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The Zero Boil-Off Tank Experiment Ground Testing and Verification of Fluid and Thermal Performance

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By

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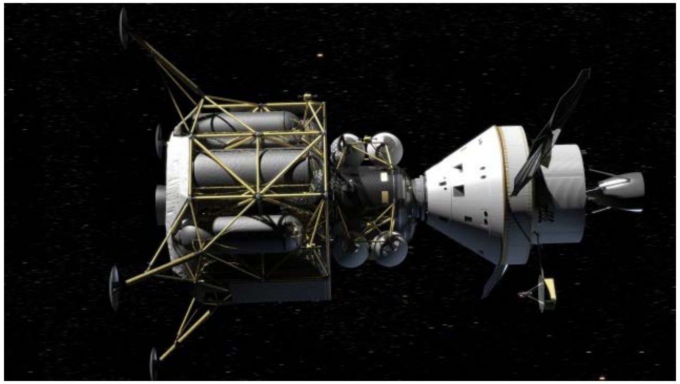
NASA Exploration Challenge:

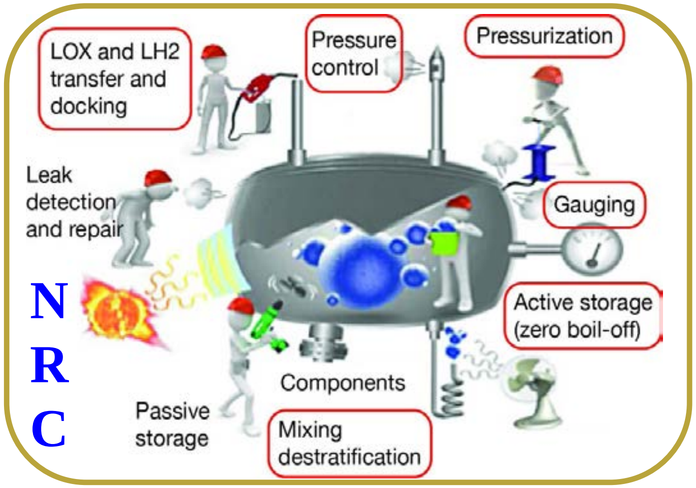
- Reliable cryogenic storage for use in propellant systems is essential to meeting NASA's future exploration goals.
- Heat leaks from surroundings lead to cryogen boil-off and excessive tank pressures.
- Cryogen mass loss occurs when tank is vented
- Predicting boil-off and self-pressurization rates is important.



Why Small-Scale Experiment Simulant Fluid?

NRC Decadal Report on CFM:

- "1G empirically-based predictive methods in the design of the future multiphase technologies are of limited use "
- "a new predictive capability and design methodology needs to be adopted that relies in particular on physically-based multiphase models that quantify accurately the effects of gravity."
- "to be effective, such models must necessarily be assessed against, appropriate small scale reduced-g data, and they must be capable of accurately scaling-up these data to the large multiphase systems for NASA's future human exploration missions."



ZBOT:
- Controllable BCs -accurate measurements
- Flow visualization & velocimetry
- Extensibility Gap in scale and fluid closed by the model

- **Proposed ISS experiment will be able to bridge ground test extensibility gaps with future mission applications**

Specific Objectives of ZBOT-1

- Obtain microgravity data for tank pressurization, mixing, pressure reduction, ullage penetration time constants as a function of heat input, fill level, mode of heating, jet velocity and jet temperature during storage without noncondensables.
- Elucidate the roles of the various interacting transport and phase change phenomena that impact tank pressurization and pressure control in microgravity to form a scientific foundation for storage tank engineering.
- Derive empirical microgravity engineering correlations *for back-of-the-envelope design calculations* and implementation into the zonal-based engineering models.
- Develop a *state-of-the-art* CFD two-phase model for storage tank pressurization & pressure control.
- Validate and Verify CFD-based tank models using the pressure, temperature ullage penetration and PIV microgravity data. Use the model to optimize and scale-up future storage tank design

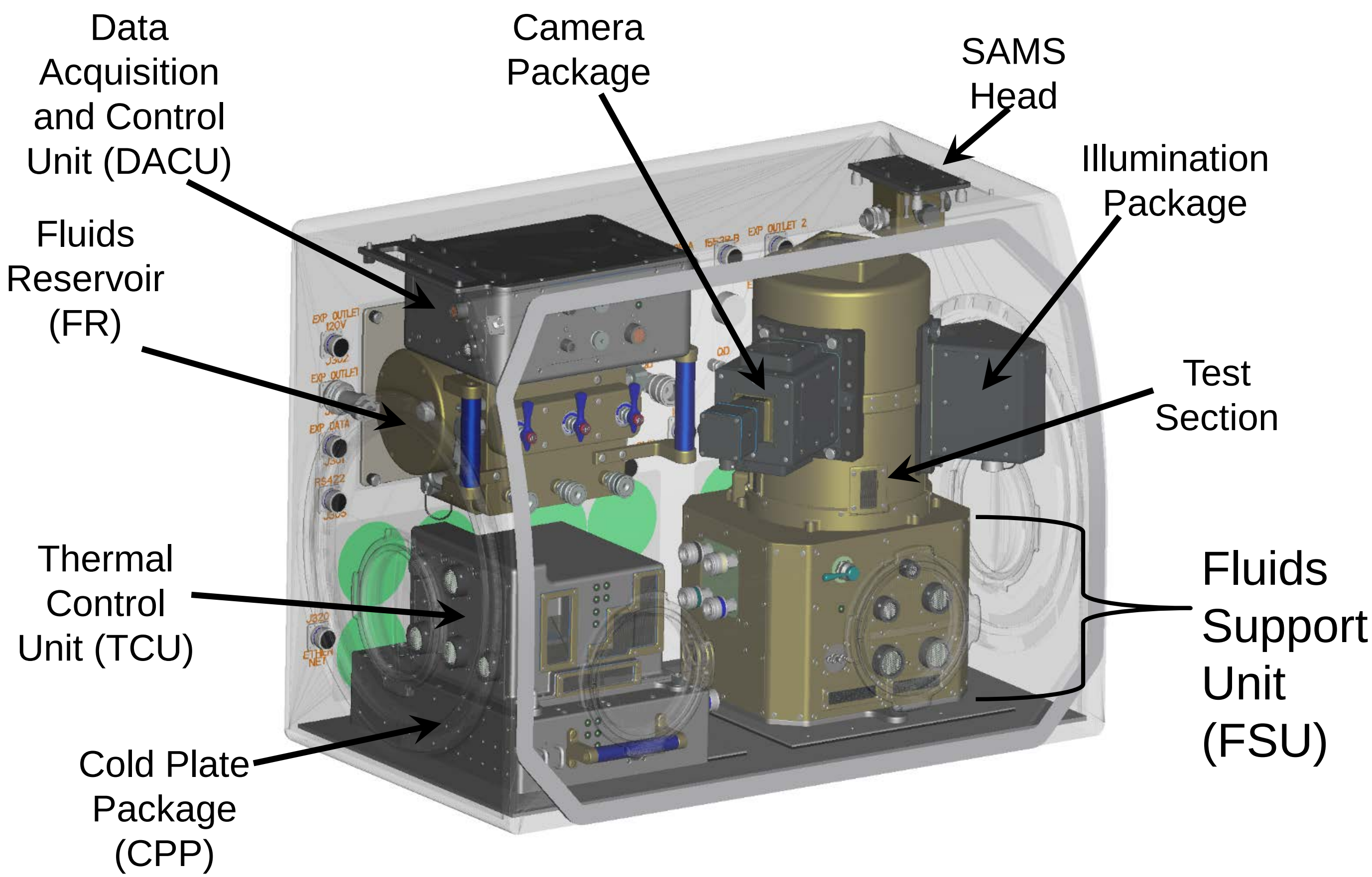
ZBOT-1 Engineering Questions: Pressurization & Pressure Control

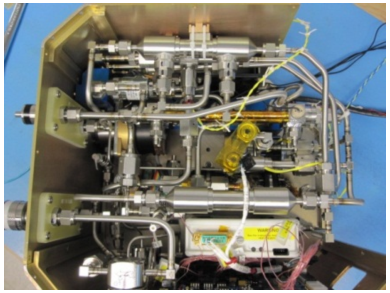
- How much natural mixing will take place in a given tank during operation at various gravitational levels?
- How much forced mixing is needed to thermally de-stratify the tanks without active cooling?
- Under what conditions will it be necessary to augment the thermal destratification through active cooling?
- How effectively do mixing-only and/or mixing-with-active-cooling decrease the pressure reduction times?

Need: reliable engineering correlations for mixing, destratification, and pressure reduction times as functions of relevant tank parameters such as heat leak rates, mixing flow rates, and fill levels

Application: sizing of the pumps, determining forced mixing modes, possible placement of flow control structures, and sizing and implementation of the active cooling mechanisms (TVS, Cryocooler, etc.)

ZBOT Hardware

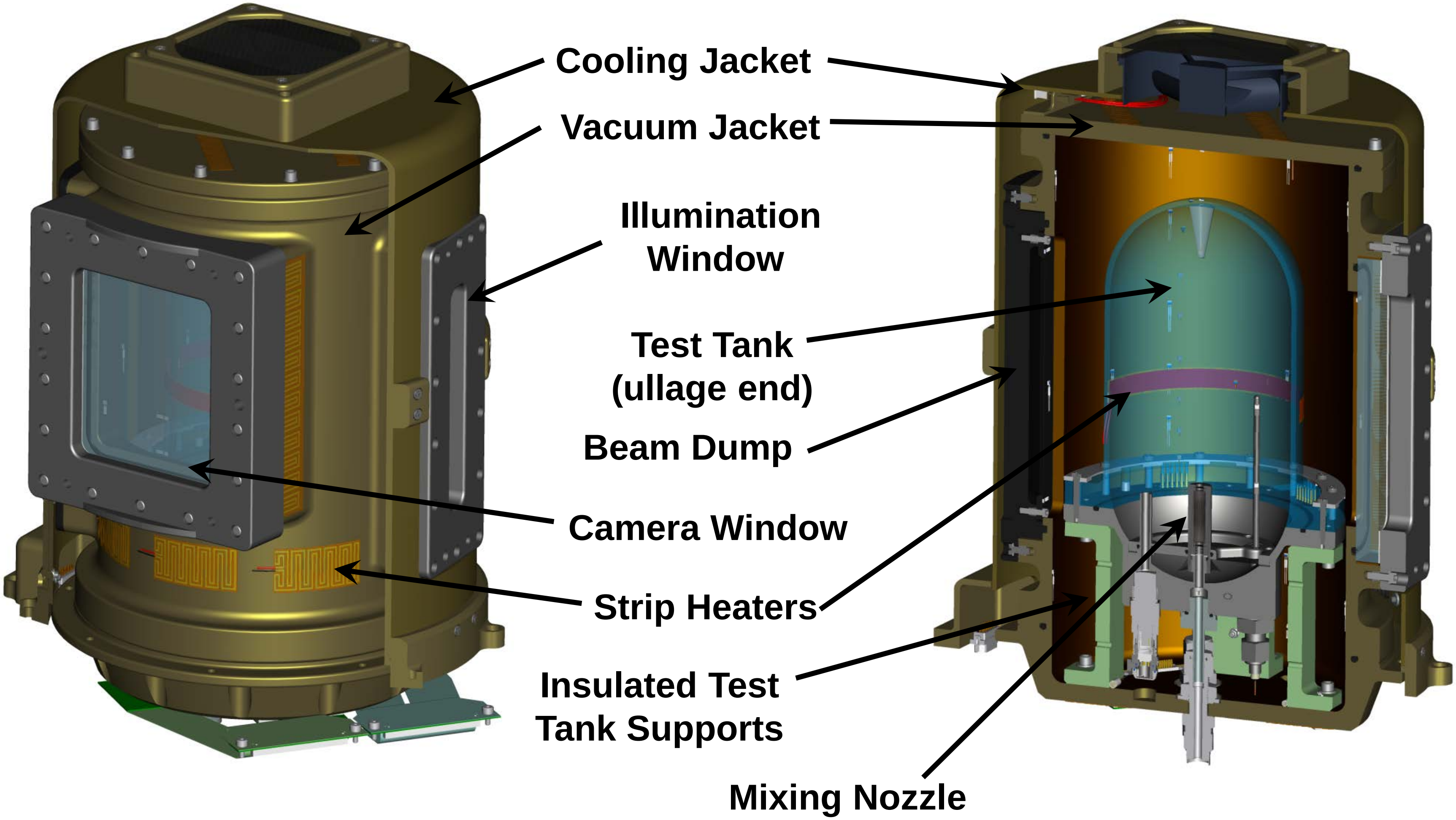


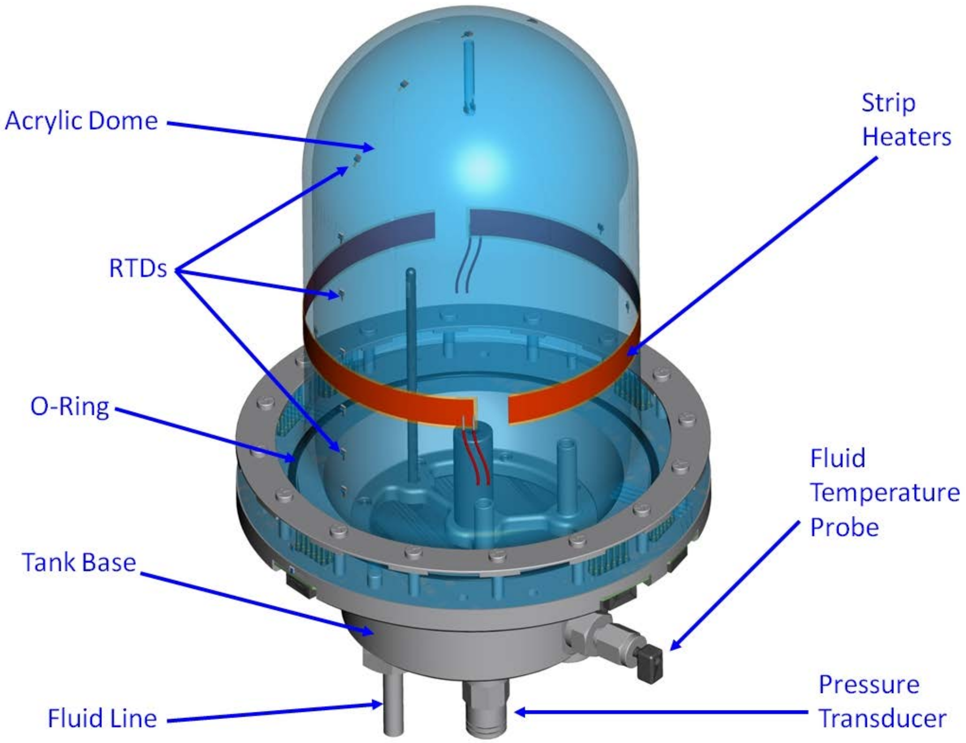


- ZBOT Engineering Model Fluids Support Unit (FSU)

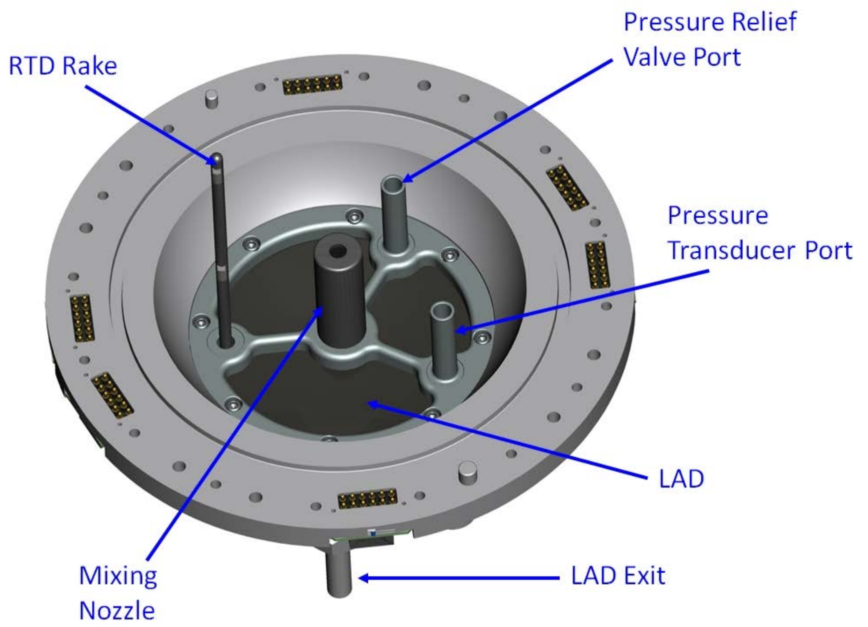
- ZBOT Engineering Model in the Microgravity Science Glovebox (MSG) Work Volume Mockup

Test Section Subassembly





PMMA (Acrylic) Test Tank Dome



Stainless Steel Test Tank Base

Requirements verified by Thermal Ground Test

Number*	Requirement Statement
1010.3	The system shall have the capability to degas the fluid on-orbit when the test tank pressure is 5 Torr above the baseline saturation curve.
1015a.2	The heater power shall be recorded at a rate of 1/60 Hz.
1015b.1	Before the start of all pressurization runs, the test tank shall be at an initial uniform temperature as specified in the test matrix column “$T_{initial}$ after preconditioning (° C)” for each run, subject to a tolerance of +/-0.25° C
1015b.2	Before the start of all pressurization runs, the fluid shall be at an initial uniform temperature as specified in the test matrix column “$T_{initial}$ after preconditioning (° C)” for each run, subject to a tolerance of +/-0.25° C
1015d.1	For each self-pressurization test, the flight software shall be able to run for the duration specified in the test matrix captured in Table 3A of the Science Requirements Definition.
1015d.2	The system shall have the capability to run self-pressurization tests for the duration specified in the test matrix; Table 3a in the Science Requirements Definition.
1016a.1	The system shall maintain the temperature uniformity of the vacuum jacket to within 2.7° C.
1016b.1	All of the RTDs located on the outer surface of the test tank shall be used to determine the area- average surface temperature of the test tank.
1016b.2	All of the RTDs located on the inner surface of the vacuum jacket shall be used to determine the area- average surface temperature of the vacuum jacket.
1016c.1	The electrical controls shall be provided to control the average vacuum jacket temperature to within 0.2° C of the average outer wall temperature of the test tank.
1016d.1	For all of the test runs where the jacket is used to heat the tank, the measured area-average jacket temperature shall be within a pre-specified offset of the measured area-averaged outer wall temperature of the tank, with a tolerance of 0.2° C. The magnitude of the offset is stated in the test matrix (Table 3a) for each of the test runs.
1019a.2	The system shall set the jet velocity from 2 cm/s - 25 cm/s.
1019b.1	The system shall control the jet velocity as described in the test matrix with a tolerance of 10% reading
1019c.1	The jet velocity shall be set as described in the test matrix with a measurement accuracy of +/- 5% reading.

* ZBOT-PLN-52

Requirements verified by Thermal Ground Test (cont)

Number*	Requirement Statement
1020.1	The system shall record the jet flow at a minimum rate of 1/60 Hz during jet operation.
1022a.1*	Before the start of tests that require isothermal tank preparation, the test tank shall be at an initial uniform temperature as specified in the Test Matrix column "$T_{initial}$ after preconditioning (° C)" with a tolerance of +/- 0.25 ° C
1022a.2*	Before the start of tests that require isothermal tank preparation, the fluid shall be at an initial uniform temperature as specified in the Test Matrix column "$T_{initial}$ after preconditioning (° C)" with a tolerance of +/- 0.25° C.
1022b1.1	The jet temperature range shall be as specified in Table 3a of the SRD.
1022b2.1*	The system shall control the jet temperature range with a tolerance of +/-0.125 ° C.
1023.1	For the mixing only cases, the heat imbalance in the fluid between tank inlet and outlet shall be less than 150 mW, for the time span of the jet mixing case. This translates into the following max. ΔT for each Test Matrix Jet Speed [q = m-dot*Cp*DT]: 2cm/sec: Max. DT = 0.26 ° C 4cm/sec: Max. DT = 0.13 ° C 6 cm/sec: Max. DT <= 0.09 ° C
1023.4	For jet mixing, the temperature and pressure in the fluids loop shall keep vapor bubbles generated in the fluids loop below 2 ml (the limit changes the ullage volume by less than 3%).
1023.5	Vapor transfer rate into the tank shall be less than 0.1 ml per second. This rate limits the heat leakage rate between the fluids loop and the tank to less than 150 mW.
1024a.1*	The system shall have the capability and control to reach the designated jet temperature set point within [(25/jet speed)+5] seconds of being activated
1024a.3	The fluid in the jet shall be pre-conditioned in the fluid temperature control loop before directing flow through the jet.
1024c.1	The system shall have the capability to run Jet mixing tests for the duration specified in the test matrix; Table 3a in the Science Requirements Definition (SRD).

* ZBOT-PLN-052

Ground Tests

Table 1: Non-test-matrix-derived data acquisition run

Run ID	Fill Level	Test Goal	Date
NS1	70%	Use the membrane contactor to degas the fluid	8/31 and 9/1/2015

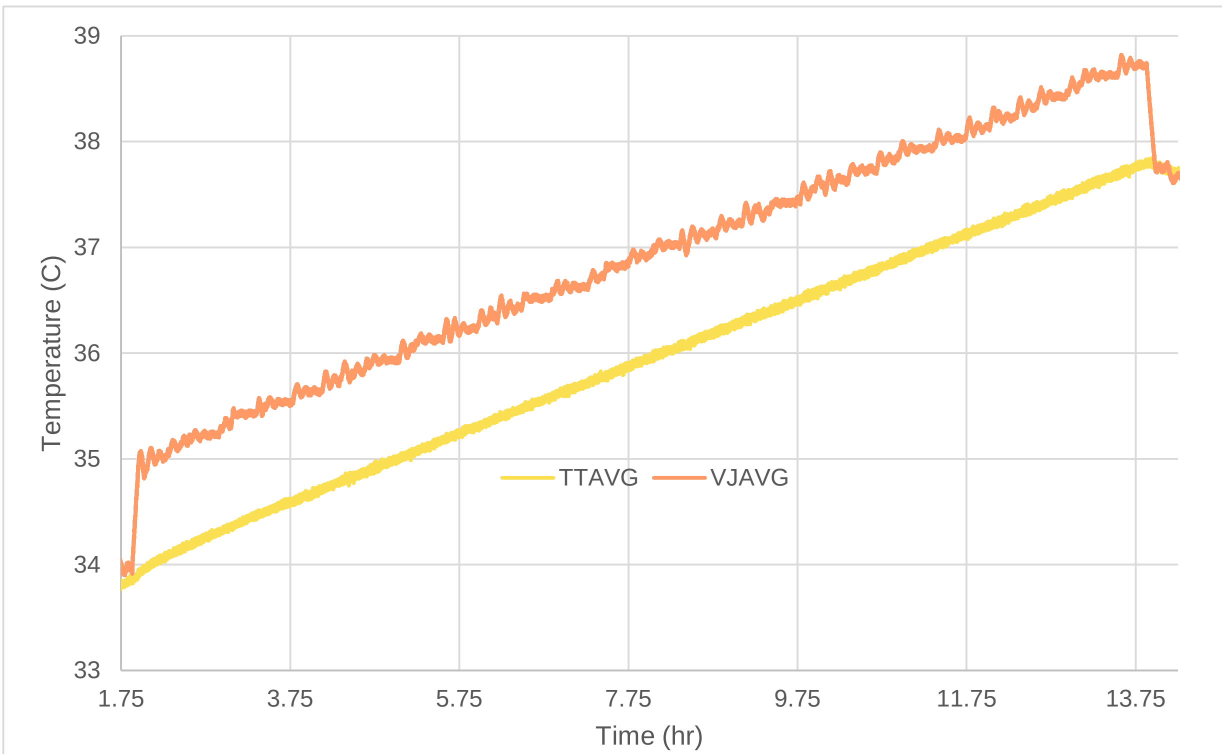
Test NS1 was run on two consecutive days as the system was not sufficiently degassed after the first day. After NS1, the six science test matrix-derived tests were performed:

Table 2: Science test-matrix-derived data acquisition runs

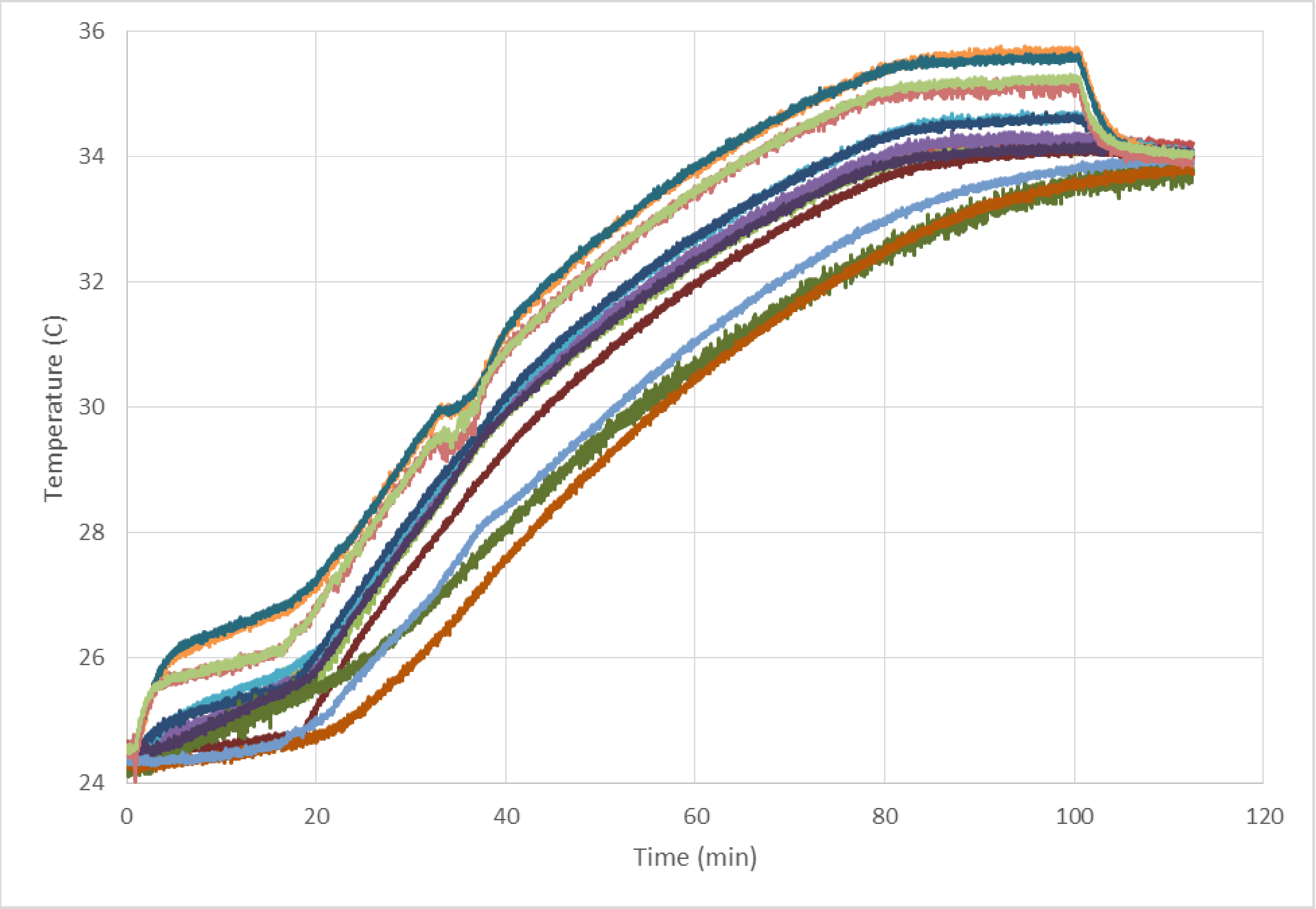
Run ID	Fill Level	T_0	Self-Pressurization Method and Duration	Inlet Temperature during Mixing	Jet Speed	Mixing Duration	Date Performed
J3	70%	38 ° C	None	$T_{in}=T_{out}$	4 cm/s	30 min	9/2/2015
SC1	70%	38 ° C	None	T_0-6	6 cm/s	30 min	9/3/2015
J1	70%	34 ° C	Vacuum Jacket ($T_{vj}=T_t+1$) 12 hours	$T_{in}=T_{out}$	2 cm/s	30 min	9/8/2015
SC2	80%	38 ° C	None	T_0-2	6 cm/s	30 min	9/9/2015
J4	90%	38 ° C	None	$T_{in}=T_{out}$	25 cm/s	30 min	9/9/2015
J2	90%	34 ° C	Tank Heaters (1 W total) 3.5 hours	$T_{in}=T_{out}$	6 cm/s	30 min	9/11/2015
J3R	70%	38 ° C	None	$T_{in}=T_{out}$	4 cm/s	30 min	12/30/2015
SC1R	90%	38 ° C	None	T_0-6	6 cm/s	30 min	1/6/2016

The science tests were rearranged so as to group fill levels together and thus require only two fill level changes – from 70% to 80%, and from 80% to 90%. Tests J3 and SC1 were repeated due some issues with the original test setup

Vacuum Jacket Performance

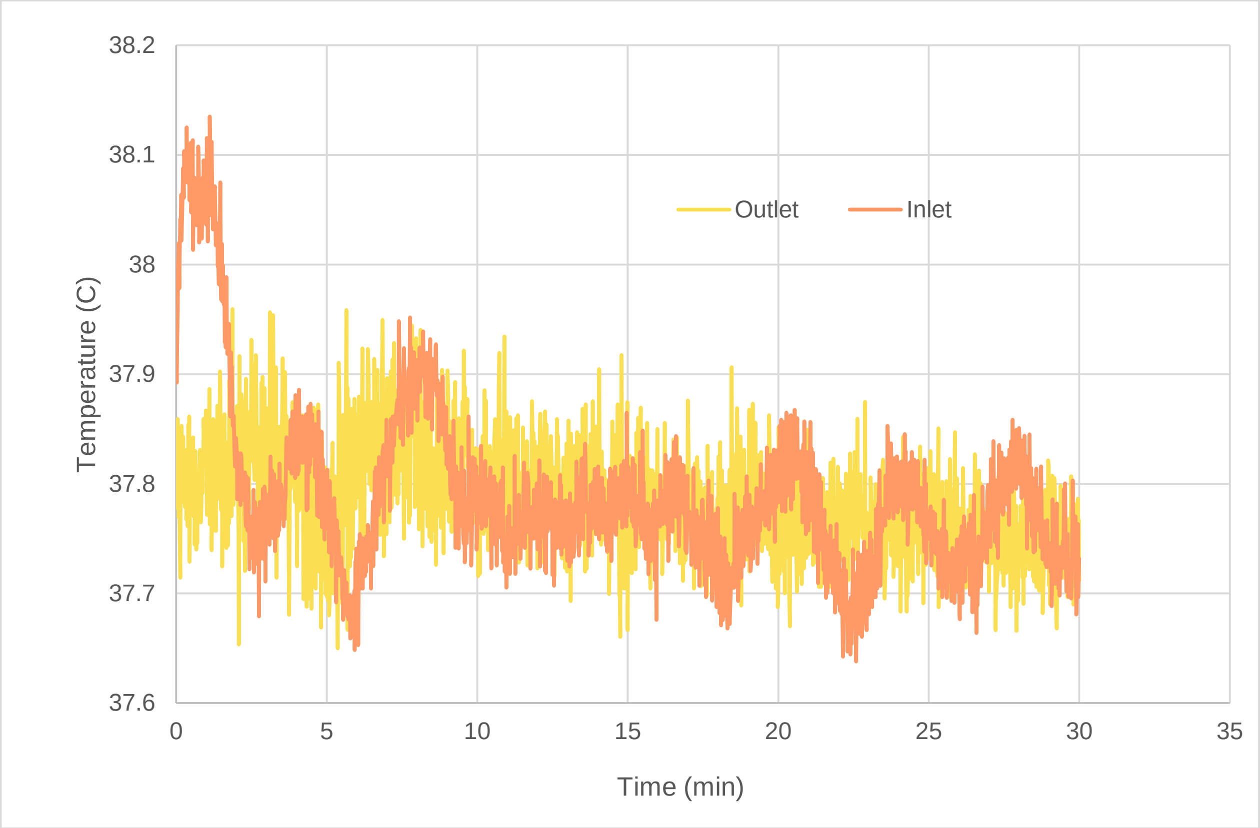


Self Pressurization phase of test J1, showing vacuum jacket offset above the test tank



Test Tank Temperatures during the tank prep phase of test J1.

Tank Mixing Performance



Tank inlet and outlet temperatures during the mixing phase of test J3R

Tank Camera Image

Image of the interior of the test tank approximately two minutes after start of mixing.

Requirement Failures

- 1015.b.1 spread +/-0.27 C rather than +/-0.25 C
- 1019.c.1 at 2cm/s uncertainty is 5.11% rather than 5%
- 1023.1 at 6 cm/s meeting this requirement requires a temp difference of less than +/-0.02 C actual test matched within +/-0.041 C
- 1023.2 at 6 cm/s meeting this requirement requires a temp difference of less than +/- 0.02 C actual test matched within +/- 0.041 C
- 1024a.1 None of the tests had a start-up transient less than 2 minutes, which far exceeds the maximum transient time requirement of 17.5 seconds for the 2 cm/s flow

Requirement Failures Discussion

- Most failures minor and close to the required specification and therefore easily waived.
- 1024a.1 not close:
  - Due to lag caused by the length of the plumbing
  - Cannot be corrected without major rework.
- 1024a.1 resolution:
  - While the system cannot achieve the jet flow temperature response time required, the actual result can be used as an input into simulations, and thus will not hinder science
  - Also waived.

Implications for flight article

- Thermal performance of ZBOT sensors demonstrated
- Thermal conditioning of ZBOT demonstrated (as much as possible in ground test)
- 19 out 24 requirements met
- 4 requirements show minor deviations and are accepted as is
- 1 requirement not met but can be corrected for in data analysis
- This portion of ZBOT is ready for flight

Concluding remarks

- ZBOT flight preparation continues with testing of non-thermal aspects of flight hardware
- ZBOT planned for on-dock delivery this winter for flight on OA-7
- The ZBOT team looks forward to presenting flight results next year

ZBOT Project Team

SCIENCE AND MANAGEMENT

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Dan Williston– Quality Assurance, ZIN