

Addressing CFM Modeling Gaps For Application Into NASA's Future Cutting Edge Missions

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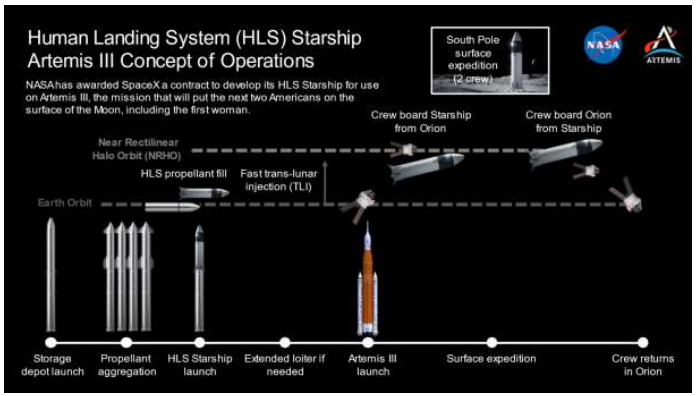
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Glasgow, United Kingdom

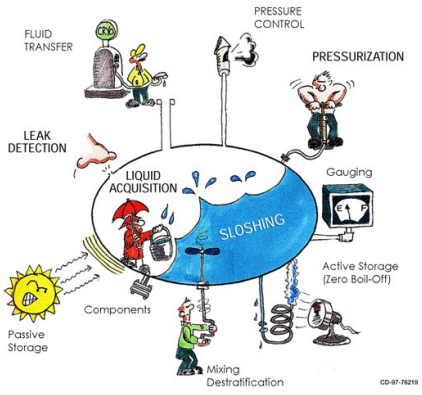
Advanced Predictive Models for Cryogenic Propellant management

- **Cryogenic Propellants for NASA's Future Missions**
  - Planned Future NASA missions are adopting High-performance cryogenic propellants to achieve significantly higher ISP compared to traditional room temperature propellants.
- **Addressing Challenges**
  - Facing unique storage and transfer challenges with cryogenic propellants, particularly in zero-gravity environments where gravity does not aid in settling.
  - The absence of gravity complicates the prediction of two-phase thermodynamics of cryogenic propellants during storage and transfer operations.
- **Advanced Predictive Models**
  - NASA is actively developing advanced predictive models through the Cryogenic Fluid Management portfolio within the Space Technology Mission Directorate (STMD).
  - These models utilize computational fluid dynamics (CFD) with advanced algorithms to accurately simulate the two-phase heat and mass transfer at the liquid/vapor interface of cryogenic propellants.
  - Utilizing ground test data and microgravity experiments to anchor models to ensure accurate performance forecasting.

NASA HLS Starship Artemis III Concept of Operations



*Source: Watson-Morgan, U.B. (2022). "NASA's Initial Artemis Human Landing System" 73rd International Astronautical Congress(IAC) 18-22 September 2022, Paris, France,

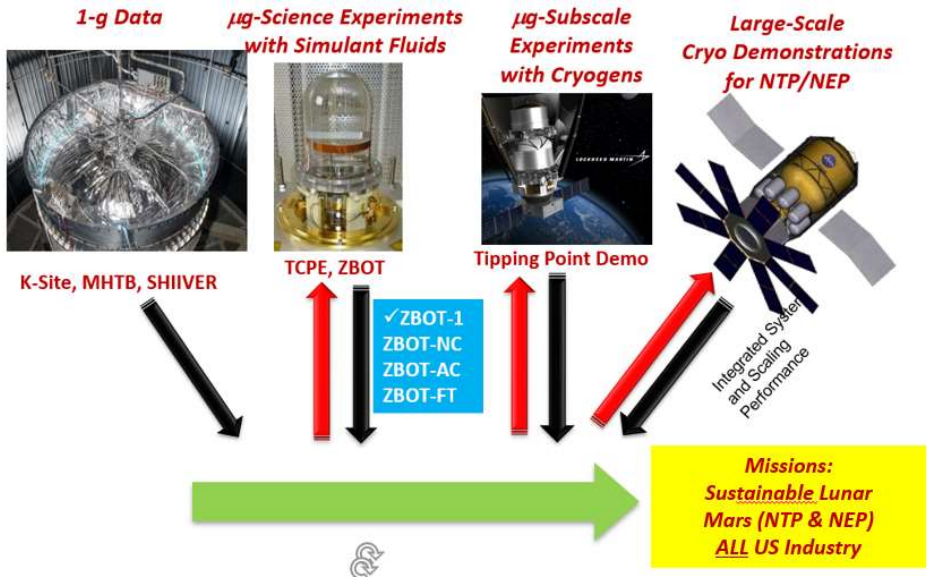


Cartoon Credit: J. Jurns

CFM Modeling Overview

- More work is needed to close gaps in predicting the performance of cryogenic propellant in a low-gravity environment.
  - In low-g, capillary forces dominate body forces leading to non-intuitive and un-expected physics.
  - Better understanding and accurate models are critical for sizing hardware and operations for storage and transfer of cryogenic propellant in a low-gravity environment.
  - Need to understand specific fluid physical phenomena, both isolated on their own, and integrated into a system.
- Predictive Model Development work Includes:
  - First Principal Physics CFD model
  - Empirical based multi-node lumped models
- Models that are developed need to be anchored to experimental data in a relevant environment (large scale cryogenic propellant in a μ-g environment)

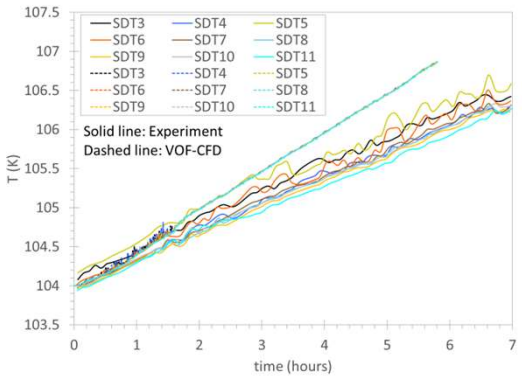
Infusion of Tipping Point Demonstrations to Anchor Cryogenic Models



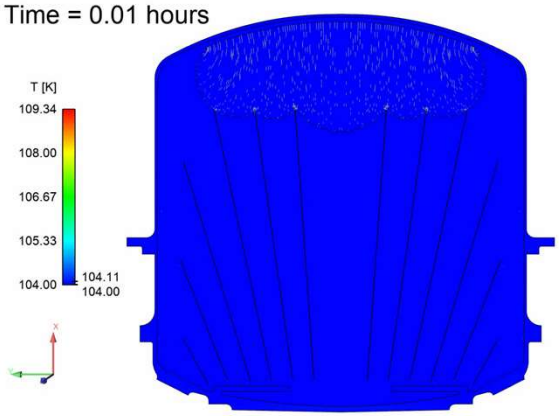
RRM3 On-orbit Cryogenic Methane Storage

- The RRM3 experiment successfully demonstrated zero-boil-off (ZBO) storage of cryogenic methane in microgravity using a cryocooler for over four months.
- Two multiphase CFD models (Sharp Interface(SI)-CFD and VOF-CFD) previously developed were validated against experimental data.
  - Both Models accurately predicted tank pressure and temperature during self-pressurization on Earth.
  - VOF-CFD model provided better microgravity predictions, capturing dynamic ullage convection.

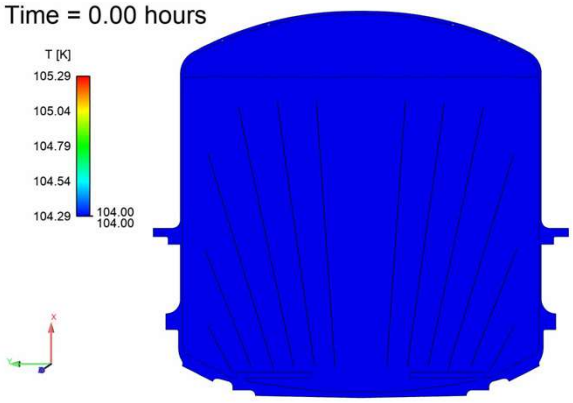
Fluid and Wall Temperatures, CFD vs Exp



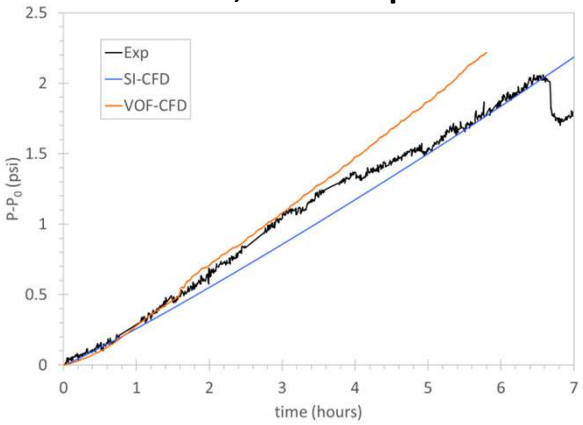
Sharp Interface CFD Model (micro-g)



VOF CFD Model(micro-g)



Tank Pressure, CFD vs Experiment



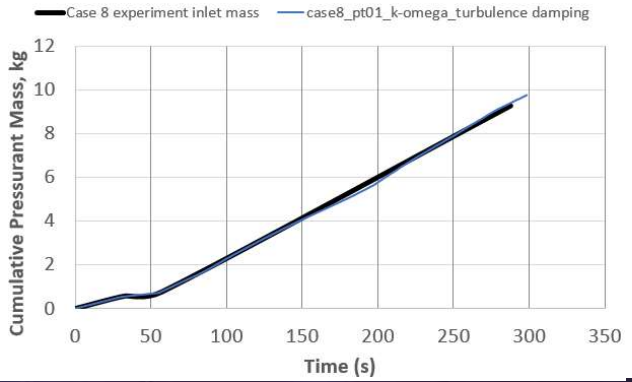
KSITE METHANE EXPULSION TEST'S DESCRIPTION

- In 1974, pressurization and expulsion experiments were performed at the Armstrong Test Facility using a 5-foot diameter spherical aluminum tank with liquid methane, incorporating both sloshing and non-sloshing scenarios.
- Multiple gaseous pressurants like methane, helium, hydrogen, and nitrogen were used in the expulsion test.
- Results from these tests were crucial for validating and refining FLUENT VOF CFD models, as they provided a comparison between predicted and experimental values for pressurant mass and temperatures.
- Various CFD simulations were conducted to explore grid/mesh independence, accommodation coefficient, different turbulence models, and turbulence damping.

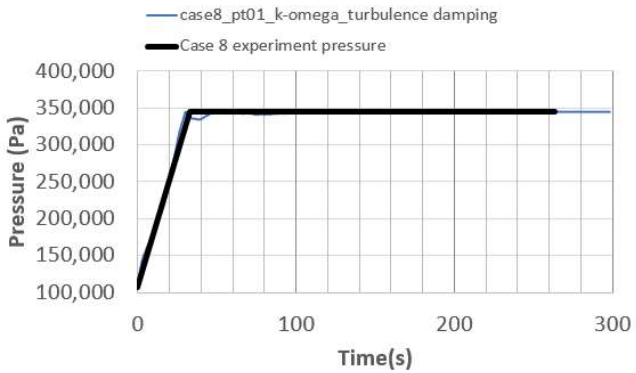
5 ft Diameter Spherical Tank and Test PI(Robert Stochl)



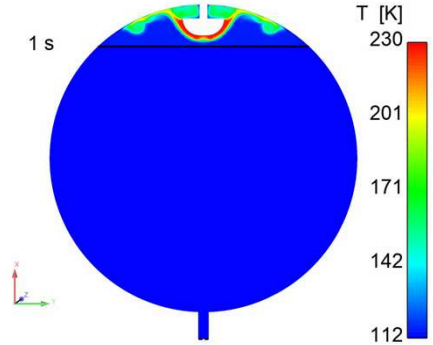
Predicted Pressurant Mass vs Exp Pressurant Mass



Predicted vs Exp Pressure



ANSYS FLUENT CFD Predicted Temperatures During Static Drain (Case 8)

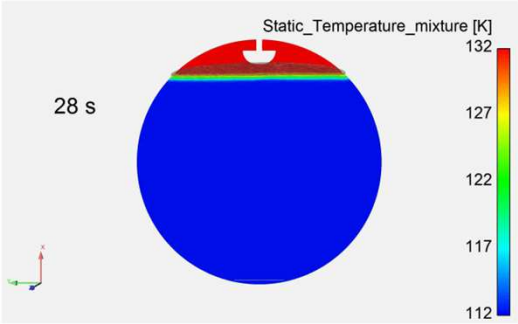


DeWitt, R. L., & McIntire, T. O., "Pressurant Requirements for Discharge of Liquid Methane from a 1.52- Meter- (5-ft-) Diameter Spherical Tank Under Both Static and Slosh Conditions," NASA-TN-D-7638, 1974.

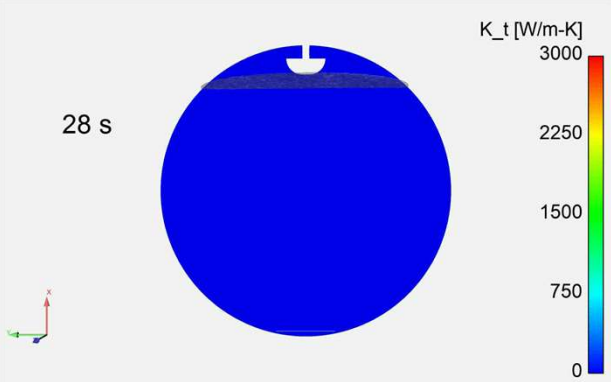
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KSITE LIQUID METHANE SLOSHING VALIDATION

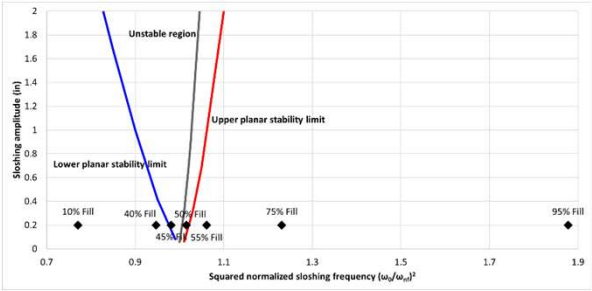
Predicted Liquid Propellant Temperatures During Drain



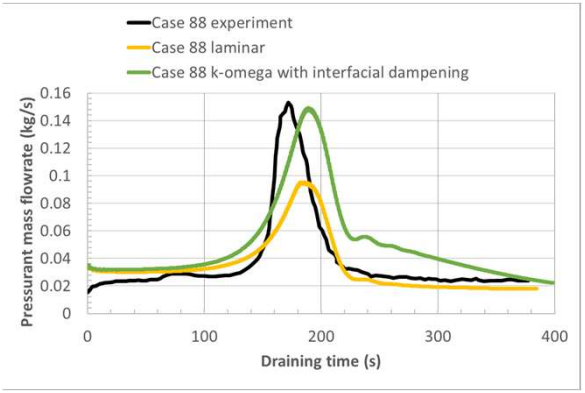
Predicted Effective Thermal Conductivity During Drain



Slosh Stability Map for Case 88 Liquid Expulsion (with annotated fill levels)



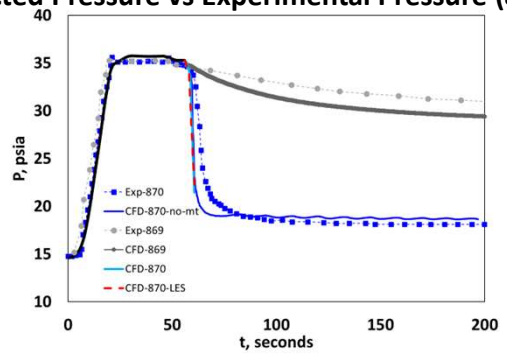
Predicted vs Experimental Pressurant Flow Rate



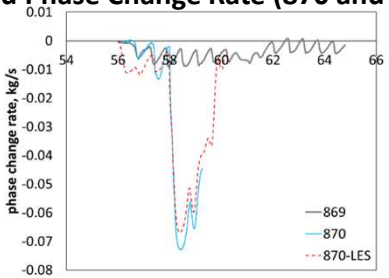
Sloshing in cryogenic propellant tanks causes additional ullage collapse increasing the pressurant demand and the warming of the liquid due to the heat released from the condensation of the autogenous pressurant.

KSITE LH2 PRESSURIZATION AND SLOSHING VALIDATION

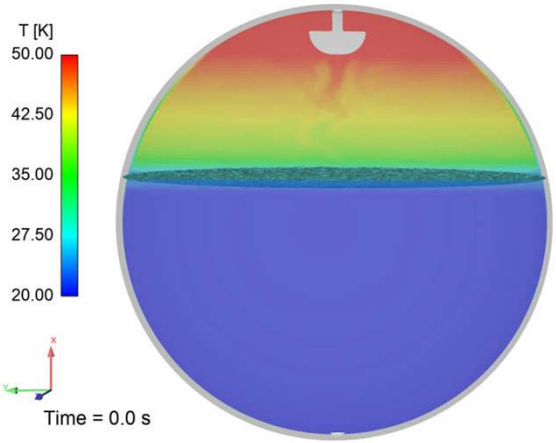
Predicted Pressure vs Experimental Pressure (870 and 869)



Predicted Phase Change Rate (870 and 869)



Case 870



Test Schematic

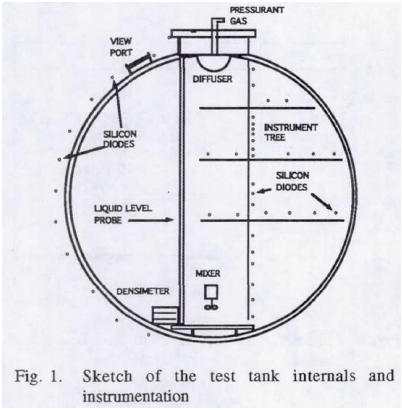
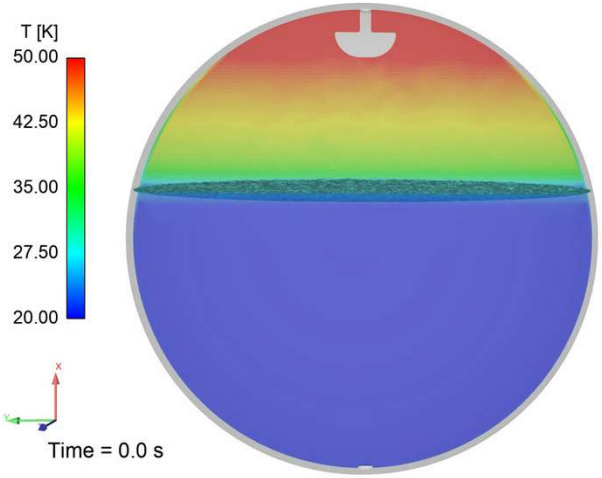


Fig. 1. Sketch of the test tank internals and instrumentation

Case 869

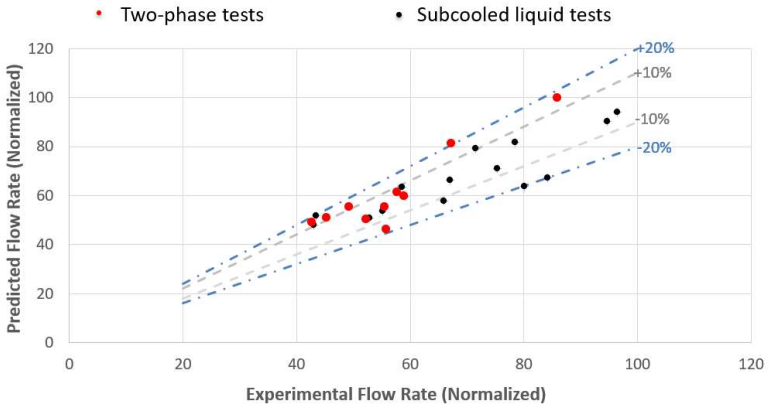


The predicted ullage collapse for both tests align well with the experimental measurements.

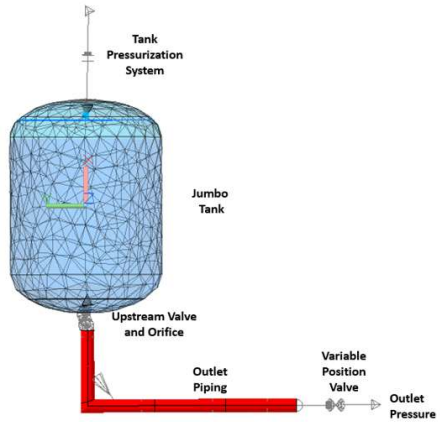
Propellant Transfer Performance Modeling

- SpaceX conducted a liquid oxygen propellant transfer test to study the impact of different thermodynamic conditions like inlet/outlet pressure and temperature on propellant transfer flow rates.
- Thermal Desktop was used model the test to predict the flow rates before and after the test, adjusting the model with experimental data to improve accuracy. The measured flow rates were then compared with model predictions to validate the model's effectiveness.
- The results show that if the transfer system is adequately modeled to capture the two-phase flow thermodynamic and fluid dynamics across the entire system, the performance can be predicted with an accuracy on the same order of magnitude as single-phase flow.

Predicted vs Experimental Flow Rates(Normalized)



SpaceX Propellant Transfer Thermal Desktop Model



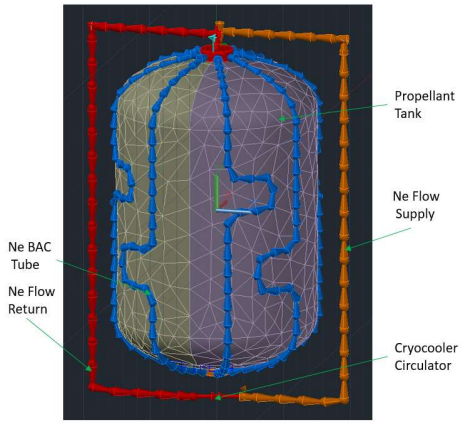
CryoFILL Propellant Liquefaction Modeling

- A Thermal Desktop model was developed of the CryoFILL prototype tank
  - Incorporates a neon Broad Area Cooling (BAC) network and liquid/vapor propellant states within the tank into the model
- Models the testing with warm Gaseous Oxygen (GOX) introduction for constant and variable liquefaction scenarios.
  - Assessment of various conditions such as environmental temperature changes and liquefaction power variations
- Predicted temperature, pressure, and liquefaction rate within the tank were compared against experimental data
  - Adjustment of model parameters based on experimental results to improve accuracy
- Analysis of model performance under different thermodynamic conditions during pressurization and liquefaction tests
- Future modeling enhancements suggested for fluid dynamics understanding via Computational Fluid Dynamics (CFD) simulation

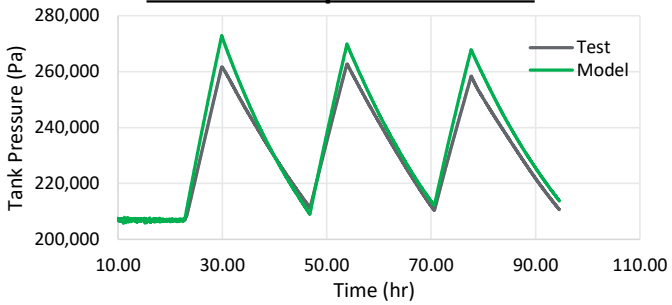
CryoFILL Tank and BAC Tubes



Prototype Tank Thermal Desktop Model



Predicted vs Experimental Pressures During Transient Liquefaction Test



Conclusions

- NASA and its partners are planning for the use of cryogenic propellants for their high efficiency.
  - A key challenge with cryogenic propellants is managing the volatile nature of the propellants.
  - In low gravity environments, handling these propellants is more complex. Unlike on Earth, the propellant doesn't stay at the tanks bottom and is more likely to float freely.
- To address this, Computational Fluid Dynamic (CFD) models, enhanced with specialized algorithms, have been developed. These models are designed to accurately predict the heat and mass transfer between the liquid and vapor phases of cryogenic propellants.
- Validation efforts have shown promising results, with model predictions aligning closely with benchmark tests conducted both on the ground and in simulated low-gravity conditions using cryogenic propellants or room temperature two-phase simulant fluids.
- Further work is necessary to fully understand the impact of non-condensable gases such as a helium, on phase change processes.
- Advancing these models requires additional data from low-gravity environments, which is crucial for ensuring performance predictions.
  - NASA is procuring this through multiple sources including Tipping Points and International Space Station experiments.
  - Further testing may be required on a stand-alone integrated microgravity experiment.

Questions?