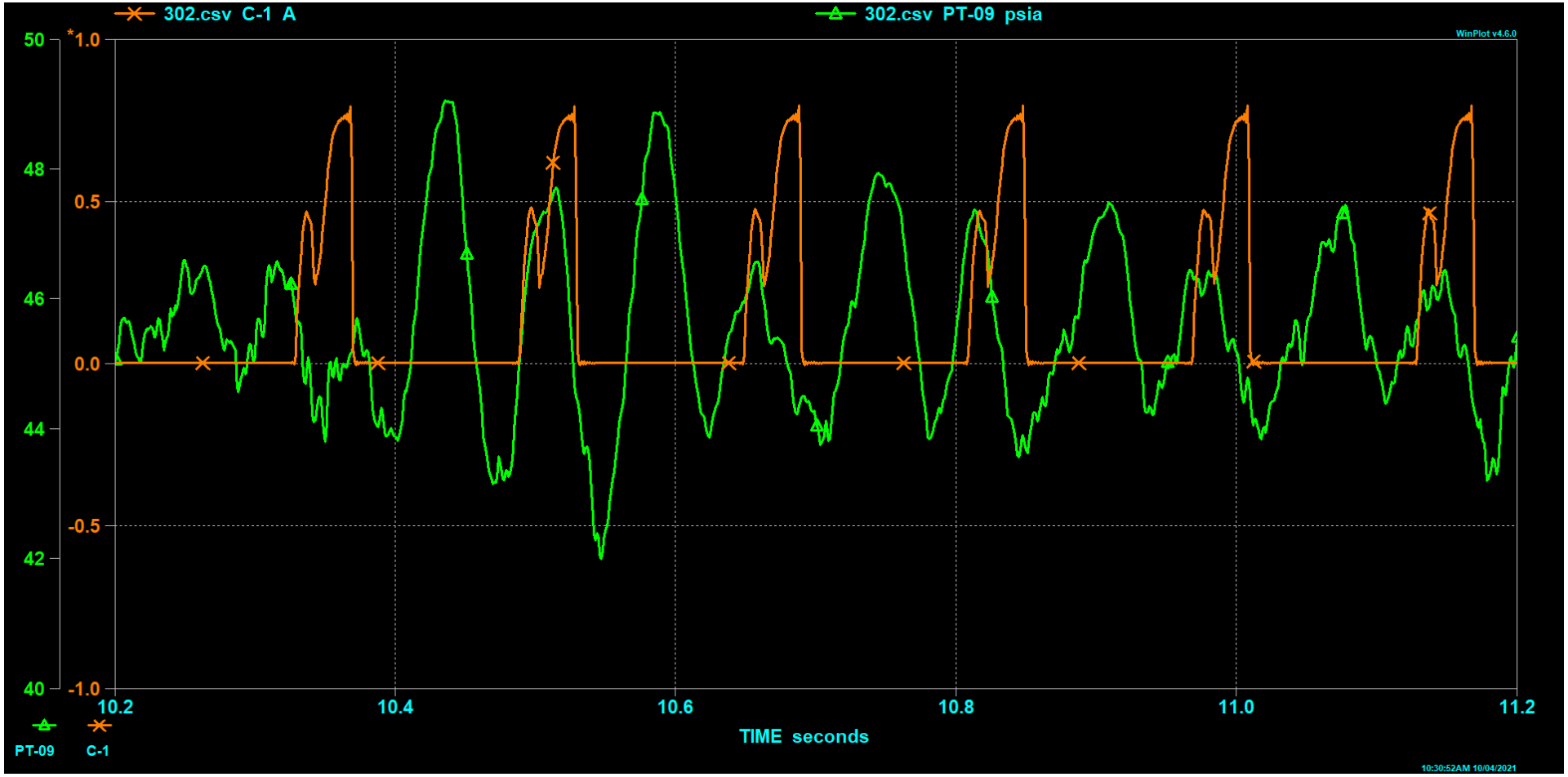
- **50 msec delay from close to pressure spike at BPR**
- **Pressure spike magnitude attenuated along flow path (30 psi)**



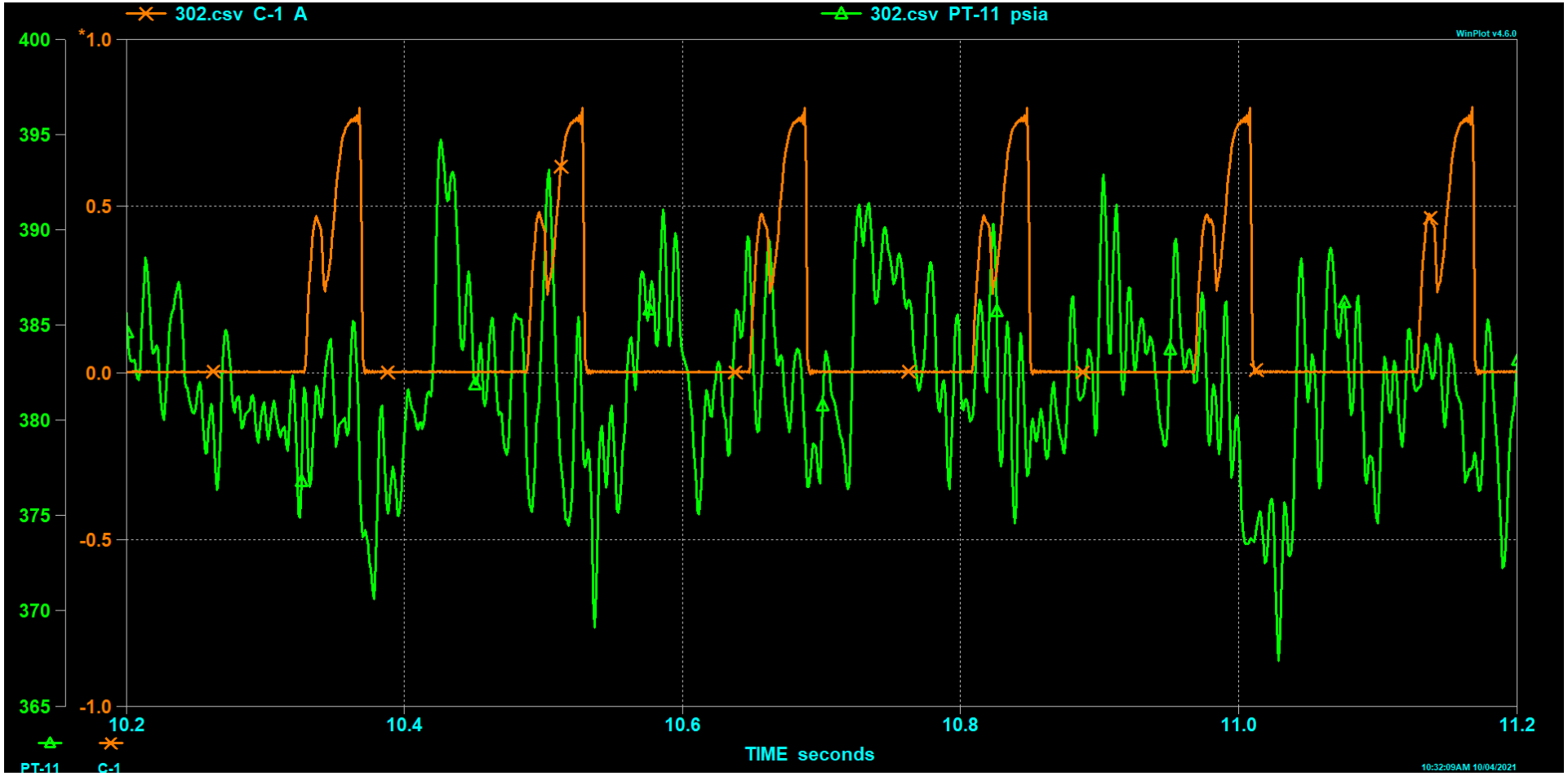
# GTO-2.3: Test #302: Flow Meters



# GTO-2.3: Test #302: Pump Inlet Pressure

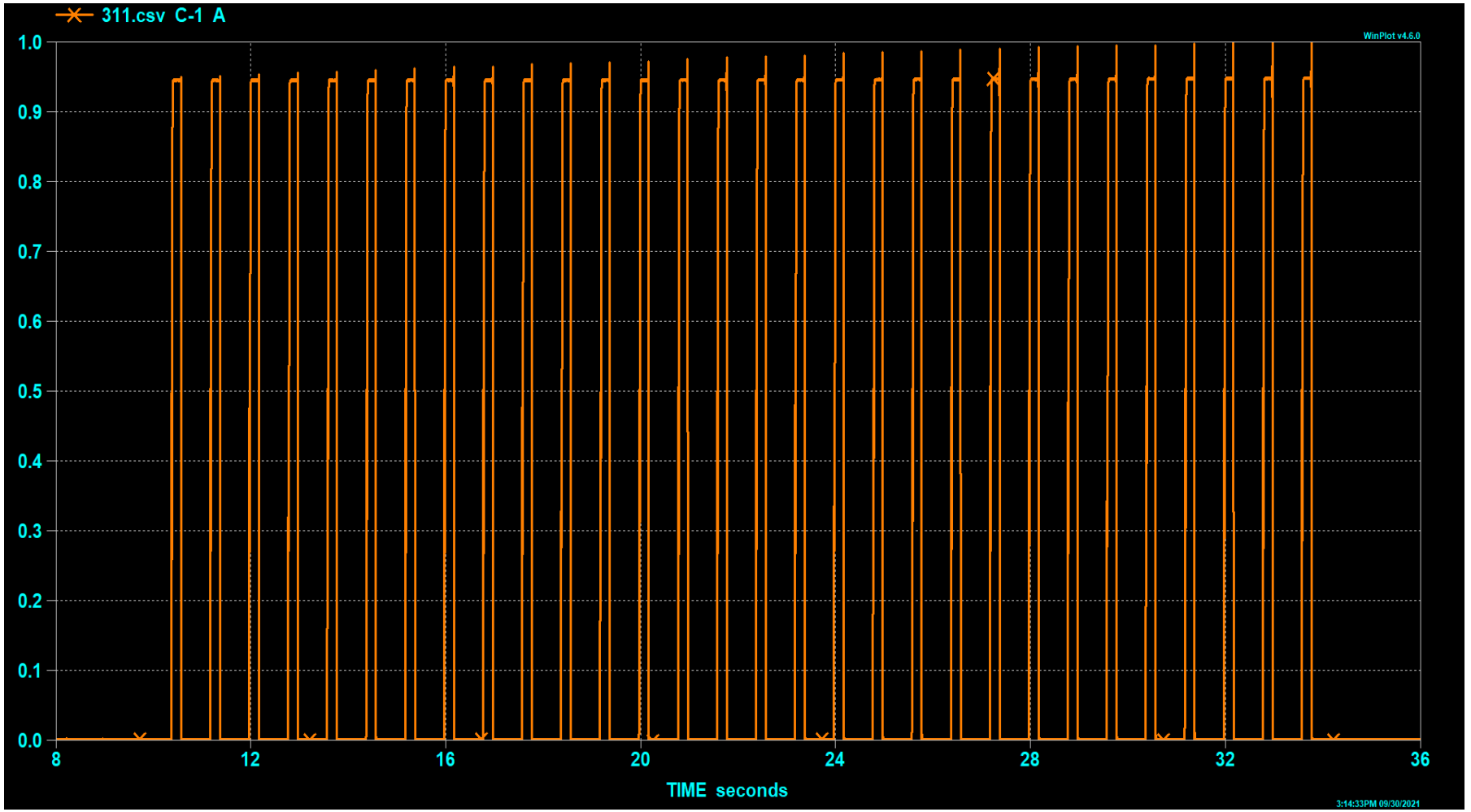


# GTO-2.3: Test #302: Pump Discharge Pressure



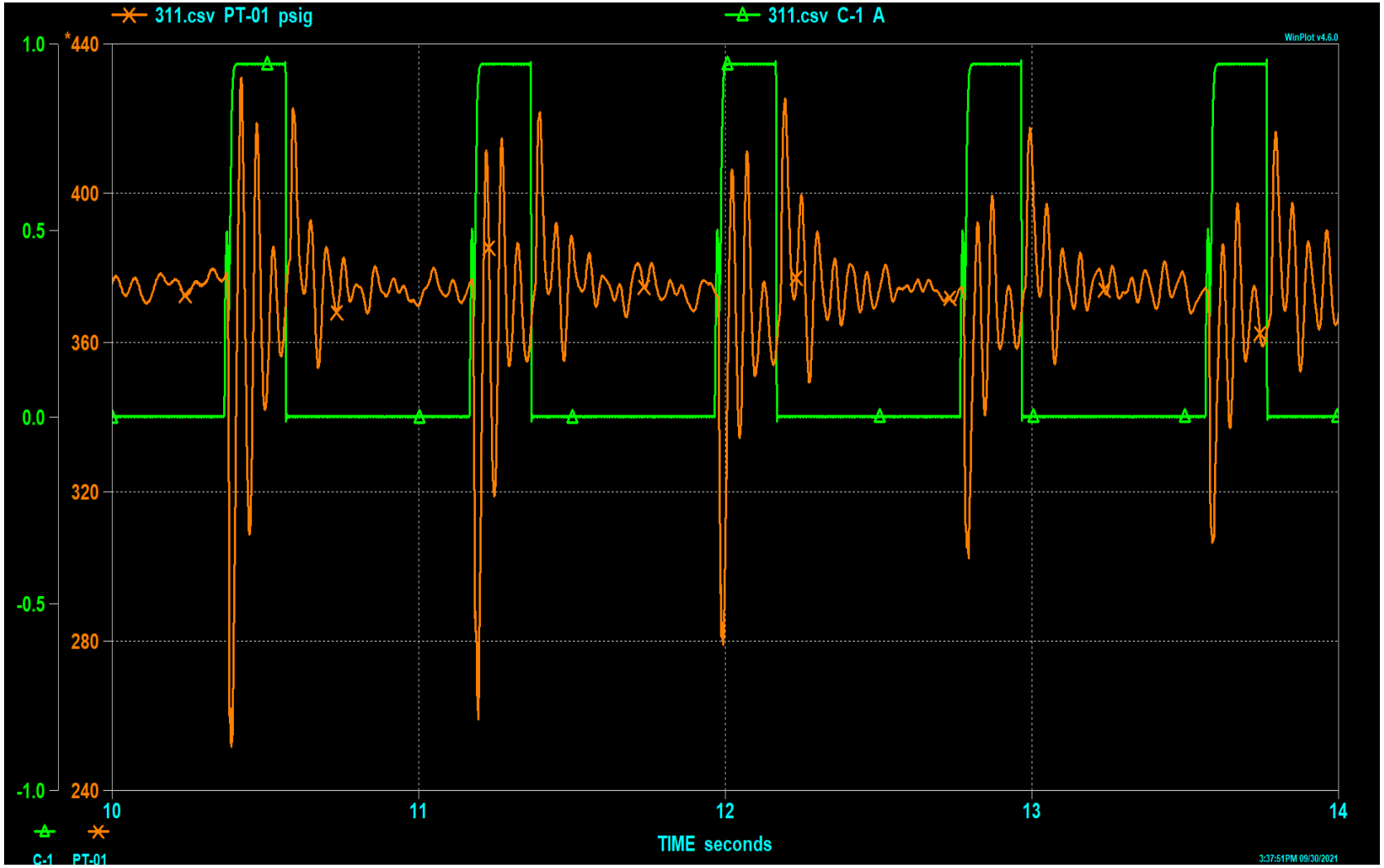
# GTO-2.3: Test #311 Thrust Pattern

- **6 thrusters, 200 msec pulses, 25% duty cycle**
  - Each peak is an open/close of a solenoid
- **Fix graphs? TK**



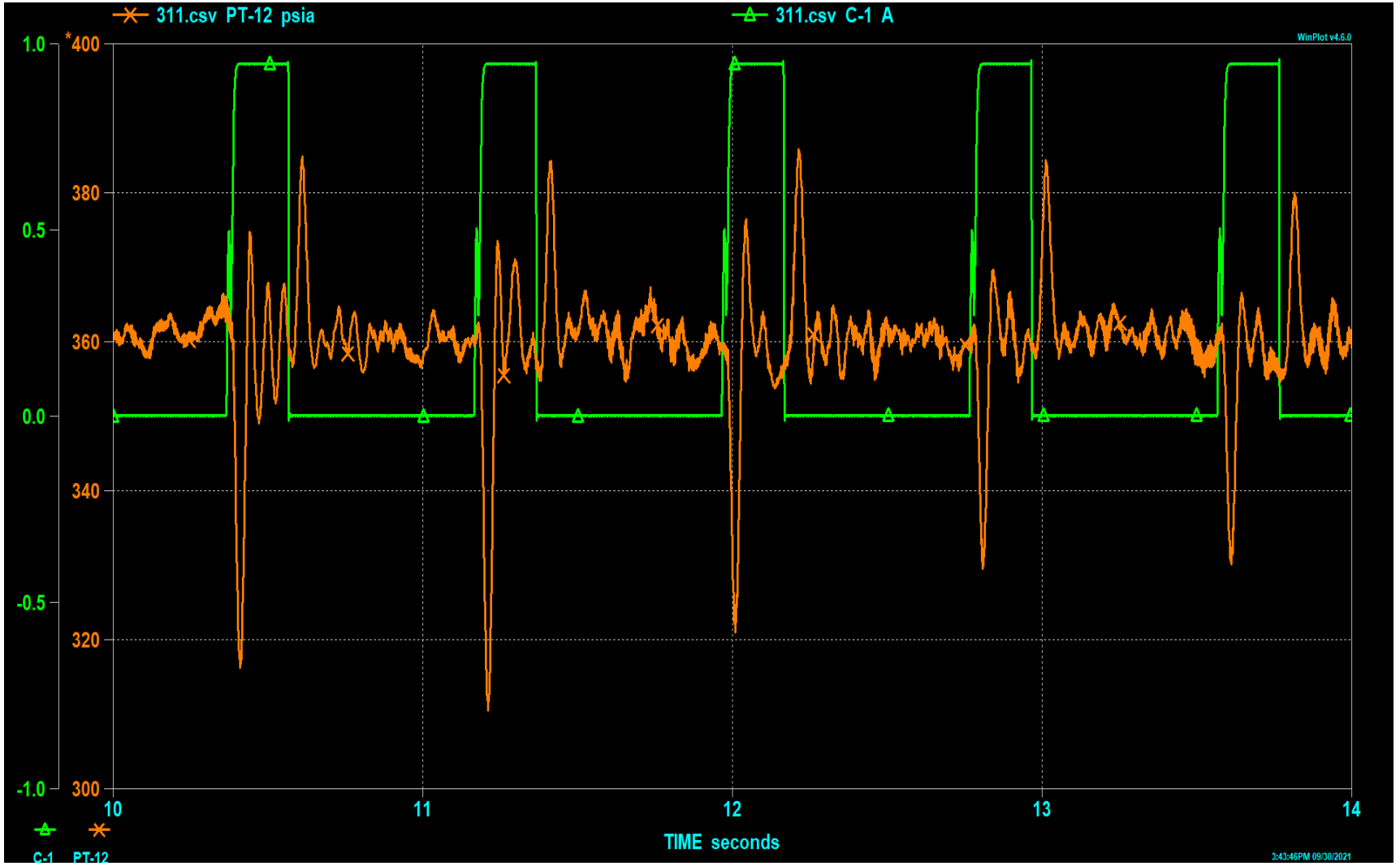
# GTO-2.3: Test #311: Inlet Pressure Response

- First five pulses
- 130 psi slump on open, 40 psi spike on close.
- Magnitude of slump decreased as test proceeded



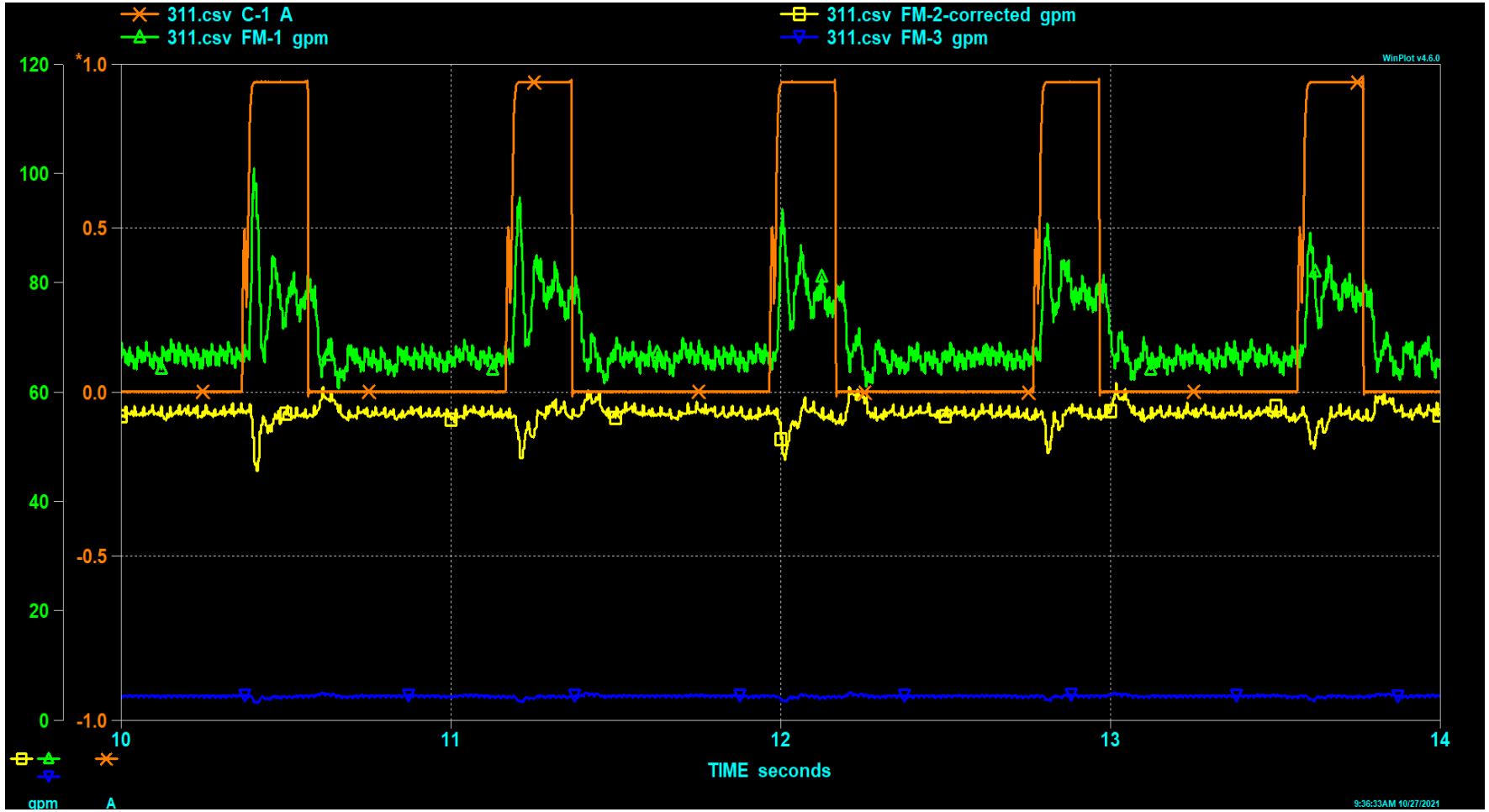
# GTO-2.3: Test #311: BPR Inlet Pressure

- **Smaller magnitude of pressure transients at BPR inlet**



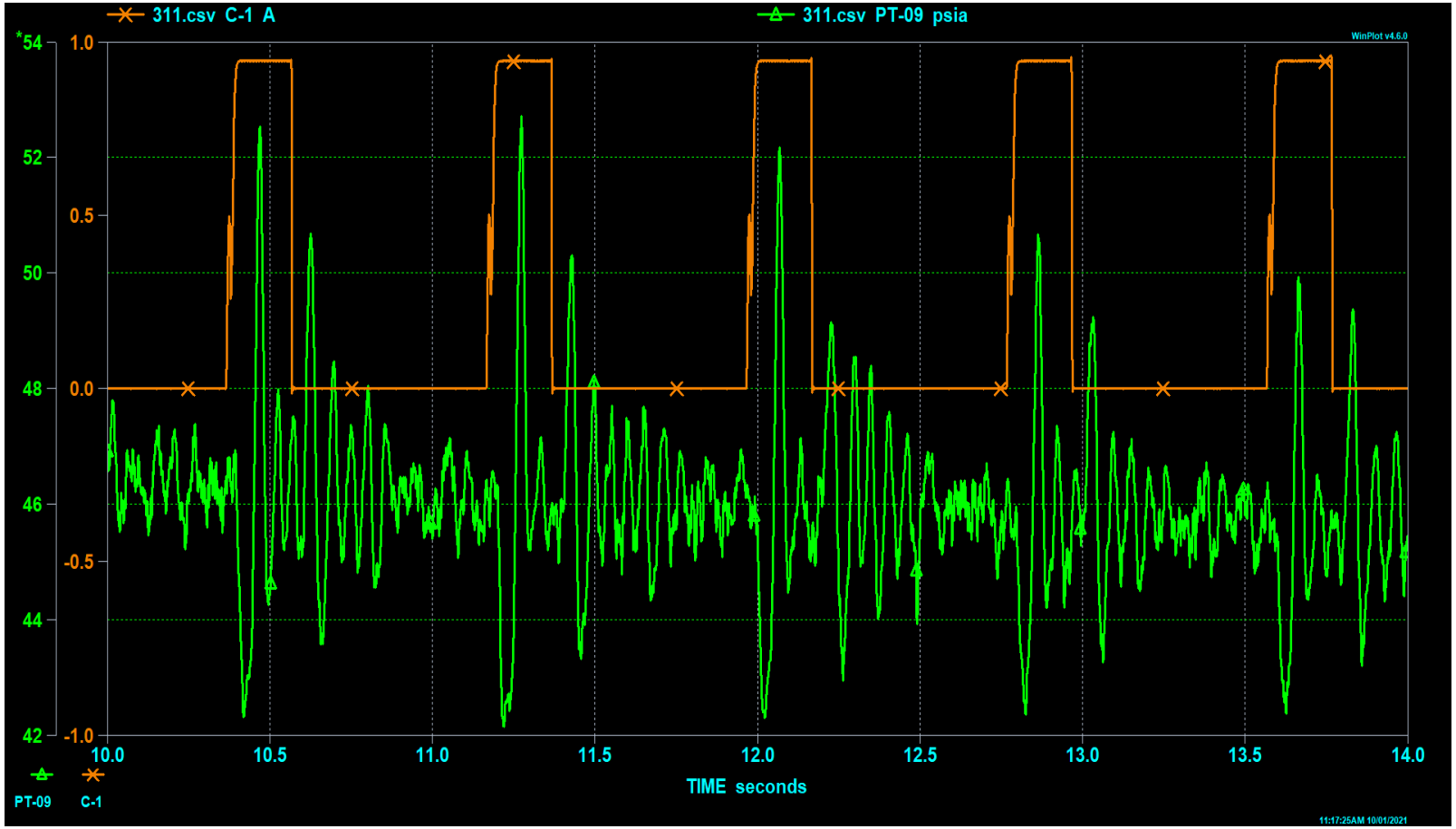
# GTO-2.3: Test #311: Flow Meters

- **Due to system design, some flow diverted through chill recirculation path (~0.4 GPM)**



# GTO-2.3: Test #311: Pump Inlet Pressure

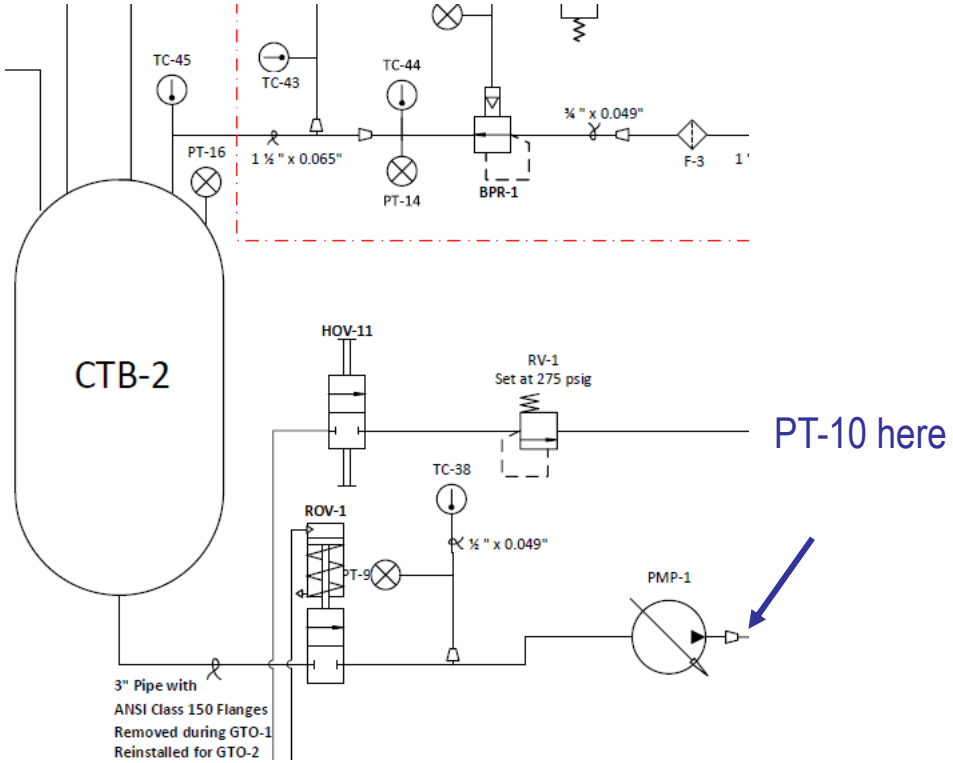
- **Pulses did not cause cavitation during pump operation**



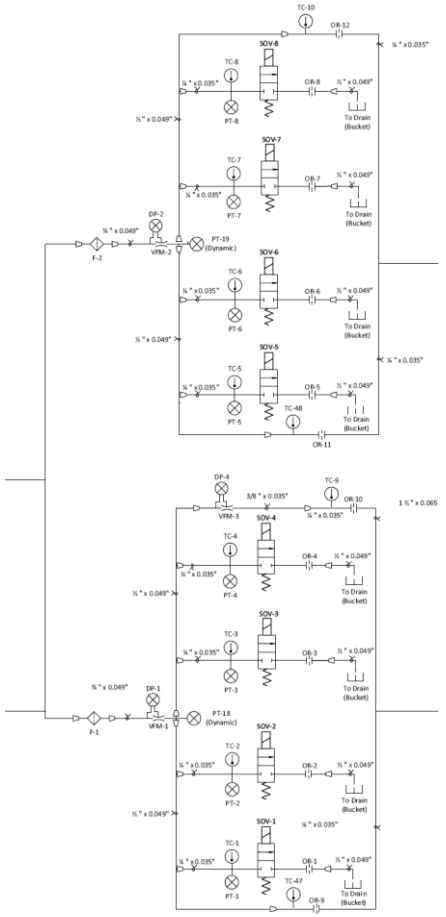
# GTO-2.3: Test #311: Pump Discharge

- **Pump discharge pressure shows a small response to valve pulses, but did not threaten pump operation.**

# Dynamic PT Locations



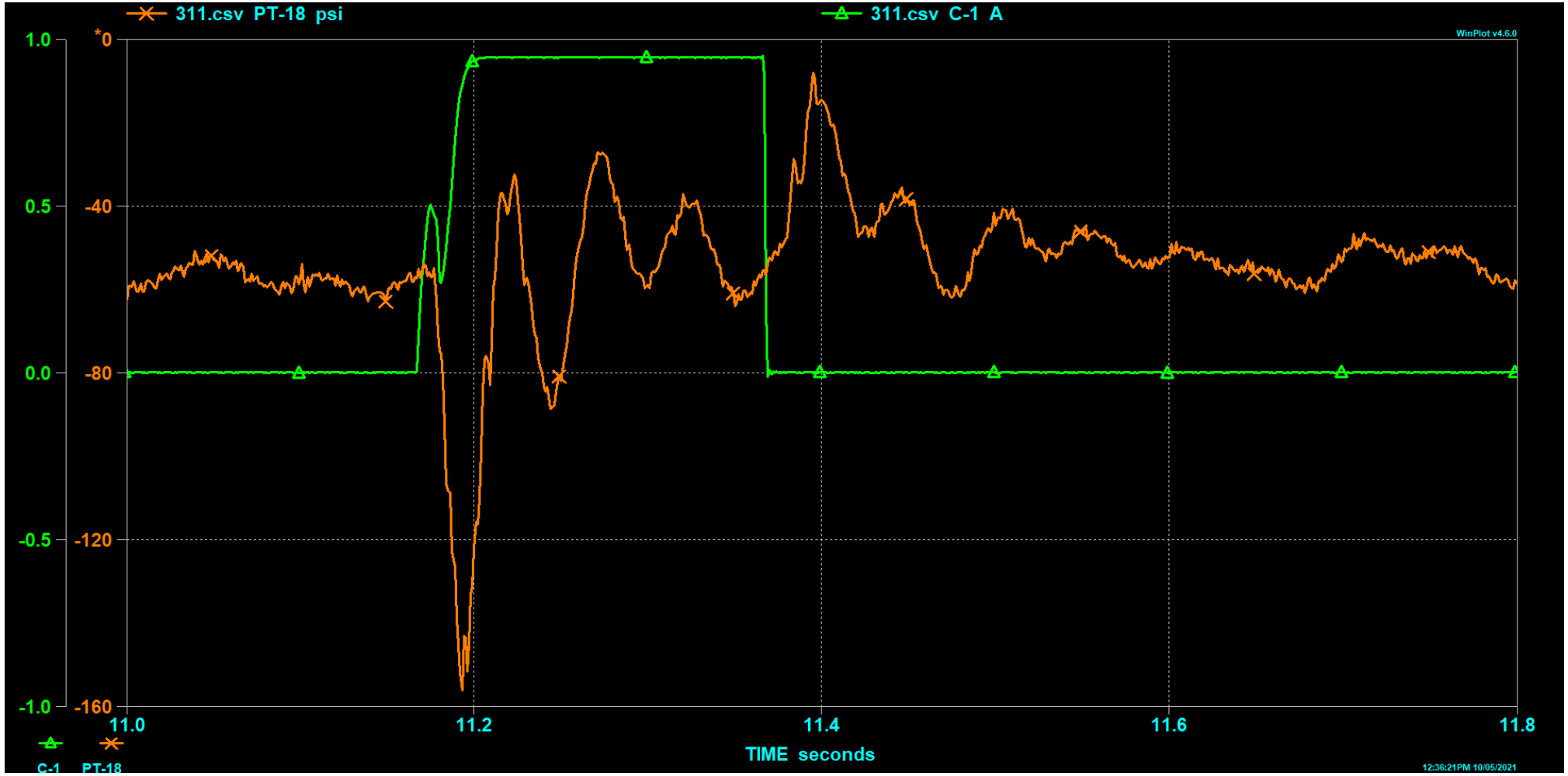

PT-10 here



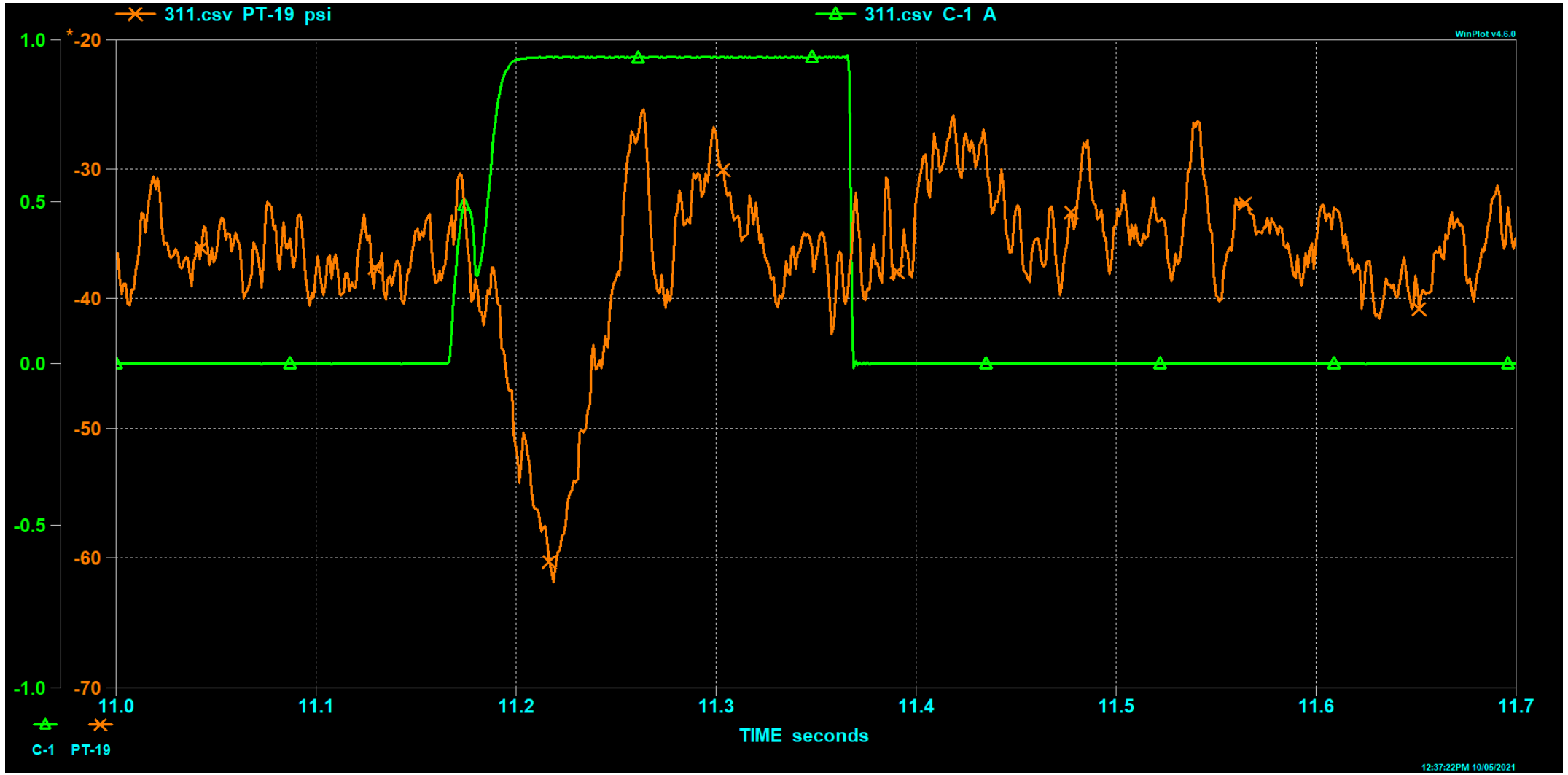
Thruster Pod 2

Thruster Pod 1

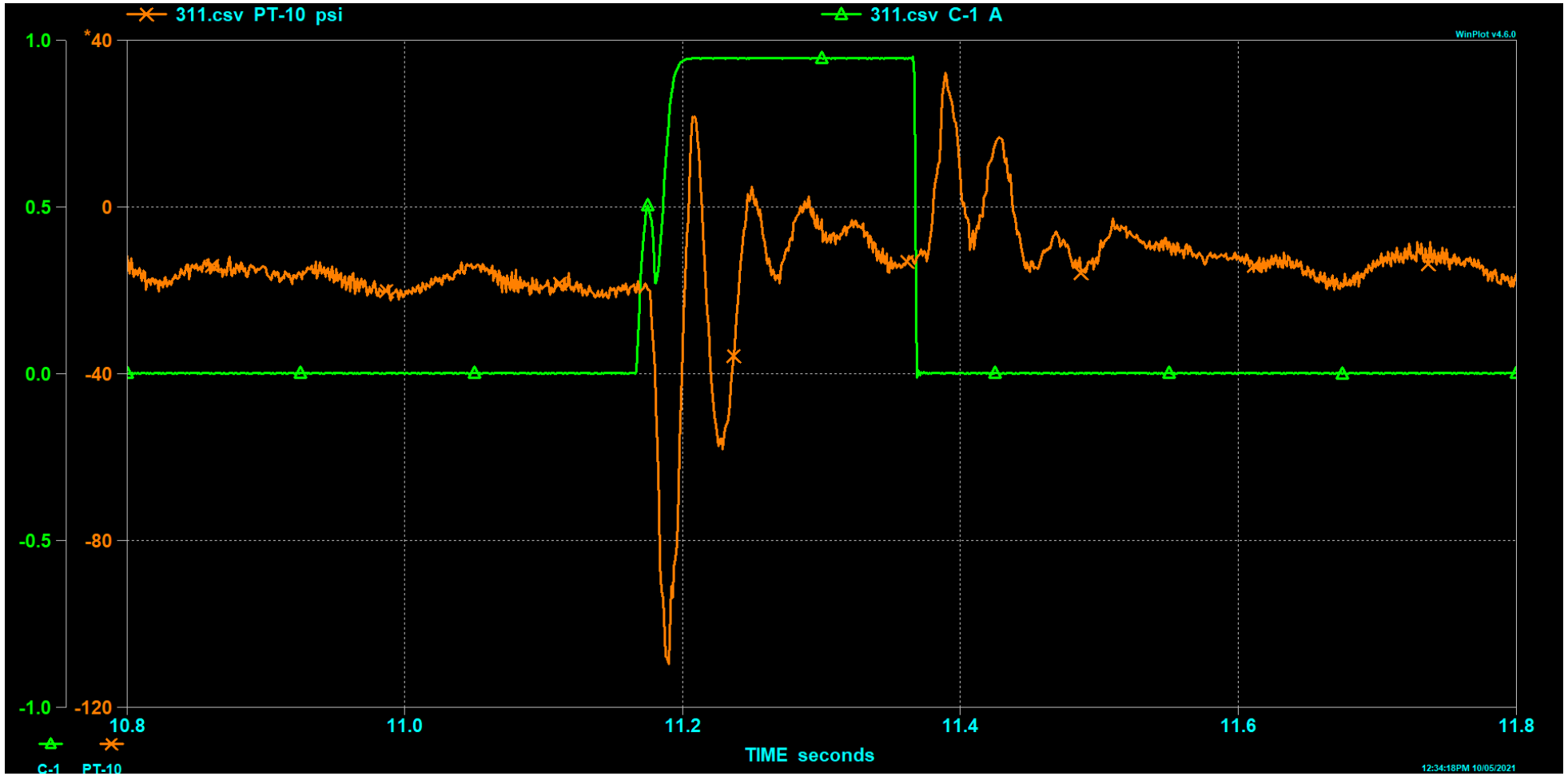
# GTO-2.3: Test #311: Water Hammer at Thruster Pod 1



# GTO-2.3: Test #311: Water hammer at Thruster Pod 2

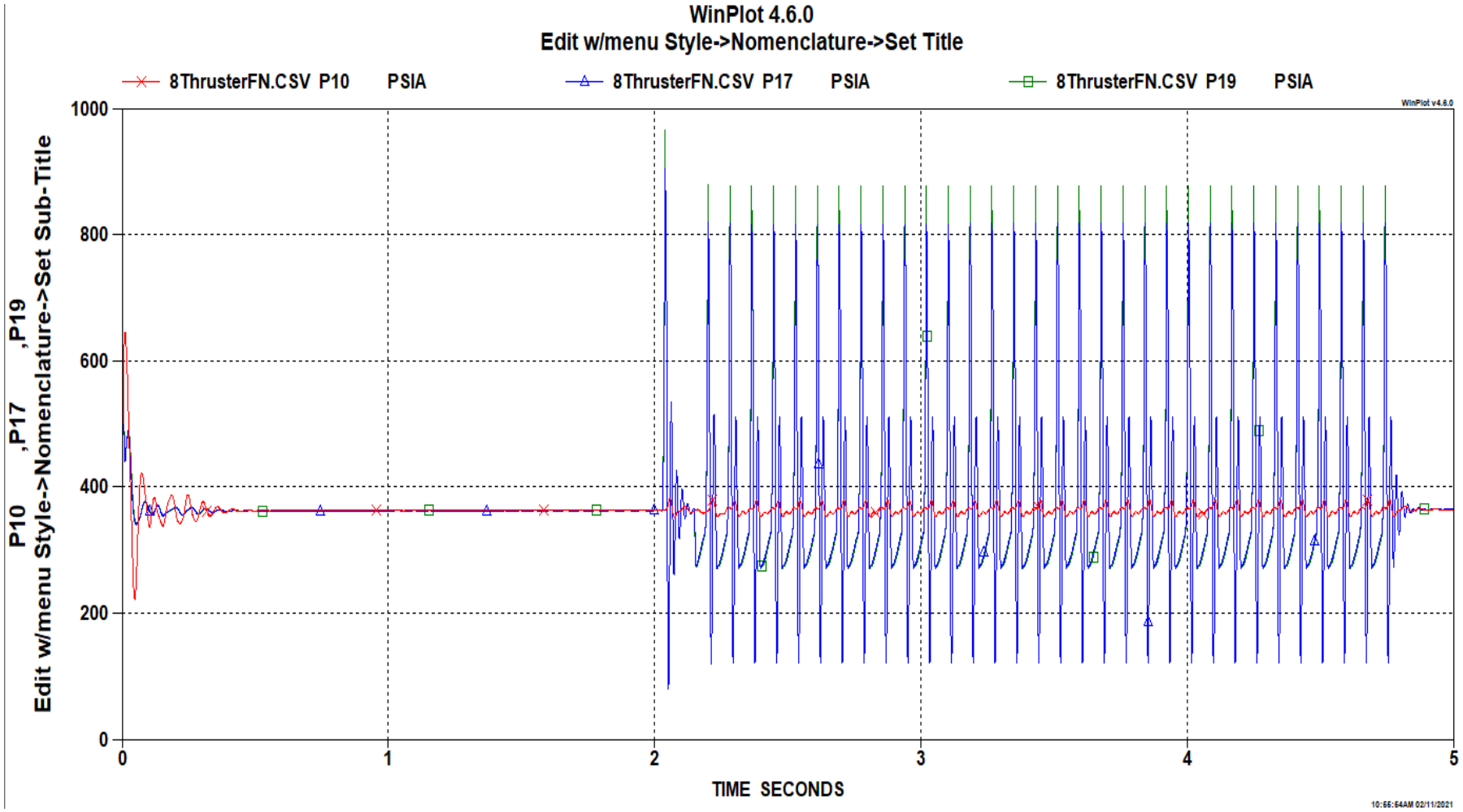


# GTO-2.3: Test #311: Water Hammer at Pump Discharge



# GTO-2.3: Pre-test Prediction Comparison

Test 302

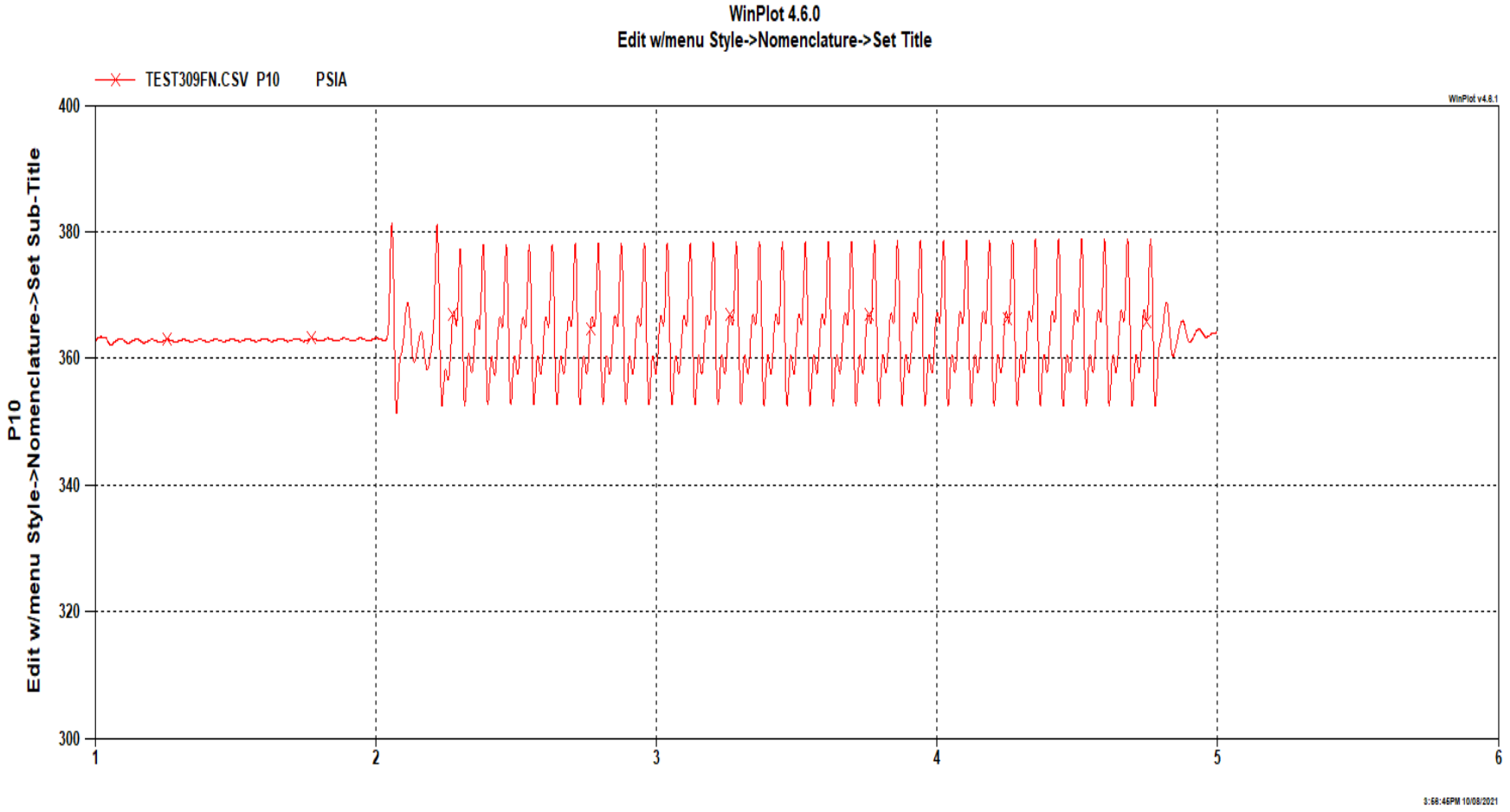



Slump:
Predicted: 88 psi drop
Actual: 135 psi drop

Spike:
Predicted: 457 psi rise
Actual: 60 psi spike

# GTO-2.3: Pre-test Prediction Comparison

## Test 302, BPR only




Slump:
Predicted: 10 psi drop
Actual: ~12 psi drop

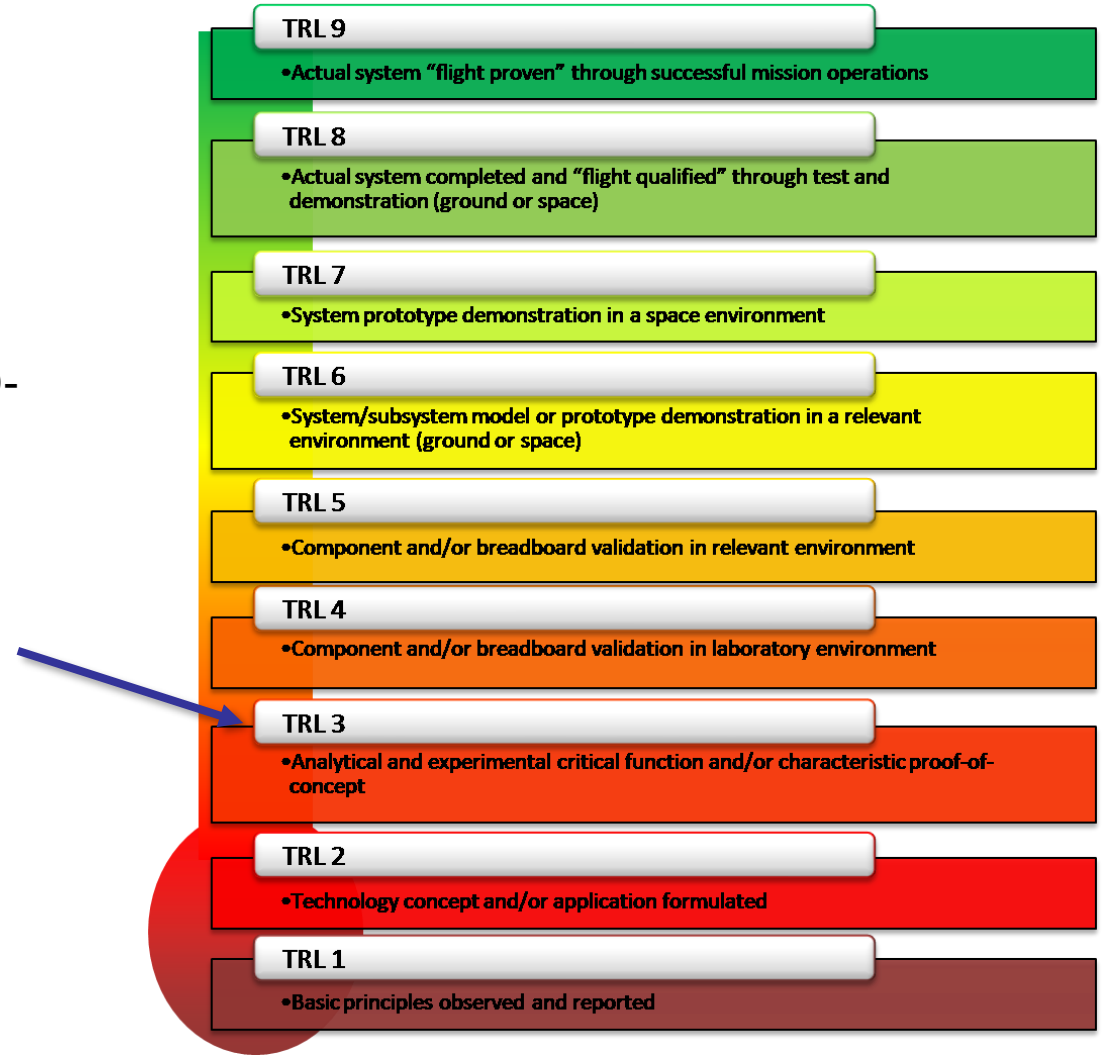
Spike:
Predicted: 18.5 psi rise
Actual: 30 psi spike

# Conclusions

- **There are a few possible explanations for the difference between predictions and test**
  - Test data collection sample rate was not high enough to record peak pressure
  - Model has one or more issues in implementation and/or numerical issues.
  - Model was based on original flowrate intentions for test – substantially less flowrate through bypass line
    - –However, issue is more pronounced at thruster inlet, not at BPR

# Summary

- **Tank Heat Load successfully measured**
- **The team has new operational experience with running a cryogenic recirculation pump**
- **Additional heat from pump measured, but with some uncertainty due to instrumentation failure**
  - Flow meter cable shields were not grounded for GTO-2.1, which led us to measuring heat load by bulk LN2 temperature changes
- **iRCS Recirculation concept now at TRL 3**



# Next Steps

- **Set up for next test series to use ER14's Digital Valve concept as recirculation loop pressure regulator**
  - Joey Hakanson in EV42 is working on a control algorithm for the digital valve
- **Research gear pumps and select one for procurement**
  - Priority is to select a smaller pump
- **Continue analyzing pulsing test series data**
- **Future tests will have dedicated objectives for water hammer characterization**
- **Will add objectives to characterize ability to control magnitude of slumps and spikes, pressure oscillation decay time, etc.**

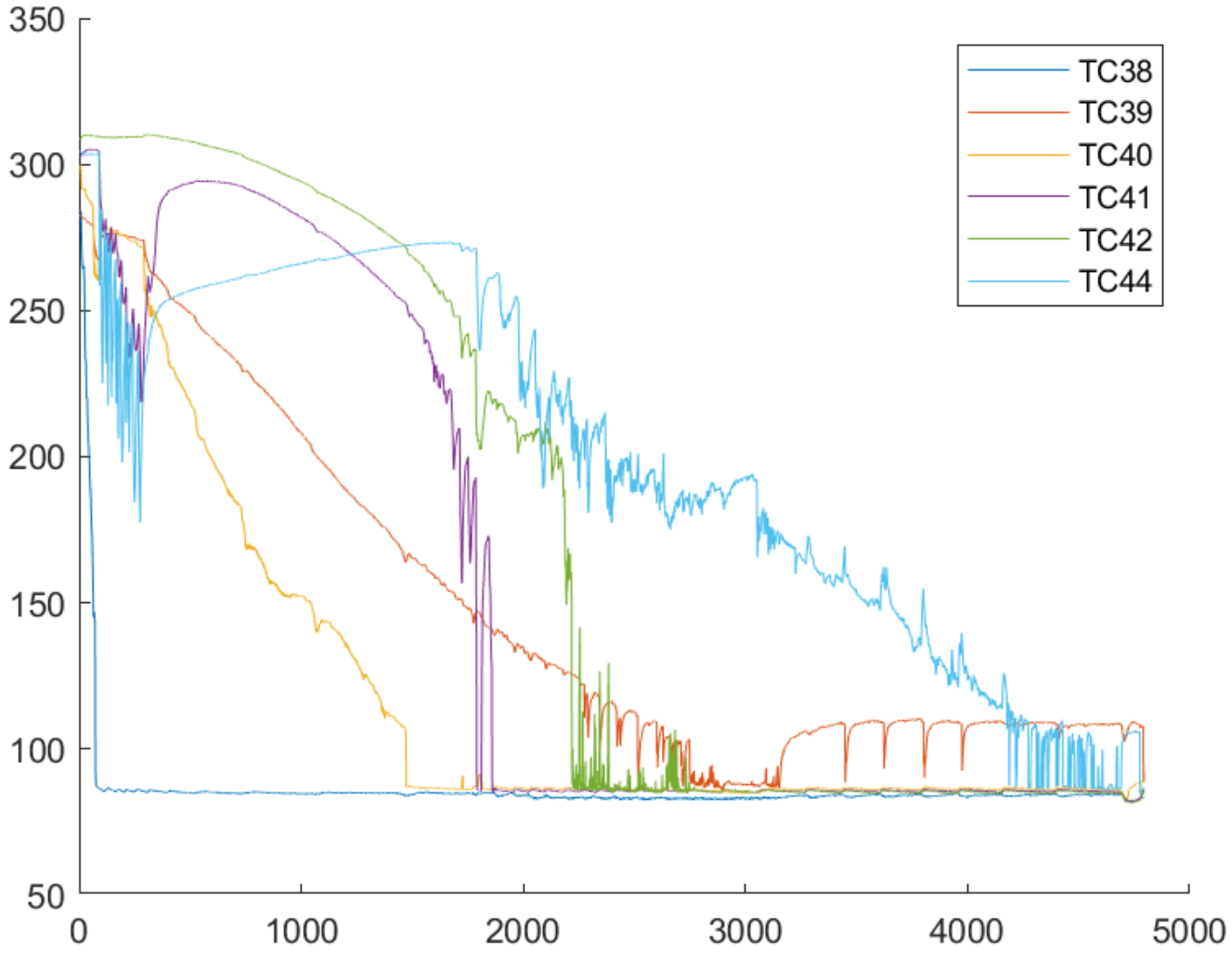
# Lessons Learned

- **Check. Flow. Meters.**
- **Use correctly sized pump for application**
- **Shield cables in the presence of high-voltage power**
- **Include extra time for system shakedown in test schedule**

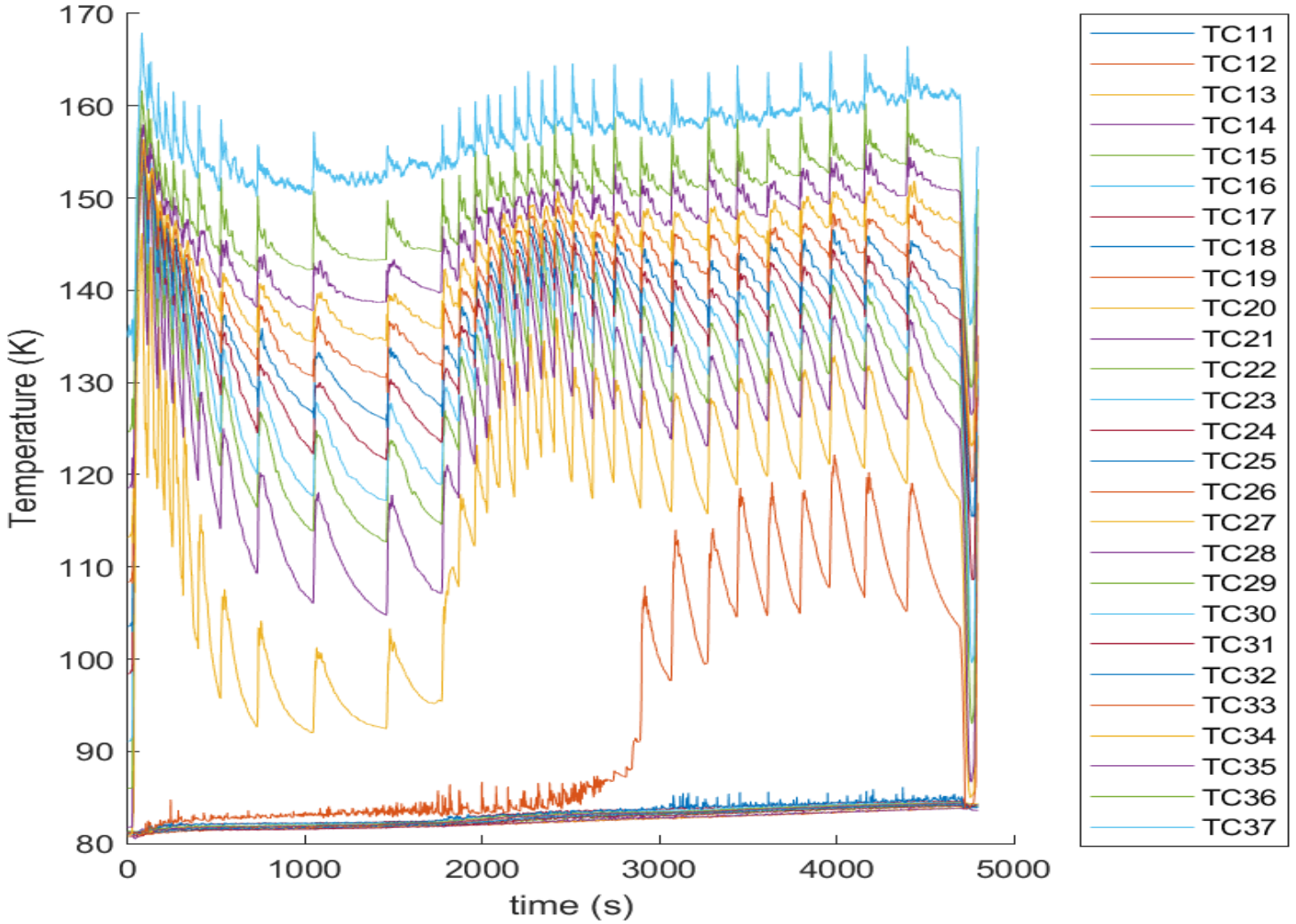
# Questions?

# Backup

# Recirculation Loop Chilldown



# Tank Chilldown



# Thruster Pod Chilldown