Progress on the Reduced Gravity Cryogenic Transfer (RGCT) Project

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2023 Space Cryogenic Workshop
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Outline

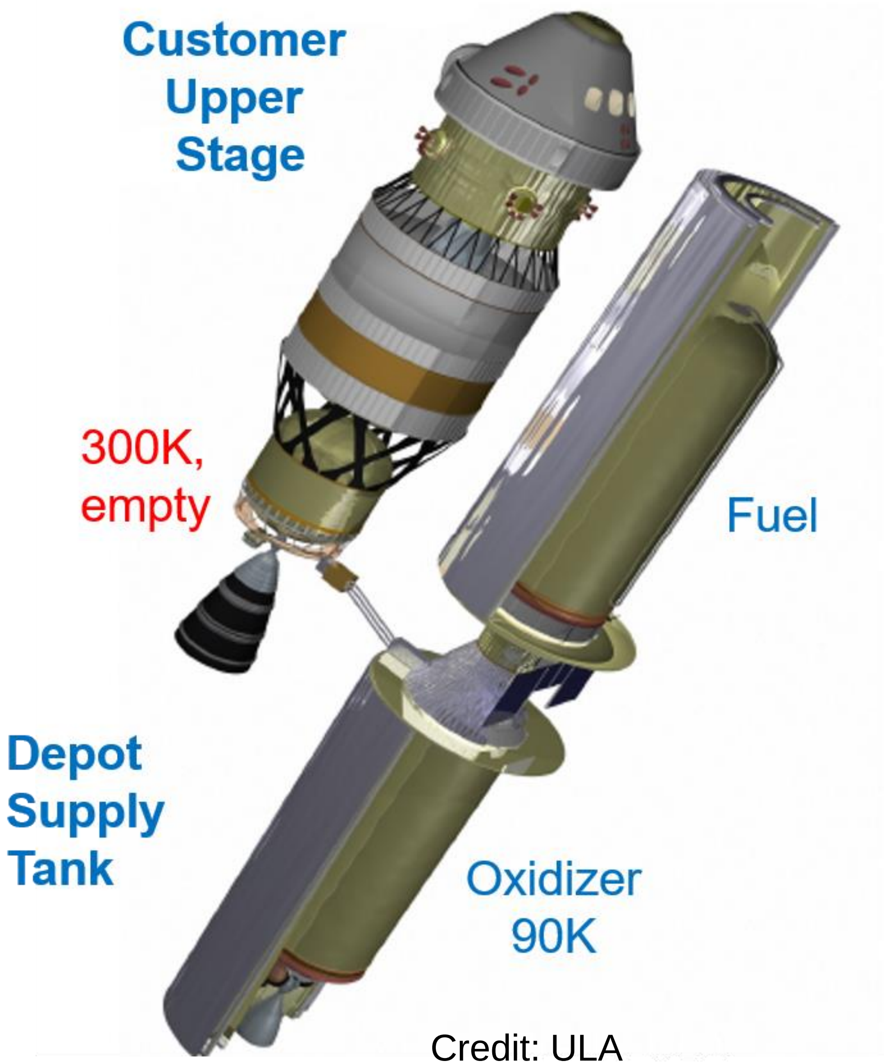
1. ***Project Overview***
2. ***Line Chilldown 1-g and 0-g Testing***
3. ***Two-Phase Pressure Drop Experiment***
4. ***Modeling (Thermodynamic, Injector Modeling, Lumped Capacitance, and CFD Modeling)***

Applicable Elements of In-Space Cryogenic Transfer

- **Cryogenic fuel depots will enable long duration human and robotic missions past LEO**
- **Depots reduce amount of launched propellant thus size of in-space stage**
- **LOX/LH2 or LOX/LCH4**

Transfer Elements

1. **Pressurization in supply tank**
2. **PMDs in supply tank**
3. **Chilldown of transfer line**
4. **Chilldown of receiving tank**
5. **Fill of receiving tank**
6. **Gauging mass during transfer**



Credit: ULA

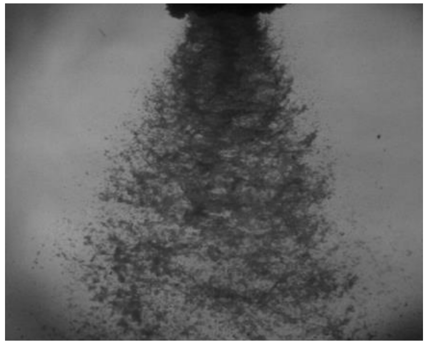
RGCT Project Goals

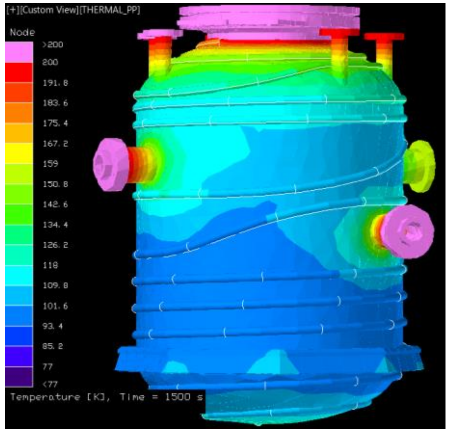
1. Understand baseline transfer line, tank chilldown, and tank fill performance
   - Consolidate & anayze world database to determine universal trends in chilldown and fill physics
   - Use historical datasets to guide and anchor model development & design of higher performance systems)

2. Obtain new well-instrumented 1-g and low-g cryogenic transfer data and visualization
   - Designing & testing two parabolic flight experiments and two ground systems using LN2 to explore issues during transfer

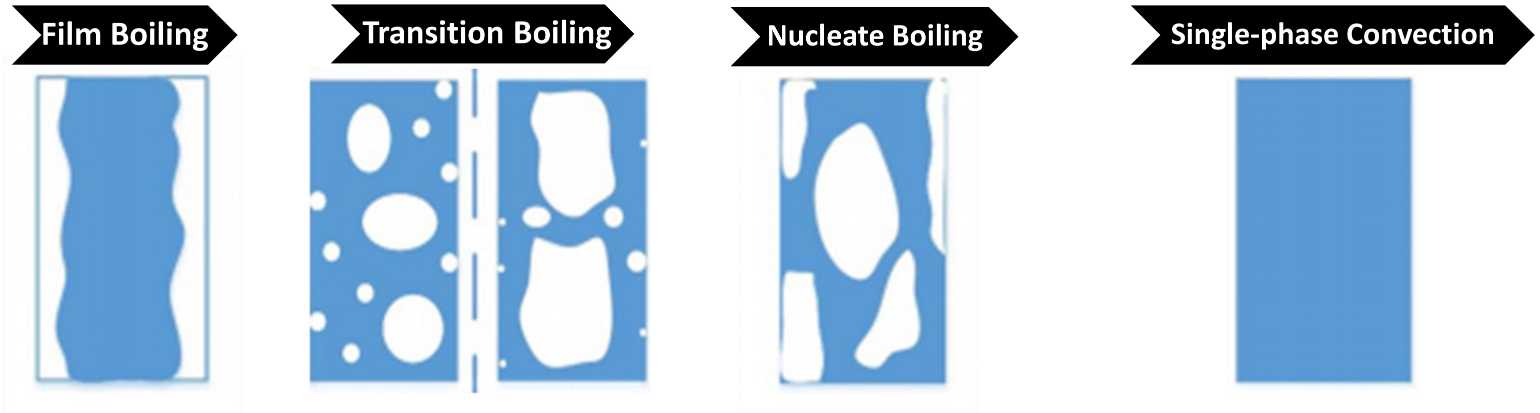
3. Design & test technology to enable higher propellant transfer performance (emphasis on reducing consumed propellant mass)
   - Line chilldown (low-thermally conductive coatings, pulse flow)
   - Tank chilldown and fill (design of high performance injection methods)

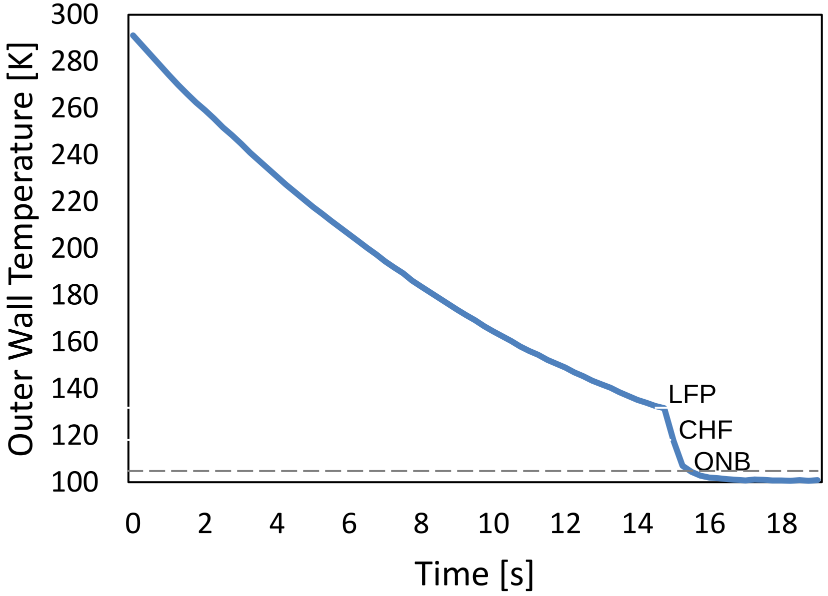
4. Develop and validate improved empirical, analytical, lumped capacitance, & CFD propellant transfer models

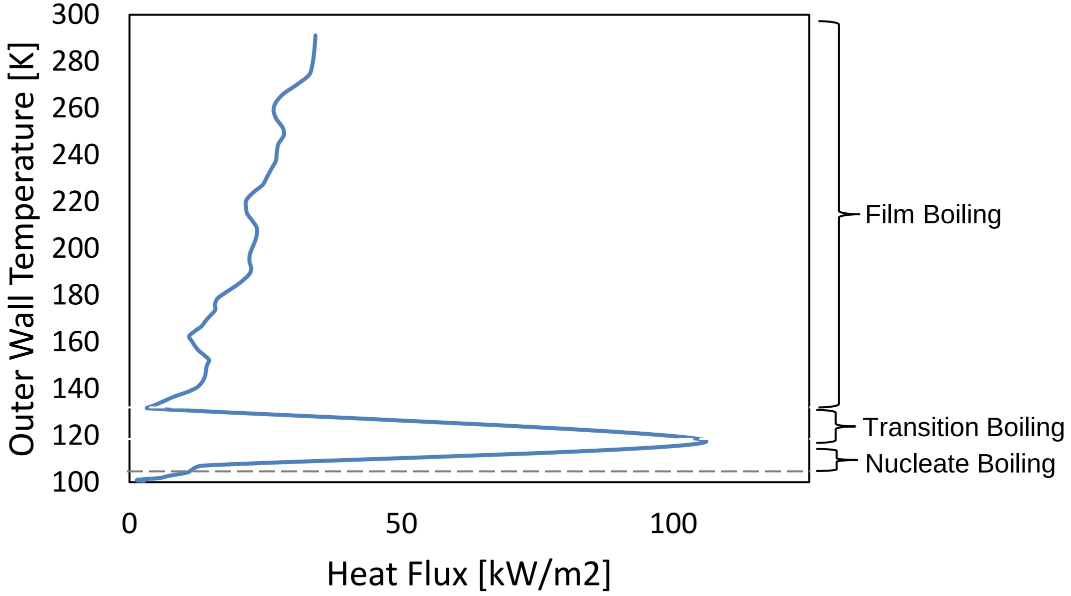




Base Case Line Chilldown Performance

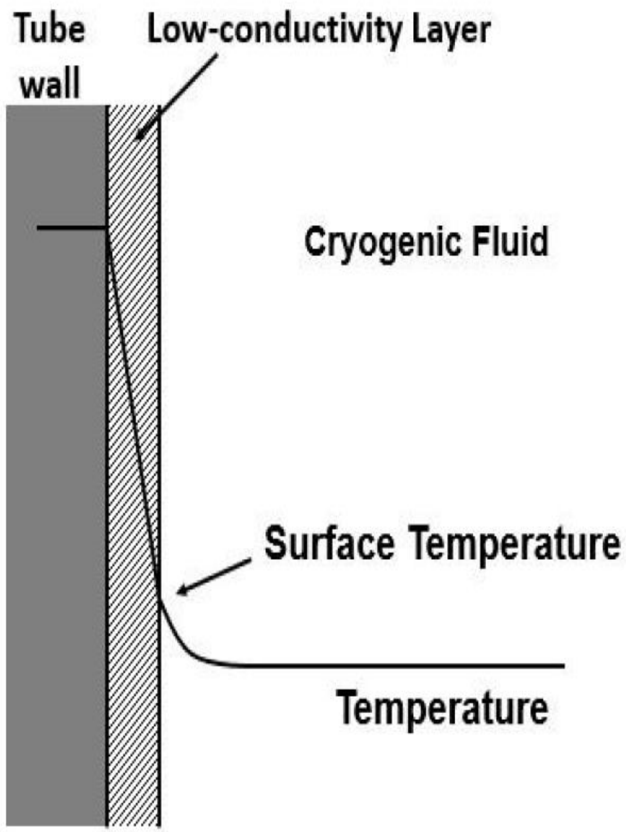


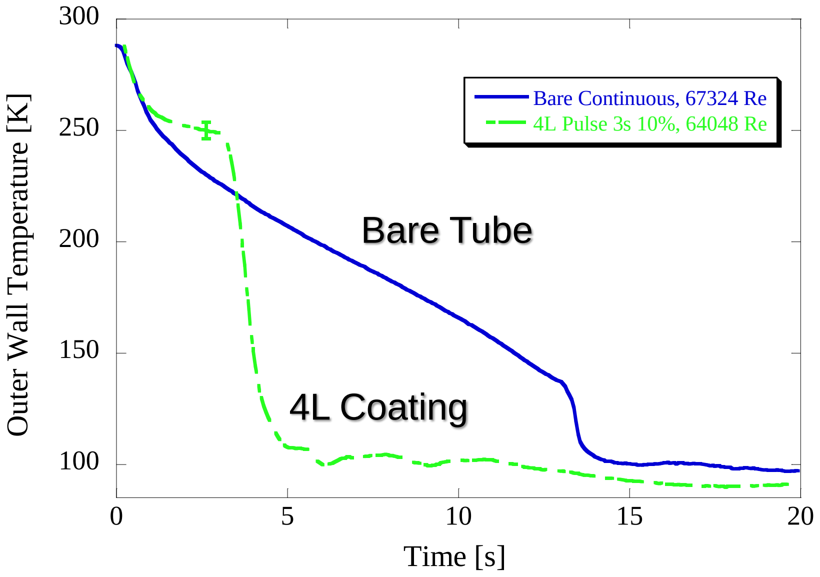


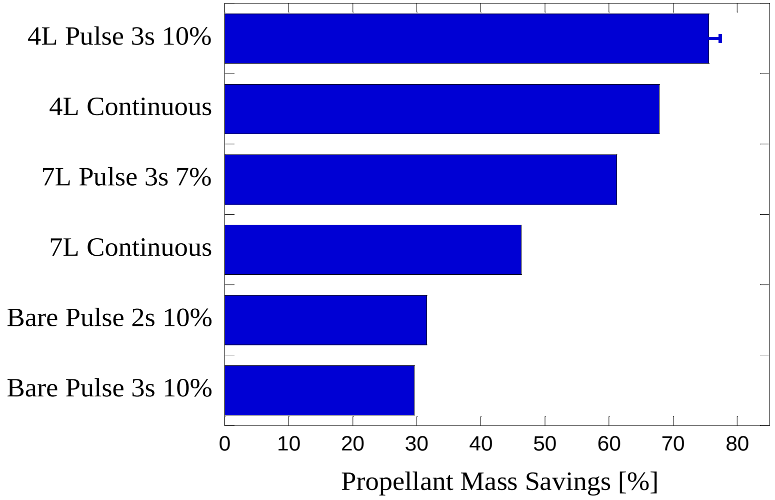


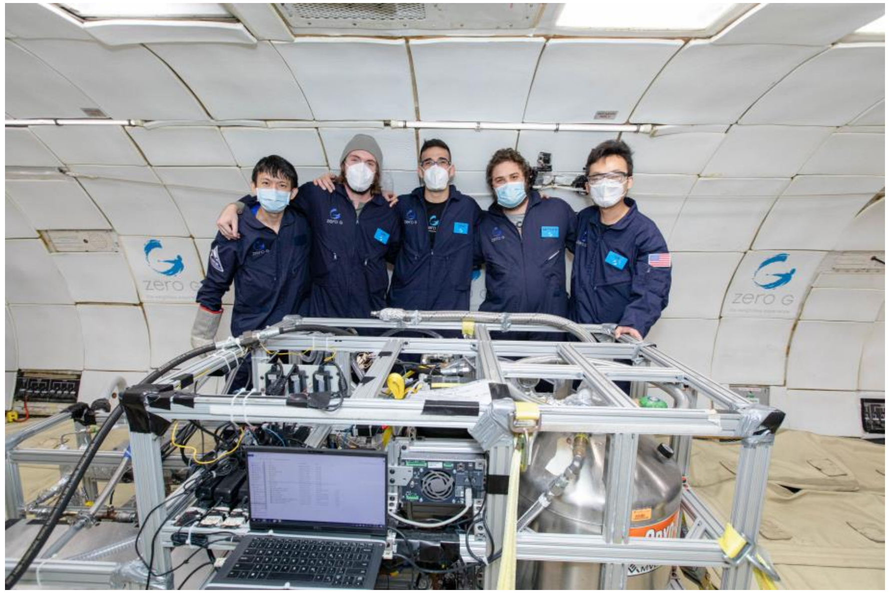
Up to 85% of chilldown is spent in the highly inefficient film boiling regime

Bare Versus Coated Tube Performance in 0-g







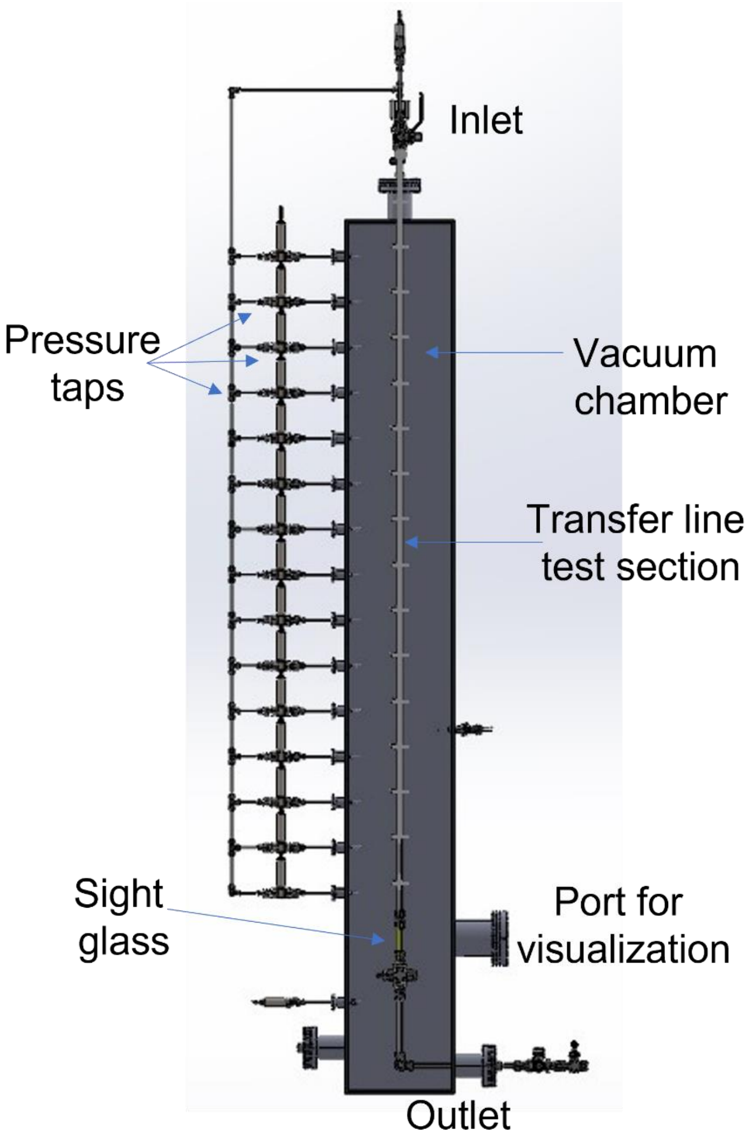


76% mass savings using coated tube & pulse flow in 0-g

Quenching Two-Phase Pressure Drop

- **There are no models for predicting two-phase pressure drop during transfer line chilldown**
  - ***Controlling parameters and properties are very different for cryogenic fluids compared to water and refrigerants***
  - ***Existing models have only been developed for heating case***
  - ***Most models have only been developed for room temperature fluids***
  - ***Existing models have not been validated against any cryogenic quenching data***
  - ***Fluid transient effects are not accounted for***

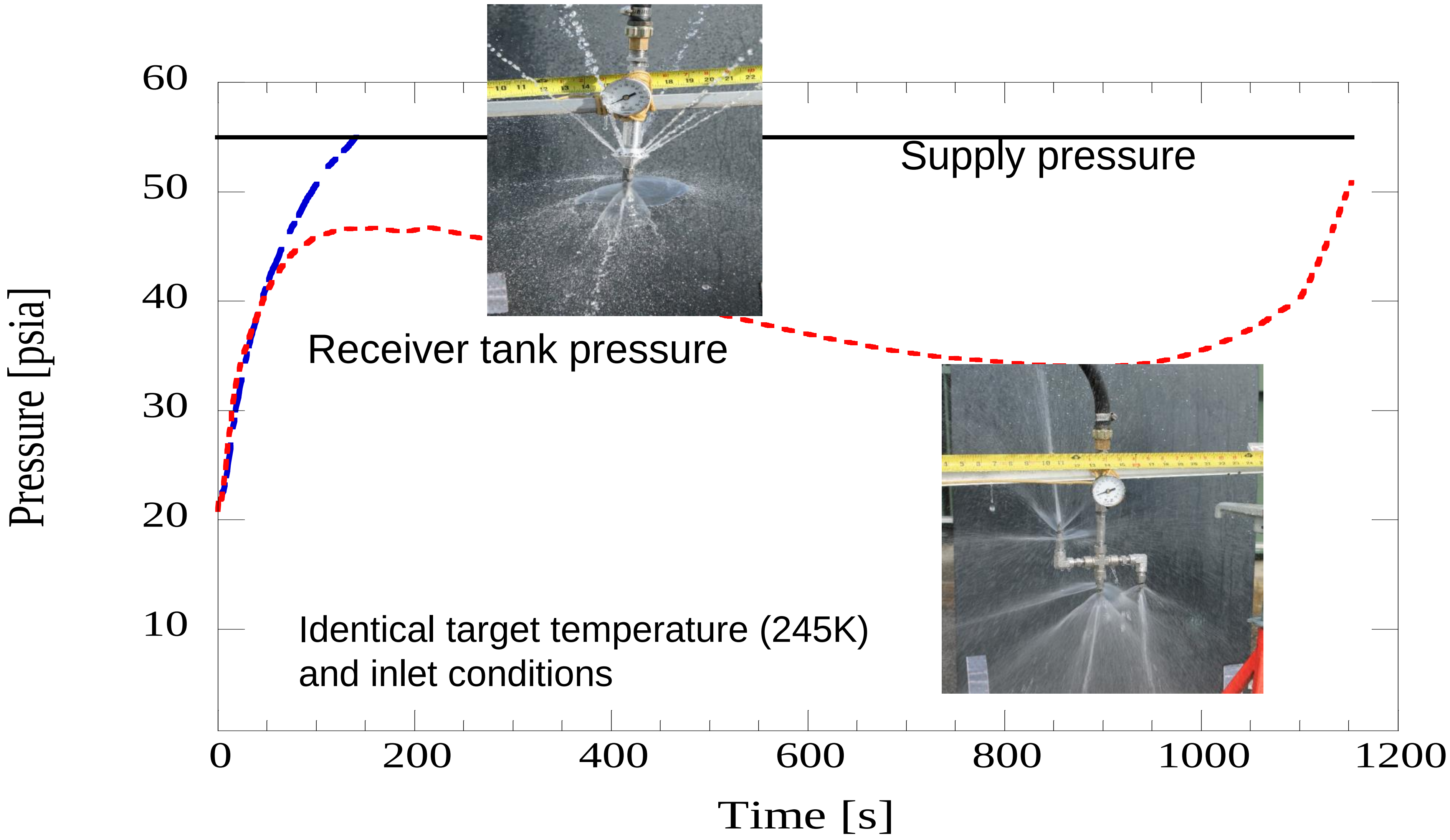
- **Test a new 2m transfer section with detailed pressure drop measurements & flow visualization**
- **Measure two-phase pressure drop across range of conditions**
- **Develop a new UDF that accounts for frictional, accelerational, gravitation, and transient pressure drop**
- **Feed UDF into higher order models to better predict flow rate**



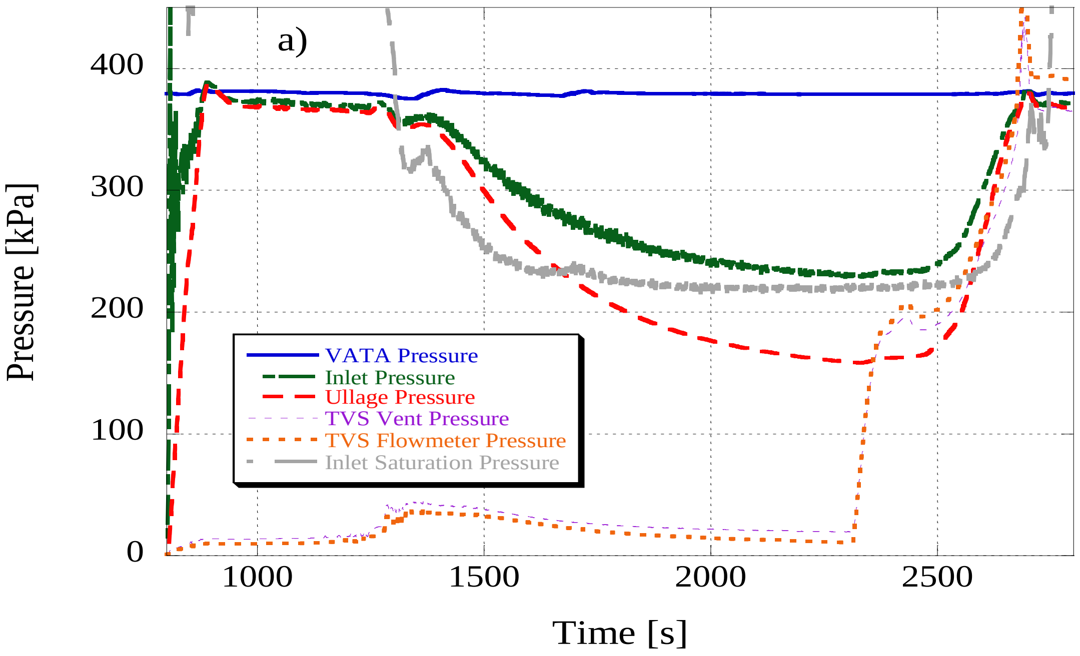
Lessons Learned during Cryogenic Propellant Transfer Data Analysis

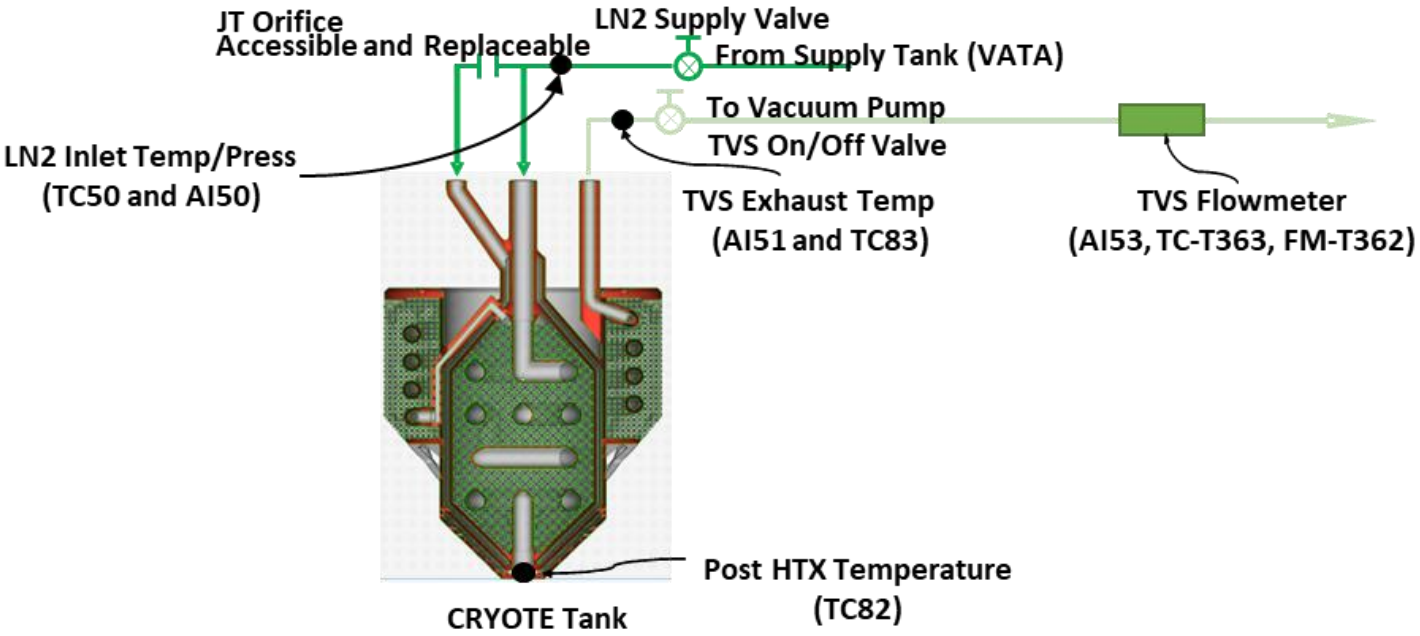
Parameters that affect no-vent fill:

1. Injection method
2. Initial state of Receiver tank
3. Fluid inlet state (T, P)
4. Flow rate



Lessons Learned during Cryogenic Propellant Transfer Data Analysis



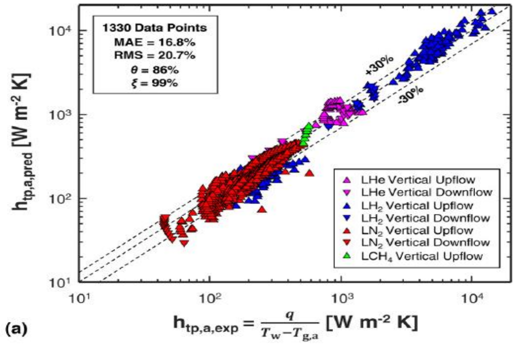


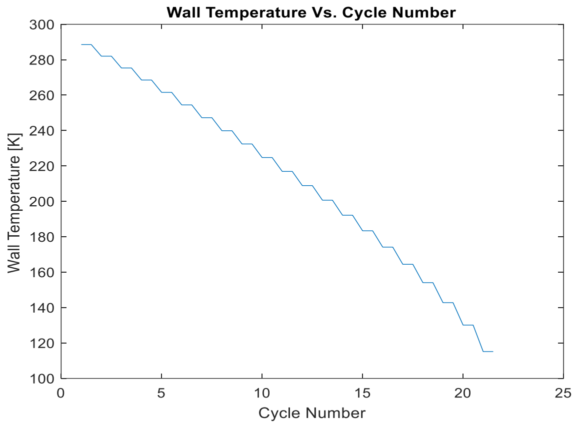
- TVS augmented injector makes it possible to restart a stalled transfer
- Success depends on timing and length of operation

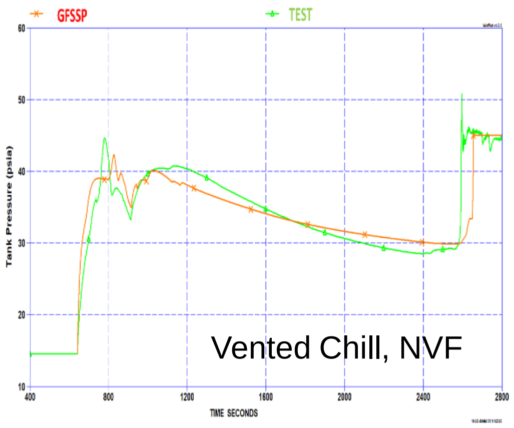
In-depth data analysis and modeling reveled that the cause for recovering a failed transfer was enhanced condensation at the injector/ullage surface

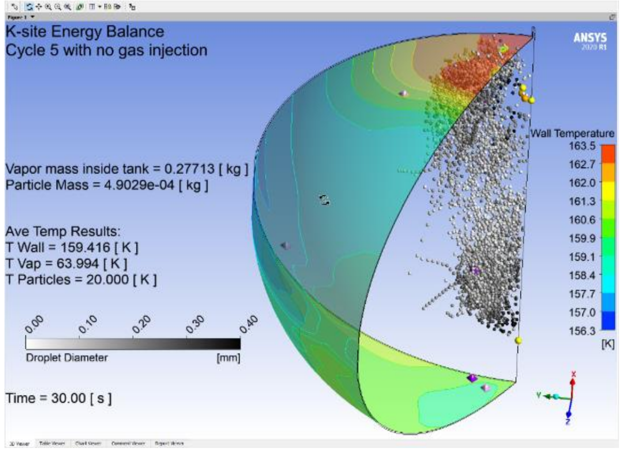
Modeling

$$\frac{h_{tp}^{\ n}}{h_{sp,f}^{\ n}} = \left[c_1 Bo^{c_2} P_R^{c_3} (1-x_e)^{c_4} Co^{c_5}\right]^n + \left[c_6 \left(\frac{1}{X_{tt}}\right)^{c_7} \left(\frac{\rho_f}{\rho_g}\right)^{c_8} Co^{c_9}\right]^n$$









FLUENT Tank wall temperature contours and particle trajectories

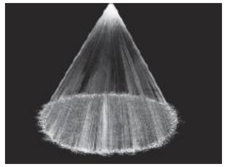
Fundamental UDF & Correlation Development

Thermodynamic Modeling

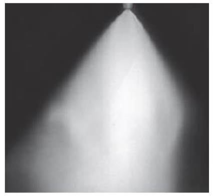
Lumped Capacitance Modeling

Computational Fluid Dynamics Modeling

Injector Modeling

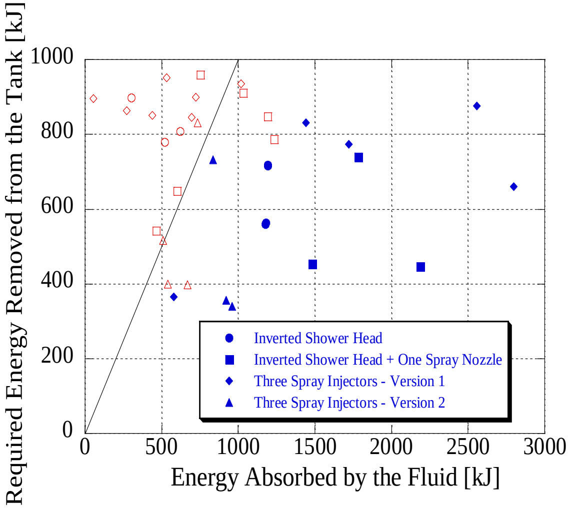


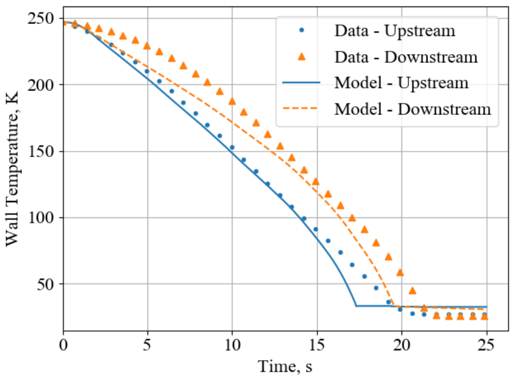
Mist flow



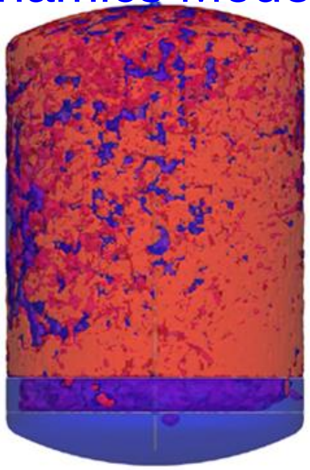
Jet flow

Tank wall coverage





LH2 chilldown



LN2 Tank Mixing and Expulsion

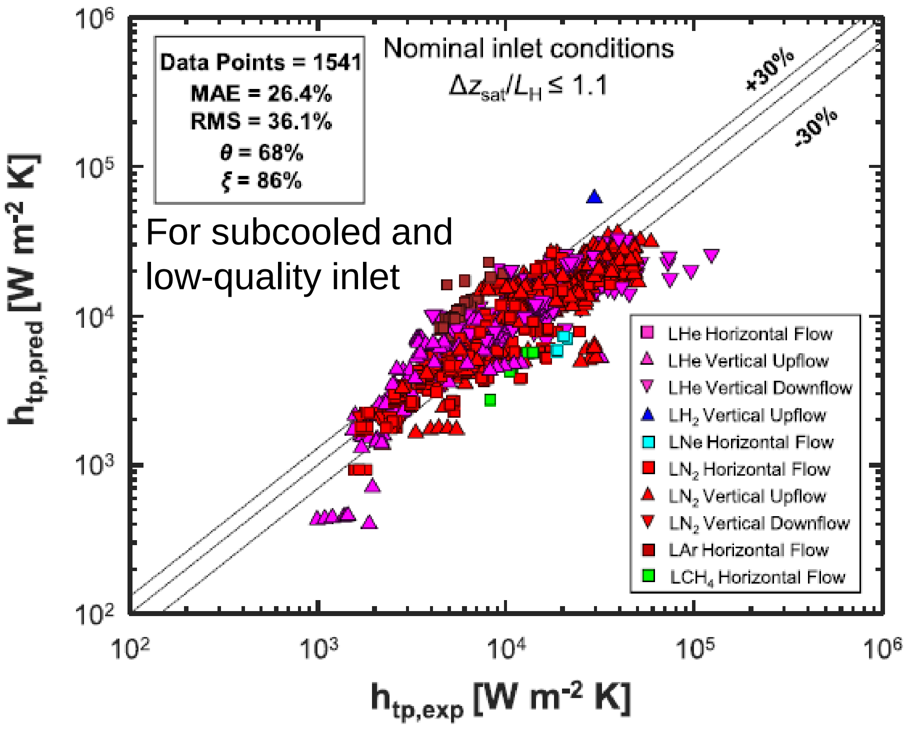
Universal Cryogenic Correlation Development and Validation

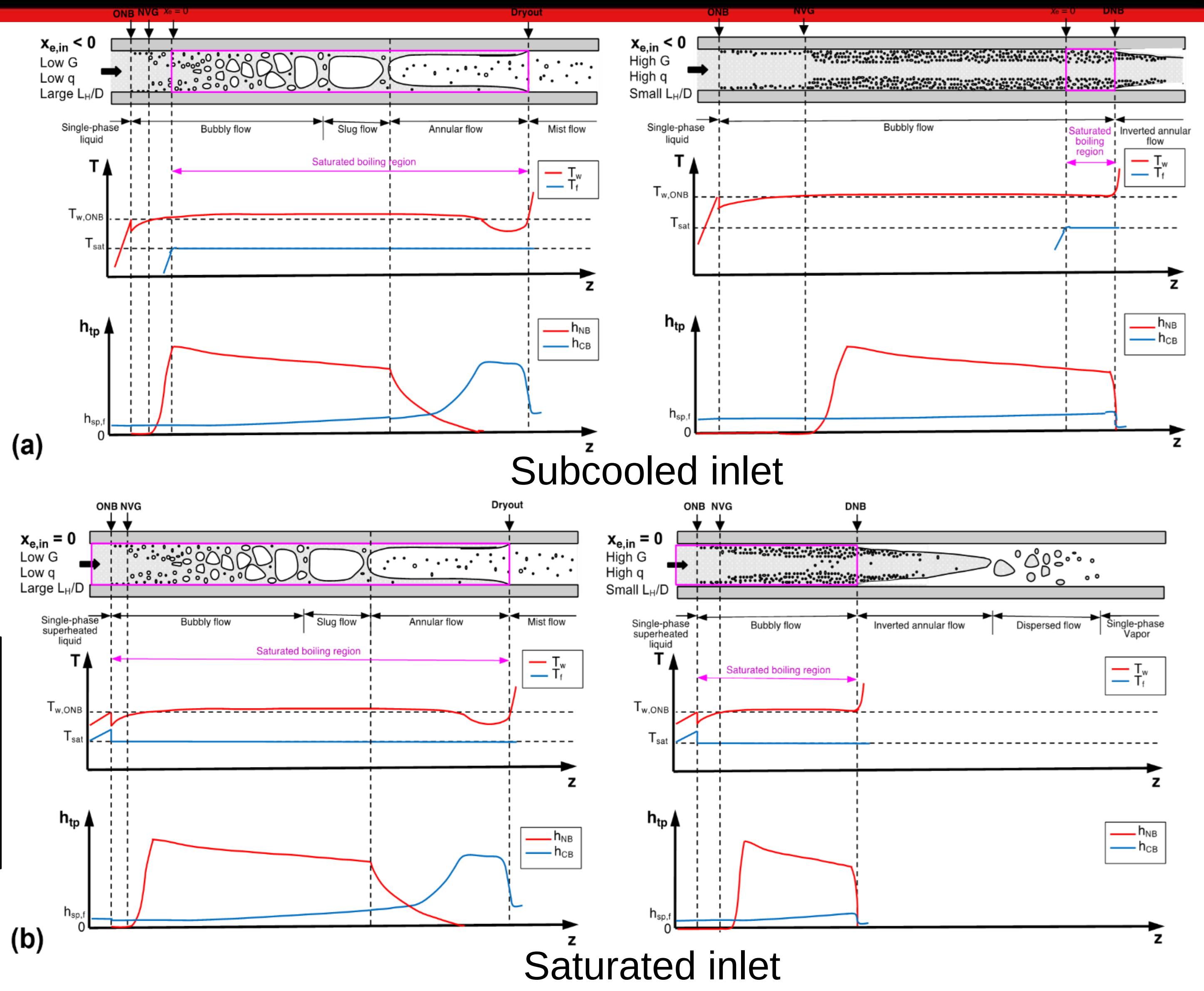
- **In two phase flow literature, each new set of data yields a new set of correlations**
- **Each correlation is generally only fit to a select group of data**
- **Majority of correlations applicable only for room temperature liquids**
- **Recent drive towards developing so-called universal correlations**
- **Dimensionless groups generally fit to wide range of data**
- **Requires careful filtering scheme**
- **Universal correlations are highly desirable because they will enable design reference books for two phase systems and simplify thermal/fluid models**
- ***Answers the question: With hundreds of correlations in the literature, which one do I use?***

- **Aerospace Corp & Purdue University developed the pioneering universal correlations for line chilldown and flow boiling with heating, respectively**
- **Correlations fed into GFSSP & Thermal Desktop to predict: 1) location of ONB and CHF during steady state heating, 2) set insulation requirements, 3) chilldown time, 4) chilldown mass**

All correlations generally predict data within +/- 25% across all cryogens & flow conditions
Prediction of flow boiling heat transfer coefficients and zCHF improved by factor of 3-10 over base predictions

Universal Cryogenic Flow Boiling Correlation Development and Validation





New NB HTC model covers:

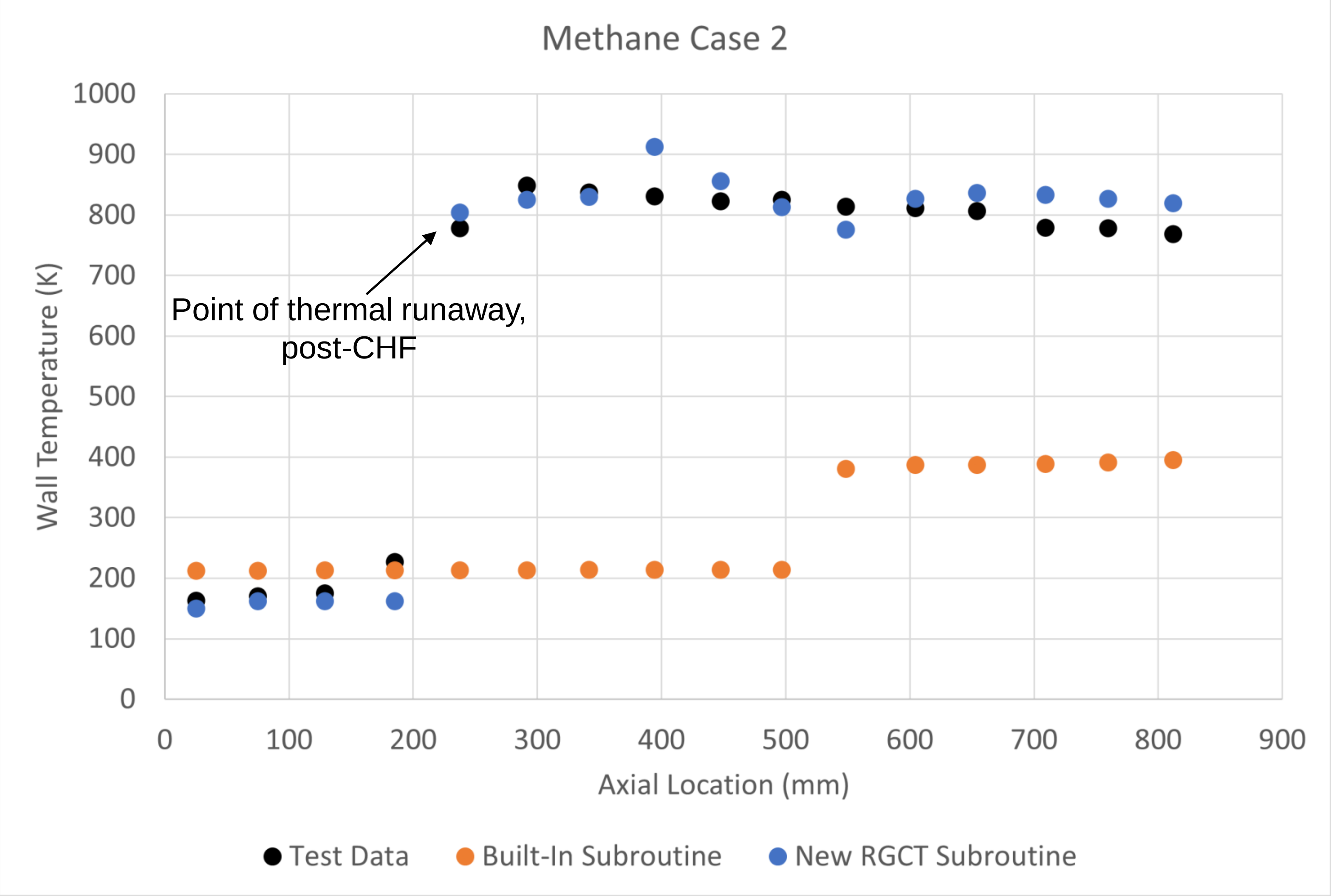
- 3252 data points
- LHe, LH2, LNe, LN2, LAr, LCH4
- Subcooled, saturated, two-phase inlet
- Multiple flow orientations

Cryogens generally exhibit stronger nucleate-boiling heat transfer mechanism (as opposed to convective-boiling heat transfer mechanism)

Universal Cryogenic Flow Boiling Correlation Development and Validation

- Heated tube correlations were patched together to form smooth continuous prediction of wall superheat as a function of z

- Original set of correlations handles nucleate boiling well for Glickstein et al. LCH4, but fails to capture location & magnitude of CHF and film boiling regimes; MSA=75%
- With new subroutine, wall temperature with MSA= 8% using the new subroutine across all regimes

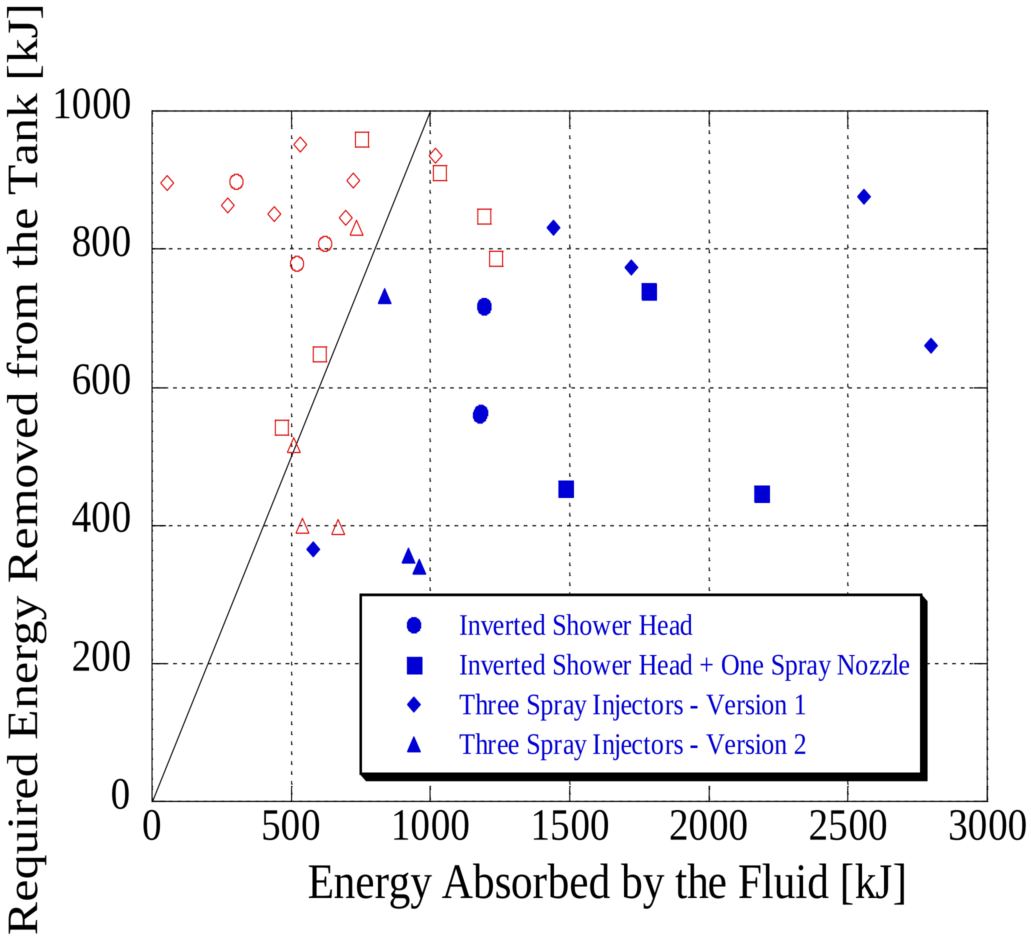


New Purdue correlations demonstrate superior predictive performance over baseline correlations in Thermal Desktop

No-Vent Fill Ttarget Thermodynamic Prediction Model

$$m_{fluid,final}u_{fluid,final} - m_{fluid,initial}u_{fluid,initial} - (m_{fluid,final} - m_{fluid,initial})h_{inlet} = \dot{Q}_{para,avg}\Delta t - m_{tank}\int_{T_{initial}}^{T_{final}} C_{tank}\,dT$$

- **Energy balance to compute the maximum allowable TTarget for a given set of initial conditions**
- **Validated against 158 tests**
- **Predicts failed transfers with 100% accuracy**
  - Any tests initiated on the left-hand side of the black line will always fail
- **Successful transfers have the added dependency on efficiency of injection method**



Injector Modeling

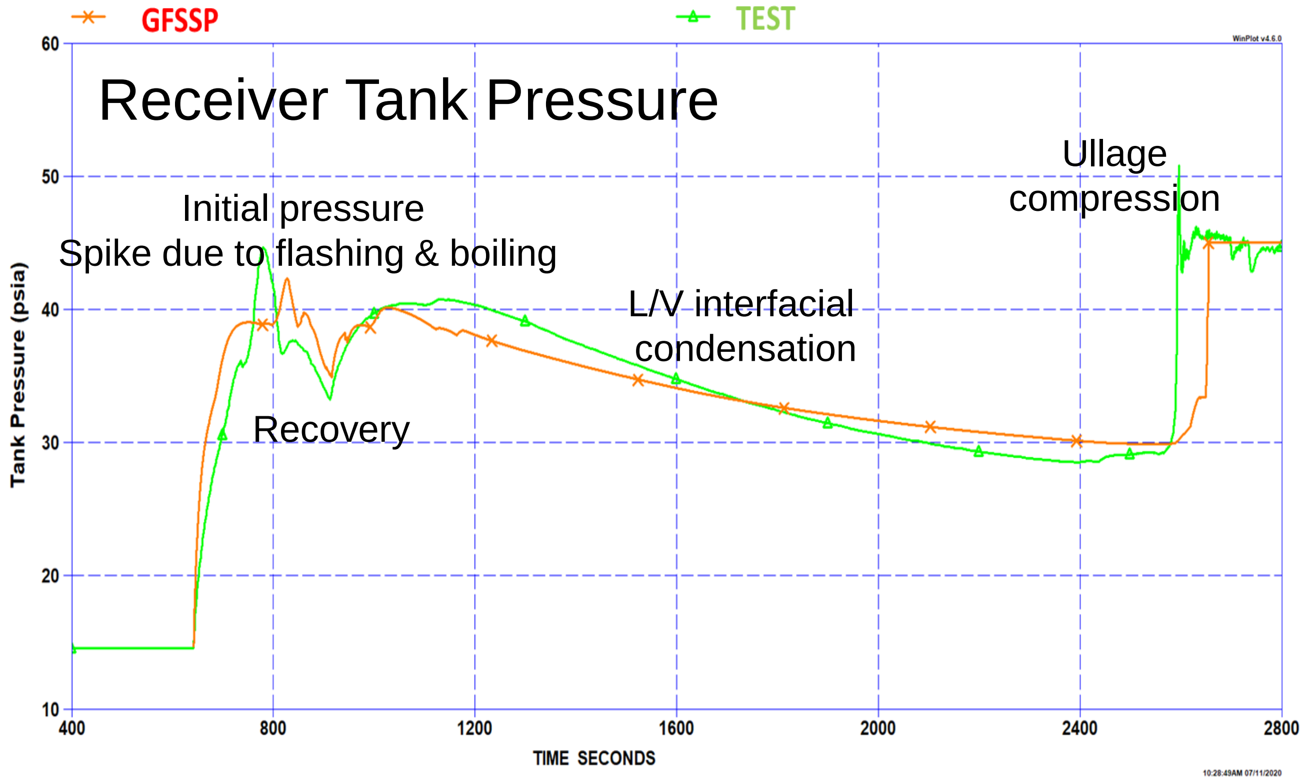
- **RGCT evaluated over a dozen models for how best to model saturated two-phase flow through restrictions (valves, orifices, etc.)**
  - Isentropic models
  - Isenthalpic models
  - Choked flow models

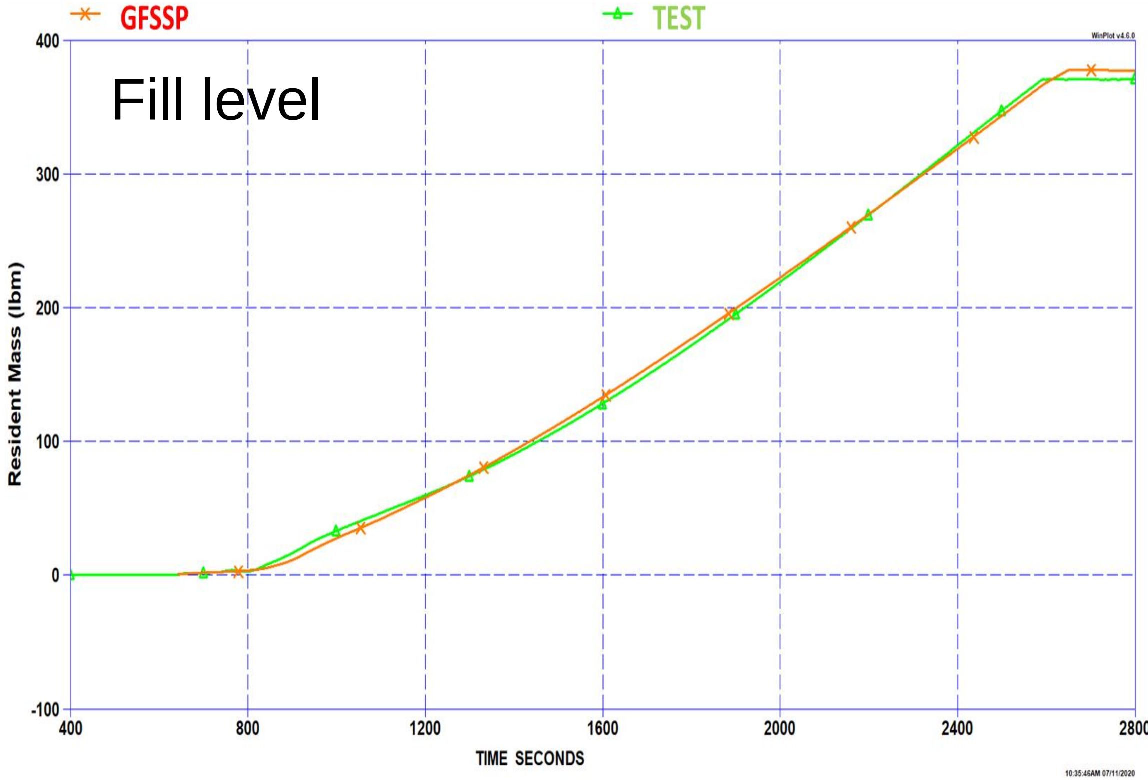
- **Needed to predict transient two-phase flow rate during tank chill & fill, to bound expected flow rate during prop transfer, and to determine choked flow conditions**

- **Evaluated the models over historical data sets where two-phase flow was encountered at tank inlet during tank chilldown**
- **Explored sensitivities in operating near the saturation line for tank chilldown and fill**

- **Work was leveraged by SpaceX on the 2020 Tipping Point to improve predictive performance for multiple phases of their prop transfer, to improve mass flow rate predictions, and to reduce uncertainty in propellant mass transferred**

Lumped Capacitance Modeling





- **Numerous lumped capacitance models are being developed and validated against historical databases for line chilldown, heated tube, tank chilldown, and tank fill**
- **New interfacial condensation and injector condensation model developed and implemented**

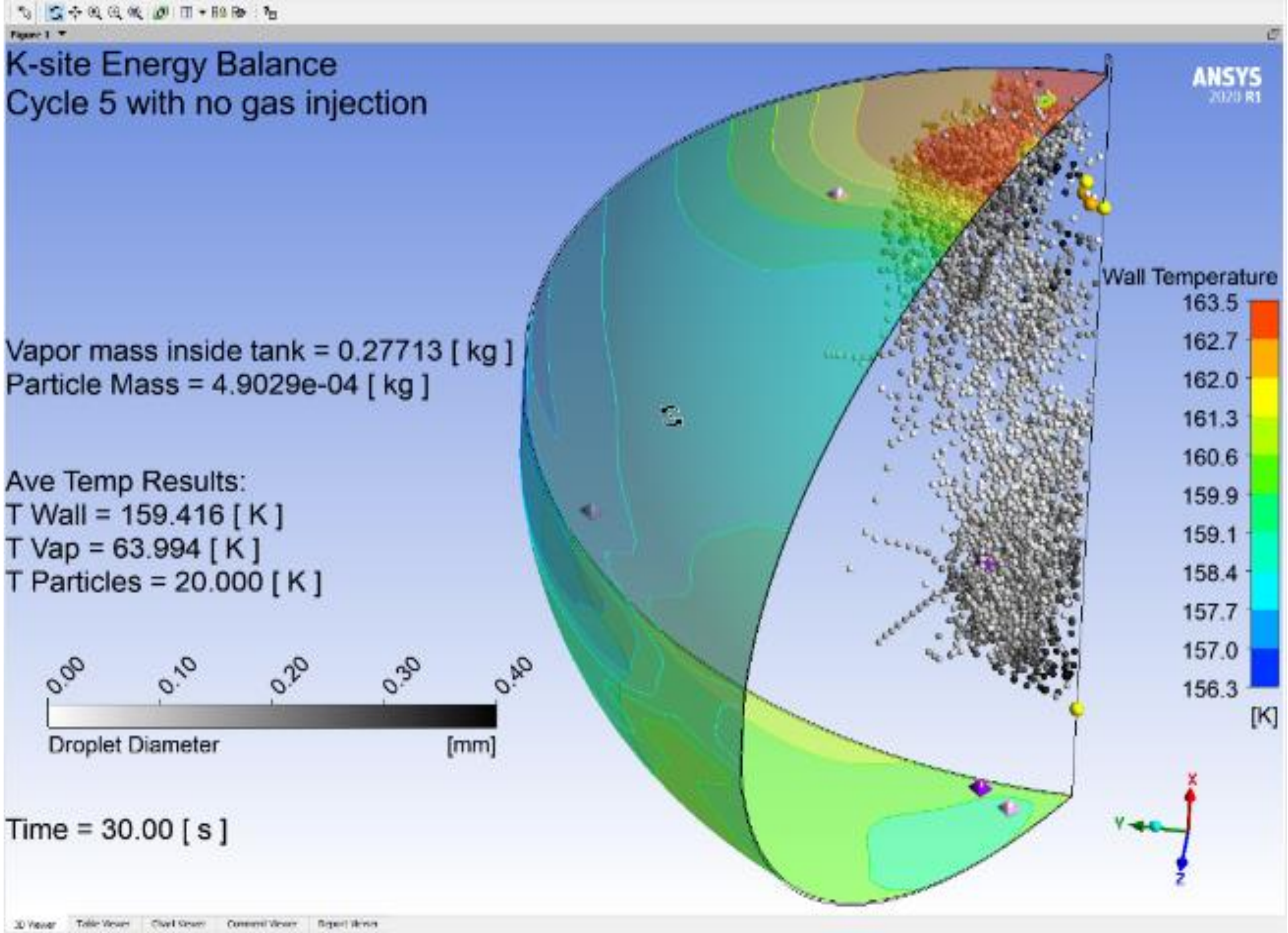
GFSSP demonstrates superior predictive performance, predicting receiver tank pressure and fill level within 6% of the data across all phases of a high delta-T tank chill/fill no-vent fill test

FLUENT CFD Tank Chilldown Modeling

- **Extended full 3D CFD simulations with conjugate heat transfer, focusing on the injection phase of a classic charge/hold/vent tank chilldown using FLUENT**

- **New cryo-based DHM subroutine updated and implemented into FLUENT**

- **Reasonable improvement in predicted tank pressure and tank wall temperature from baseline study conducted previously**

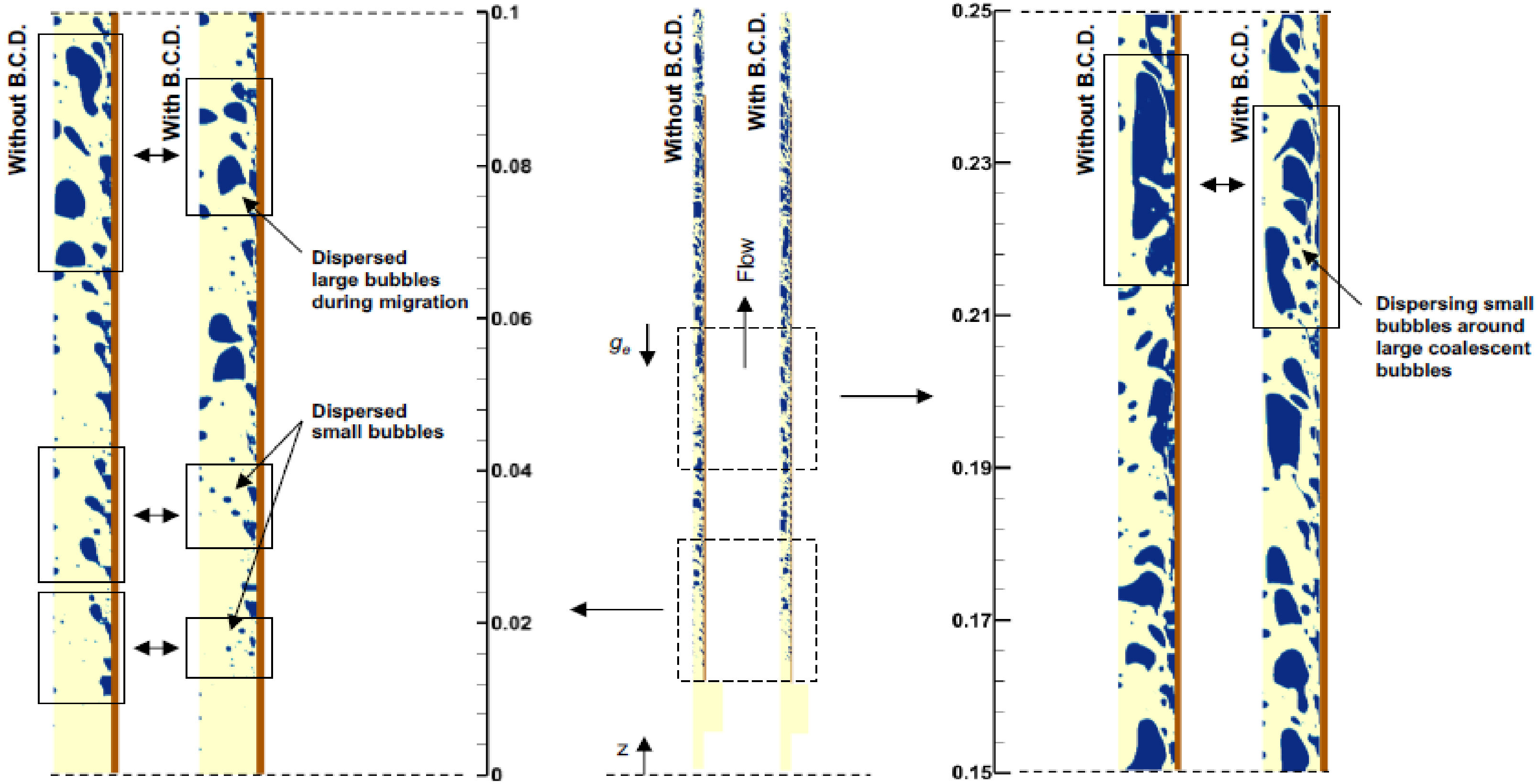


Tank wall temperature contours and particle trajectories (colored by diameter) at 30.0 sec into the simulation

FLUENT Heated Tube CFD Modeling

- **Built-in VOF model showed (a) inaccurate surface tension calculation which degrades interface tracking and (b) under-representation of bubble-to-bubble interaction**
- **Stems from the innate nature of employing single momentum equation in VOF (cannot discern phase velocities)**
- **Coupled Level Set VOF (CLSVOF) was adopted in FLUENT**
- **New UDF created to account for crucial effects of bubble collision dispersion force**
- **Works extremely well for nucleate boiling**

2D Axisymmetric FLUENT simulations with and without inclusion of new Bubble Collision Dispersion Force



- *CFD simulations capture crucial details of flow boiling behavior along the heated tube, including bubble nucleation, sliding, growth, departure, dispersion, and coalescence.*
- *Predicted wall temperatures for four sets of operating conditions showed excellent agreement with the benchmark experimental data*

Team Members/Acknowledgements

NASA MSFC

- Michael Baldwin
- Andre LeClair
- Alok Majumdar

NASA GRC

- Eric Carlberg
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- Erin Tesny
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- Lockheed Martin Tipping Point
- ULA Centaur V

CEC & SCW RGCT Presentations

1. Mercado, M. and Hartwig, J.W. "Parametric Analysis of the Charge-Hold-Vent Method for Cryogenic Propellant Tank Chill Down" *2023 Cryogenic Engineering Conference*, Honolulu, HI, July 9 – 13, 2023.
2. Tesny, E. et al. "Validation of Universal Cryogenic Flow Boiling Correlations in Thermal Desktop for Liquid Helium" *2023 Cryogenic Engineering Conference*, Honolulu, HI, July 9 – 13, 2023.
3. Baldwin, M., et al. "Modeling of Cryogenic Heated-Tube Flow Boiling Experiments of Nitrogen and Methane with the Generalized Fluid System Simulation Program" *2023 Cryogenic Engineering Conference*, Honolulu, HI, July 9 – 13, 2023.
4. Hartwig, J.W., et al. "A Continuous Flow Boiling Curve in the Heating Configuration Based on New Cryogenic Universal Correlations" *2023 Cryogenic Engineering Conference*, Honolulu, HI, July 9 – 13, 2023.
5. Hartwig, J.W. et al. "Recent Computational Fluid Dynamics Modeling of Various Cryogenic Propellant Transfer Phenomena in Terrestrial and Reduced Gravity" *2023 Cryogenic Engineering Conference*, Honolulu, HI, July 9 – 13, 2023.
6. Darr, S., et al., Universal Two-Phase Convection Heat Transfer Correlations for Cryogenic Pipe Chilldown" *2023 Space Cryogenic Workshop*, Kona, HI, July 16 – 18, 2023.
7. LeClair, A., et al. "Modeling of Cryogenic Heated-Tube Flow Boiling Experiments of Hydrogen and Helium with the Generalized Fluid System Simulation Program" *2023 Space Cryogenic Workshop*, Kona, HI, July 16 – 18, 2023.
8. Majumdar, A., et al."Two-Dimensional Network Flow Modeling of No Vent Tank Filling of a Cryogenic Tank with Thermo-dynamic Vent System Assisted Injector" *2023 Space Cryogenic Workshop*, Kona, HI, July 16 – 18, 2023.
9. Tesny, E. and Hartwig, J.W. "Thermal Desktop Modeling of CRYOTE-2 Tank Chill and Fill Testing" *2023 Space Cryogenic Workshop*, Kona, HI, July 16 – 18, 2023.
10. Mercado, M., et al. "Validation of Universal Cryogenic Flow Boiling Correlations in Thermal Desktop for Liquid Methane and Liquid Nitrogen" *22023 Space Cryogenic Workshop*, Kona, HI, July 16 – 18, 2023.
11. Hartwig, J.W., et al. "Progress on the Reduced Gravity Cryogenic Transfer Project" *2023 Space Cryogenic Workshop*, Kona, HI, July 16 – 18, 2023.

Thank You!

Questions/Comments