Liquid Nitrogen Testing of an Integrated Reaction Control System

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Thermal & Fluids Analysis Workshop
TFAWS 2022
September 6th-9th, 2022
Virtual Conference

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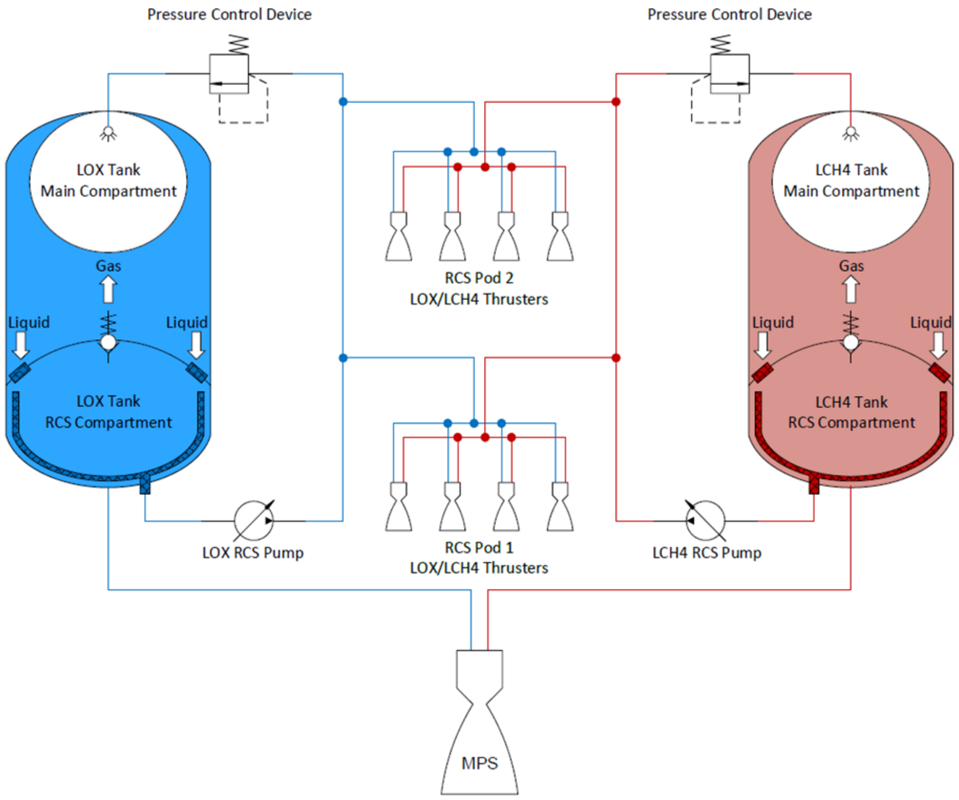
- Integrated Reaction Control System (iRCS) is an innovative concept to utilize MPS propellant for RCS thrusters
- Intended to reduce system complexity and potentially reduce attitude control system mass



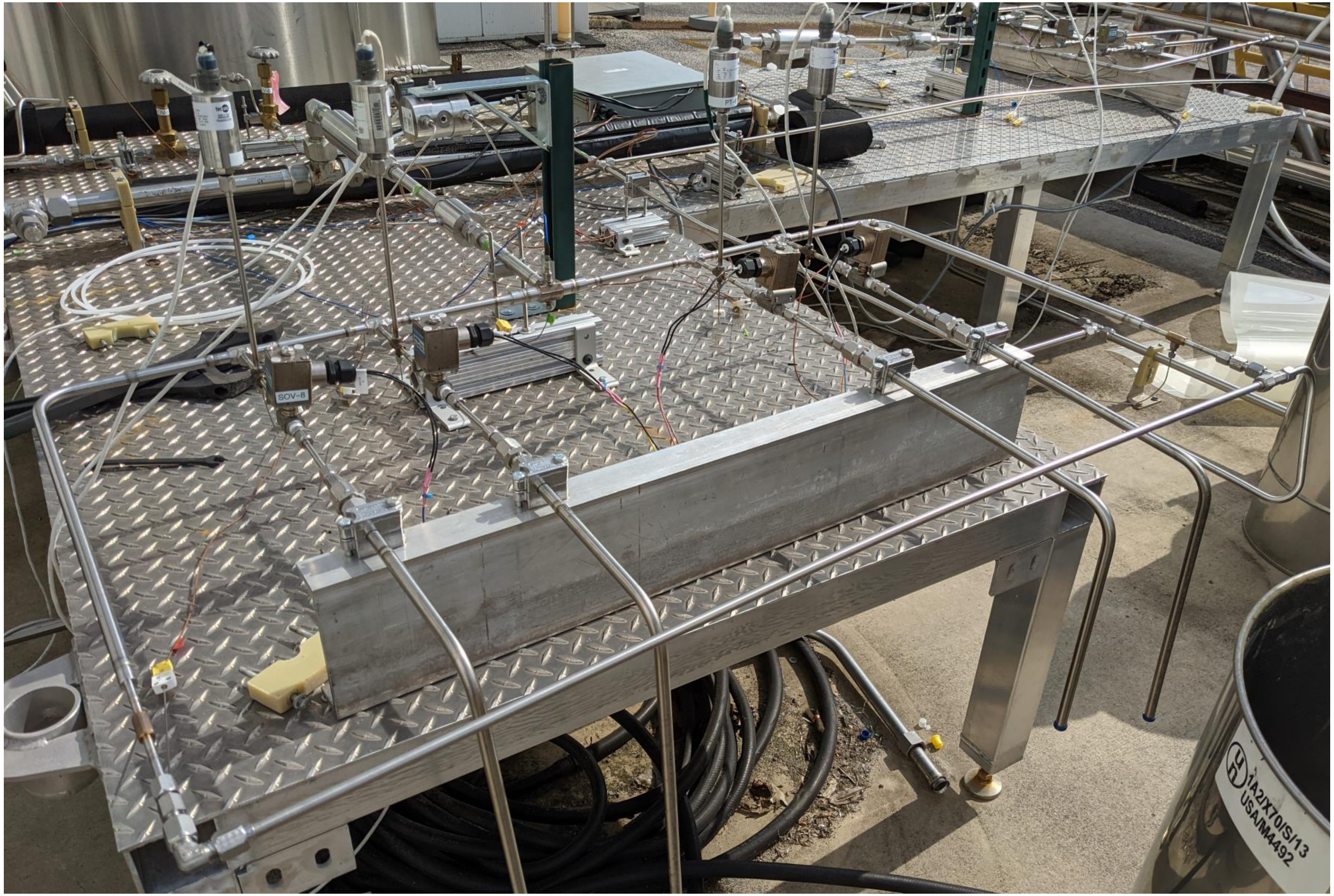
iRCS Challenges

- 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

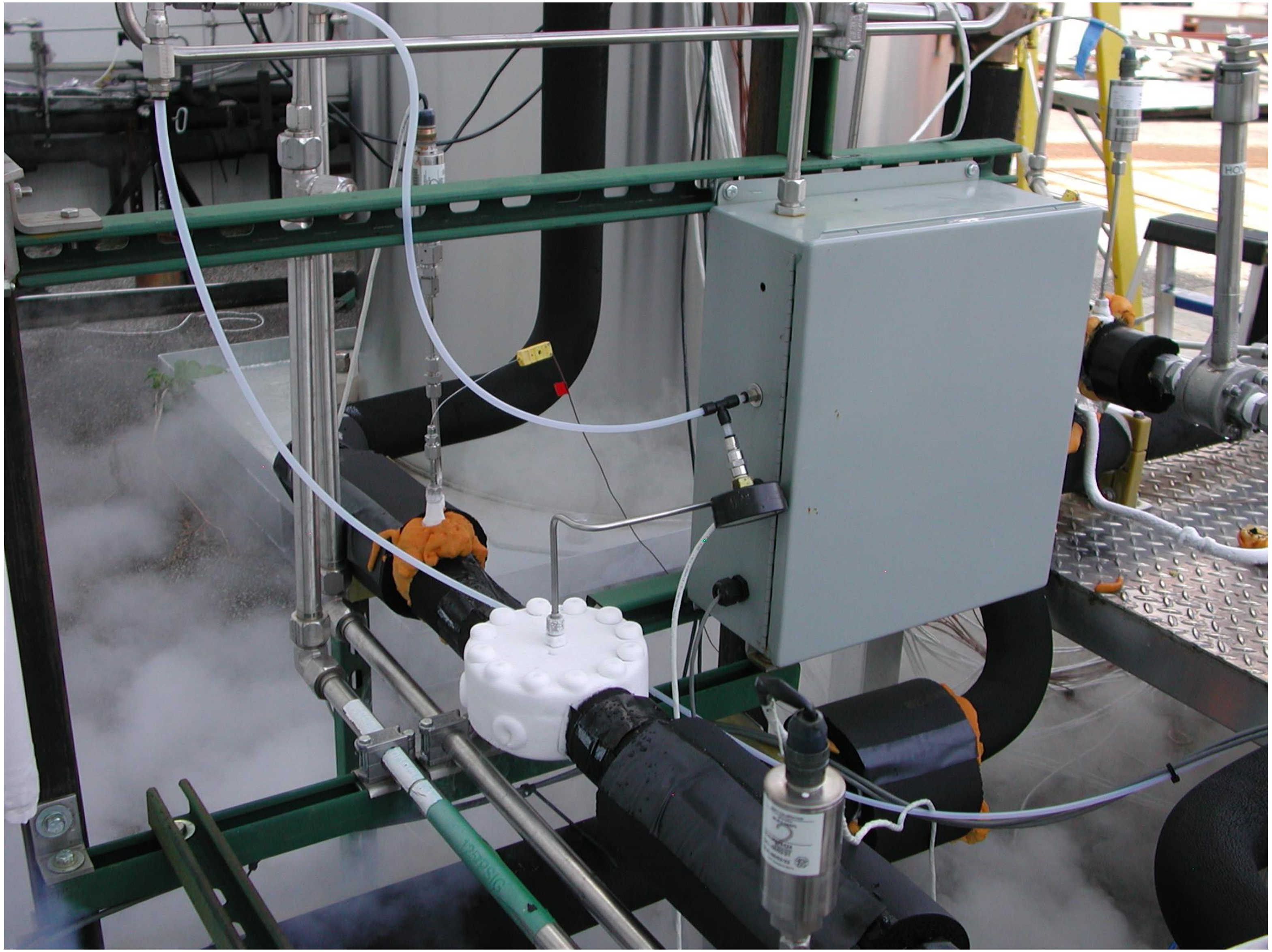
- iRCS Liquid Nitrogen testbed buildup began in late 2019 in the Propulsion Research Lab in lab 108
- CTB2 Tank used as main LN2 supply inside 108
- Recirculation loop with “thruster pods” set up outside 108
- Buildup on hold due to COVID-19, resumed in January 2021
- Test series completed in late August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

Thruster Pod Before Insulating

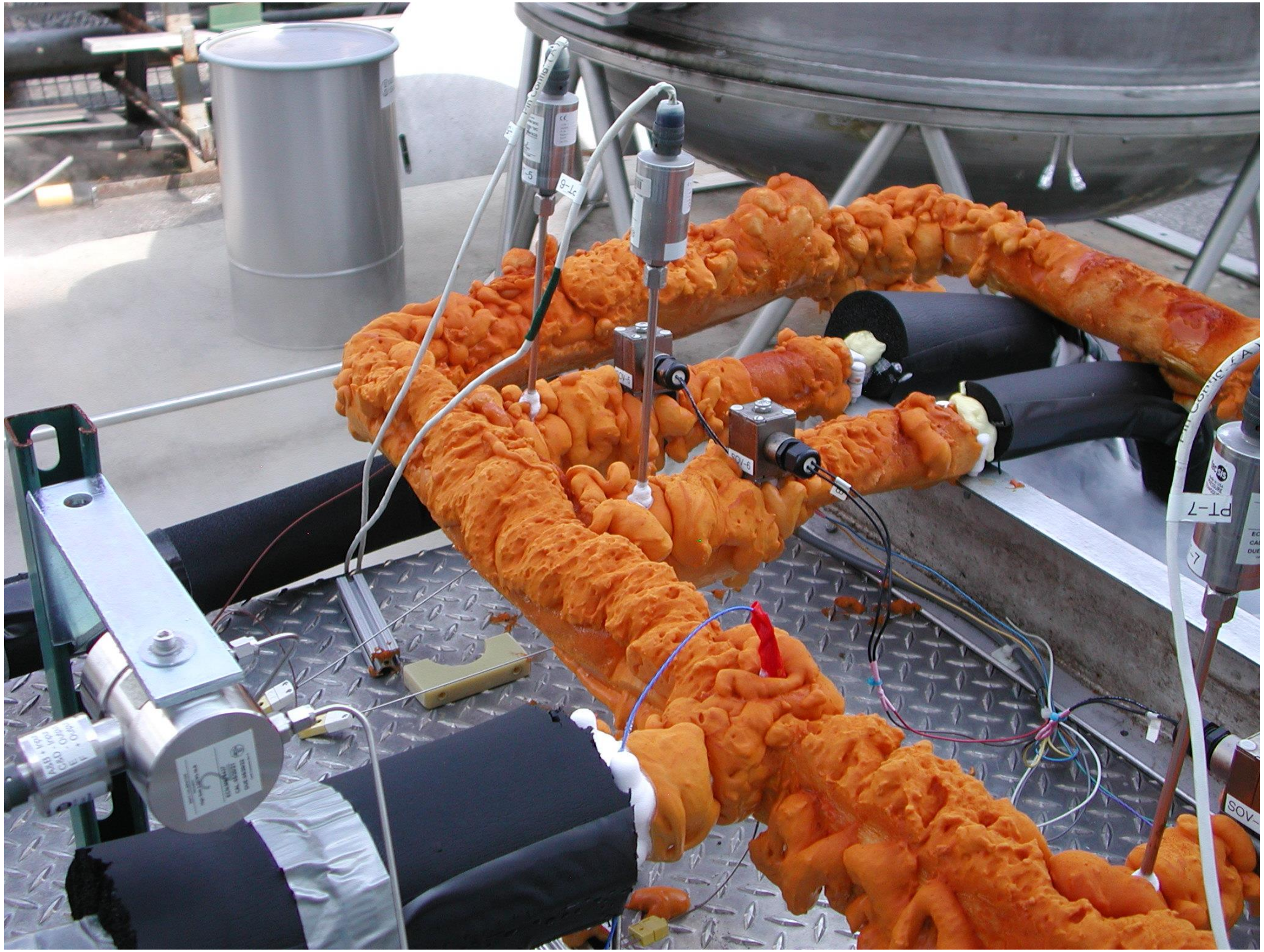


Test Article Pictures

Back Pressure Regulator

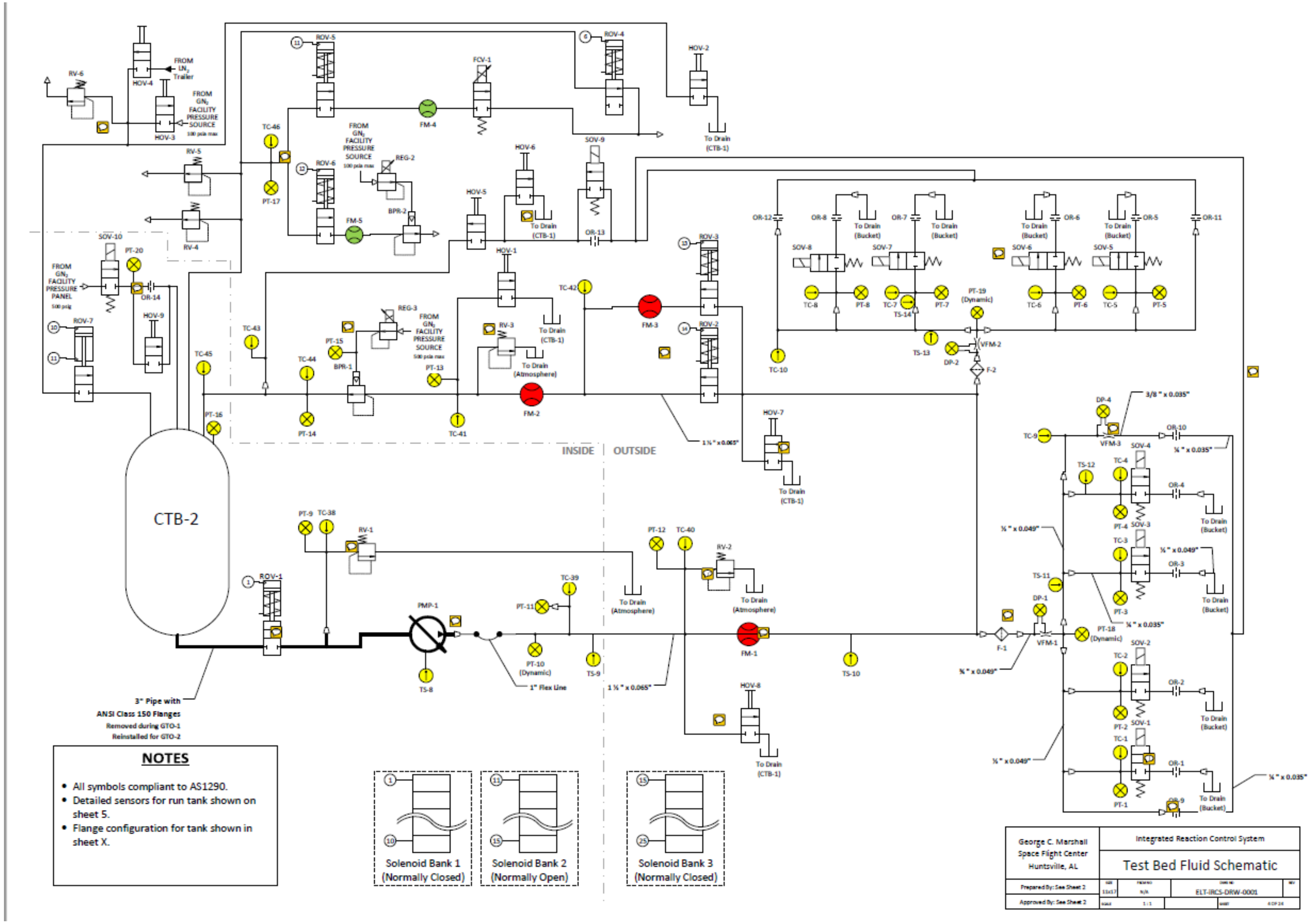


Thruster Pod Detail



System During Testing

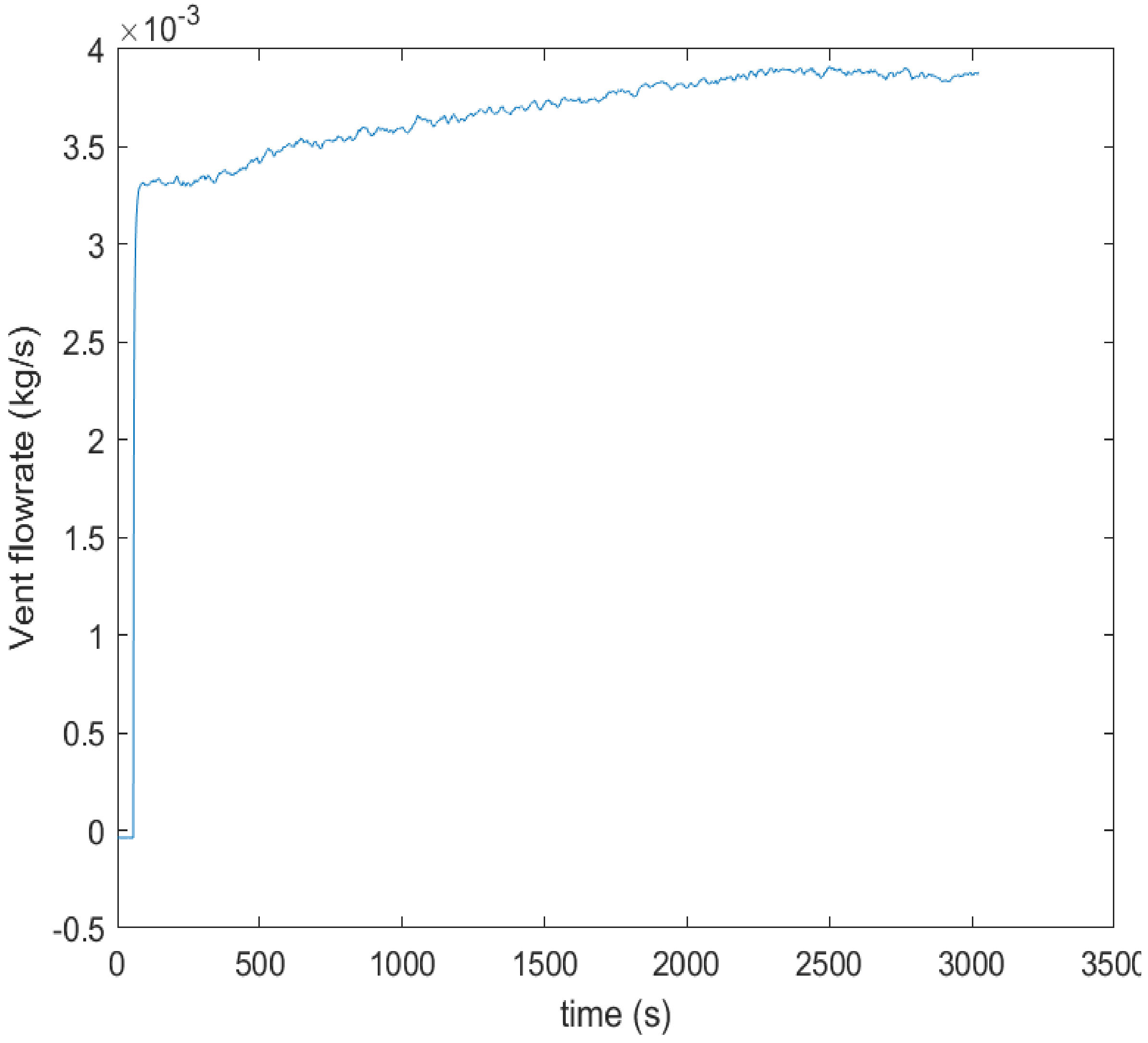
System Schematic



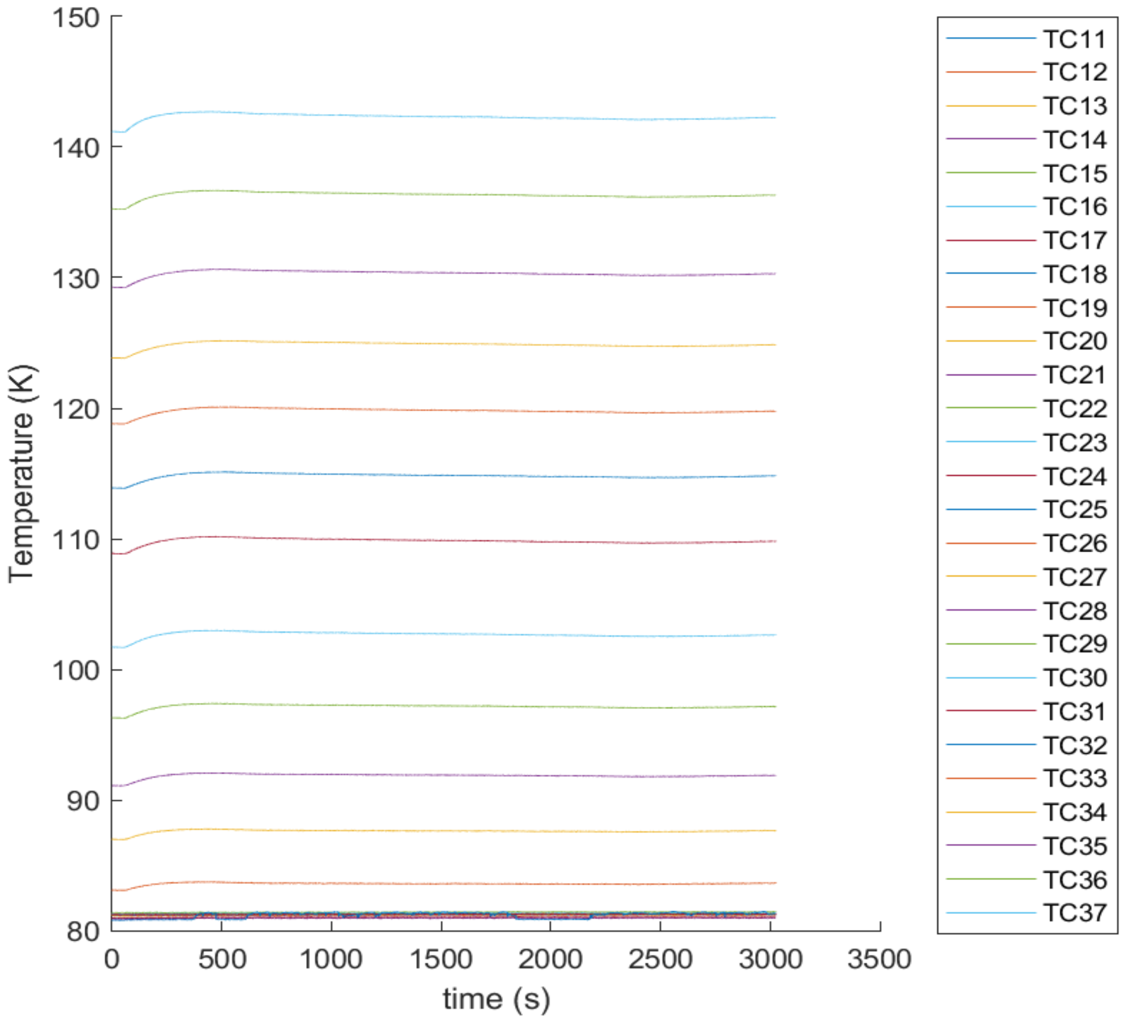
Test Objectives

- 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 52% Fill



×10^-3
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
Vent flowrate (kg/s)
0
500
1000
1500
2000
2500
3000
3500
time (s)



150
140
130
120
110
100
90
80
Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
time (s)
TC11
TC12
TC13
TC14
TC15
TC16
TC17
TC18
TC19
TC20
TC21
TC22
TC23
TC24
TC25
TC26
TC27
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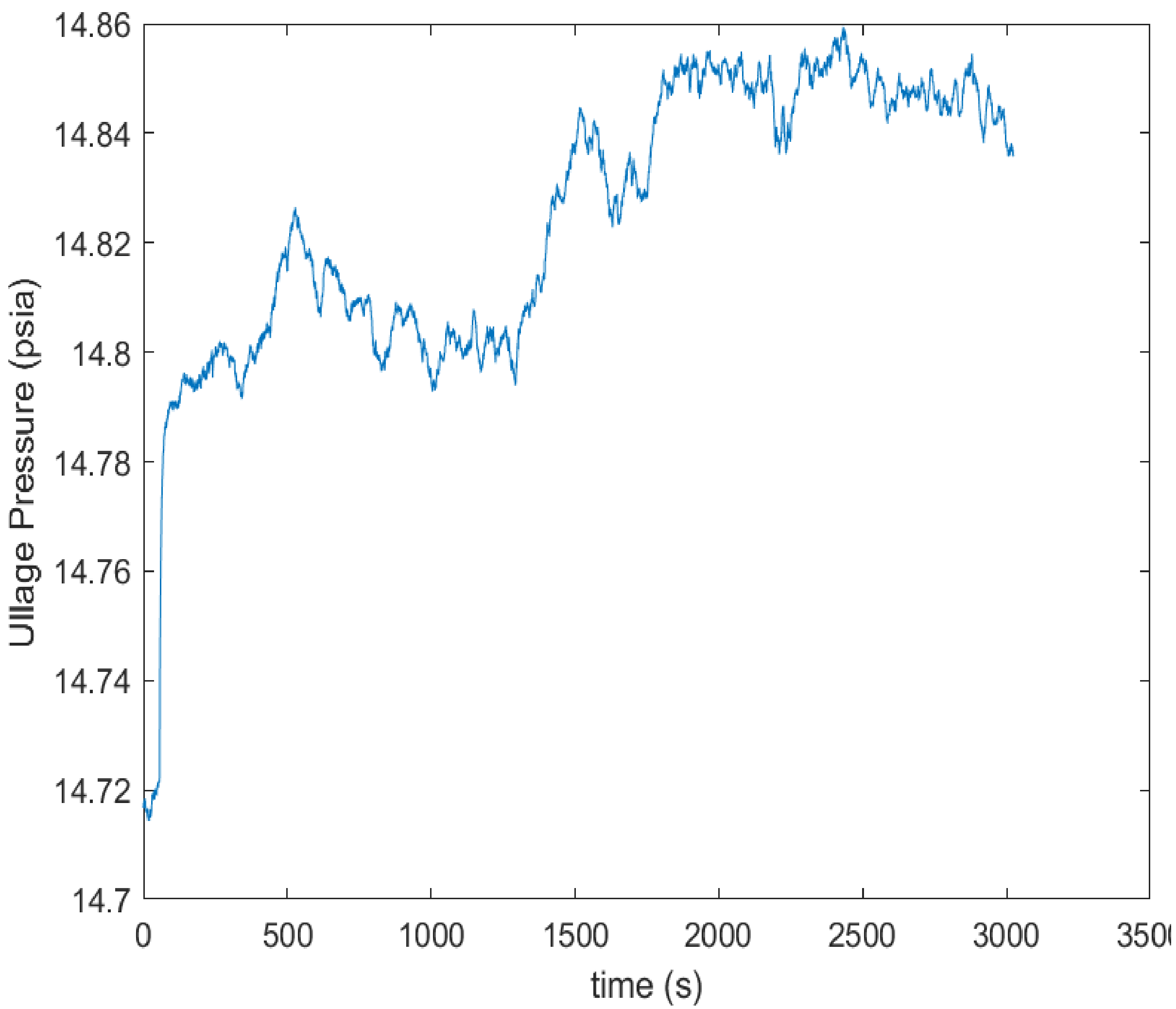
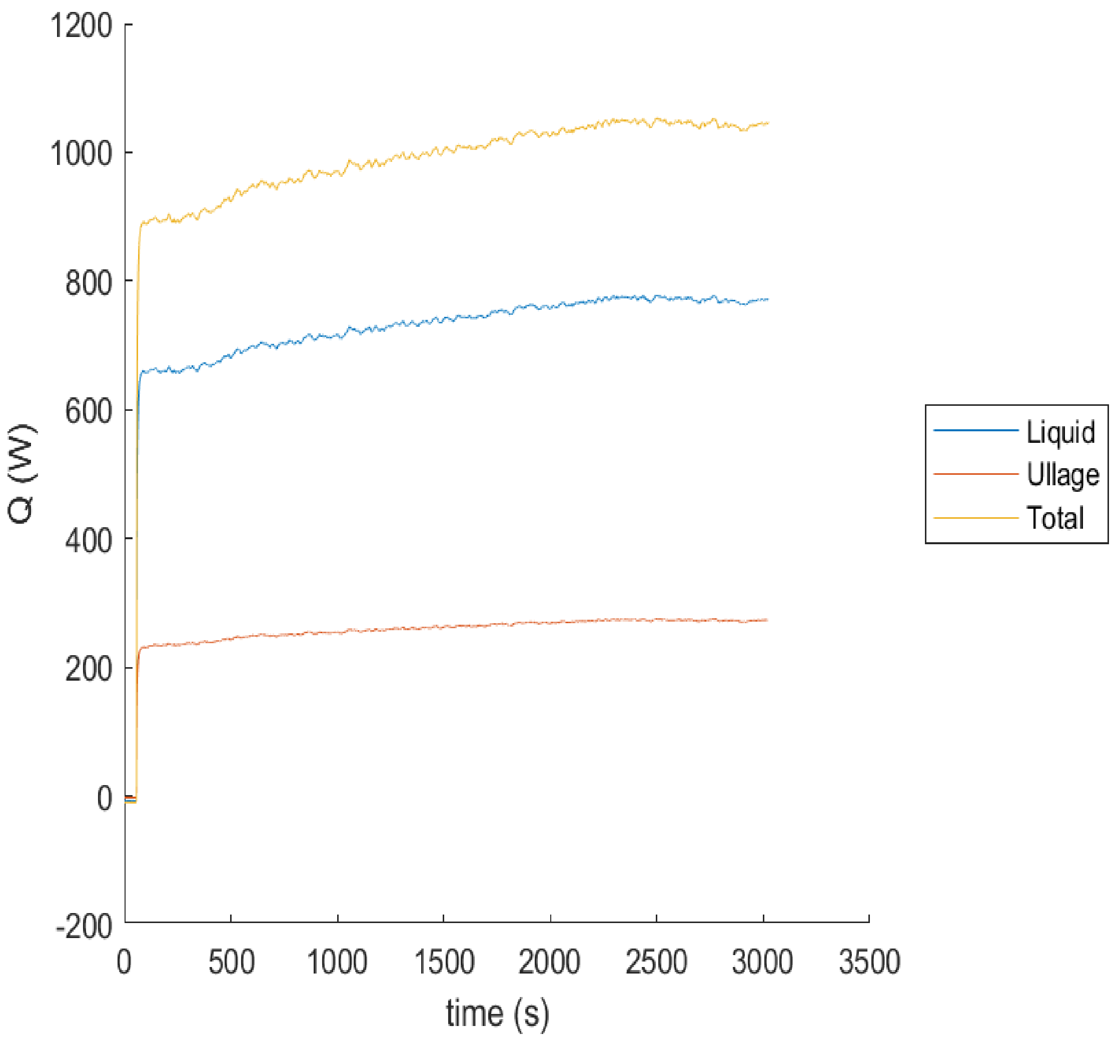
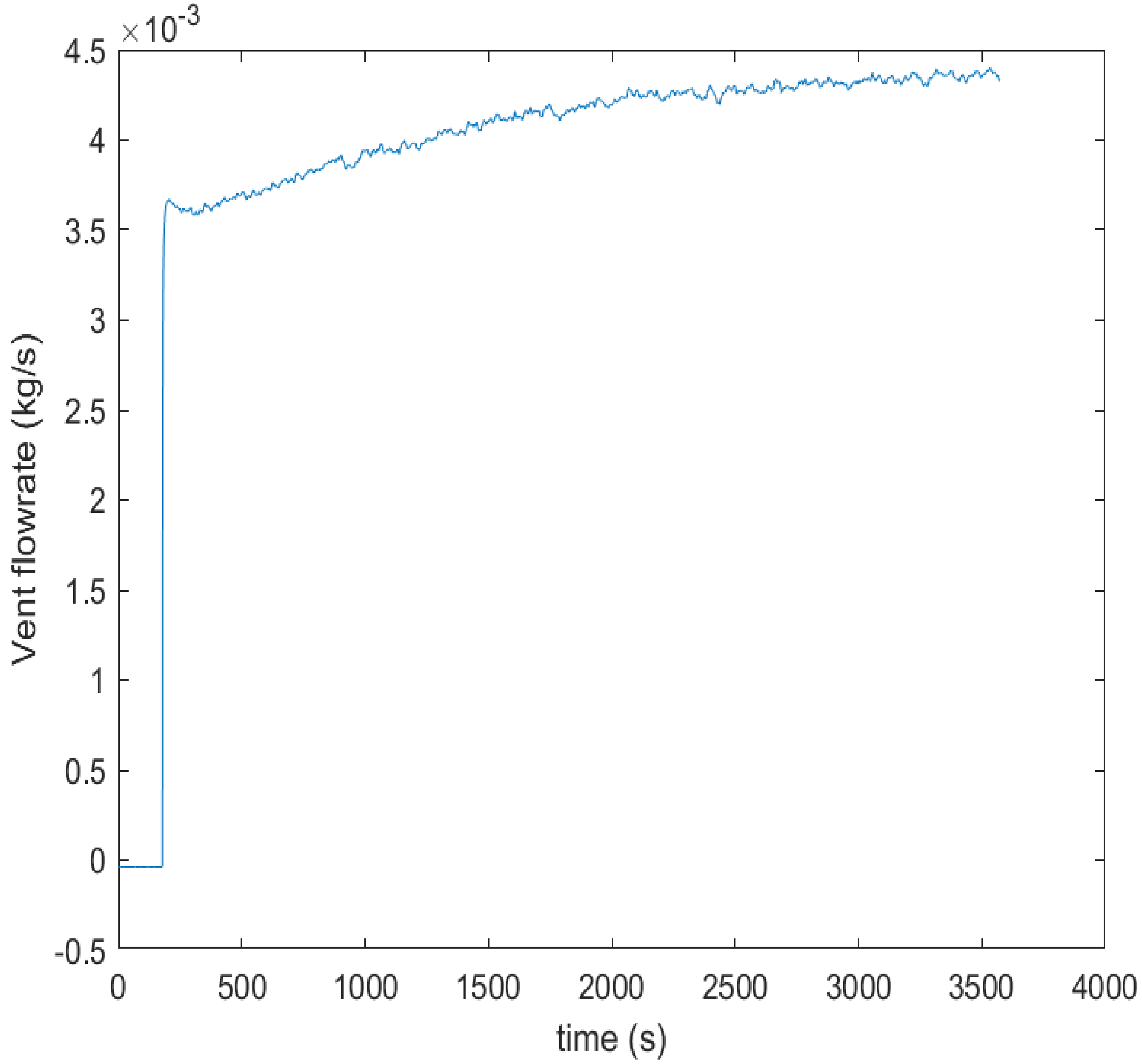
TC29
TC30
TC31
TC32
TC33
TC34
TC35
TC36
TC37

GTO-1 52% Fill ctd

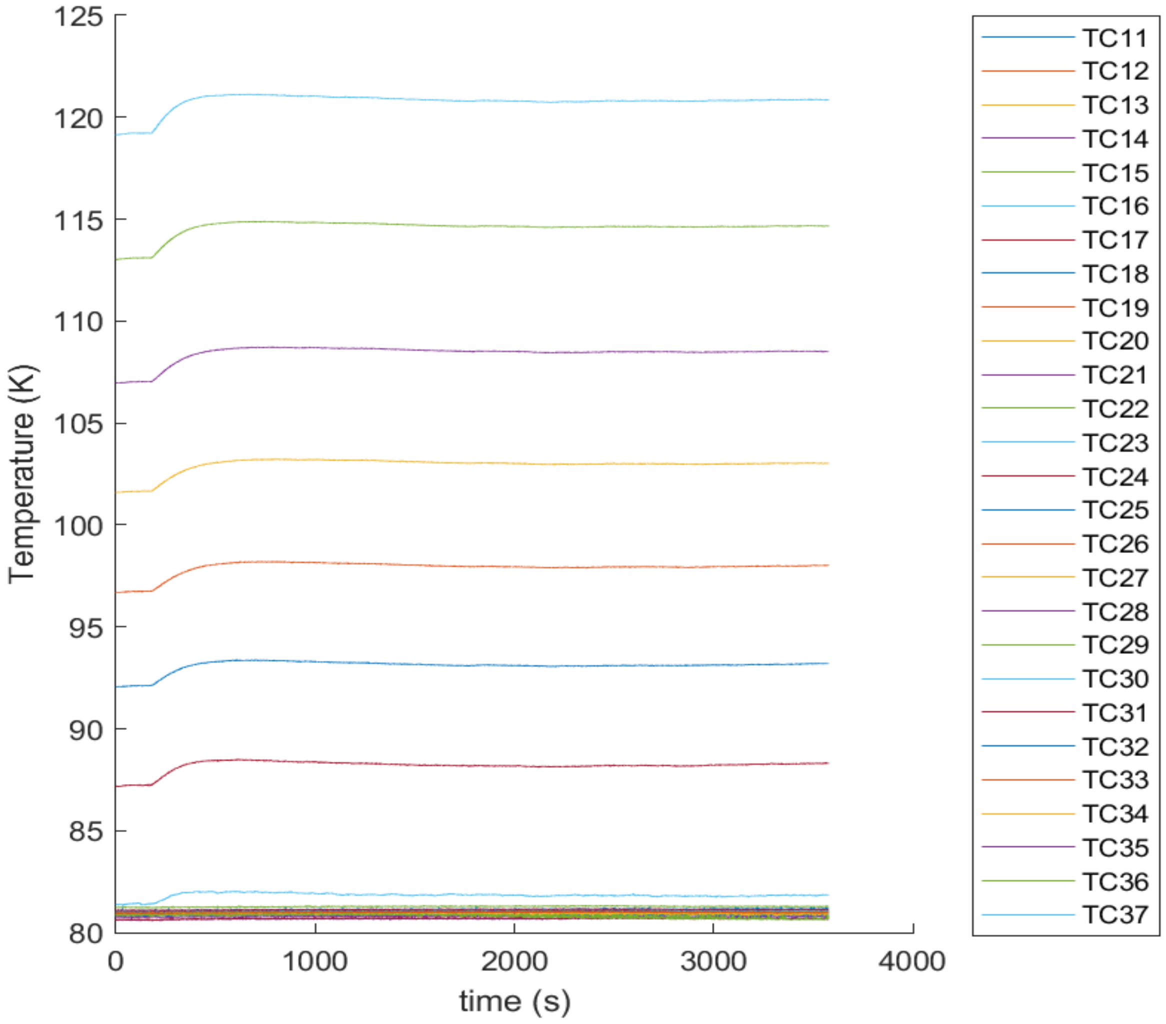




GTO-1 72% Fill



×10-3
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
Vent flowrate (kg/s)
0
500
1000
1500
2000
2500
3000
3500
4000
time (s)



125
120
115
110
105
100
95
90
85
80
Temperature (K)
0
1000
2000
3000
4000
time (s)
TC11
TC12
TC13
TC14
TC15
TC16
TC17
TC18
TC19
TC20
TC21
TC22
TC23
TC24
TC25
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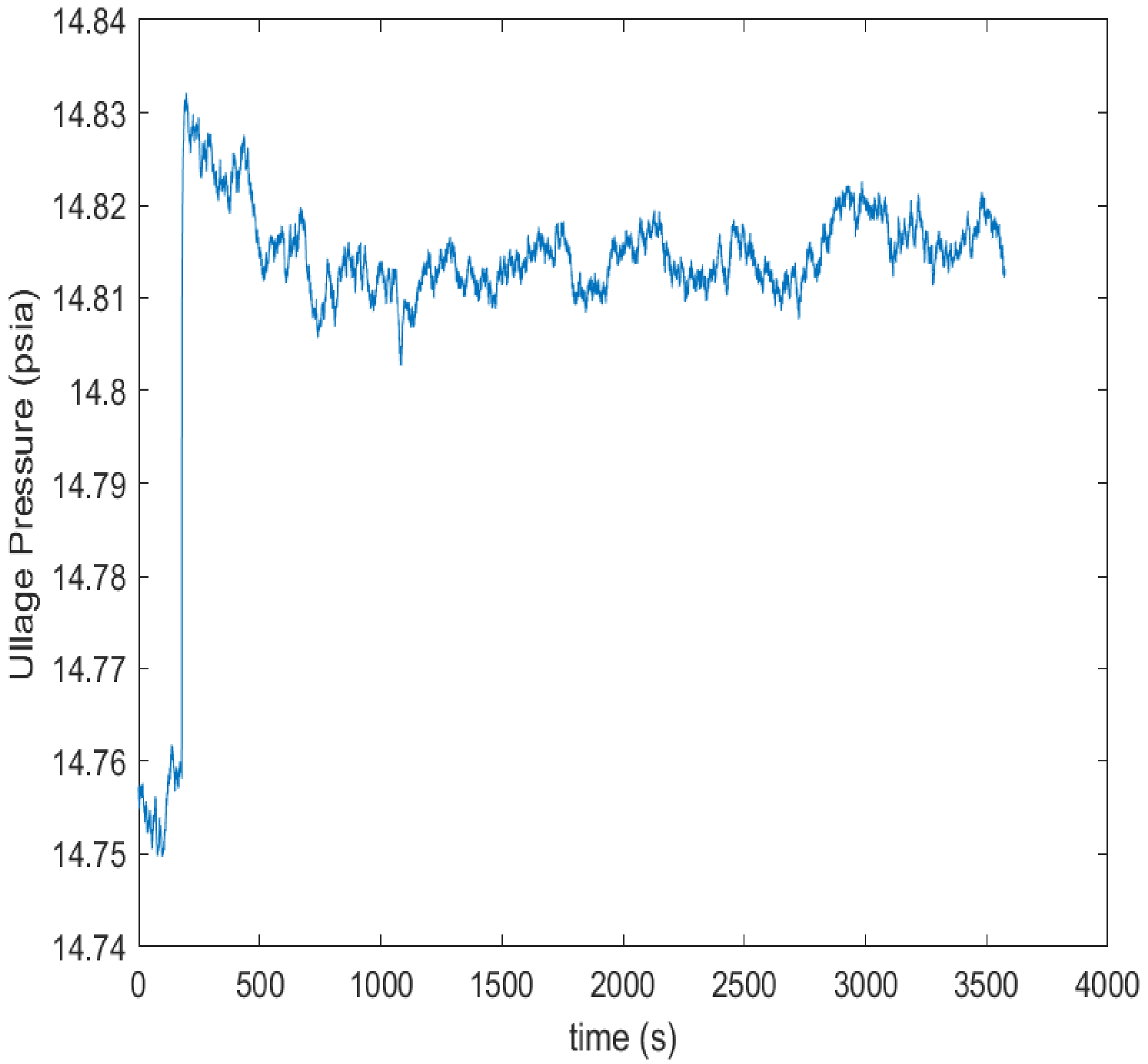
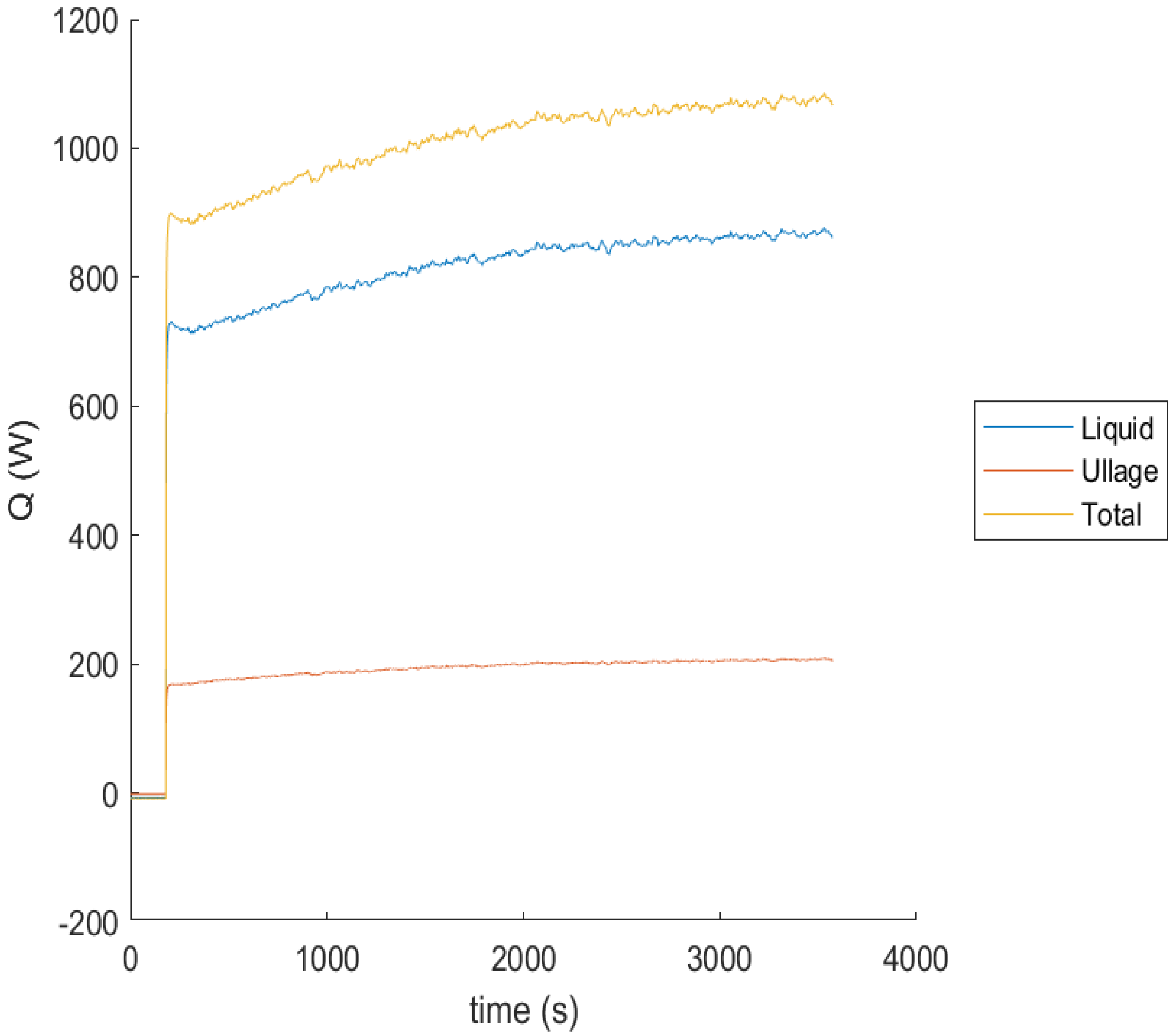
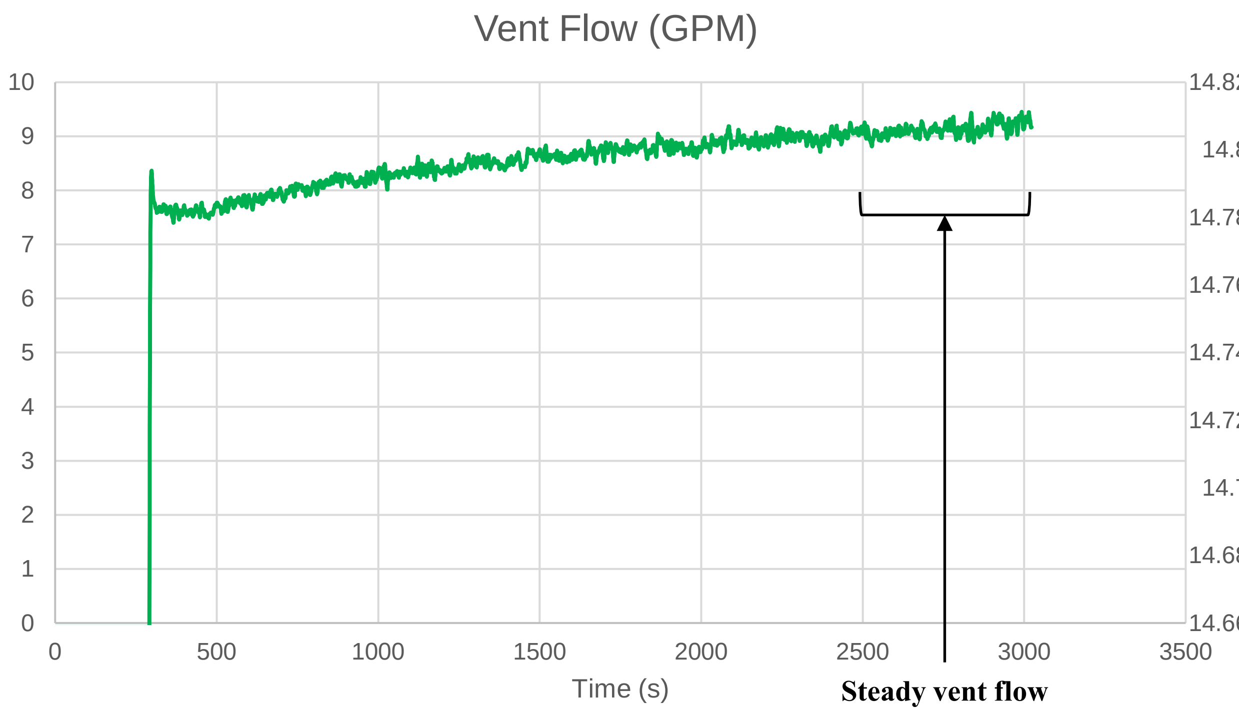
TC36
TC37

GTO-1 72% Fill ctd

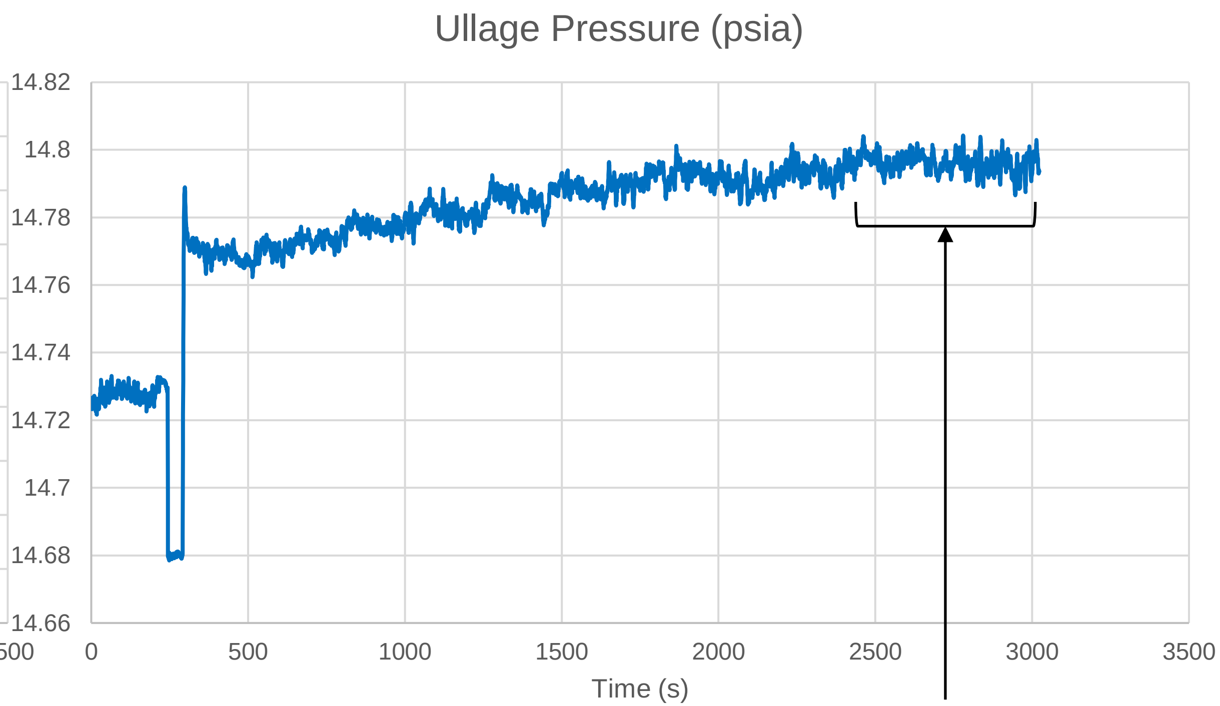




GTO-1: 90% Fill ctd



Steady vent flow
9.13 ft³/min, 0.0114 lbm/s



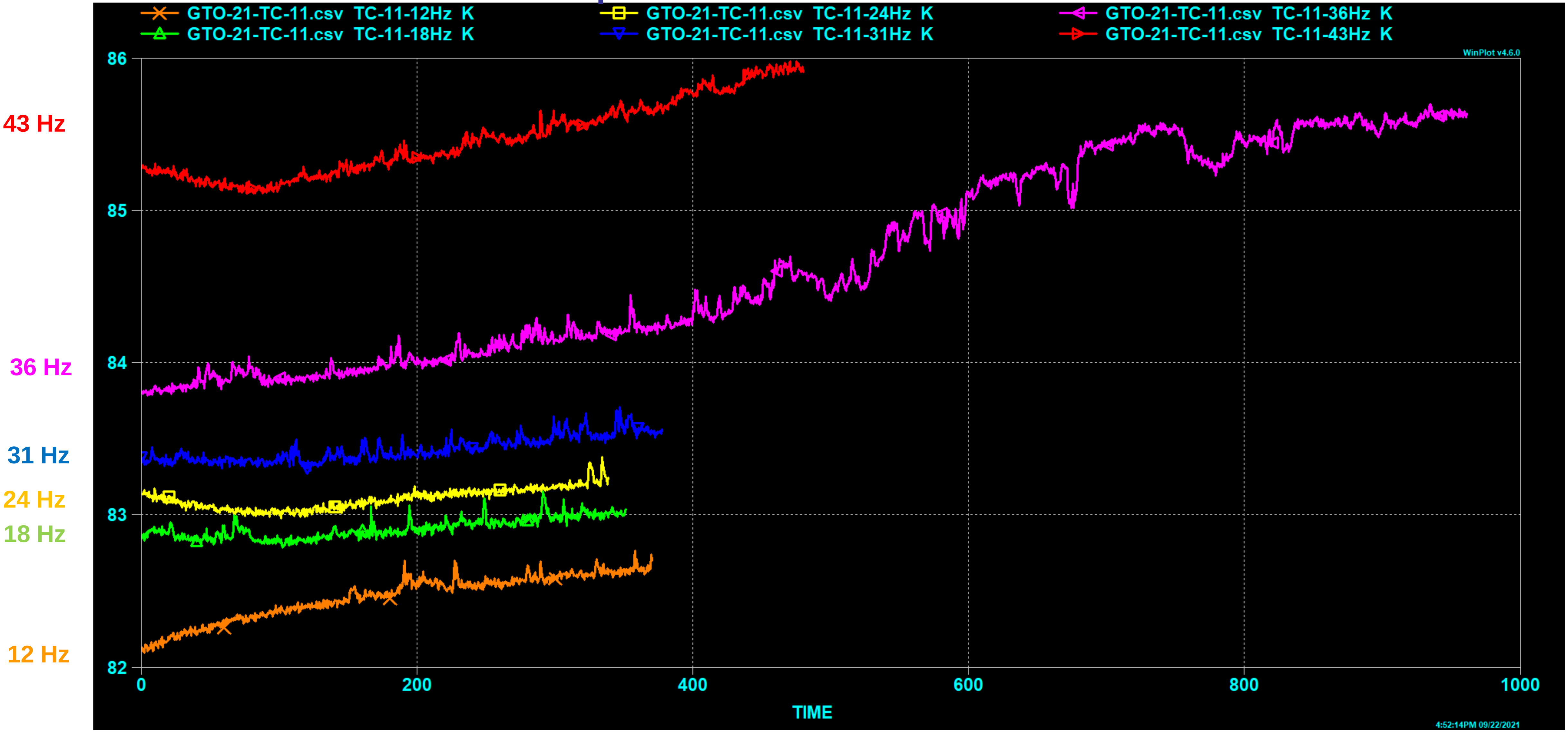
Constant Ullage Pressure
14.8 psi

$$\dot{Q} = \dot{m} h_{fg}$$

$$\dot{Q} = 1010\ W$$

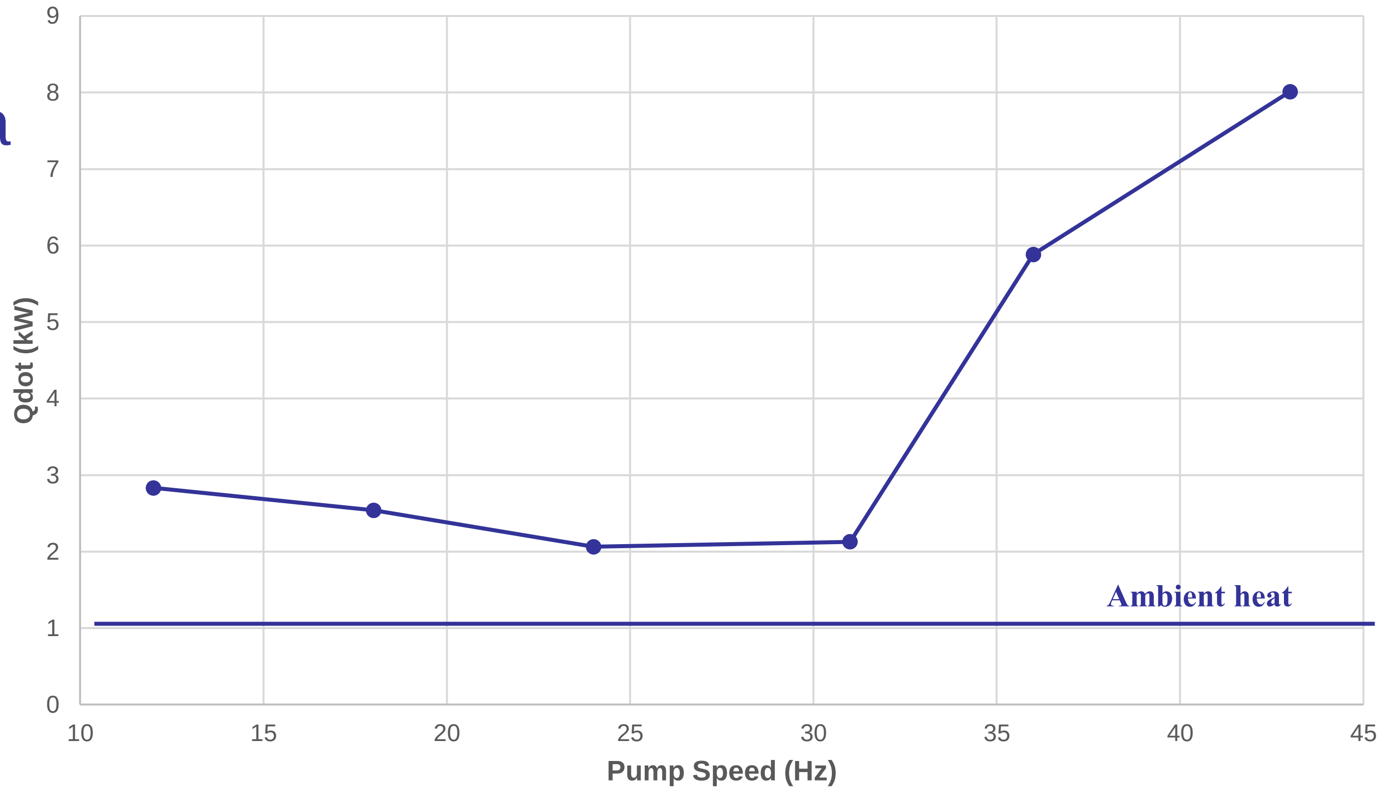
Additional Heating from Pump

Temperature at Bottom of LN2



Additional Heating from Pump

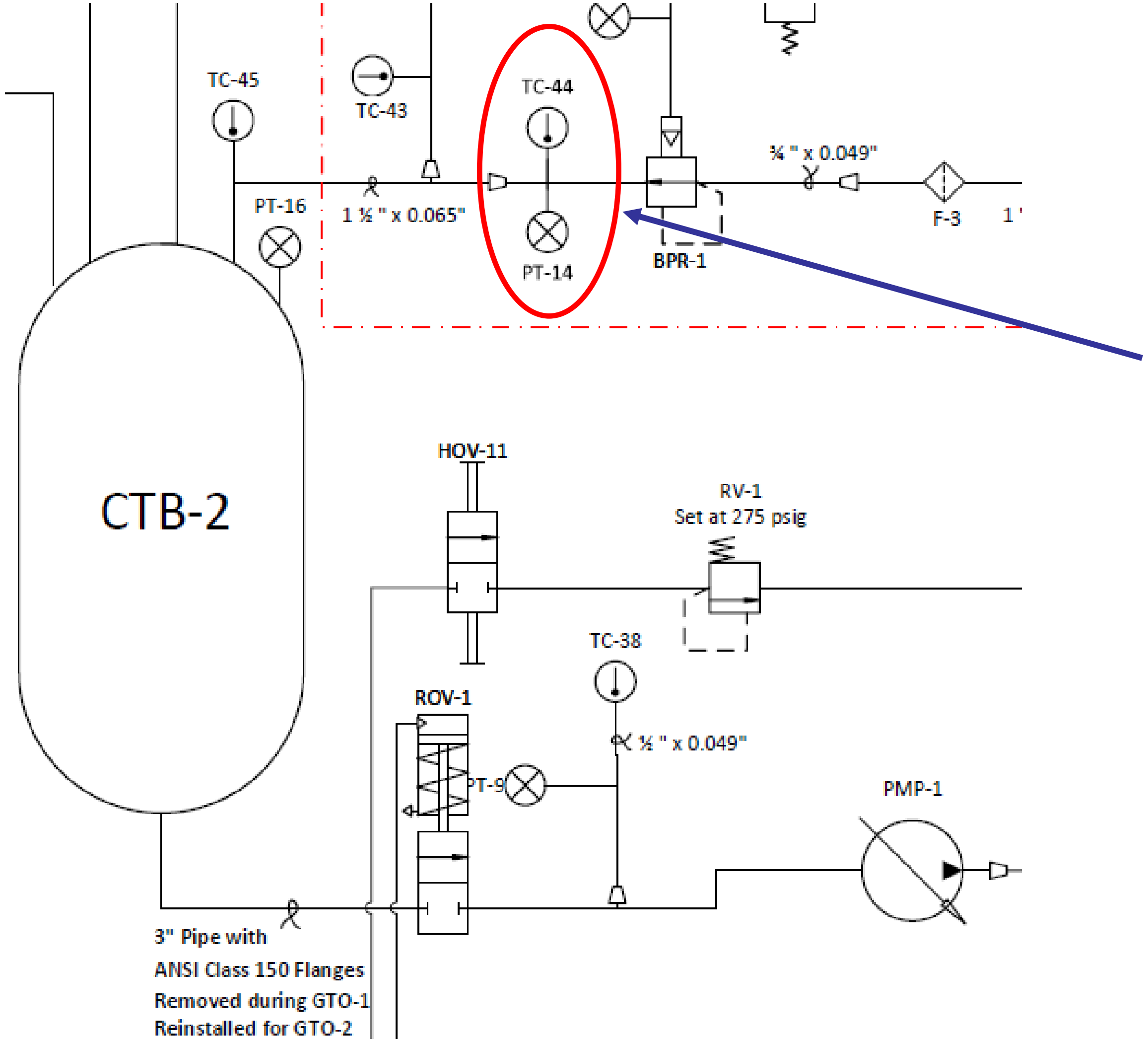
- The pump is a significant source of heat addition
- This pump is over-sized for a lunar mission
  - Acquired when the driving operational scenario was a manned Mars landing, which called for 1000-lbf thrusters



GTO 2.2

- Objective: characterize system performance under steady-state thruster firing
  - Analogous to a course correction burn performed by an RCS
- Procedure:
  - Pressurized recirculation line to 350 psig
  - Thruster valve(s) opened to admit LN2 flow

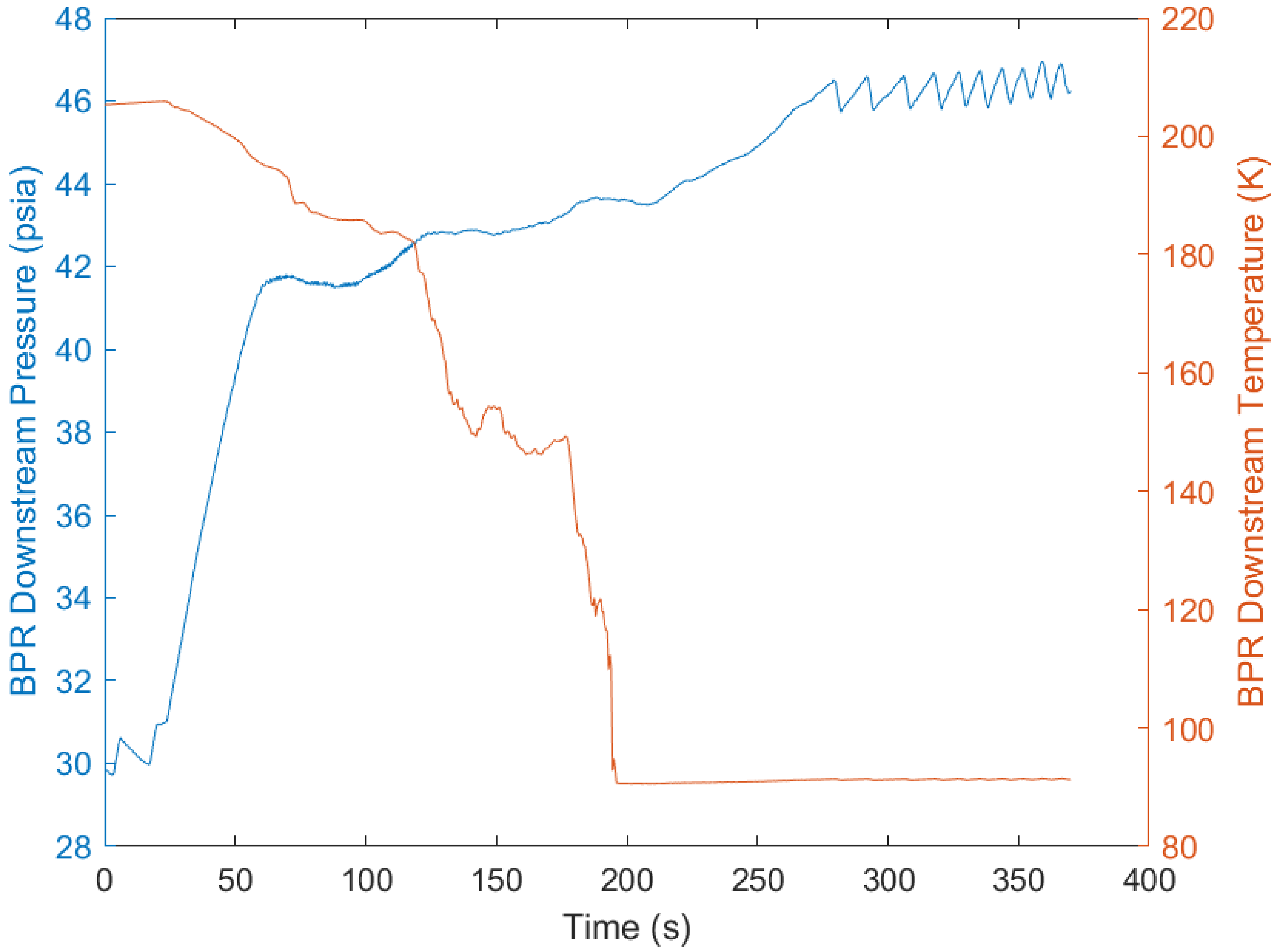
Return Flow Measurement Location during GTO-2.2



Fluid properties taken from here

GTO-2.2: Return Flow Conditions, 36 Hz

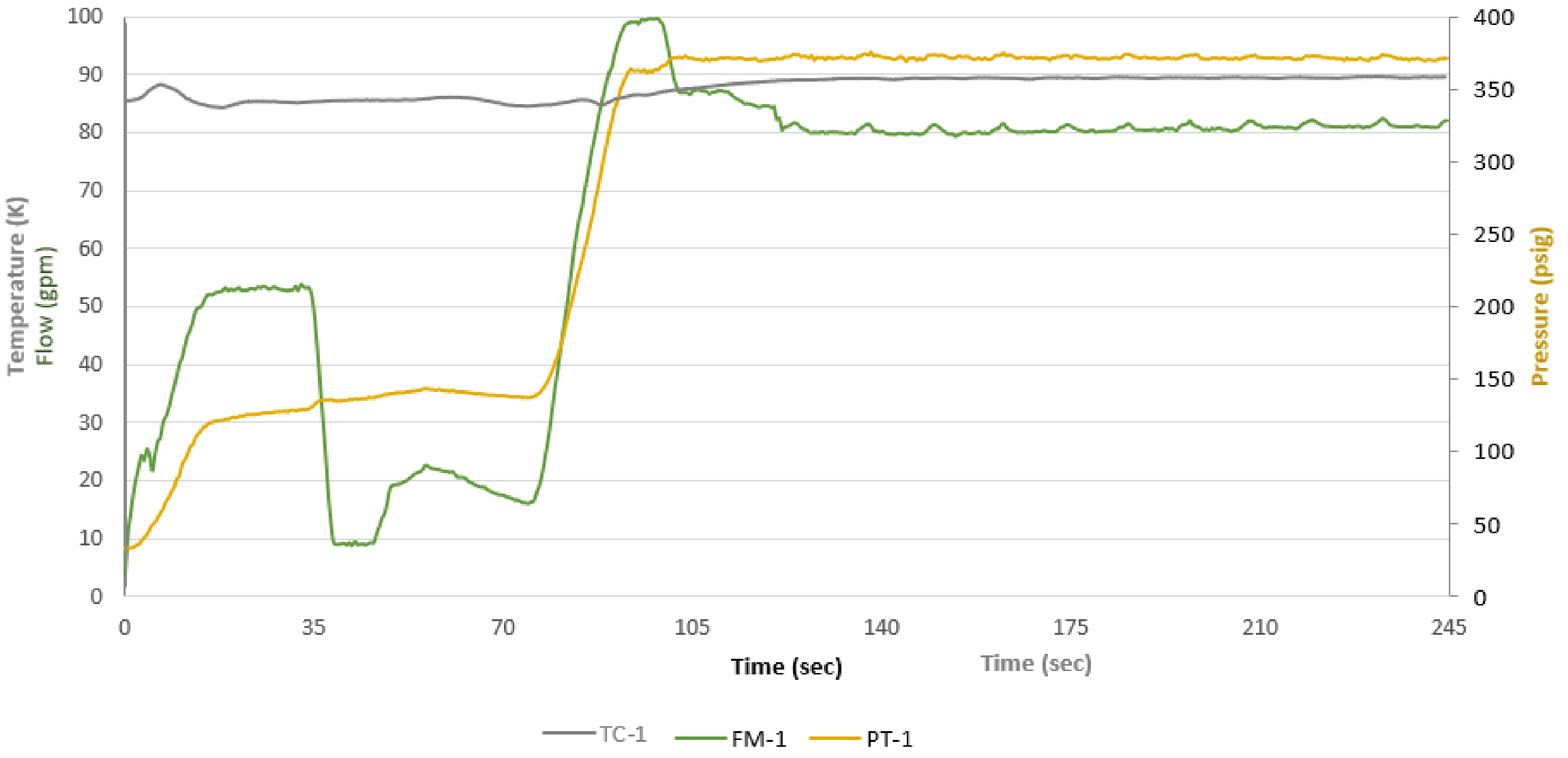
BPR downstream flow turned to liquid around 200 s.



GTO-2.2

Steady state conditions reached near 140 s.

(test sequence initiated near 70 s)



GTO-2.3: Pulsing Mode

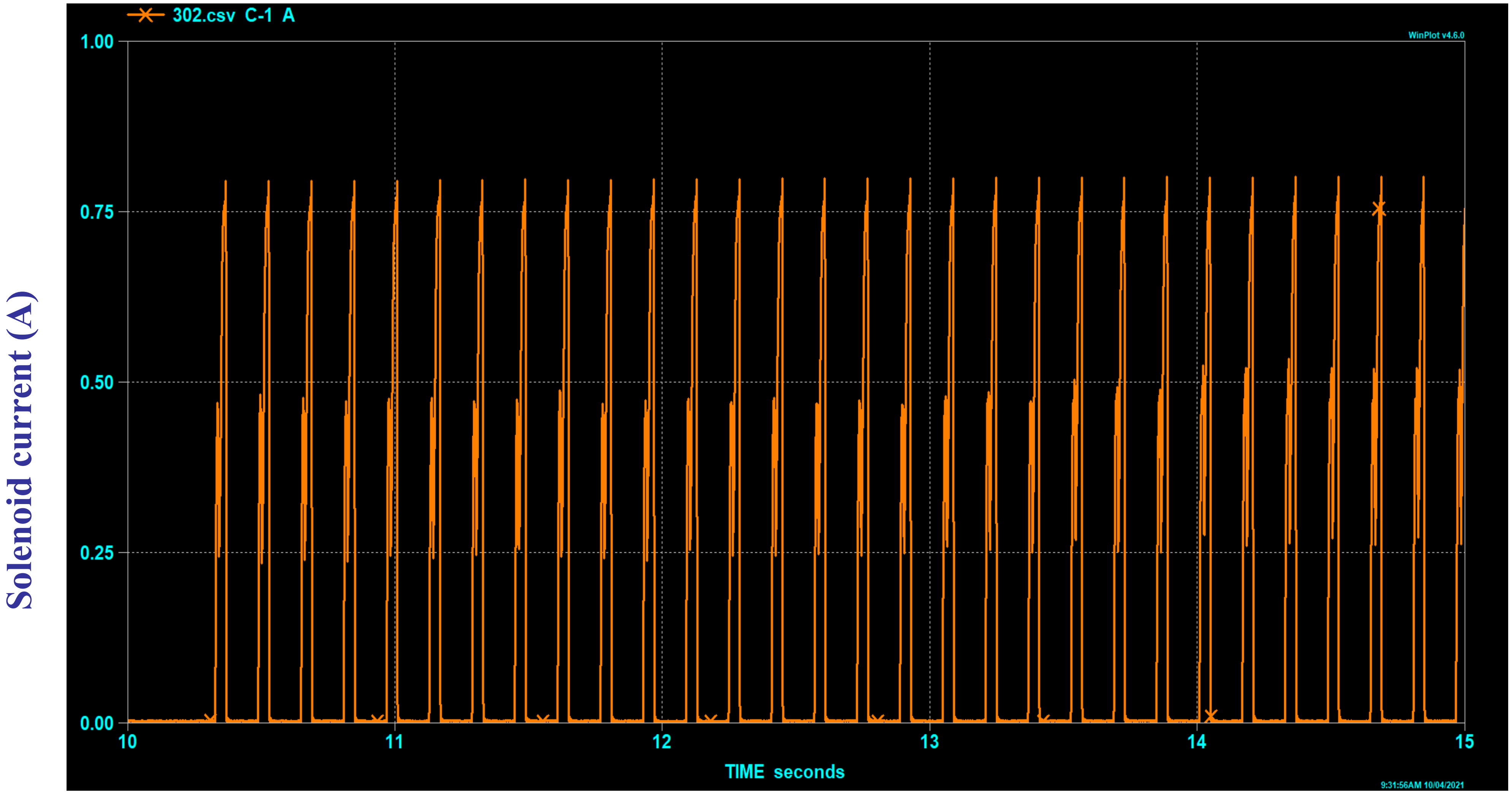
- Ran 16 different pulse profiles
  - Varied number of active thrusters, duty cycle, pulse width, and number of pulses
  - Constant pump speed and tank pressures
  - Intent was to cover a wide range of potential RCS operational scenarios

GTO-2.3 Tests: IRCS Active Mode – Pulsing																
Test ID	Description	Approx. Motor Frequency	Pump Flow Rate	Number of Active Thrusters	Thruster Capacity	Bypass Ratio Capacity	Pulse Width	Duty Cycle	Number of Pulses	Pump Head	Tank Pressure	Manifold Pressure	Duration	Sampling Rate	Pre-Test Prediction
		(Hz)	(lb/sec)	(-)	(-)	(%)	(msec)	(%)	(-)	(psid)	(psig)	(psig)	(sec)	(Hz)	(-)
301	Active Mode - Pulsing, Max Capacity	118.14	0.47	2	2	5	40	25	30	325	25	350	4.8	1000, 20000	
302	Active Mode - Pulsing, Max Capacity	118.14	0.47	2	2	5	40	5	30	325	25	350	24	1000, 20000	
303	Active Mode - Pulsing, Max Capacity	118.14	0.47	2	2	5	200	25	30	325	25	350	24	1000, 20000	
304	Active Mode - Pulsing, Max Capacity	118.14	0.47	2	2	5	200	5	30	325	25	350	120	1000, 20000	

Subset of Test Matrix

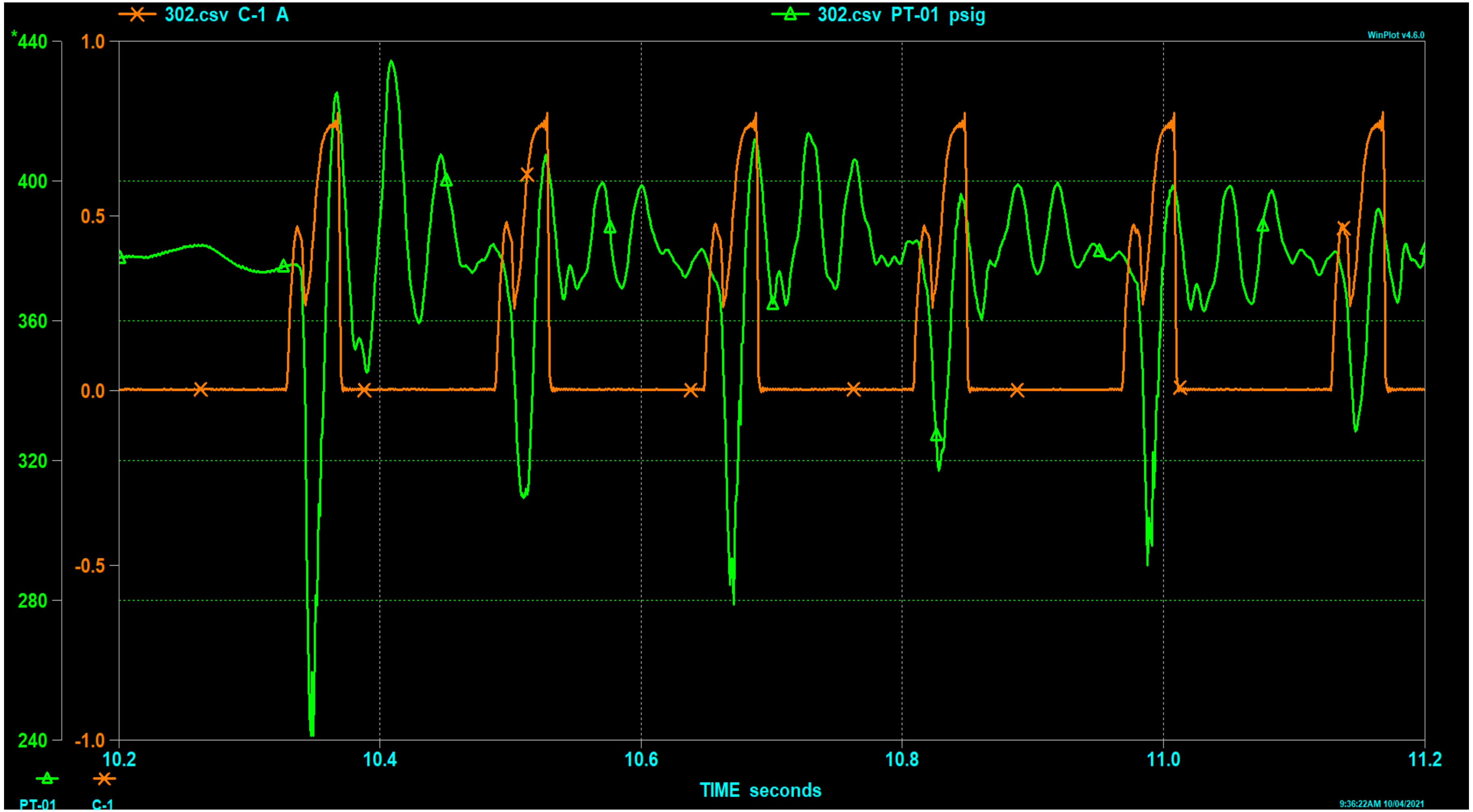
GTO-2.3: Test #302: Rapid Pulses

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



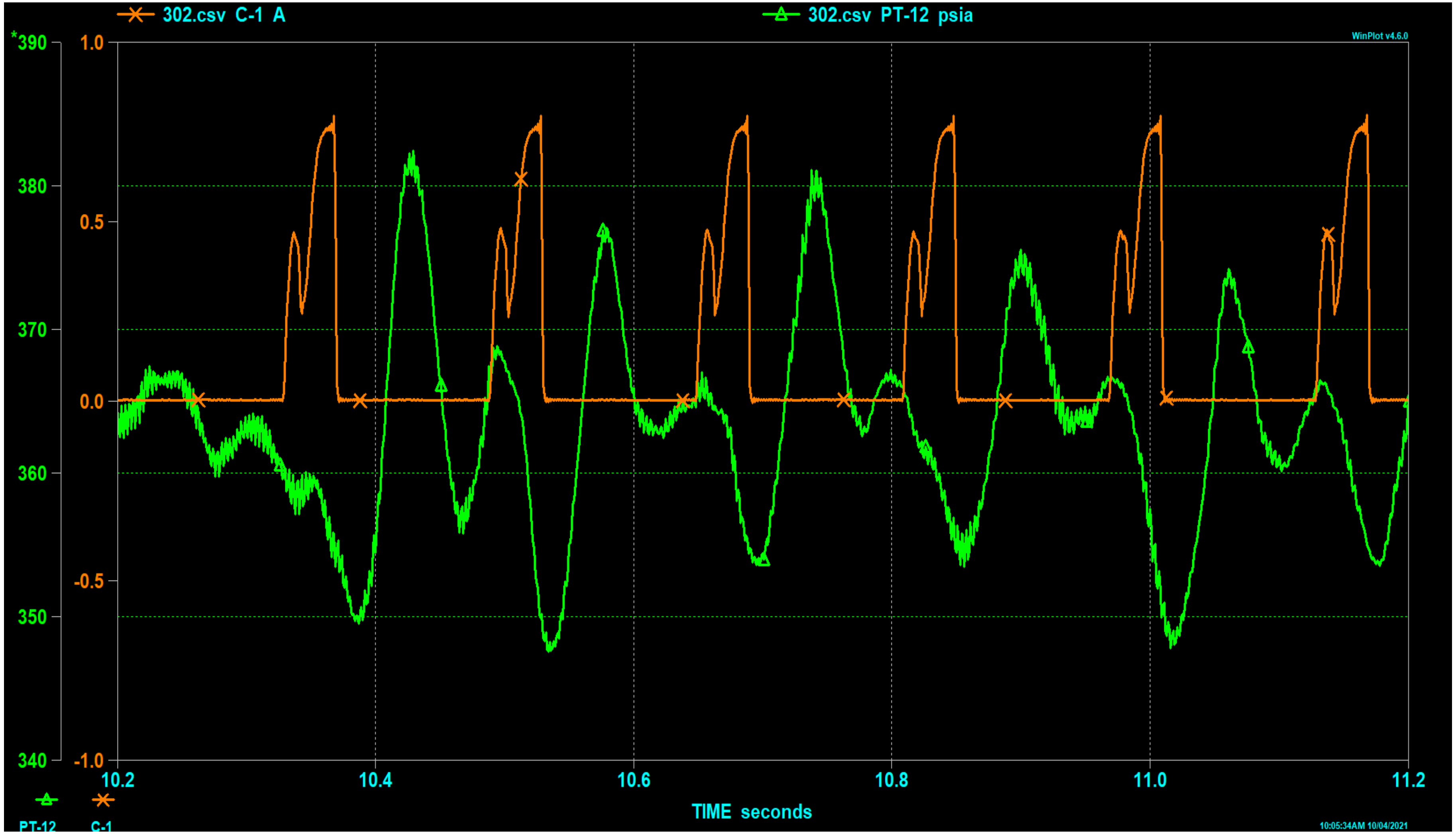
GTO-2.3: Test #302: Thruster Inlet Pressure Response

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



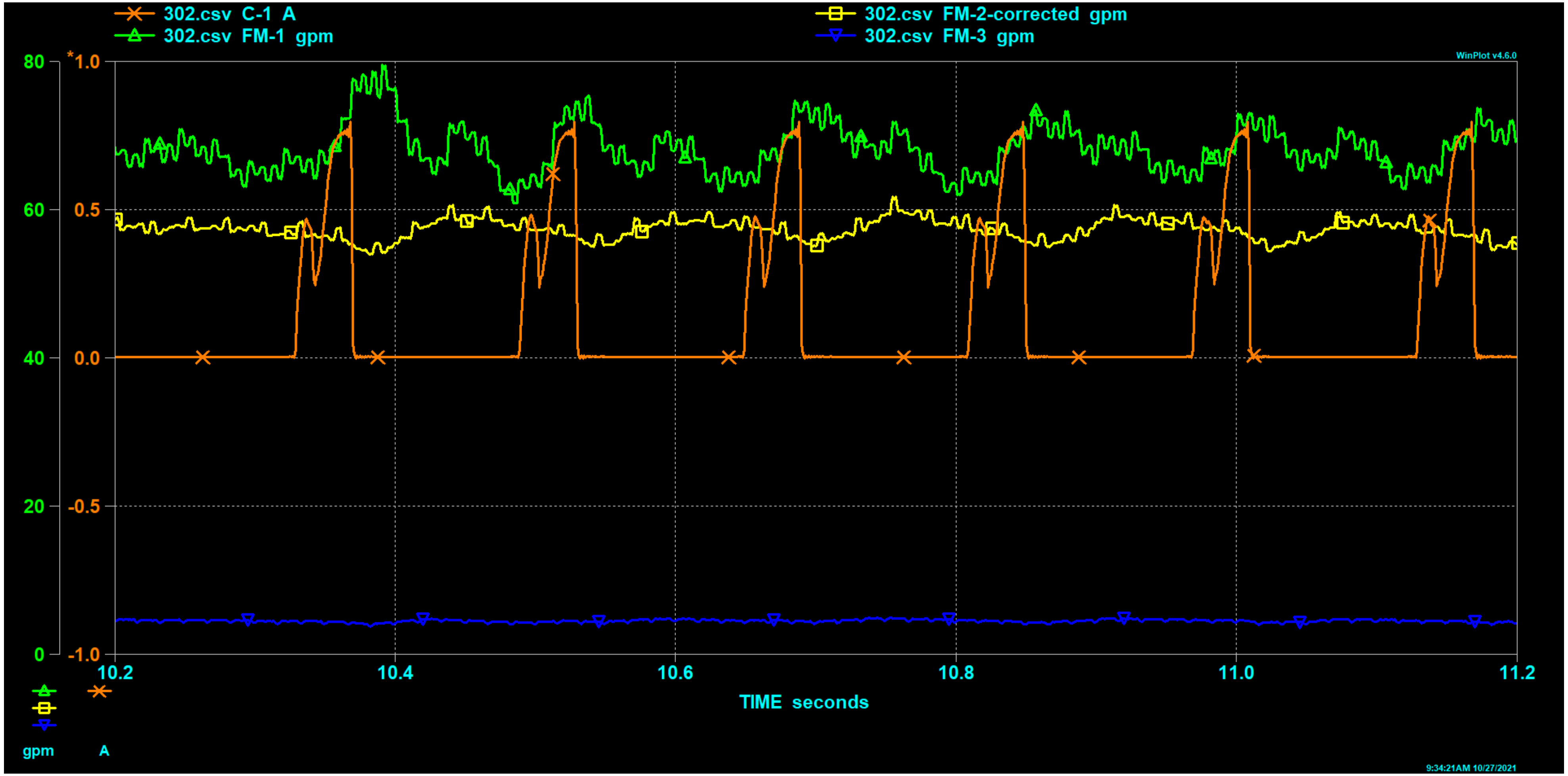
GTO-2.3: Test #302: BPR Inlet Pressure

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

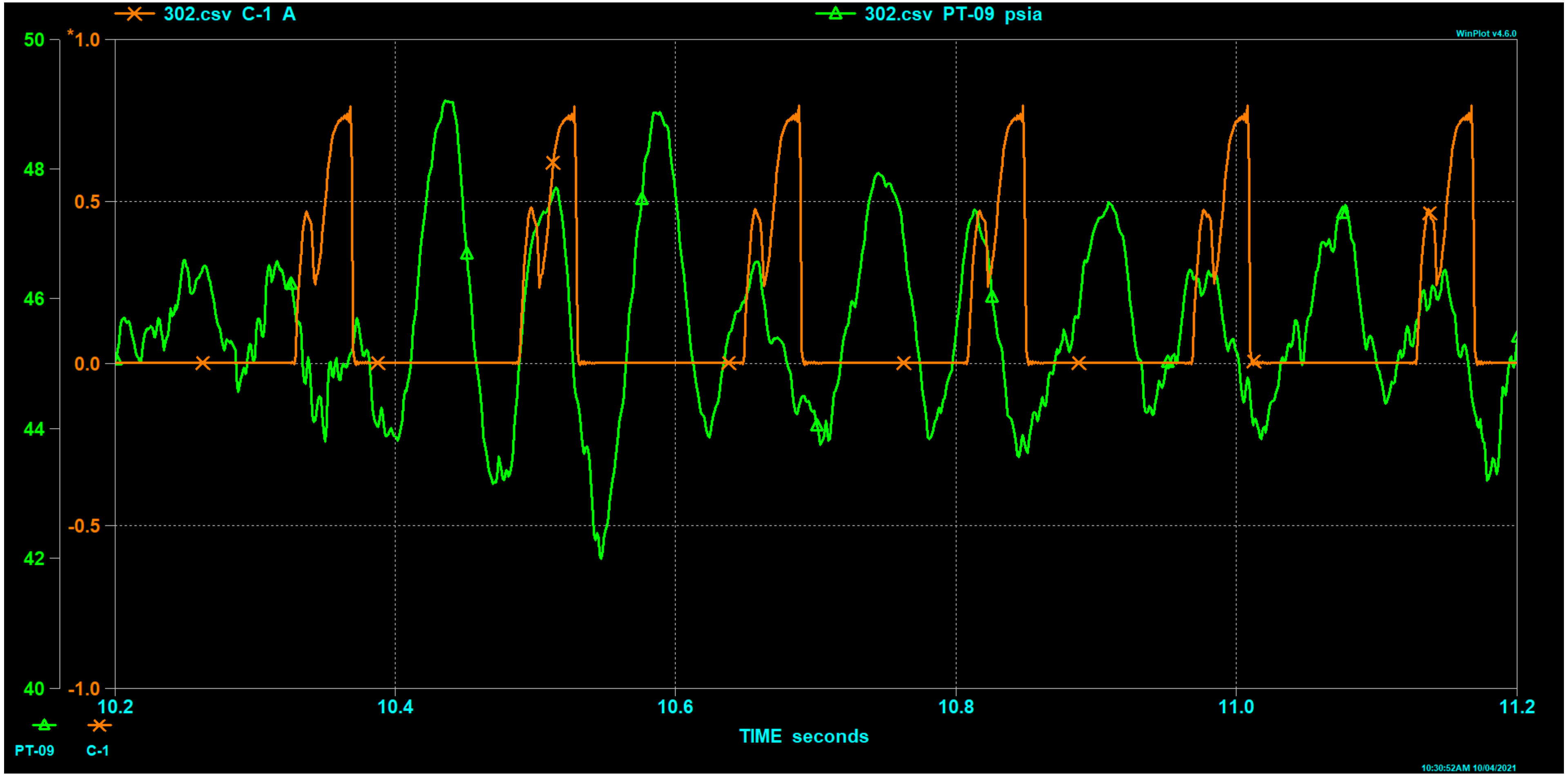


GTO-2.3: Test #302: Flow Meters

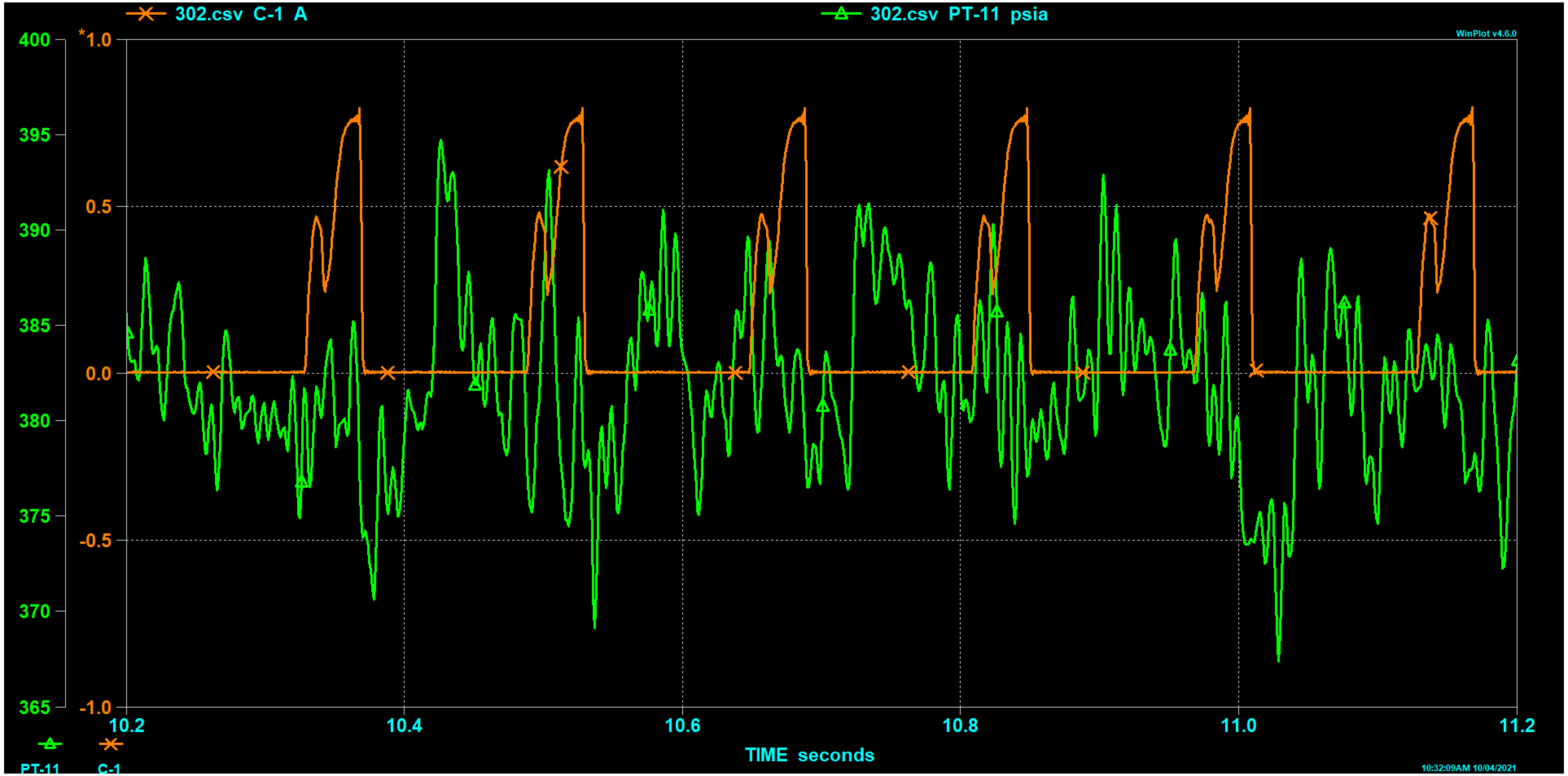
Tolerable changes to flow rate during valve transients



GTO-2.3: Test #302: Pump Inlet Pressure

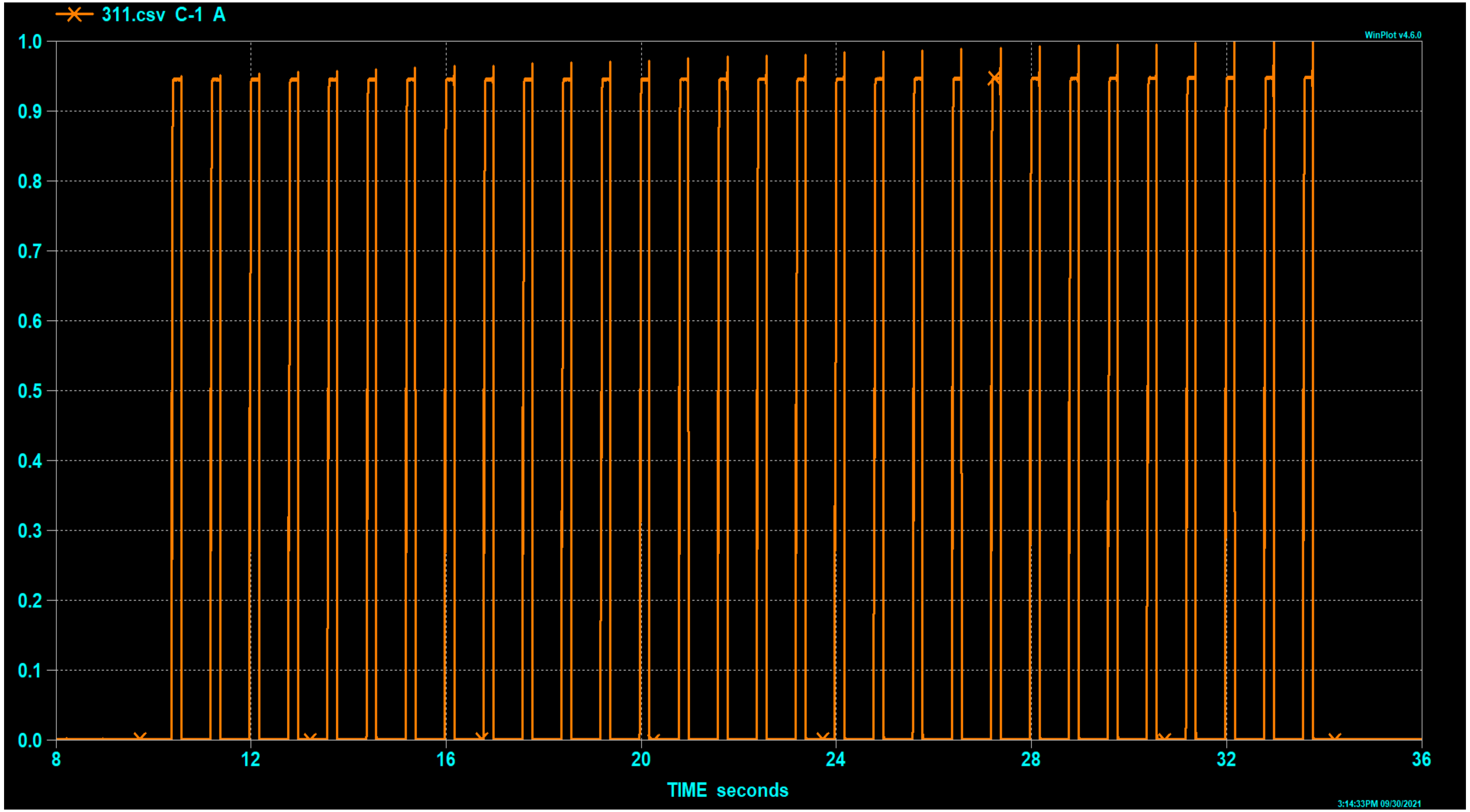


GTO-2.3: Test #302: Pump Discharge Pressure



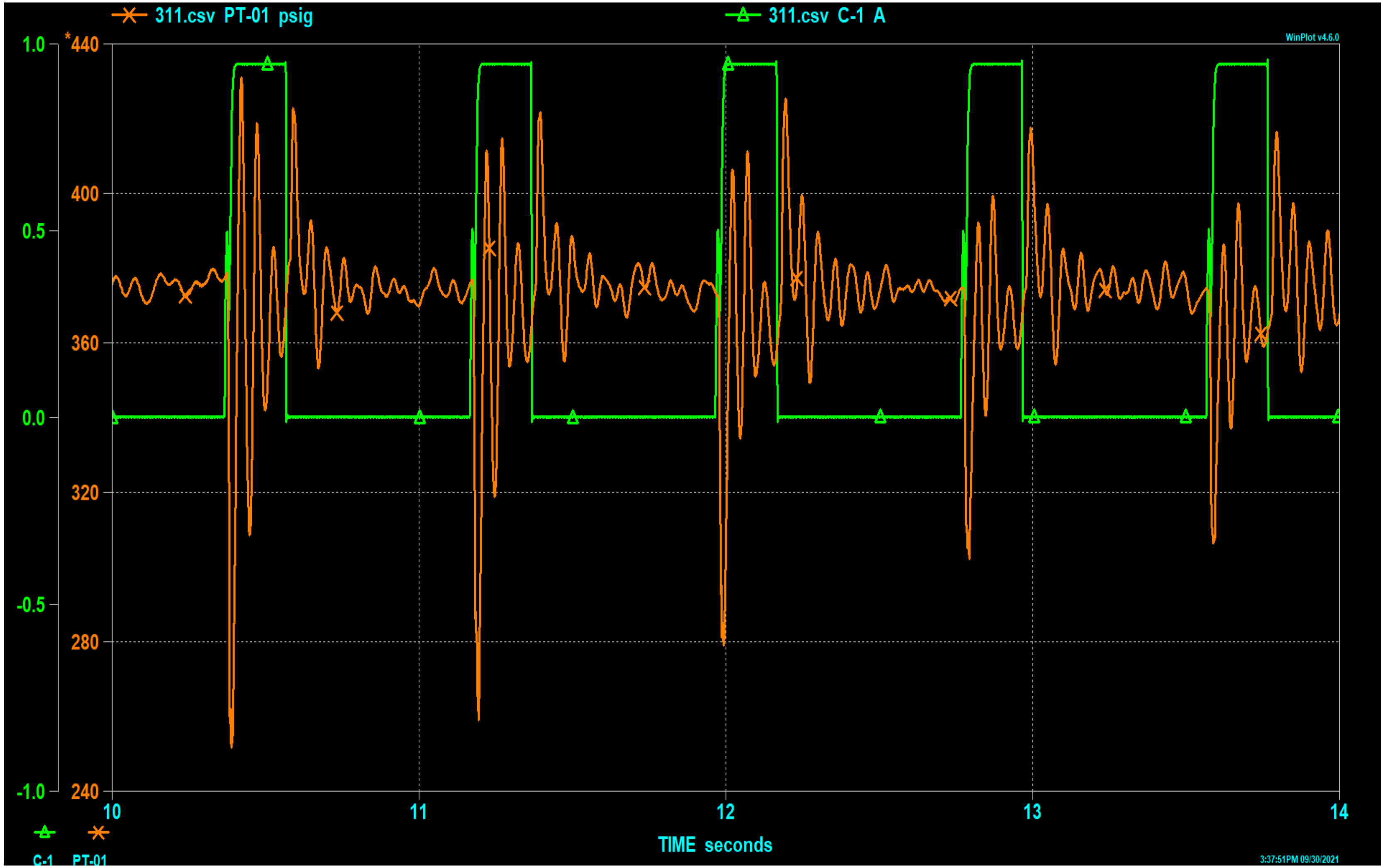
GTO-2.3: Test #311 Thrust Pattern

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



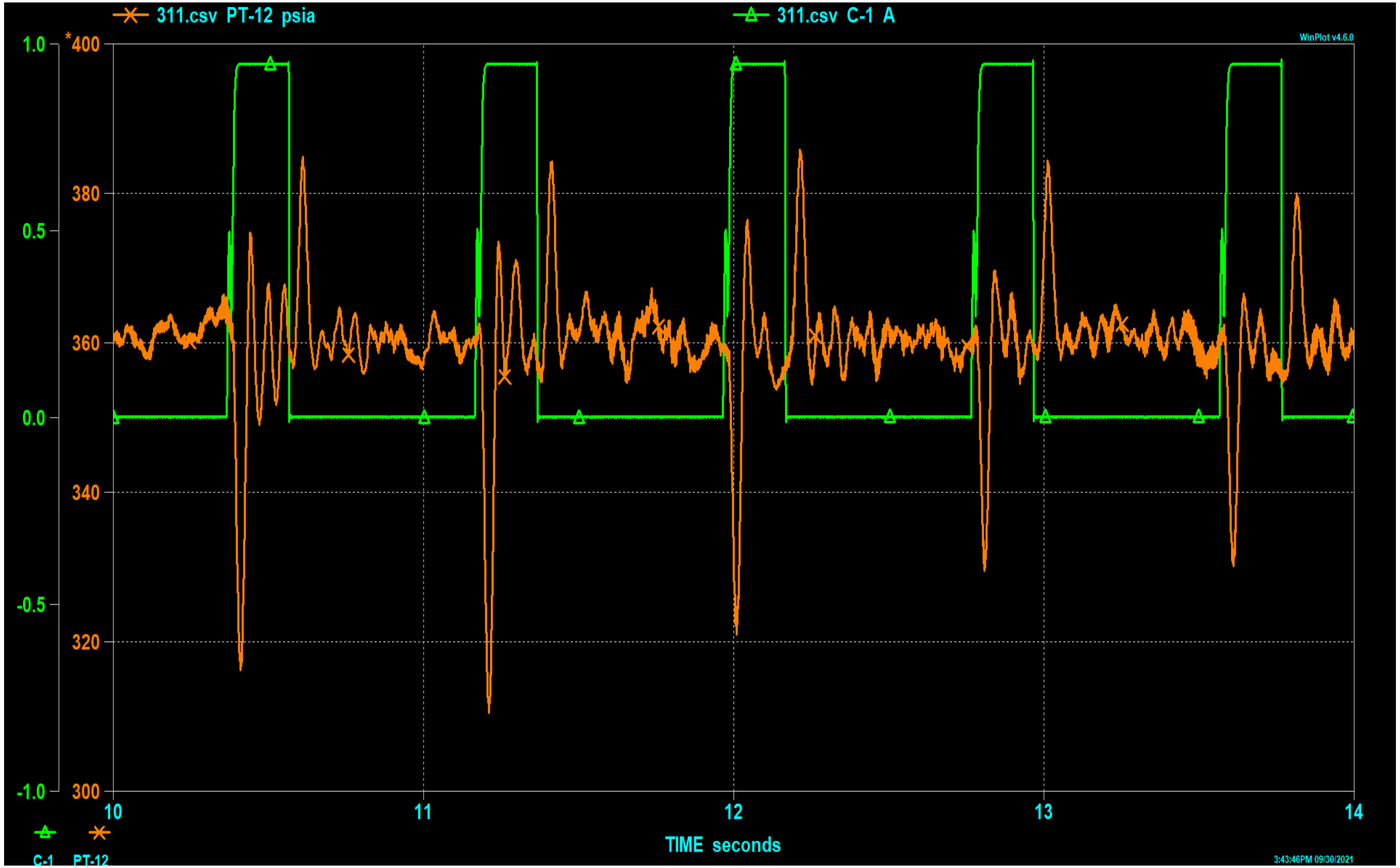
GTO-2.3: Test #311: Inlet Pressure Response

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



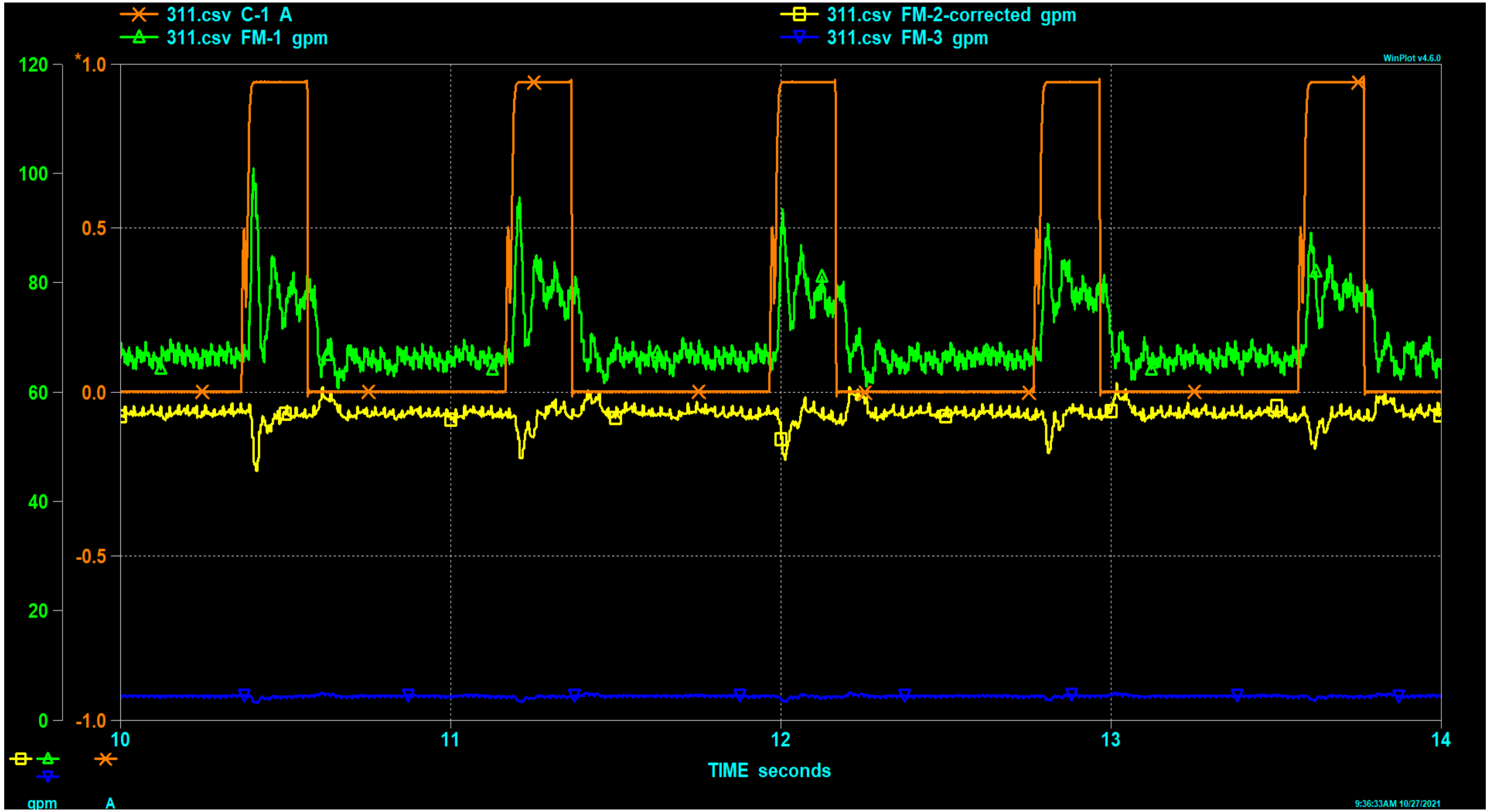
GTO-2.3: Test #311: BPR Inlet Pressure

- Smaller magnitude of pressure transients at BPR inlet



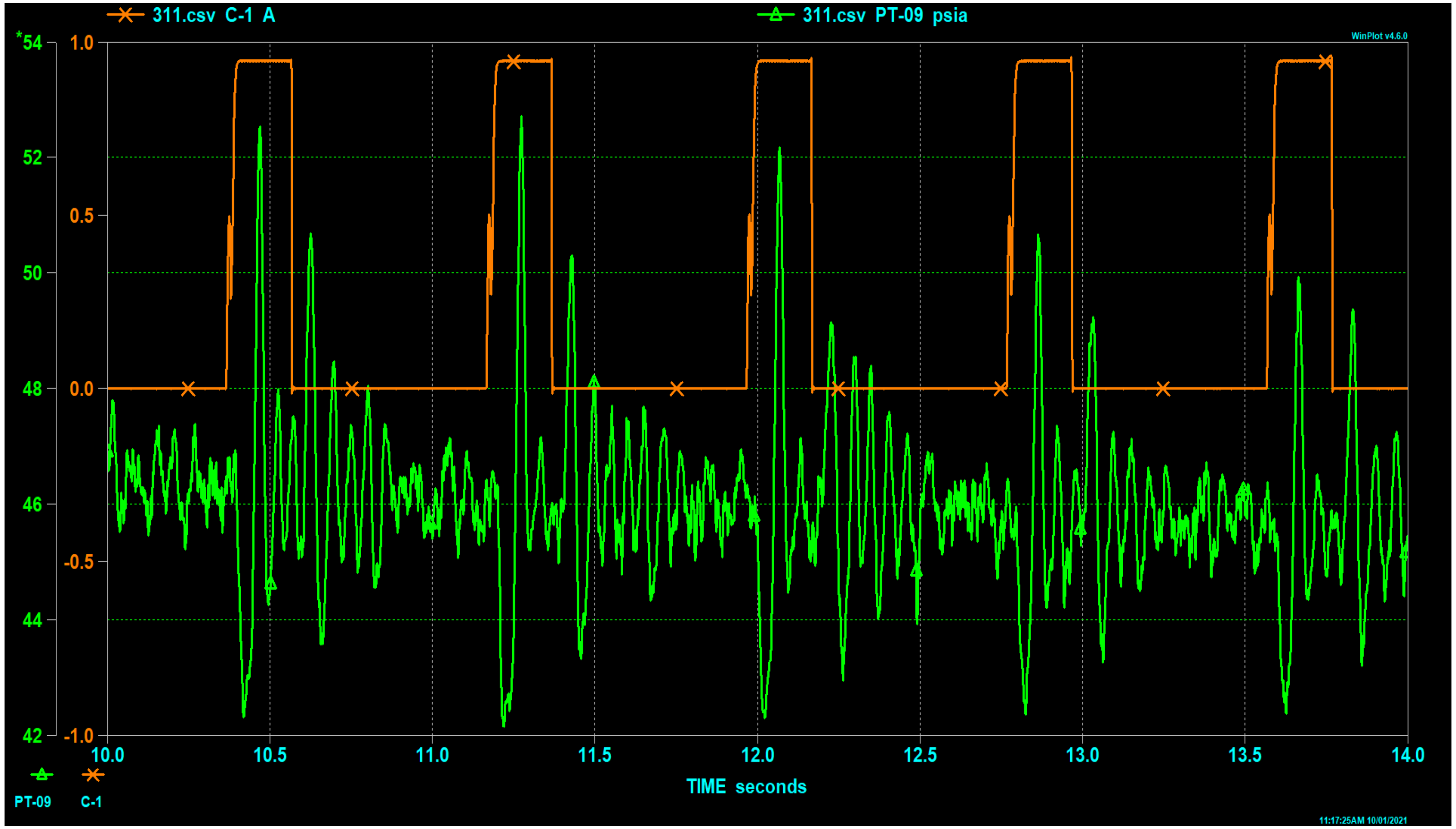
GTO-2.3: Test #311: Flow Meters

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



GTO-2.3: Test #311: Pump Inlet Pressure

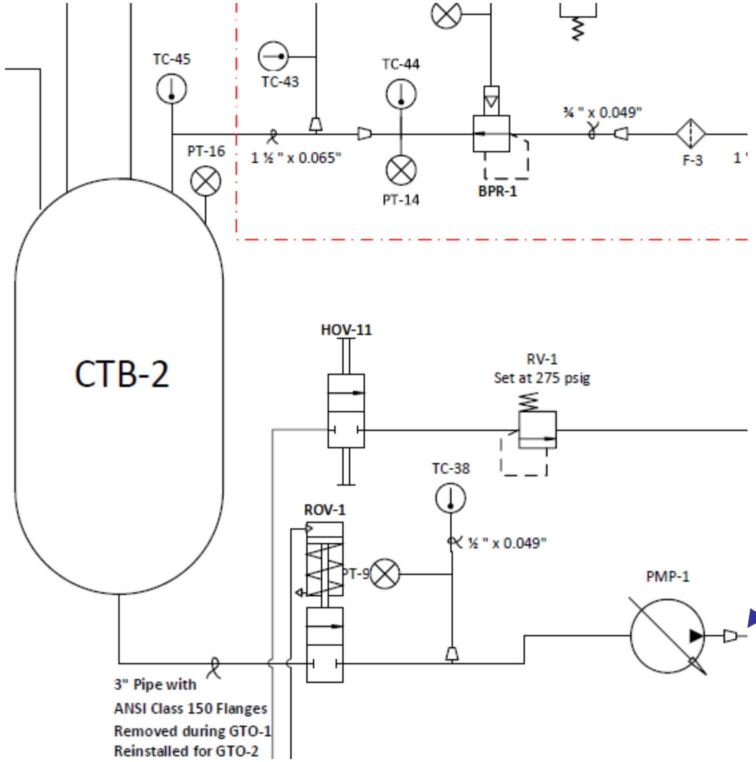
- Pulses did not cause cavitation during pump operation



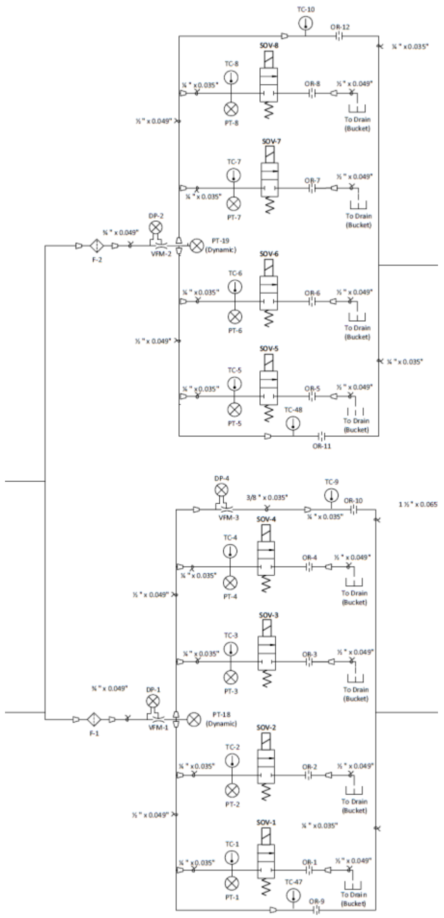
GTO-2.3: Test #311: Pump Discharge

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

Dynamic PT Locations



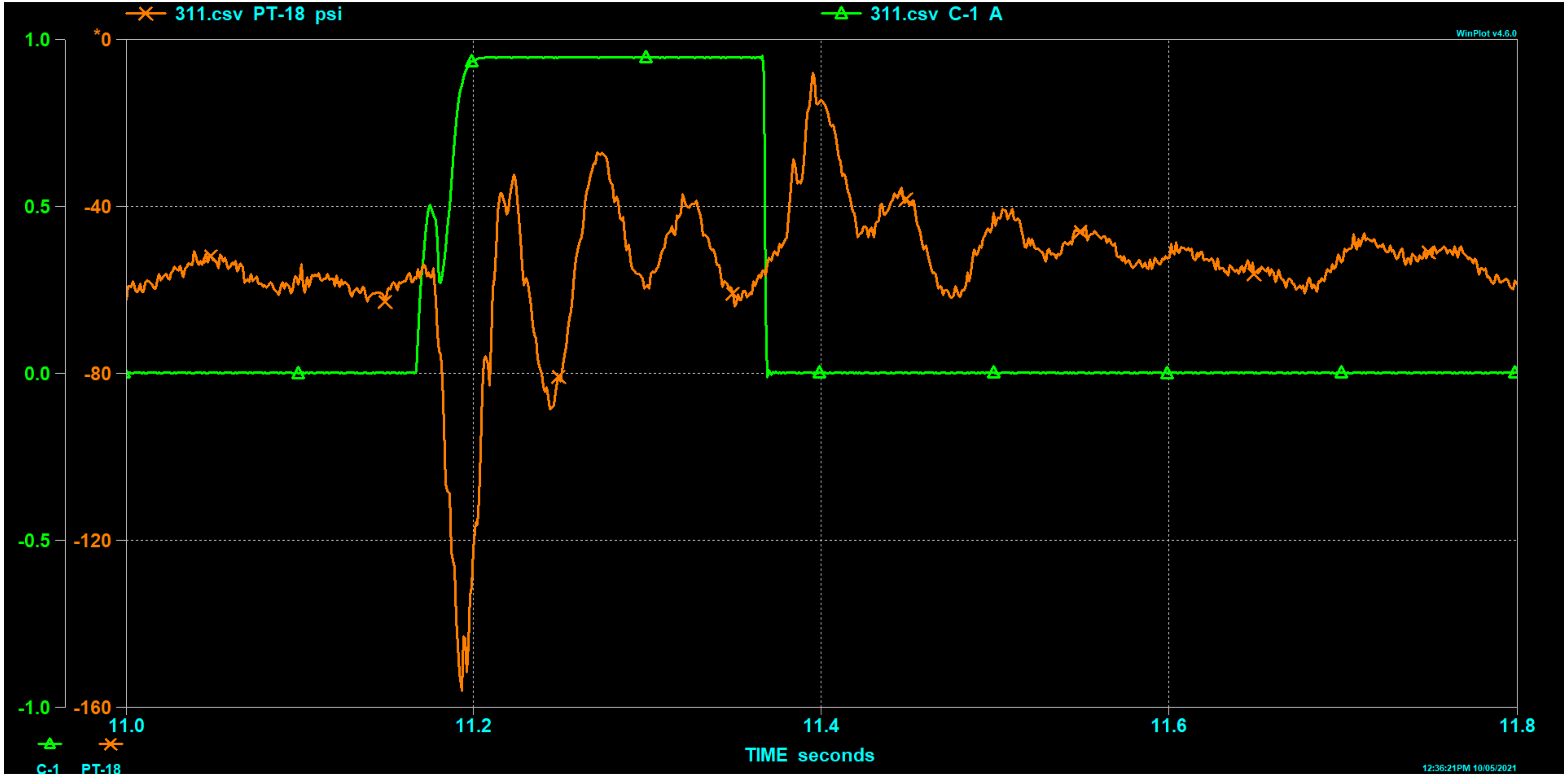
PT-10 here



Thruster Pod 2

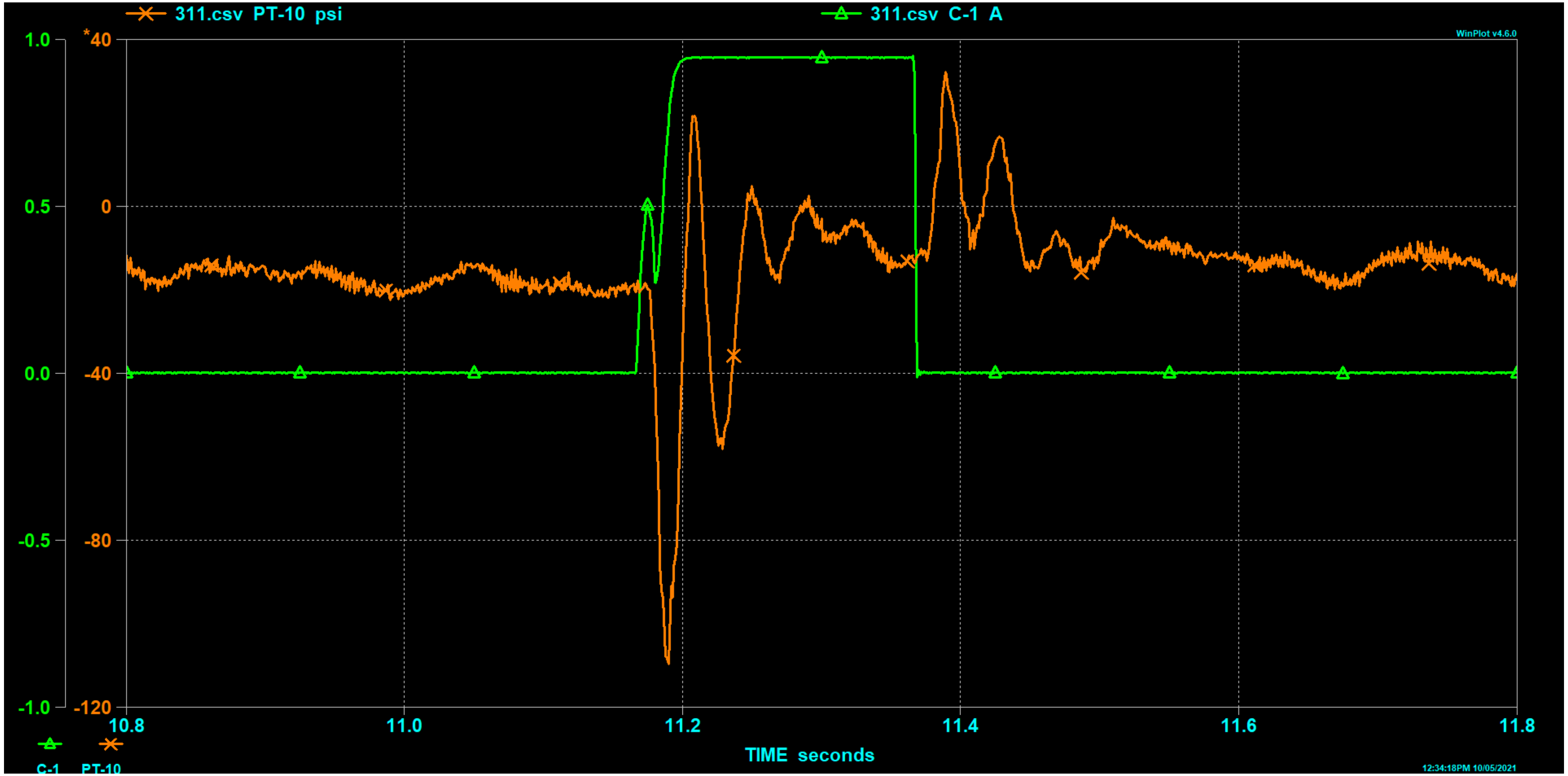
Thruster Pod 1

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



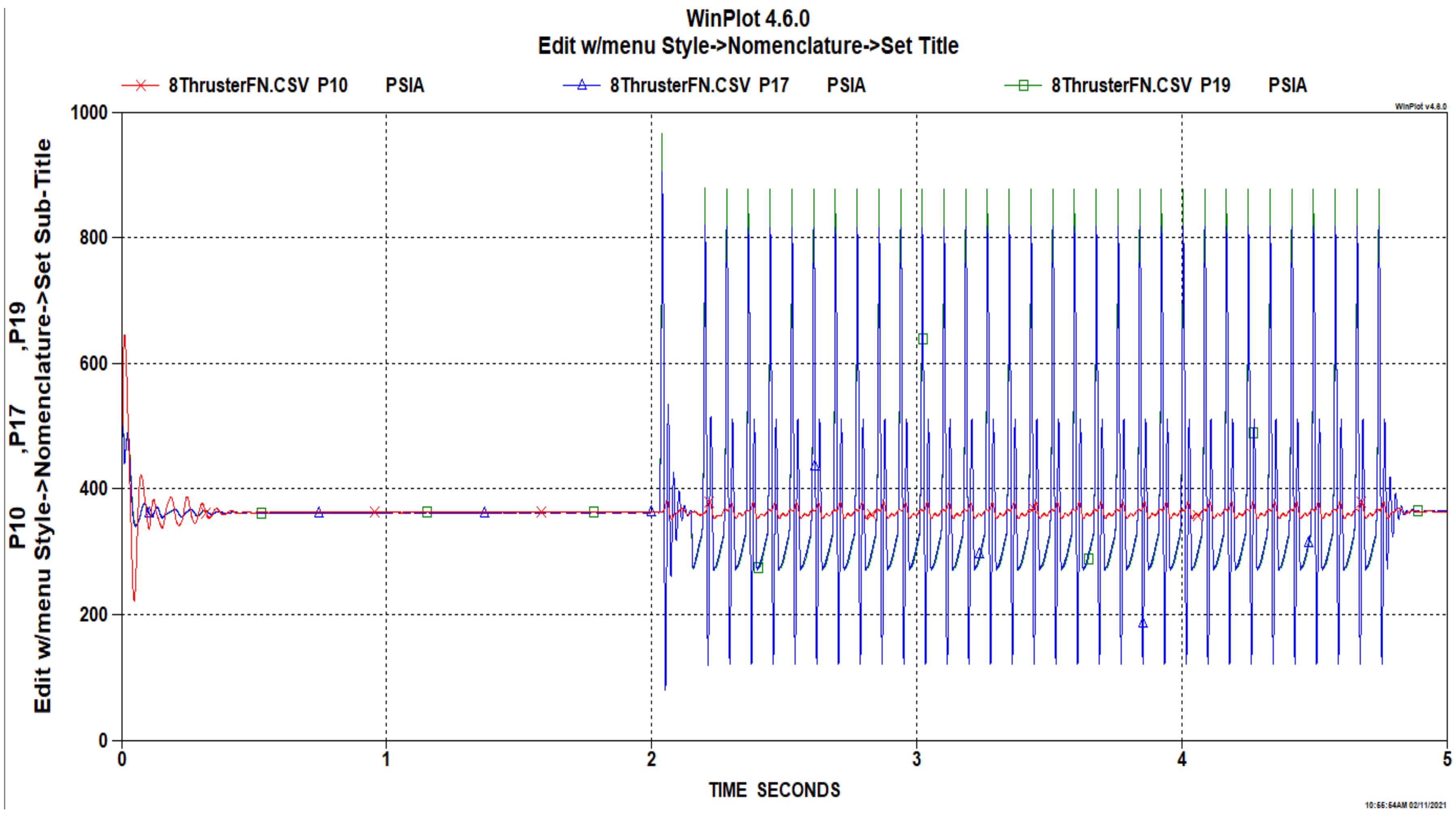
GTO-2.3: Test #311: Water hammer at Thruster Pod 2

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



GTO-2.3: Pre-test Prediction Comparison

Test 302

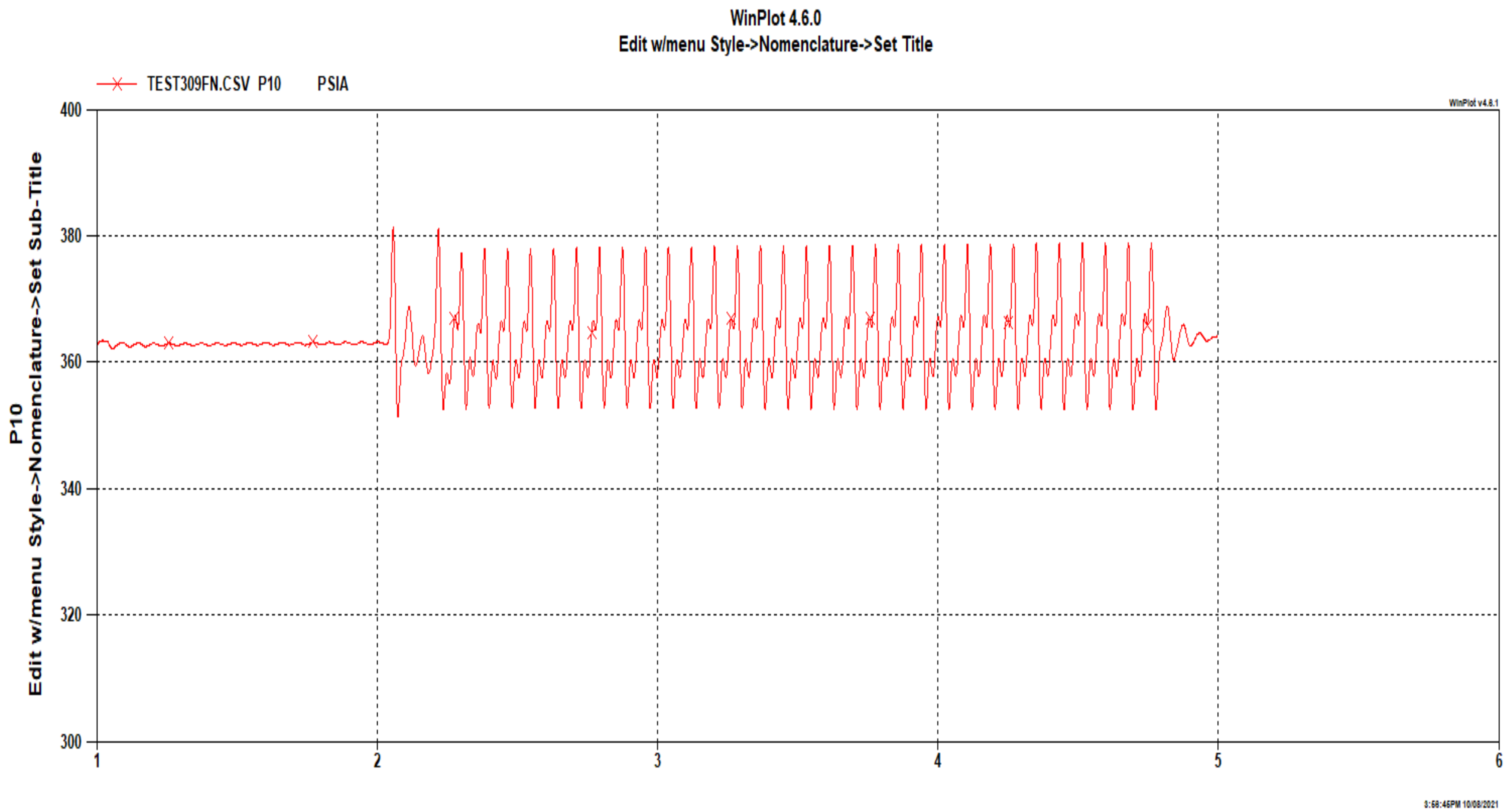


Slump:
Predicted: 88 psi drop
Actual: 135 psi drop

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

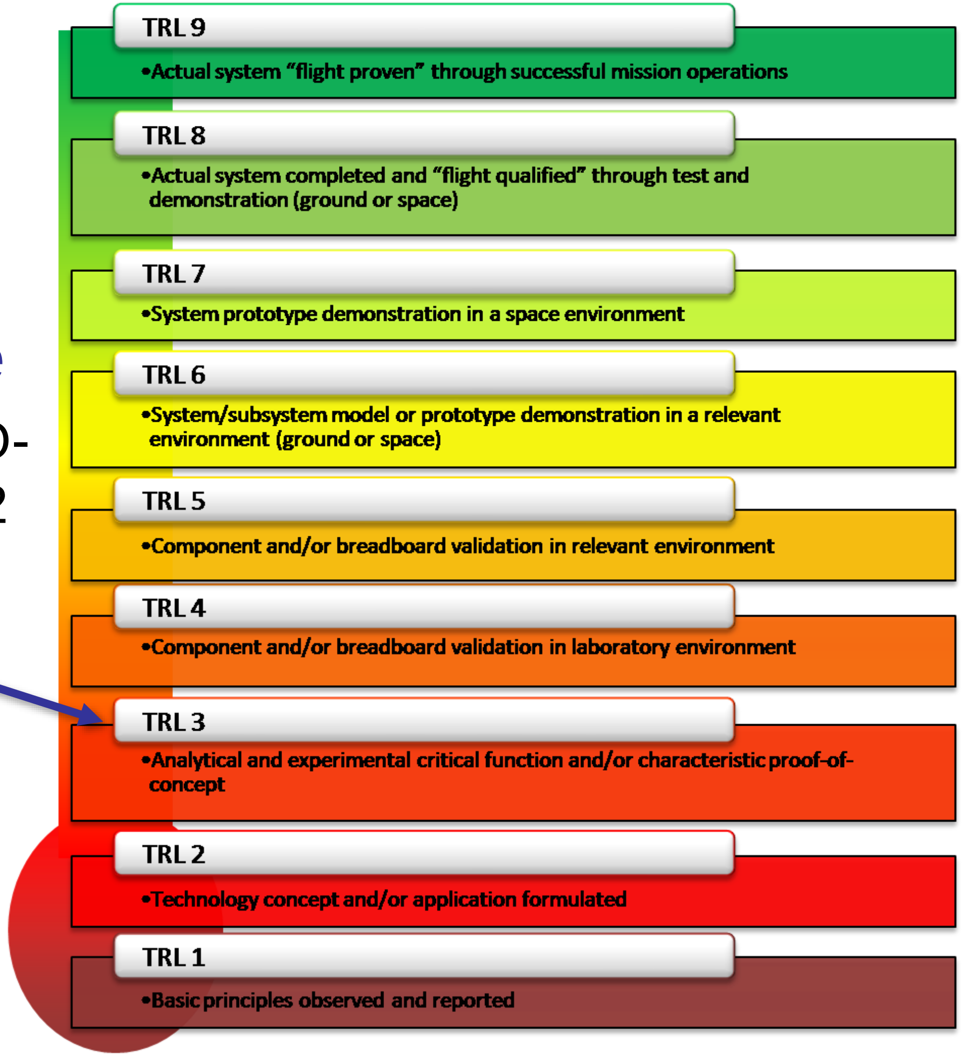
Spike:
Predicted: 18.5 psi rise
Actual: 30 psi spike

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



Future Work

- 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.

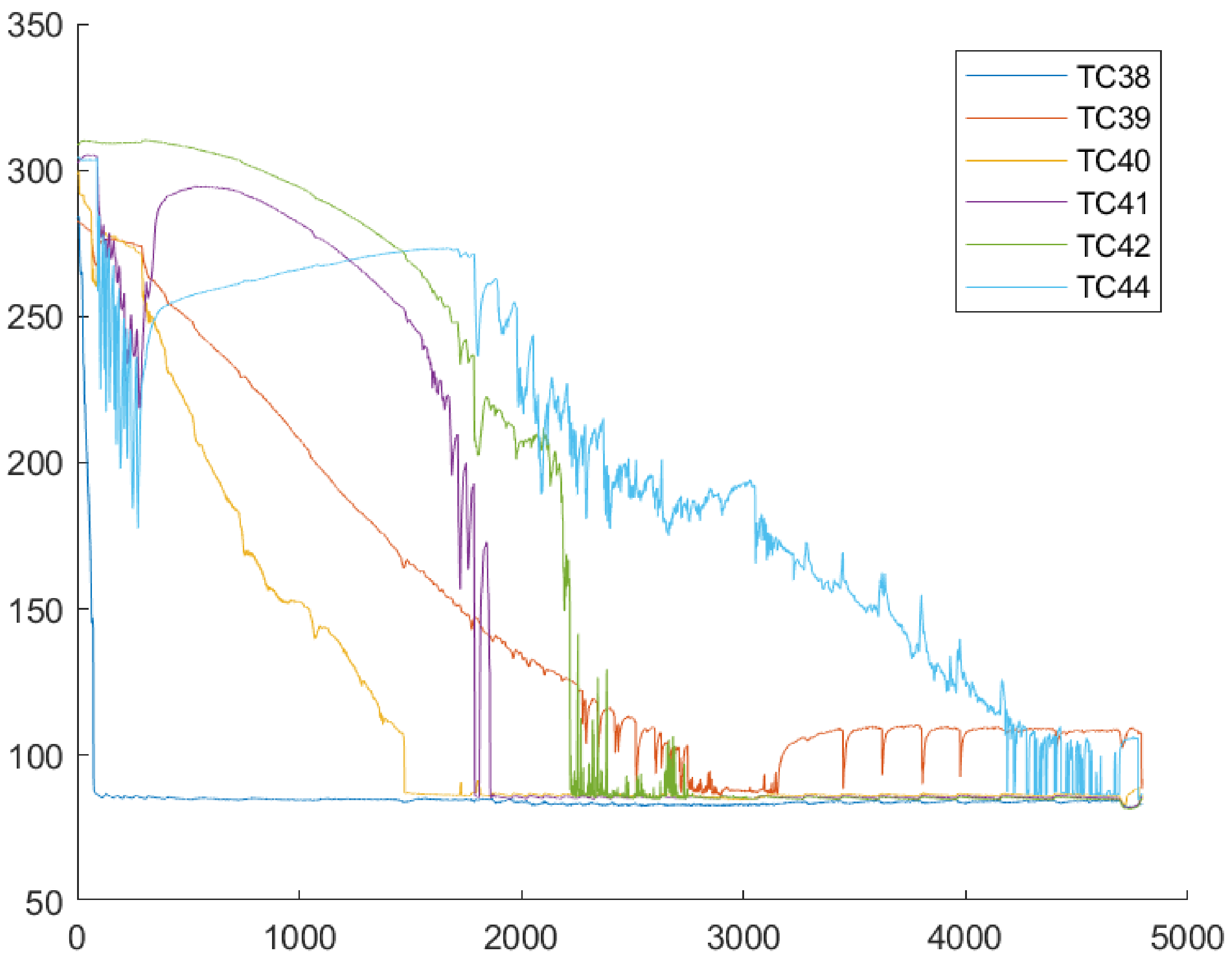
Lessons Learned

- 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

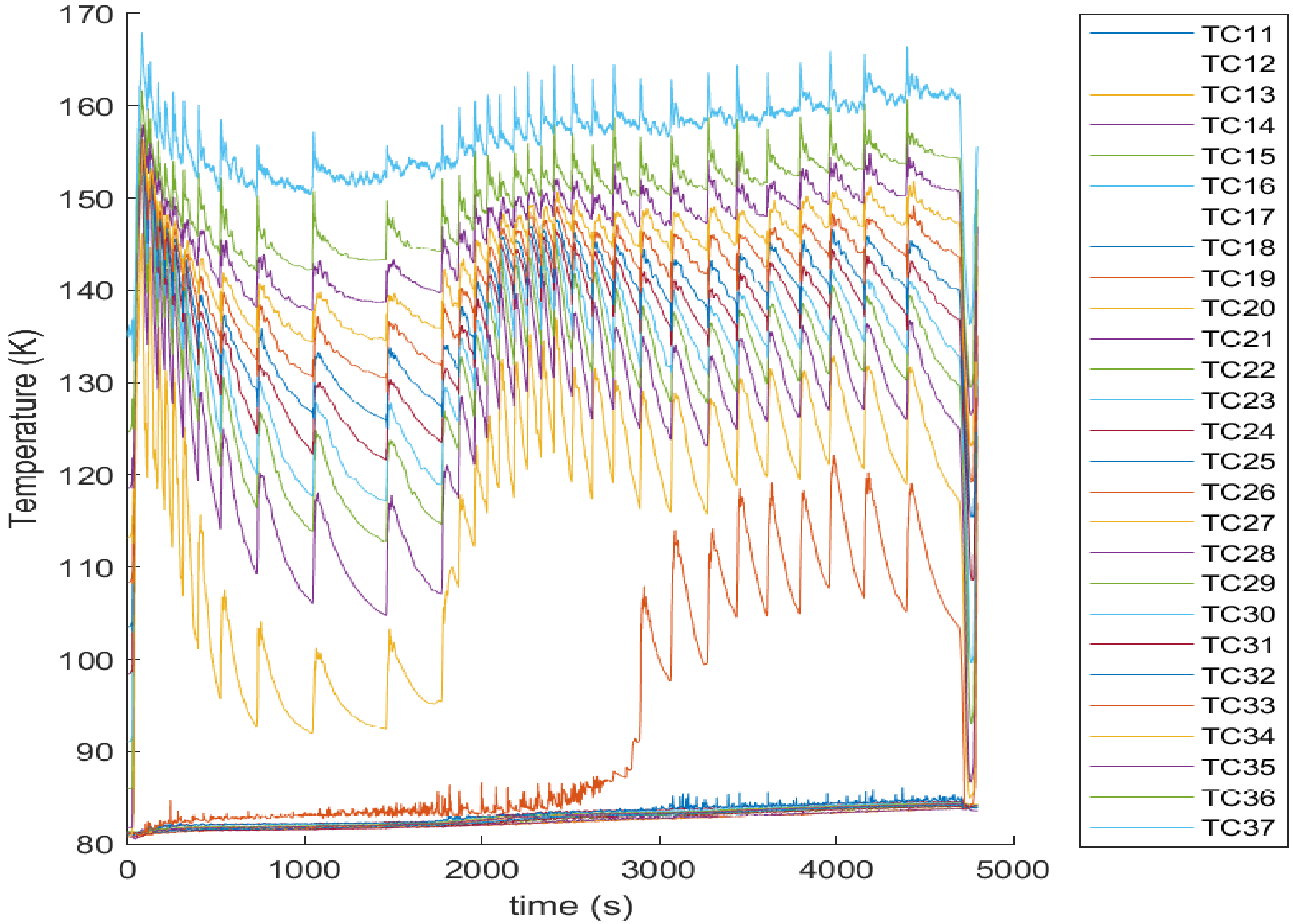
Questions?

Backup

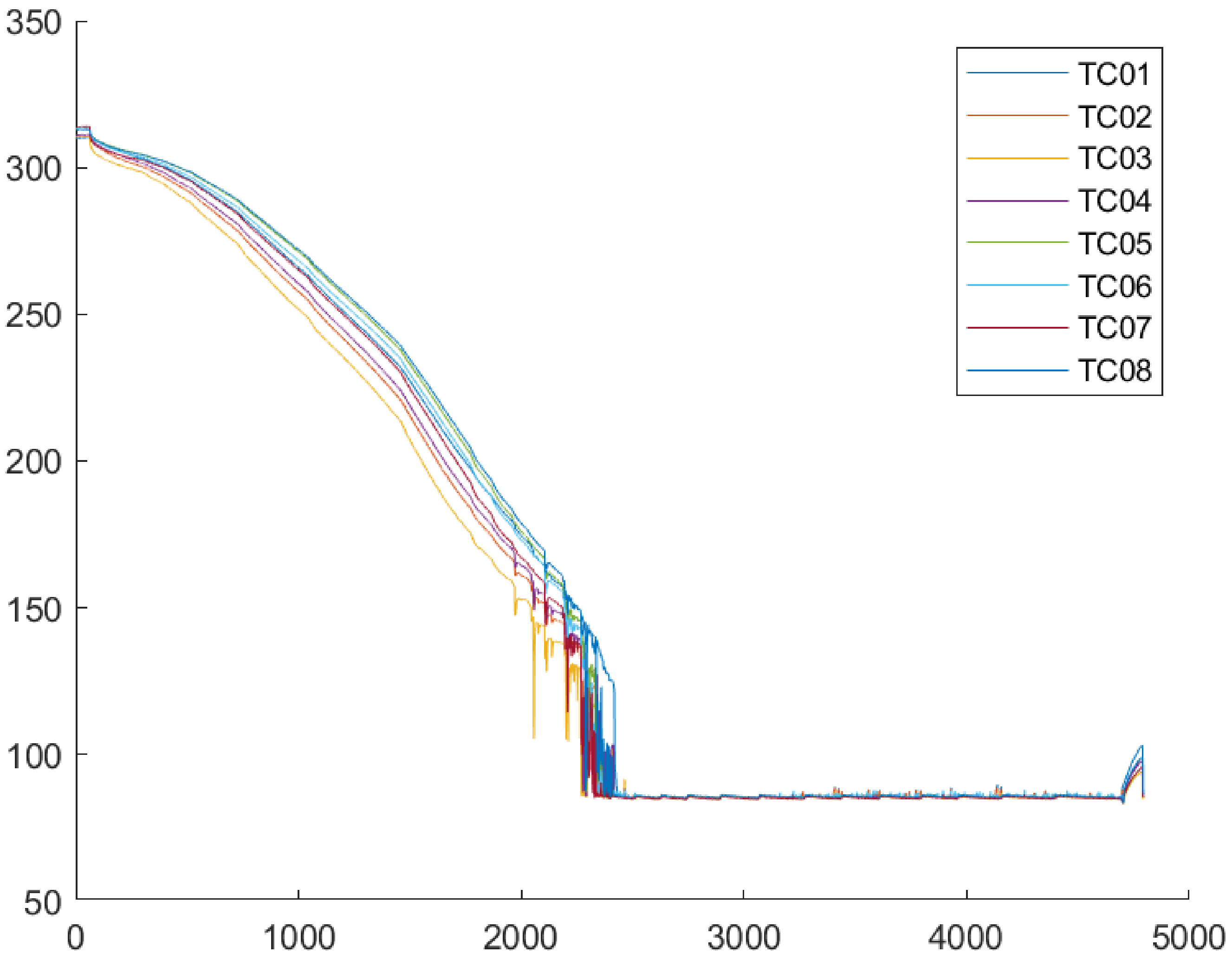
Recirculation Loop Chilldown



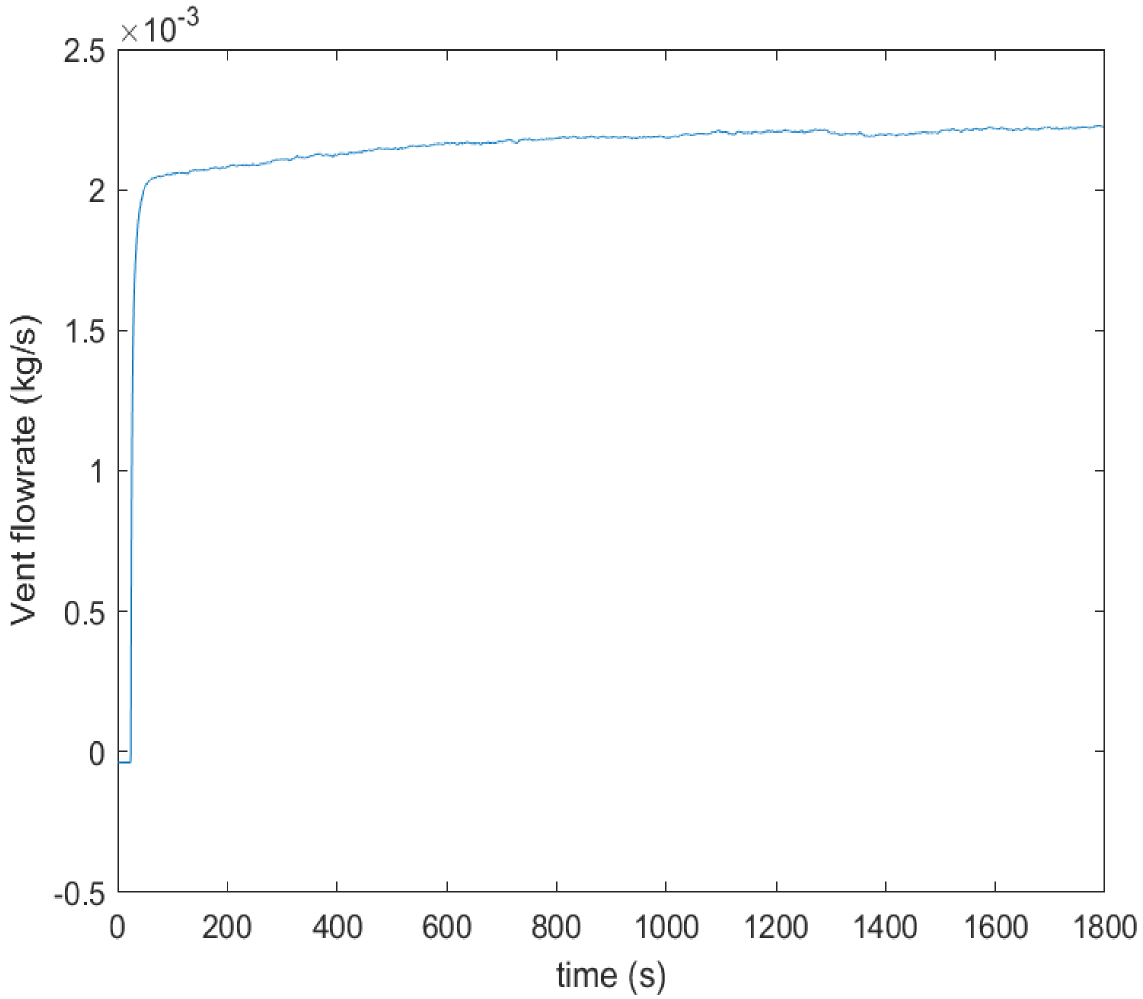
Tank Chilldown

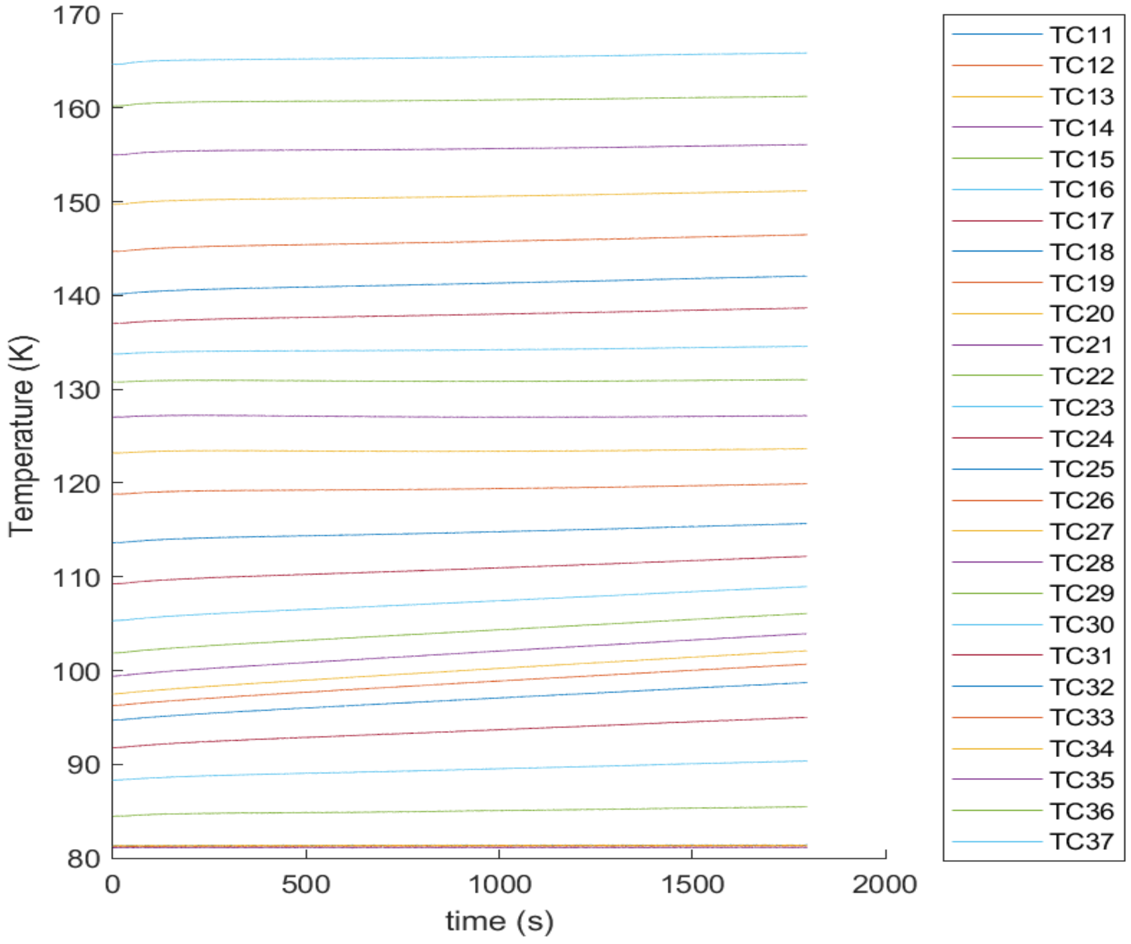


Thruster Pod Chilldown

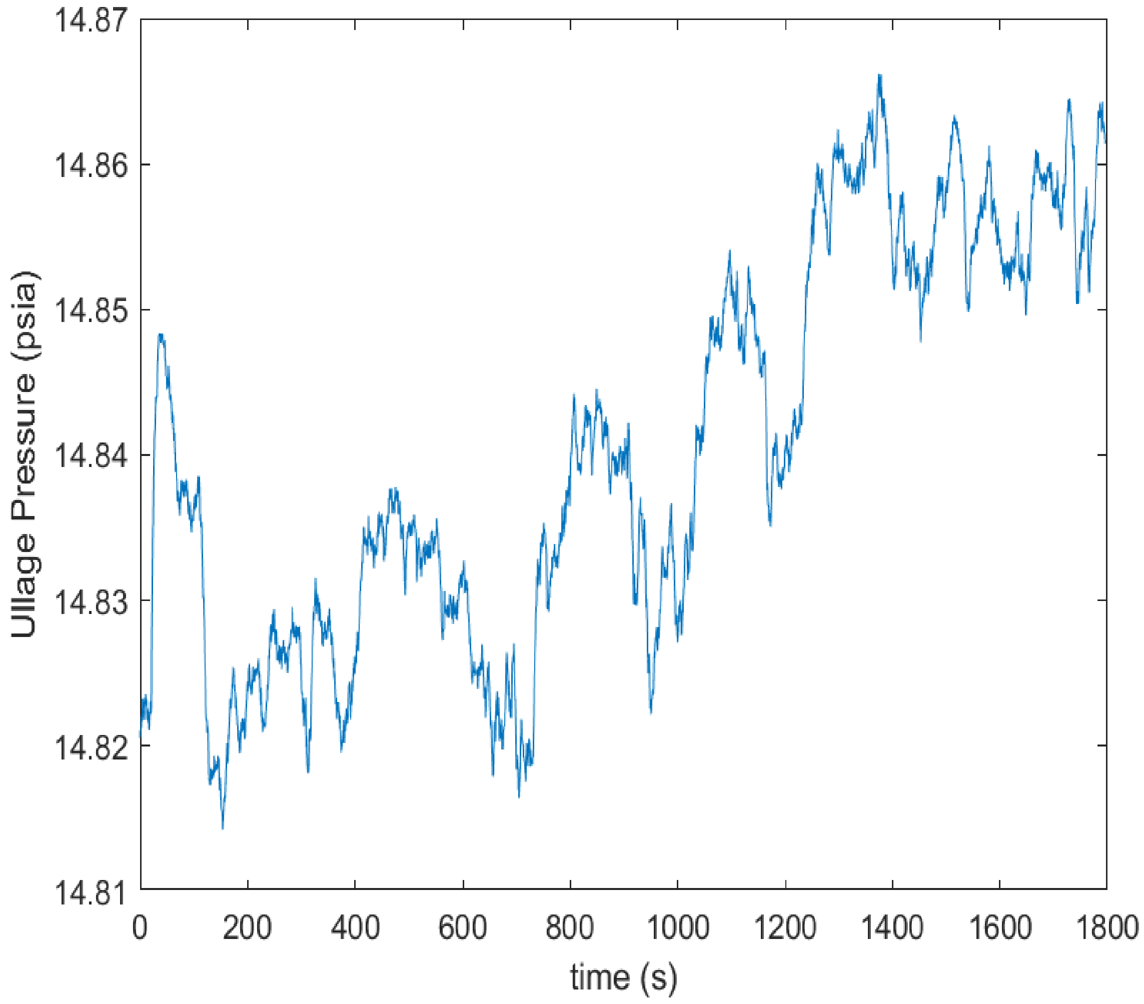


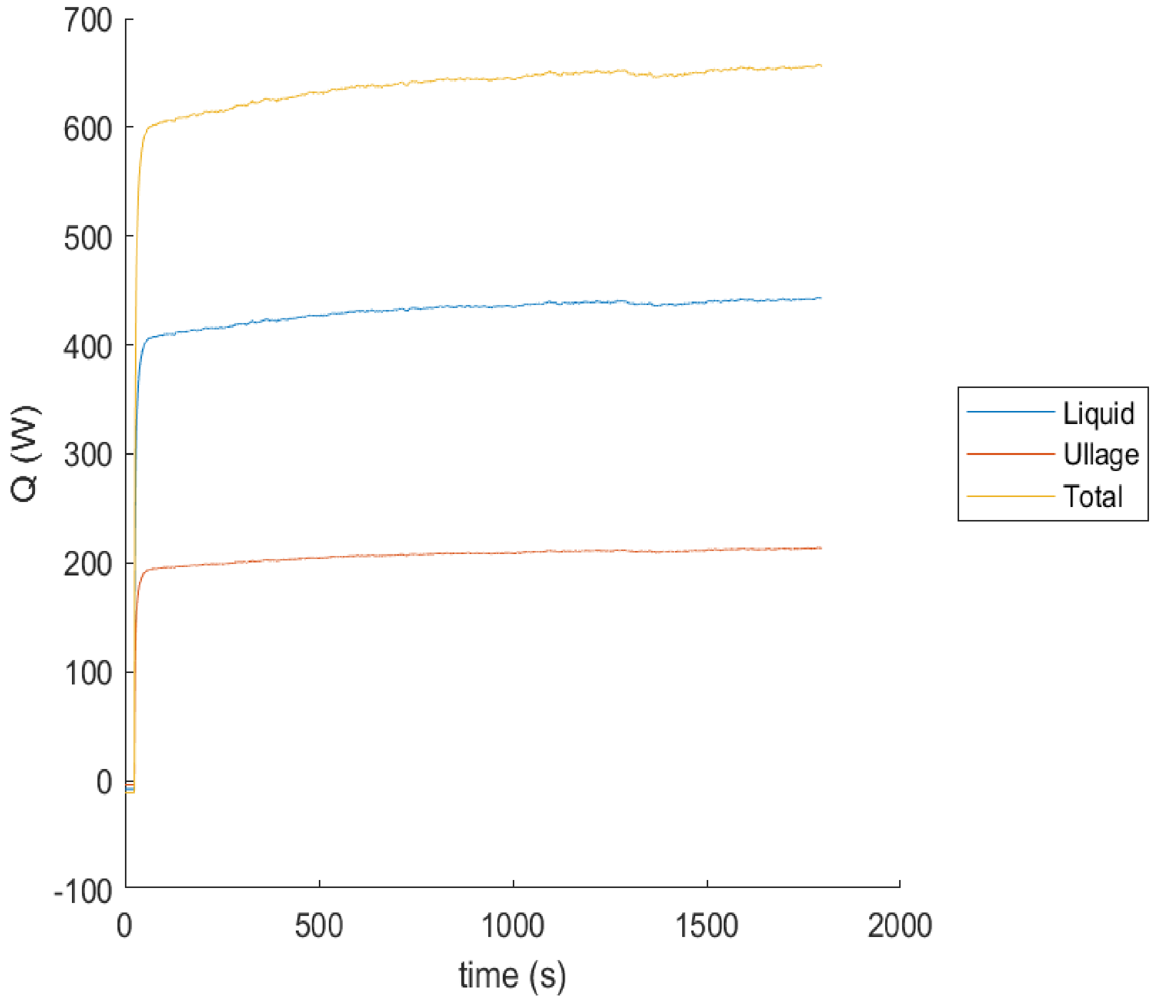
GTO-1: Amb. Heat Load Characterization 10% Fill Level



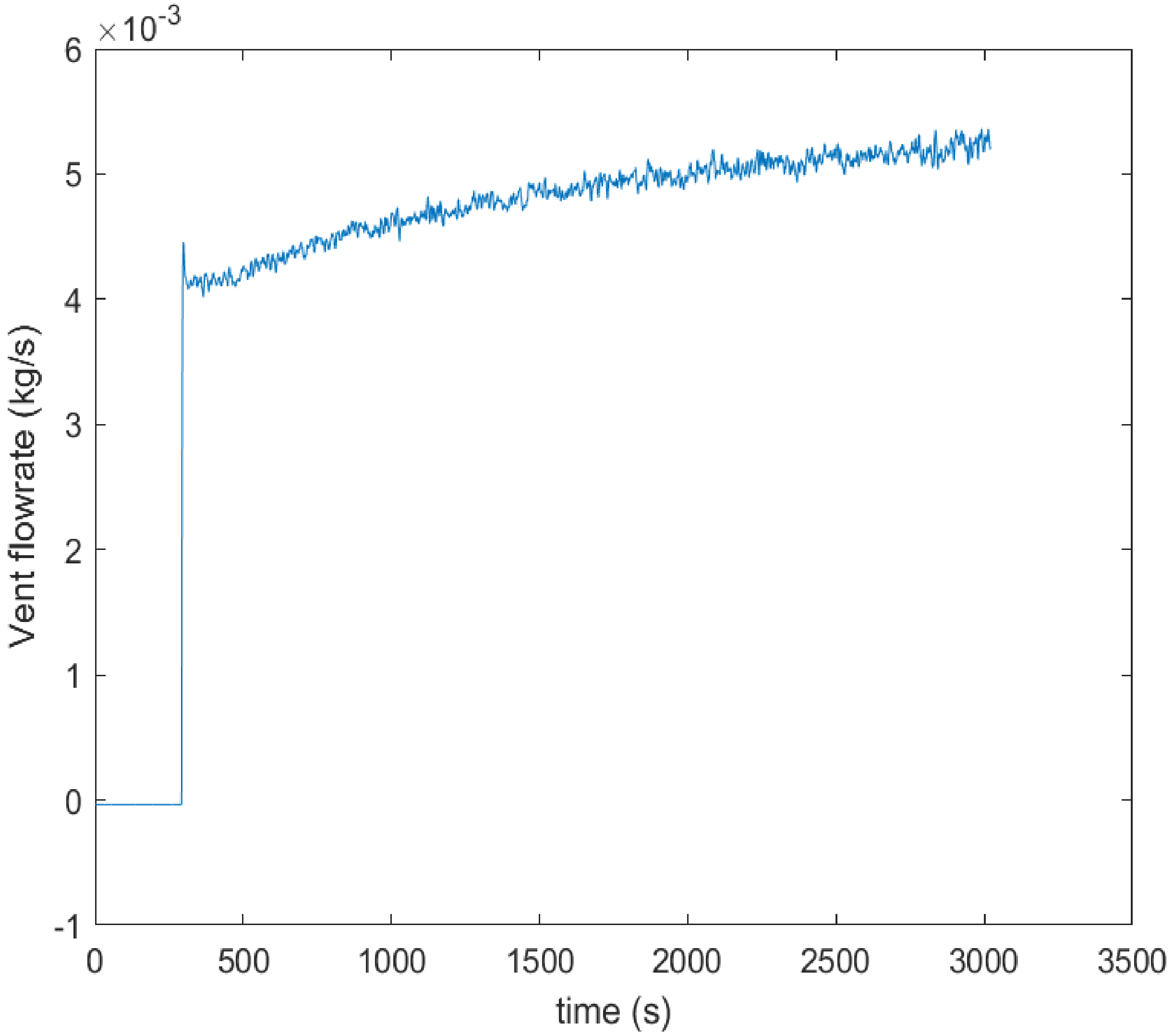


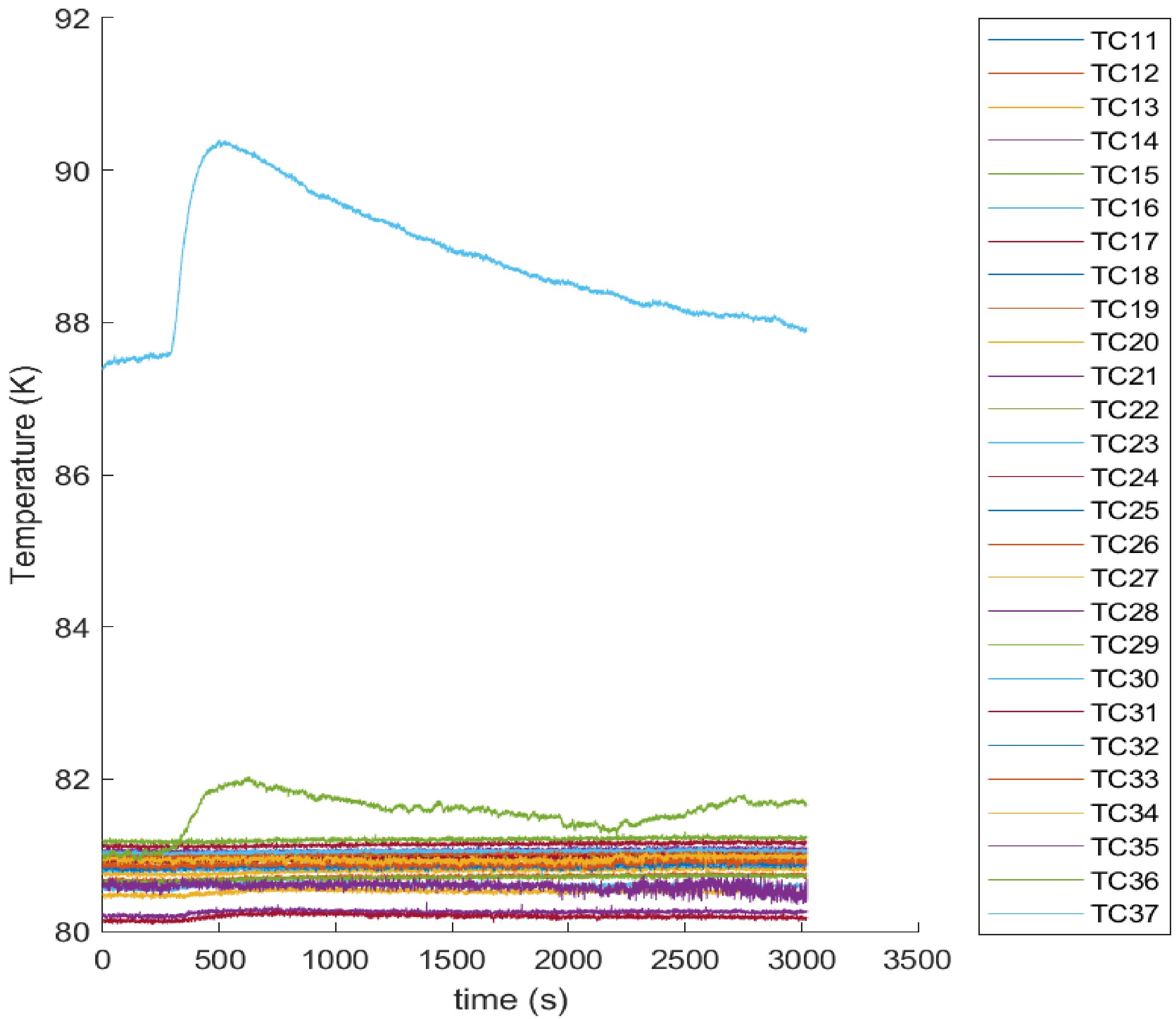
GTO-1: 10% Fill Ctd.





GTO-1 90% Fill


×10-3
6
5
4
3
2
1
0
-1
Vent flowrate (kg/s)
0
500
1000
1500
2000
2500
3000
3500
time (s)


92
90
88
86
84
82
80
Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
time (s)
TC11
TC12
TC13
TC14
TC15
TC16
TC17
TC18
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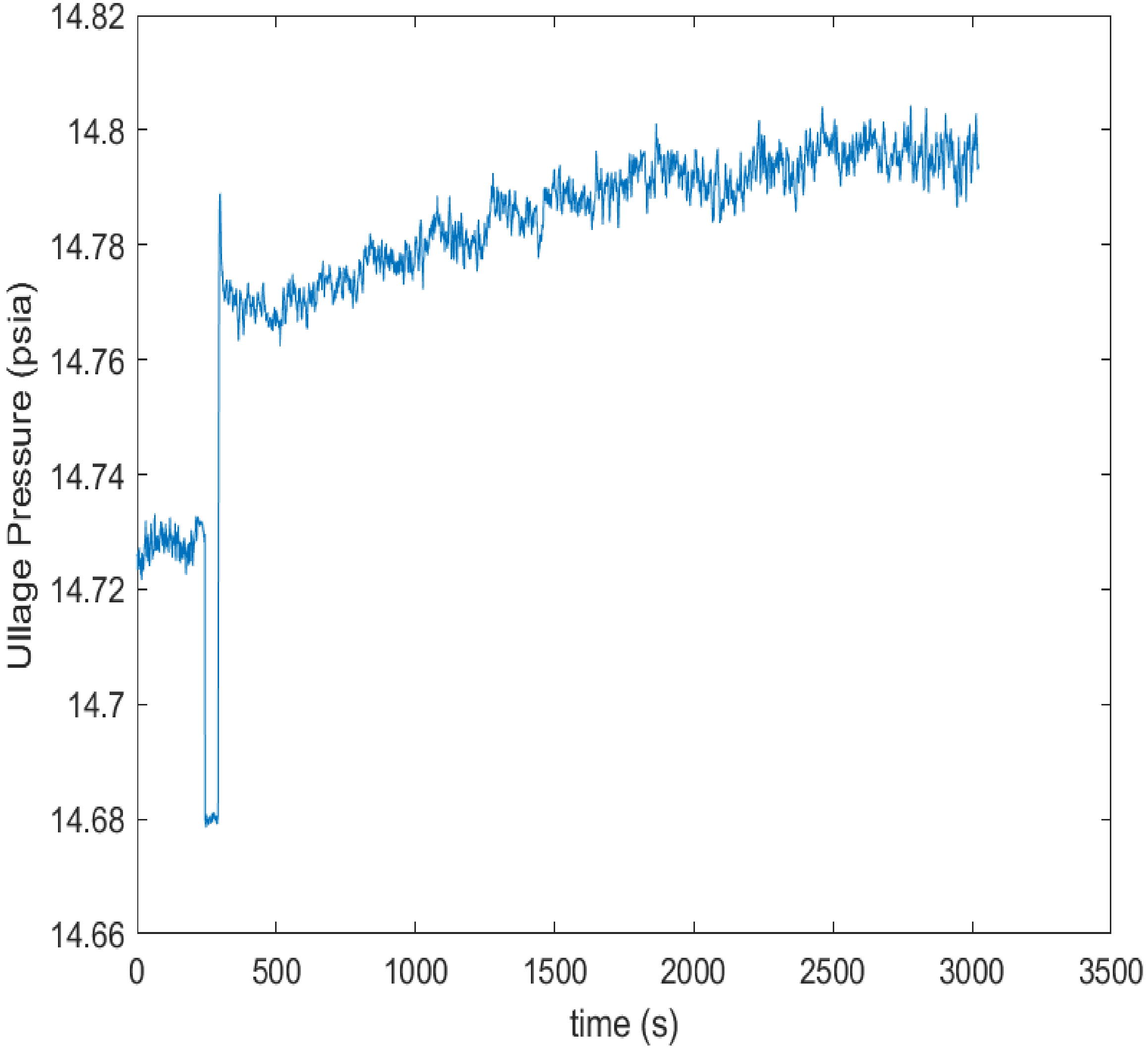
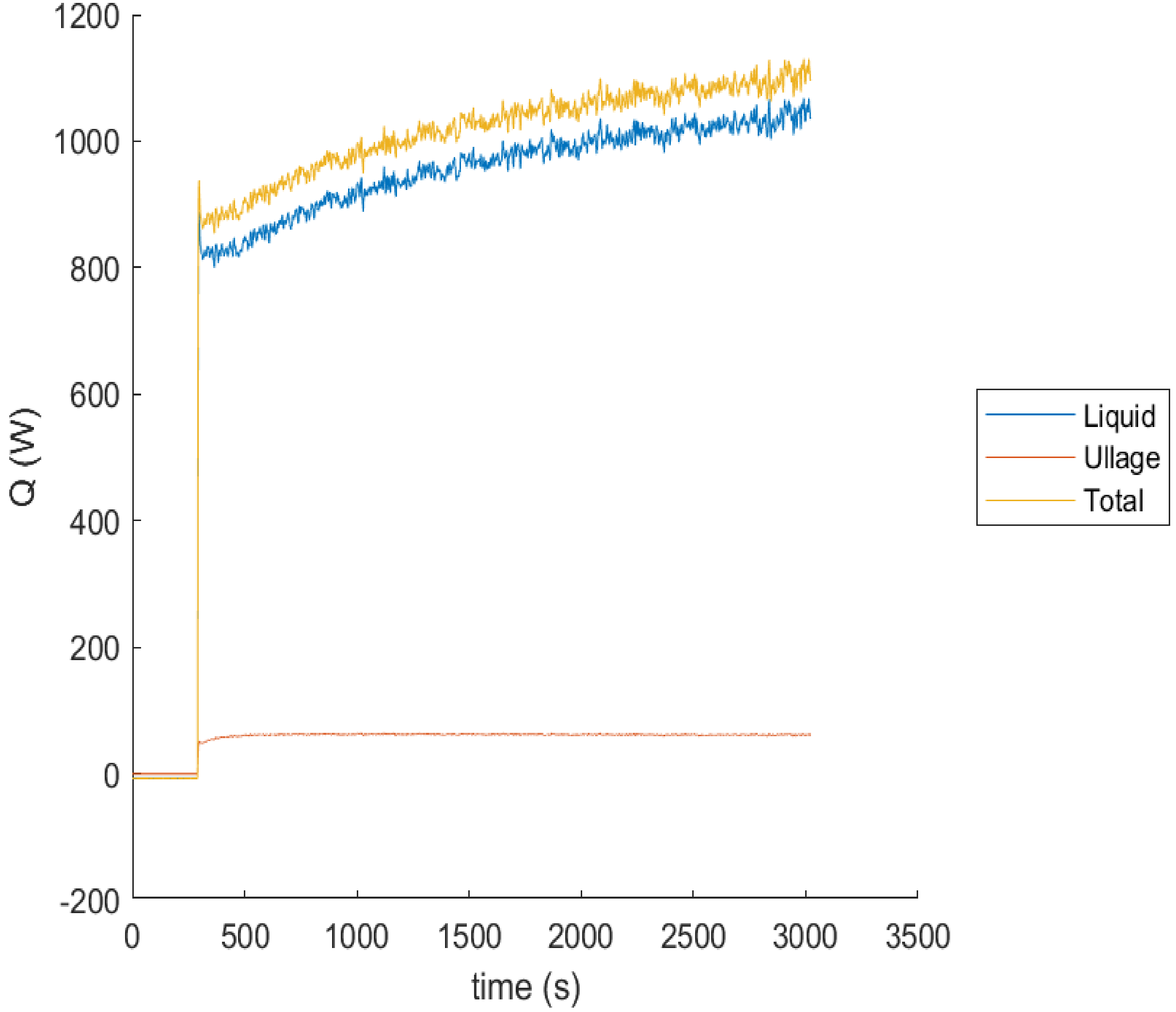
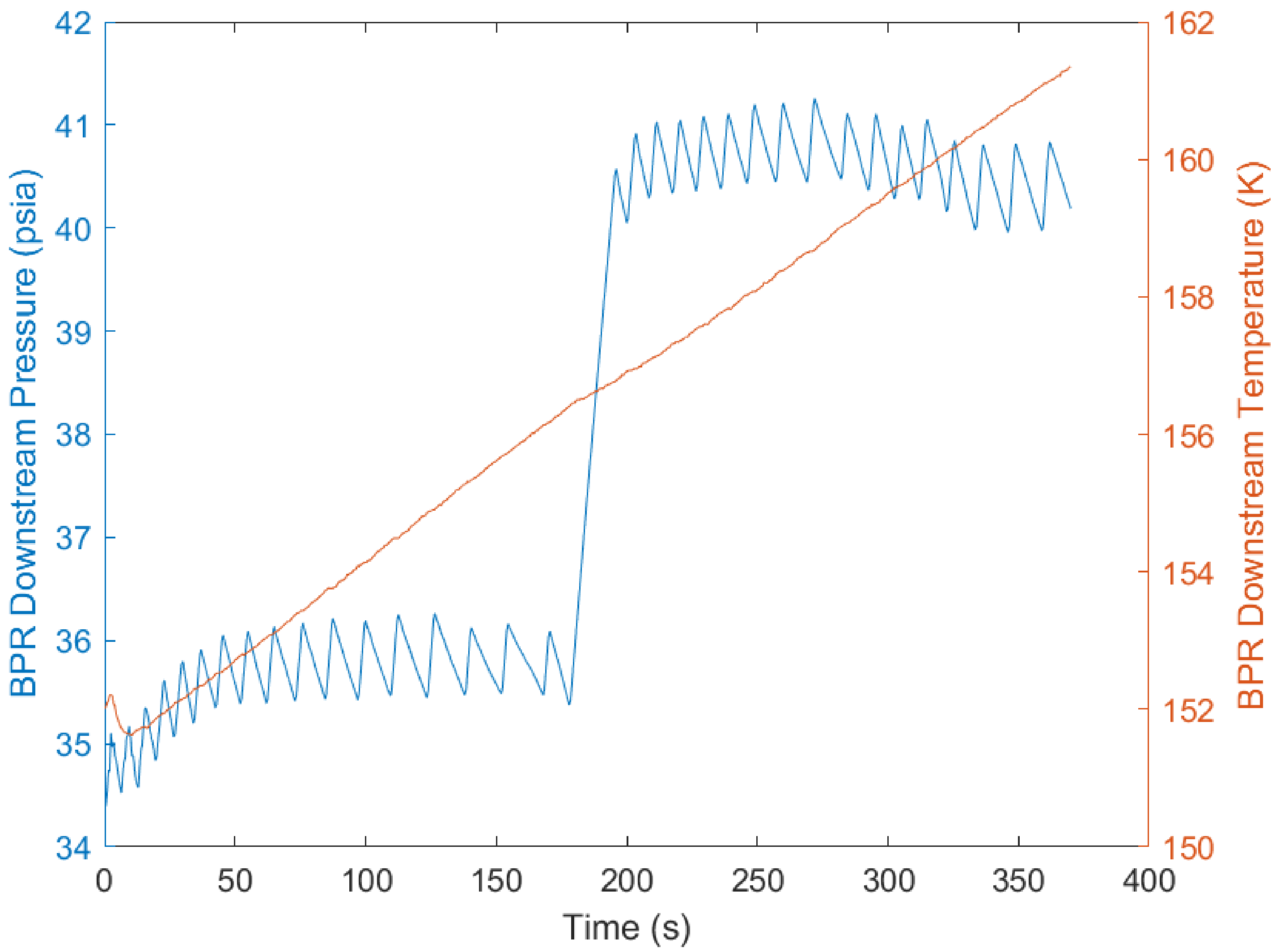
TC37

GTO-1 90% Fill ctd.

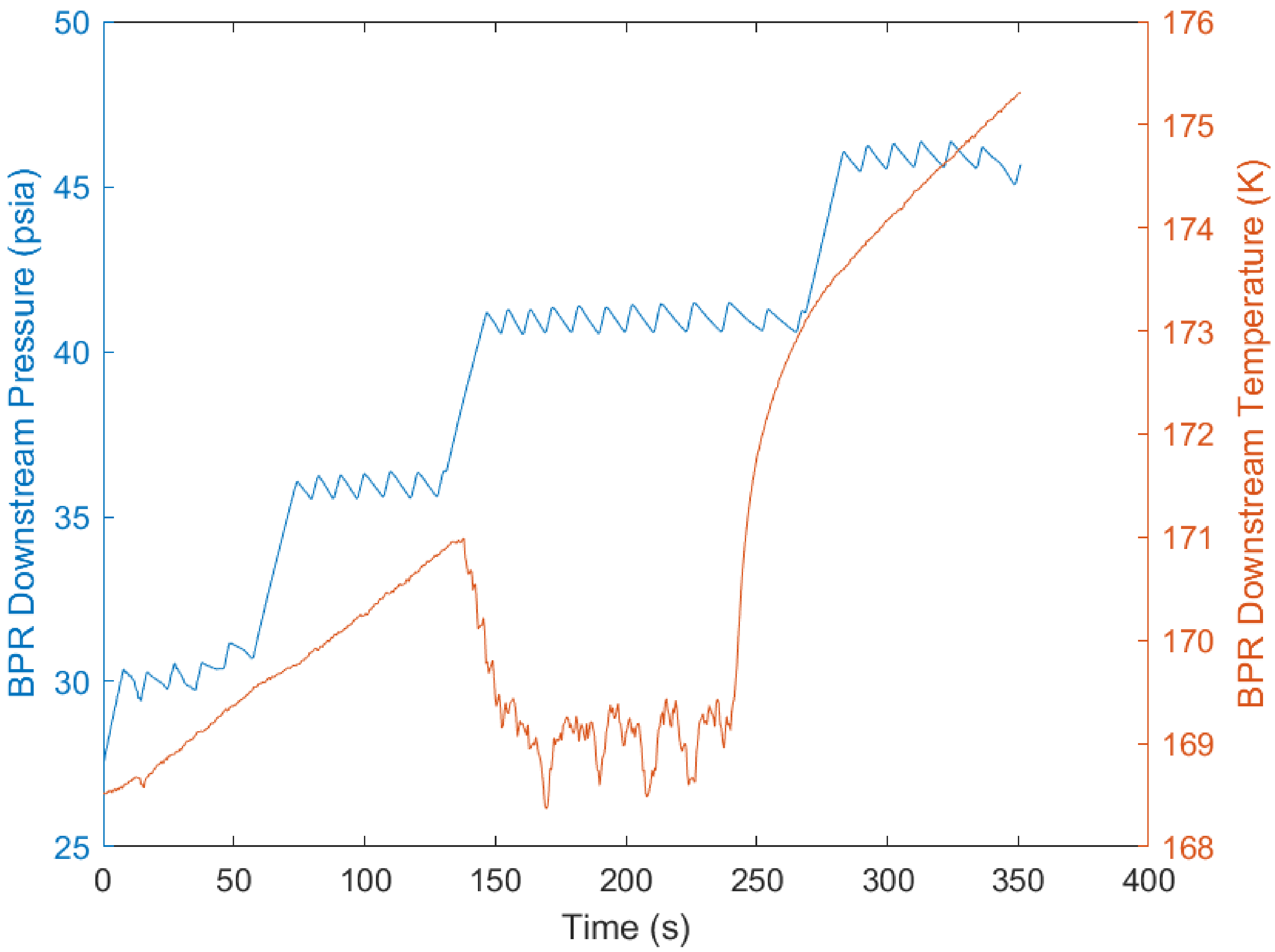




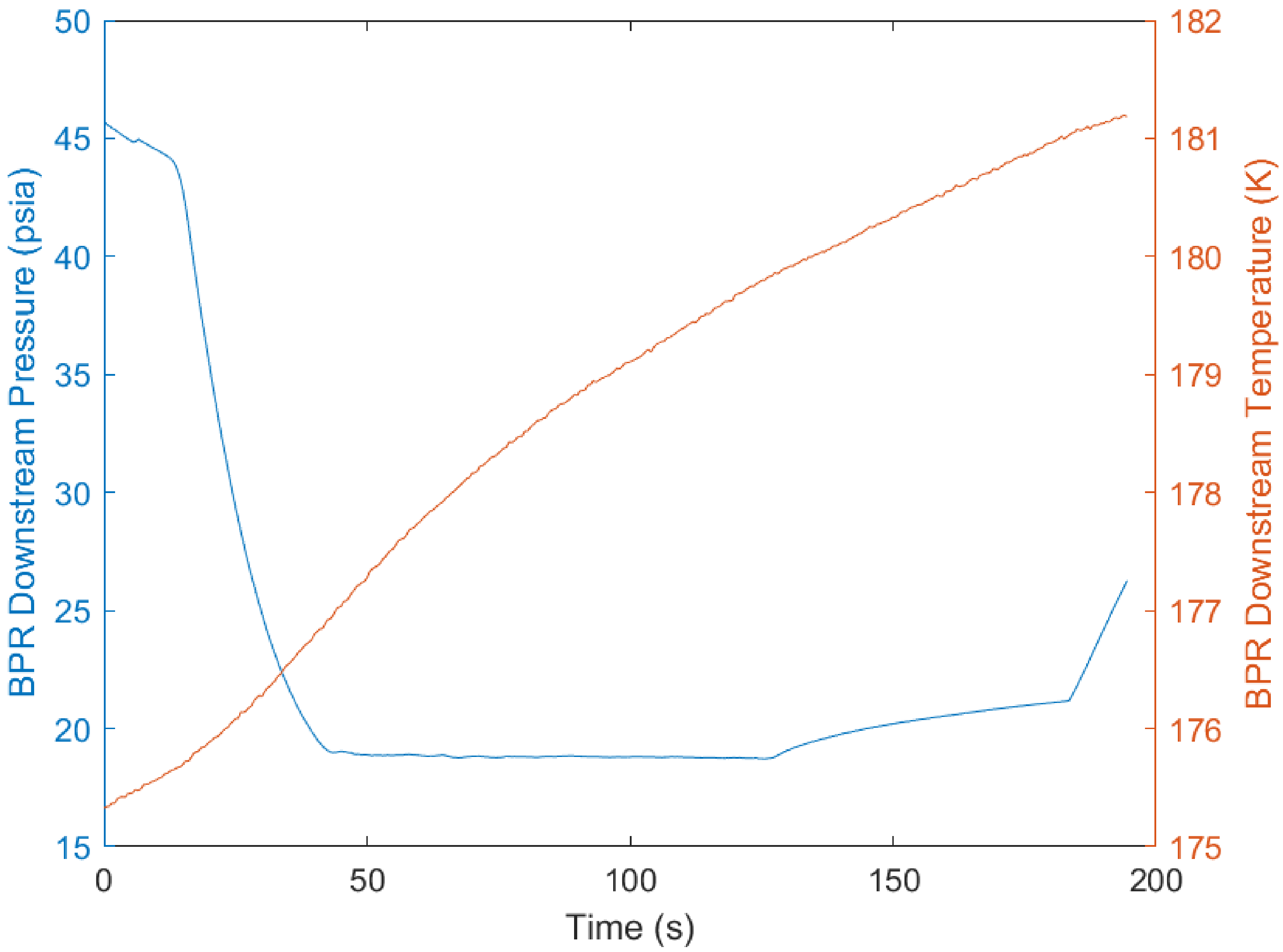
GTO-2.2: Return Flow Conditions, 12 Hz



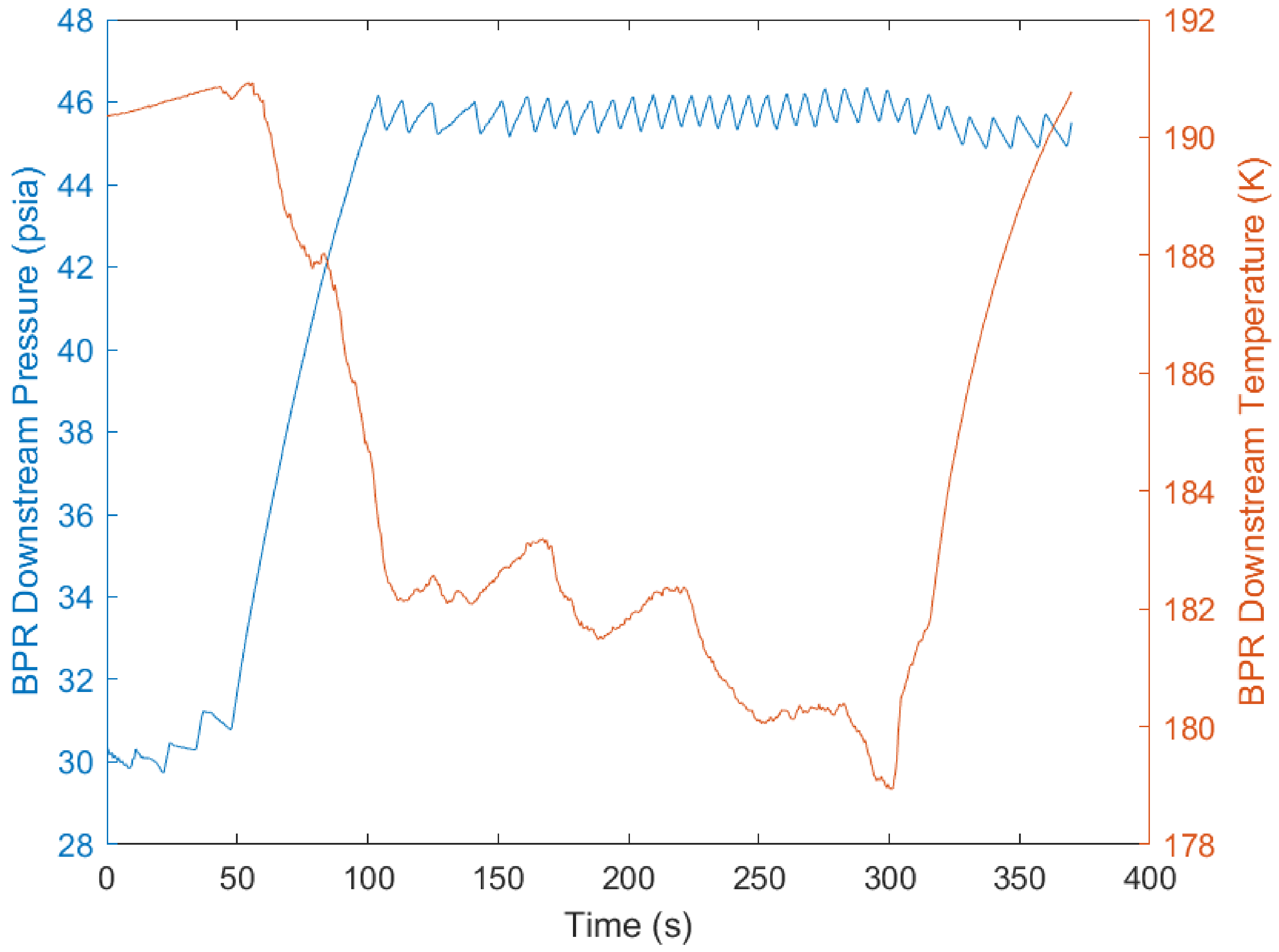
GTO-2.2: Return Flow Conditions, 18 Hz



GTO-2.2: Return Flow Conditions, 24 Hz



GTO-2.2: Return Flow Conditions, 31 Hz



GTO-2.2: Return Flow Conditions, 43 Hz