Thermal Desktop Modeling of the 2016 CRYOTE-2 Tank Chill and Fill Tests

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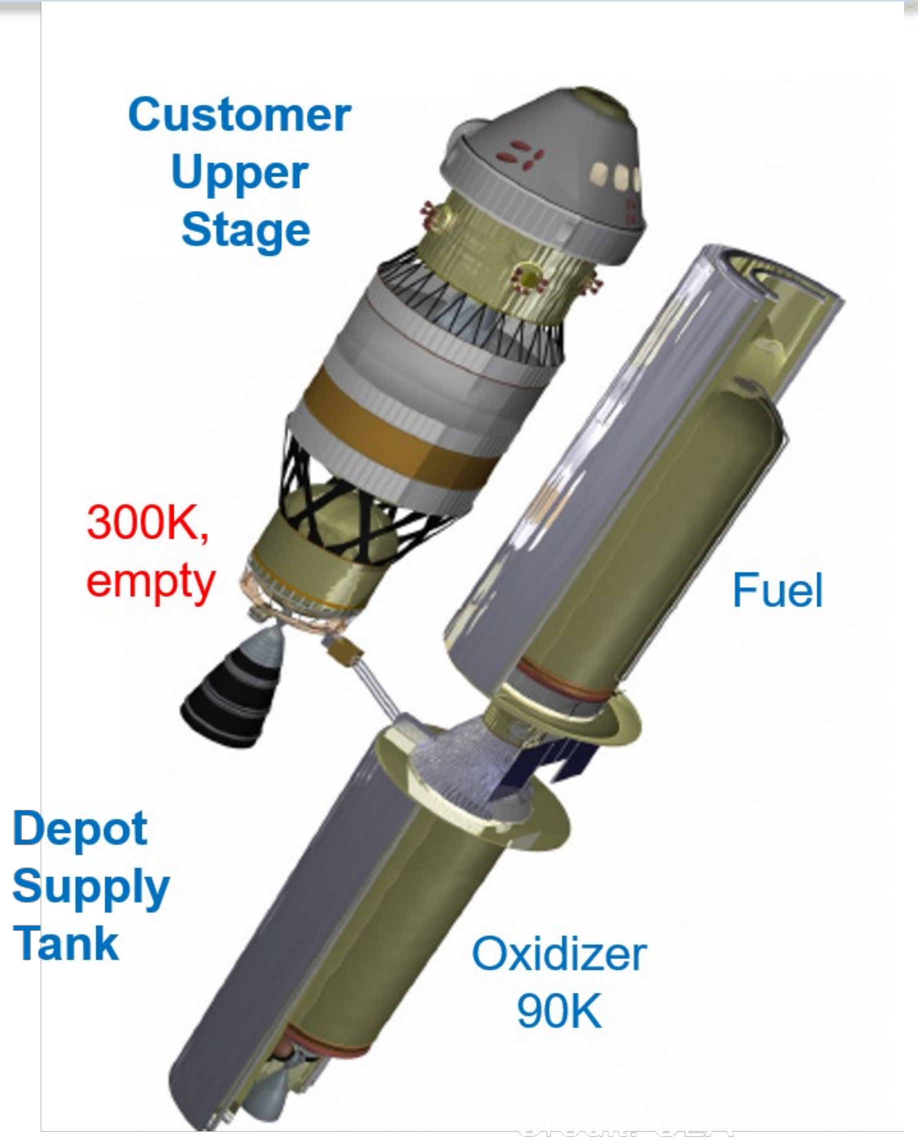
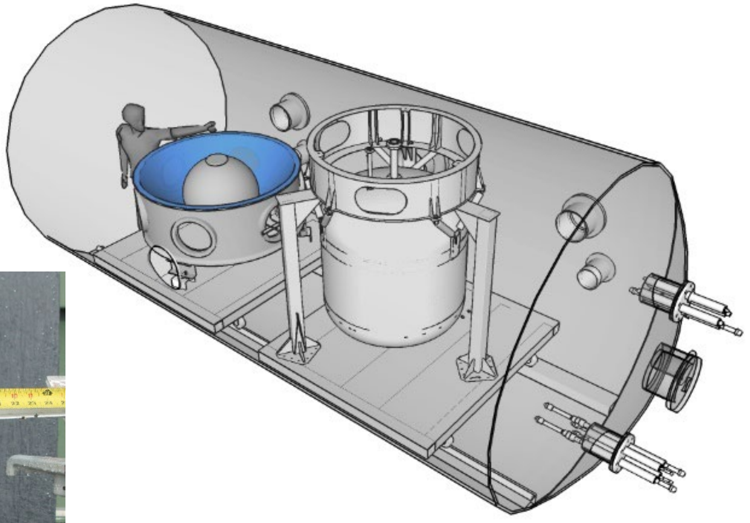
Introduction & Background

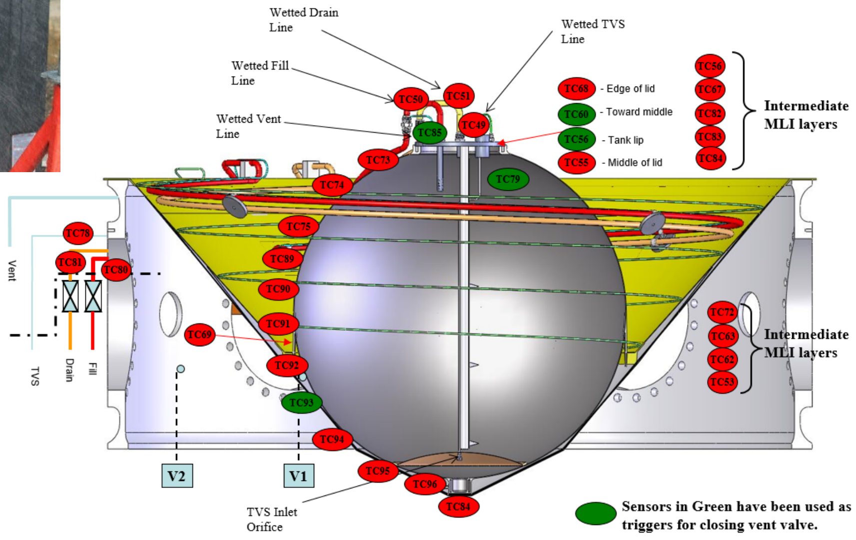
- Cryogenic fluid storage and transfer systems are key to enabling future space missions. Of particular interest are fuel depots in LEO
- Accurate modeling of chilldown and transfer methods is needed
- Previous ground tests have been conducted of tank chilldown and fill with various injectors
- These historical datasets can be leveraged to create future predictive models of tank chilldown and fill operations



CRYOTE-2 Test Overview

- Rapid chilldown and No-Vent Fill (NVF) ground tests
- Spherical Receiver Tank: 0.221m^3, 6-4 Titanium wall and 304 SS lid
- Liquid Nitrogen
- 3 Different Injectors
  - **<u>3-spray nozzle</u>**
    - 4 Successful Tests (> 90% fill)
    - 4 Failed Tests (MEOP exceeded)
  - 8-orifice inverted showerhead
  - 16-orifice inverted showerhead

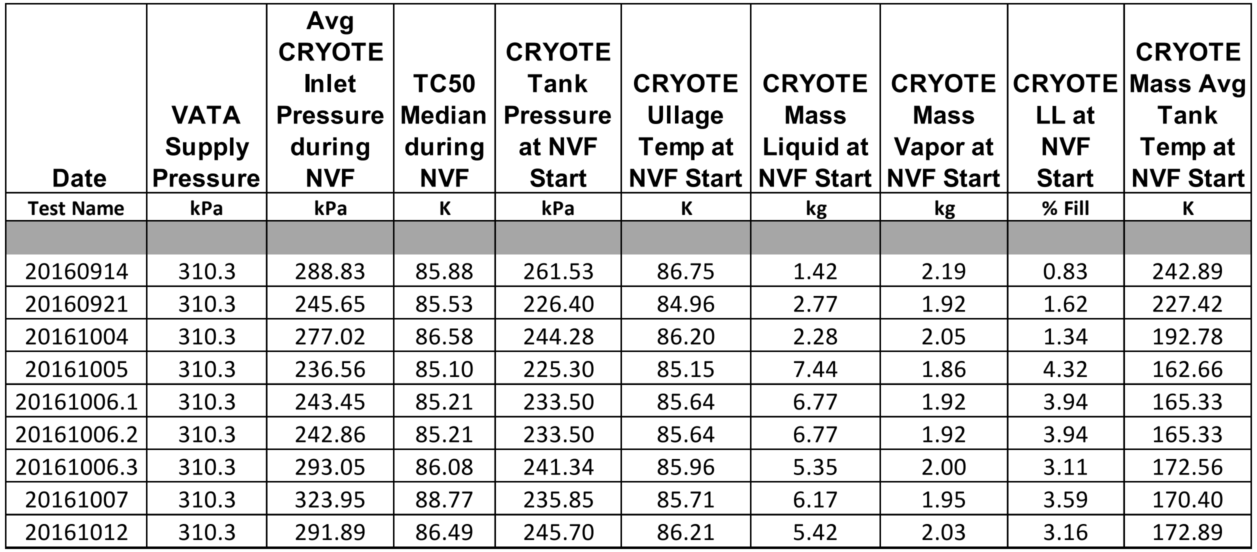




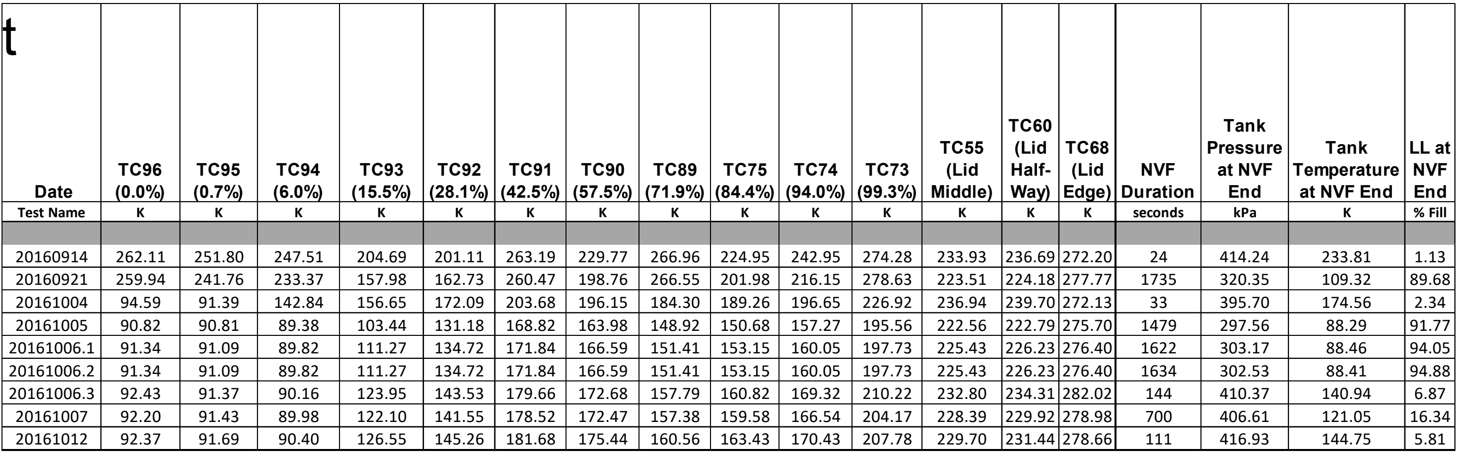
🟢 Sensors in Green have been used as triggers for closing vent valve.

CRYOTE-2 Test Overview

- Current work is among most challenging cases modeled in TD to date given high thermal gradients (high wall temperatures at start of fill)
- 2016 CRYOTE-2 tests lacked a flow meter on the inlet line
- Fill Level was calculated using the load cells under the receiver tank
- Mass flow rate can be backed out from the fill level but only during FILL, not during CHILLDOWN
  - Only FILL was modeled in TD
- Model Outputs:
  - Receiver Tank Pressure
  - Fill Level
  - Average Wall Temperature



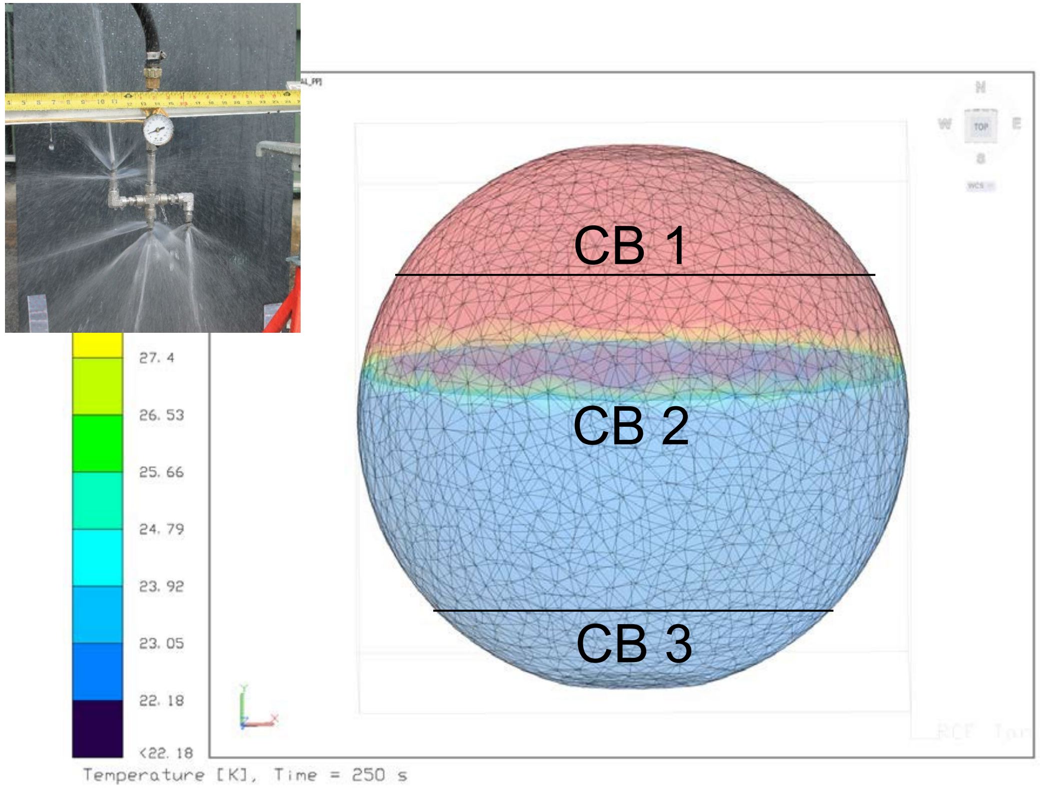
Date	VATA Supply Pressure	Avg CRYOTE Inlet Pressure during NVF	TC50 Median during NVF	CRYOTE Tank Pressure at NVF Start	CRYOTE Ullage Temp at NVF Start	CRYOTE Mass Liquid at NVF Start	CRYOTE Mass Vapor at NVF Start	CRYOTE LL at NVF Start	CRYOTE Mass Avg Tank Temp at NVF Start
Test Name	kPa	kPa	K	kPa	K	kg	kg	% Fill	K
20160914	310.3	288.83	85.88	261.53	86.75	1.42	2.19	0.83	242.89
20160921	310.3	245.65	85.53	226.40	84.96	2.77	1.92	1.62	227.42
20161004	310.3	277.02	86.58	244.28	86.20	2.28	2.05	1.34	192.78
20161005	310.3	236.56	85.10	225.30	85.15	7.44	1.86	4.32	162.66
20161006.1	310.3	243.45	85.21	233.50	85.64	6.77	1.92	3.94	165.33
20161006.2	310.3	242.86	85.21	233.50	85.64	6.77	1.92	3.94	165.33
20161006.3	310.3	293.05	86.08	241.34	85.96	5.35	2.00	3.11	172.56
20161007	310.3	323.95	88.77	235.85	85.71	6.17	1.95	3.59	170.40
20161012	310.3	291.89	86.49	245.70	86.21	5.42	2.03	3.16	172.89



Date	TC96 (0.0%)	TC95 (0.7%)	TC94 (6.0%)	TC93 (15.5%)	TC92 (28.1%)	TC91 (42.5%)	TC90 (57.5%)	TC89 (71.9%)	TC75 (84.4%)	TC74 (94.0%)	TC73 (99.3%)	TC55 (Lid Middle)	TC60 (Lid Half-Way)	TC68 (Lid Edge)	NVF Duration	Tank Pressure at NVF End	Tank Temperature at NVF End	LL at NVF End
Test Name	K	K	K	K	K	K	K	K	K	K	K	K	K	K	seconds	kPa	K	% Fill
20160914	262.11	251.80	247.51	204.69	201.11	263.19	229.77	266.96	224.95	242.95	274.28	233.93	236.69	272.20	24	414.24	233.81	1.13
20160921	259.94	241.76	233.37	157.98	162.73	260.47	198.76	266.55	201.98	216.15	278.63	223.51	224.18	277.77	1735	320.35	109.32	89.68
20161004	94.59	91.39	142.84	156.65	172.09	203.68	196.15	184.30	189.26	196.65	226.92	236.94	239.70	272.13	33	395.70	174.56	2.34
20161005	90.82	90.81	89.38	103.44	131.18	168.82	163.98	148.92	150.68	157.27	195.56	222.56	222.79	275.70	1479	297.56	88.29	91.77
20161006.1	91.34	91.09	89.82	111.27	134.72	171.84	166.59	151.41	153.15	160.05	197.73	225.43	226.23	276.40	1622	303.17	88.46	94.05
20161006.2	91.34	91.09	89.82	111.27	134.72	171.84	166.59	151.41	153.15	160.05	197.73	225.43	226.23	276.40	1634	302.53	88.41	94.88
20161006.3	92.43	91.37	90.16	123.95	143.53	179.66	172.68	157.79	160.82	169.32	210.22	232.80	234.31	282.02	144	410.37	140.94	6.87
20161007	92.20	91.43	89.98	122.10	141.55	178.52	172.47	157.38	159.58	166.54	204.17	228.39	229.92	278.98	700	406.61	121.05	16.34
20161012	92.37	91.69	90.40	126.55	145.26	181.68	175.44	160.56	163.43	170.43	207.78	229.70	231.44	278.66	111	416.93	144.75	5.81

Thermal Desktop Model Set-Up

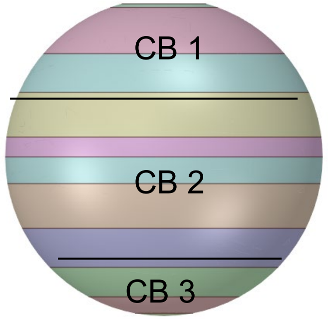
- Solid Tank wall is meshed in SpaceClaim and modeled as ~500 solid nodes with material properties of Titanium/SS 304 applied
- Fluid lump is modeled in a Flow Compartment
- Typically Compartment with a single Bay is used to model bottom-fill (dip tube)
- The 3-spray nozzle has flow directed at the wall and lid unequally, can be seen in the different tank temperatures at the start of NVF
- The Compartment was split into 3 different horizontally stacked Bays so that the flow can be directed to different tank wall areas
- Default pool boiling heat transfer coefficient used to model heat transfer at the wall
- A Single Liquid-Vapor Interface is tracked as tank fills

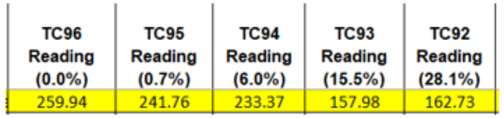


Compartment Bay #	Thermocouple Location	Flow Rate % per Compartment Bay
1	TC73-89	33.3%
2	TC90-93	55.5%
3	TC94-96	11.2%

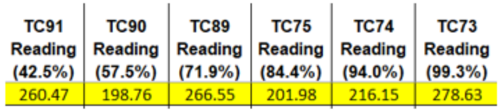
Thermal Desktop Model Set Up

- Typical Boundary/Initial Conditions for a tank chilldown case:
  - Supply Flow Rate, Temperature, Pressure, Quality
  - Vent Flow Rate
  - Wall Parasitics
  - RT initial liquid, vapor pressure, quality & temperature, and wall temperatures
- Initial Wall Temperatures:
  - Tank wall within a single Compartment Bay is further discretized to correspond to thermcouples at different fill levels
  - Temperature stratification in the wall is present at the start of Fill
  - Imposed temperature reading at start of fill on wall surface

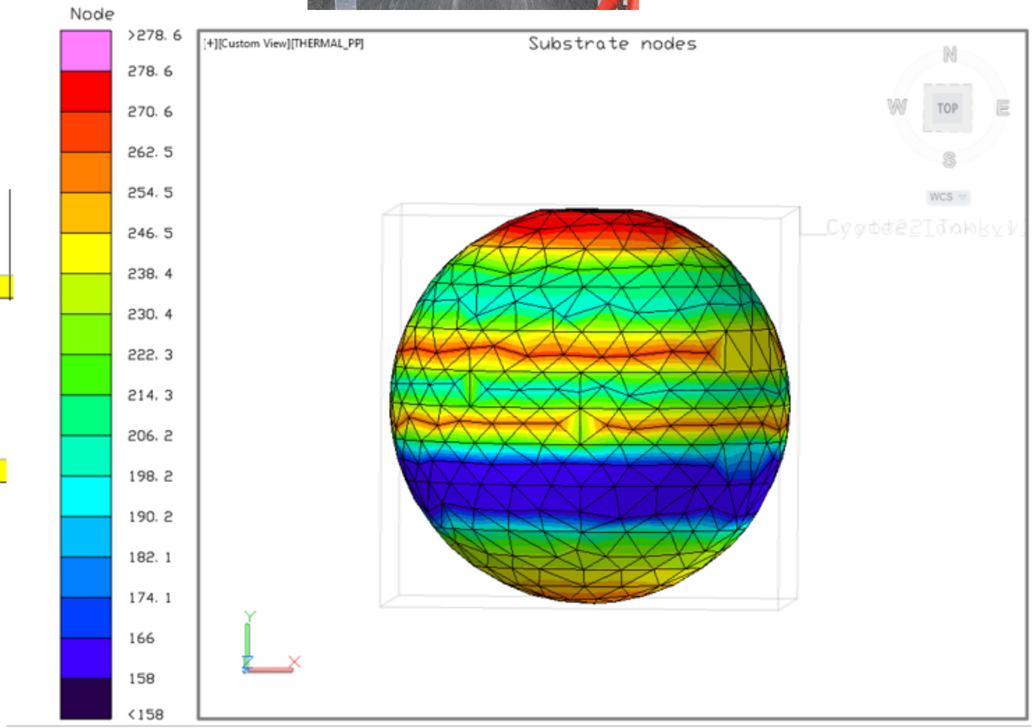




TC96 Reading (0.0%)	TC95 Reading (0.7%)	TC94 Reading (6.0%)	TC93 Reading (15.5%)	TC92 Reading (28.1%)
259.94	241.76	233.37	157.98	162.73



TC91 Reading (42.5%)	TC90 Reading (57.5%)	TC89 Reading (71.9%)	TC75 Reading (84.4%)	TC74 Reading (94.0%)	TC73 Reading (99.3%)
260.47	198.76	266.55	201.98	216.15	278.63



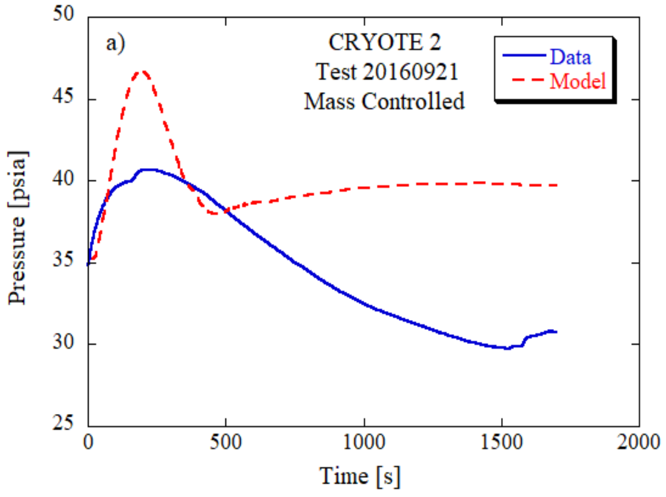
Mass vs. Pressure Controlled Model Set Up

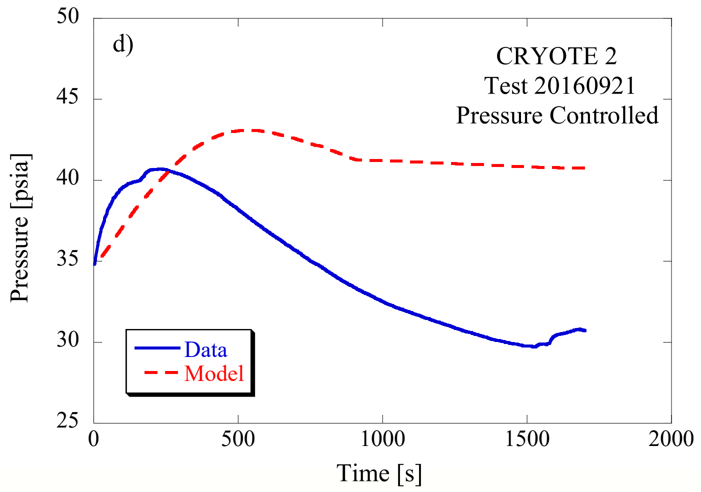
- Different methods for determining the inlet flow rate
- Can either be
  - A) Fed directly into model as an input
  - B) Determined by flow through an orifice where the pressure difference between the inlet pressure and tank pressure
- Both methods will lead to different pressure curves, fill levels, etc.
- Results will be presented for both methods, ie Mass Controlled and Pressure Controlled
- Four Successful tests and Four Failed Tests modeled for Mass Controlled and Pressure Controlled Models
- Important to know how flow will be controlled during test for accurate model results

CRYOTE-2 2016 Test Results: Receiver Tank Pressure

Successful Test:

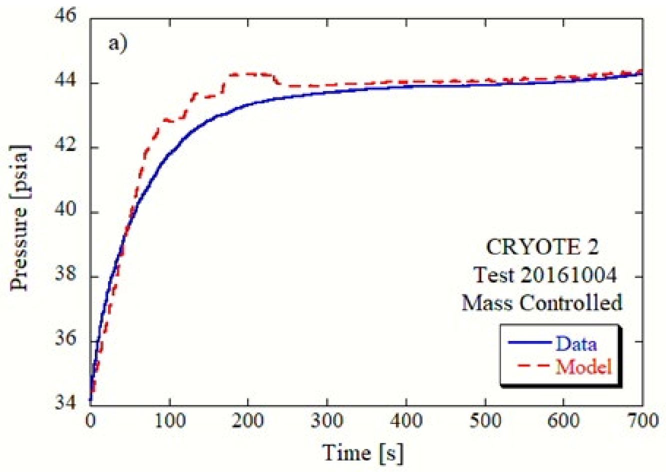
Tw,i = 227K

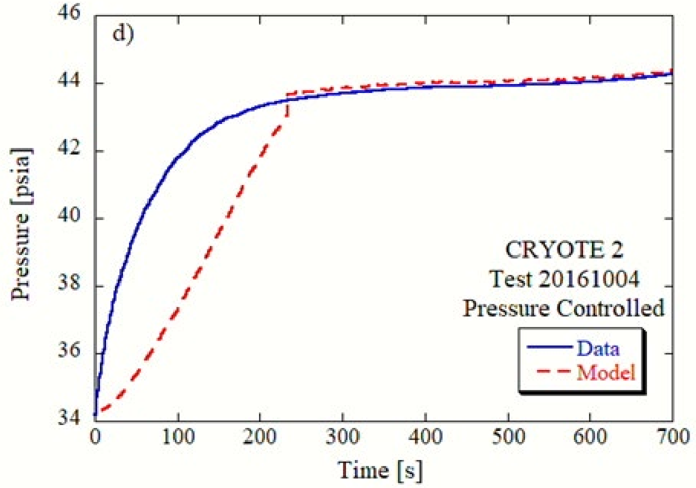




Failed Test:

Tw,i = 193K



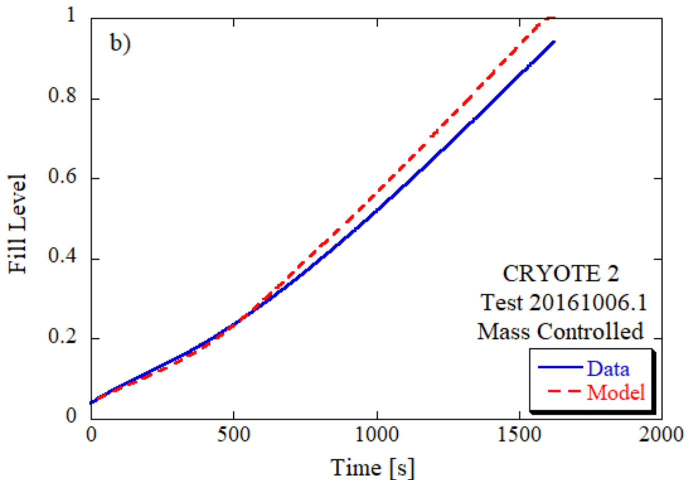


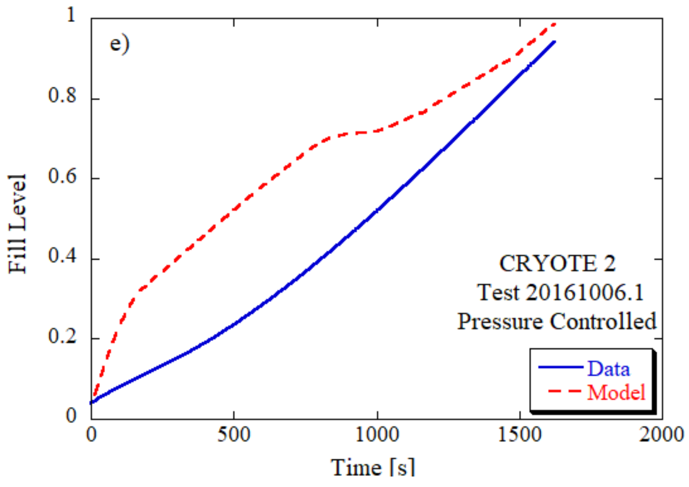
- Mass Controlled model overpredicts initial pressure spike in receiver tank due to TD underpredicting condensation at the wall for both Successful Tests and Failed Tests
- Pressure controlled model overpredicts overall pressure due to RT pressure leveling out with inlet pressure in Successful Tests
- Over shorter duration Failed Tests, pressure rise is slower and evens out more quickly as flow decreases

CRYOTE-2 2016 Test Results: Fill Level

Successful Test:

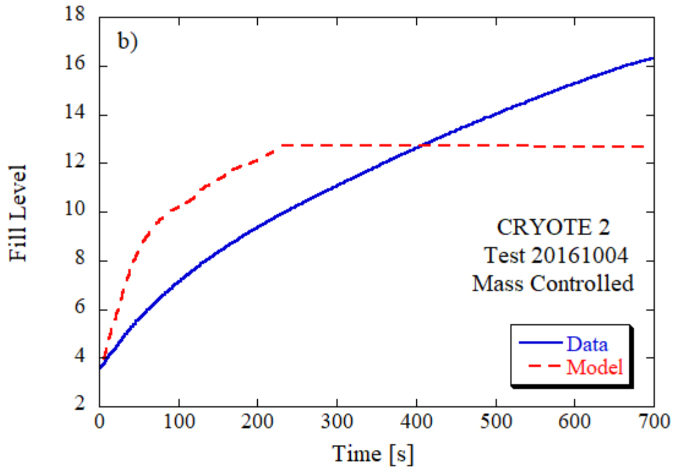
Tw,i = 165K

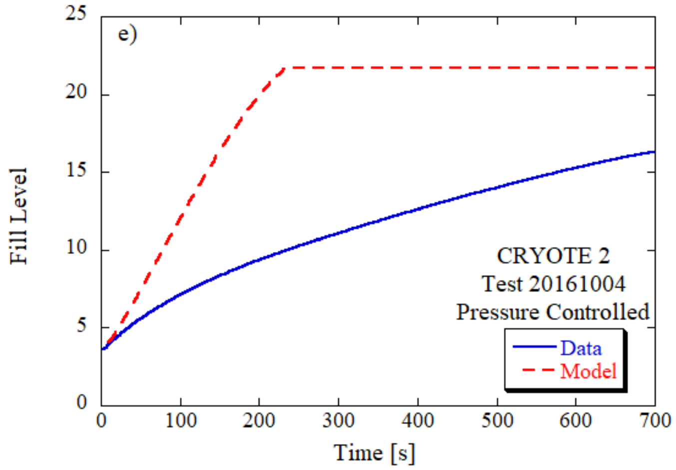




Failed Test:

Tw,i = 193K



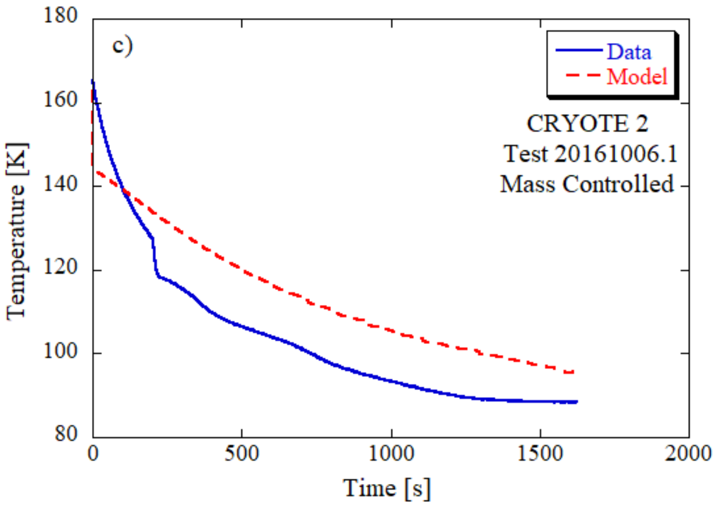


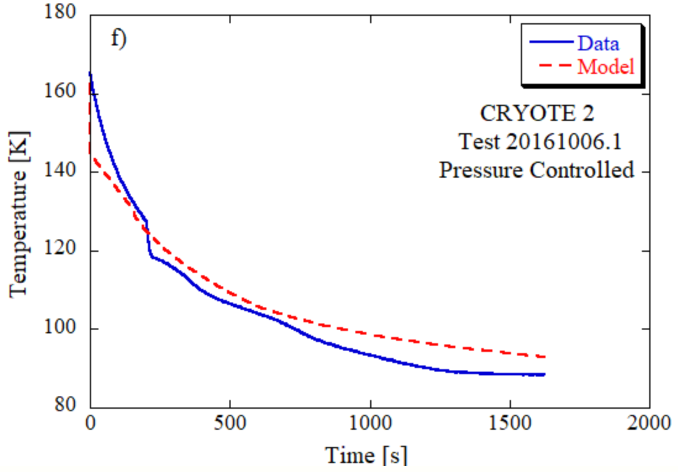
- Mass Controlled model follows data Fill Level almost exactly, as it is an input to the model in Successful Tests and Failed Tests
- Pressure controlled model overpredicts initial Fill Level spike but then levels out due to reduction in flow rate (lower deltaP)
- Final Fill Level for Pressure Controlled similar to Mass Controlled

CRYOTE-2 2016 Test Results: Avg. Wall Temperature

Successful Test:

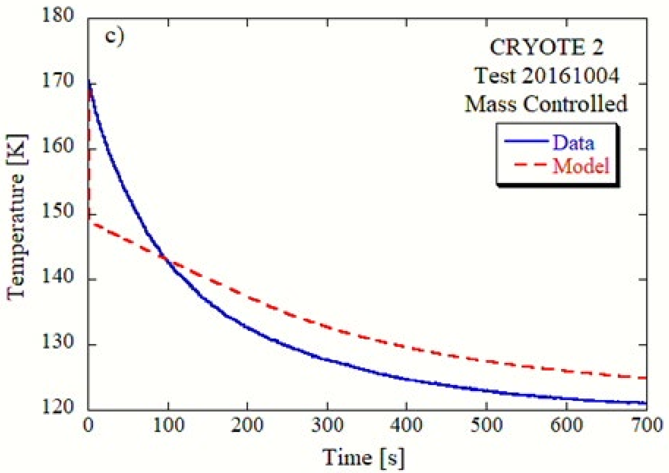
Tw,i = 165K

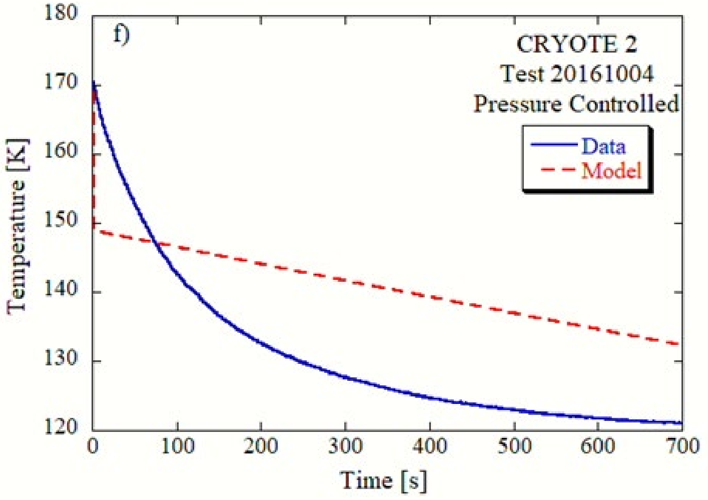




Failed Test:

Tw,i = 193K





- Mass Controlled model overpredicts overall temperature vs. Pressure Controlled
- Pressure Controlled wall cools faster due to greater flow rate (increase in fill level) at beginning of test
- Trend is consistent across Successful Tests, less pronounced in Failed Tests

Mass Flow Controlled vs. Pressure Controlled Results

Mass Controlled Results

Test	Success or Fail?	Pressure MAPE (%)	Fill Level MAPE (%)	Average Wall Temperature MAPE (%)
20160921	S	17.1	9.6	12.1
20161005	S	19.2	2.4	20.1
20161006.1	S	25.0	7.0	11.0
20161006.2	S	2.9	3.7	13.9
20161004	F	0.9	2.6	3.6
20161006.3	F	3.3	1.8	2.1
20161007	F	5.1	1.9	4.5
20161012	F	1.9	0.9	2.4

Pressure Controlled Results

Test	Success or Fail?	Pressure MAPE (%)	Fill Level MAPE (%)	Average Wall Temperature MAPE (%)
20160921	S	21.2	10.4	5.9
20161005	S	10.5	60.8	9.6
20161006.1	S	16.3	78.7	4.6
20161006.2	S	9.1	17.6	15.6
20161004	F	2.6	29.6	9.2
20161006.3	F	2.8	11.7	2
20161007	F	4.5	11.8	5.6
20161012	F	1.3	9.1	1.6

$$\mathrm{MAPE} = \frac{100\%}{n} \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right|$$

- *Flow rate input method affects chilldown results*

Conclusions

- Mass Controlled method predicts Pressure, Fill Level, Temperature within 25.0%, 9.6%, 20.1%
- Pressure Controlled predicts Pressure, Fill Level, Temperature within 21.2%, 78.7%, 9.6%
- Mass Controlled method gives better agreement in predicting receiver tank Pressure for Successful tests
  - Little difference between Mass Controlled and Pressure Controlled for Failed Tests
- Mass Controlled method gives better agreement in predicting Fill Level for all Successful and Failed tests
- Pressure Controlled method gives better agreement in predicting Wall Temperature for Successful tests
  - Little difference between Mass Controlled and Pressure Controlled for Failed Tests
- Sufficient instrumentation on future tests is critical to creating representative models
- Model can be leveraged to predict future tank fill operations

Questions?