Investigating the Explosive Hazard of Liquid Oxygen-Liquefied Natural Gas Rocket Propellant

Space Cryogenics Workshop

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Images not to scale


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Numerous LO2/LNG Propellant Vehicles are in Development

- Propellant quantities range to over 4.5 million Kg
- Launch sites include U.S. government facilities
- We currently have only interim guidance for assessing the explosive hazard of this propellant

Risk and Safety Analyses

Explosive Siting

- Development of hazard areas for protection of personnel and infrastructure during ground processing operations
- *Deterministic* approach (typically)

Range Safety

- Development of risk-based hazard areas for personnel, infrastructure, sea traffic, air traffic
- Calculation of risks to personnel and assets
- Development of flight rules to mitigate areas of excessive risk
- *Probabilistic* approach

Nuclear Safety

- Calculation of risks to personnel if nuclear material is compromised
- Determination of environments for potential mitigations
- Launch approval from appropriate authority
- *Probabilistic* approach

Crew Safety

- Calculation of risks to capsule in an abort scenario
- Determination of abort rules, such as separation time
- *Probabilistic* approach

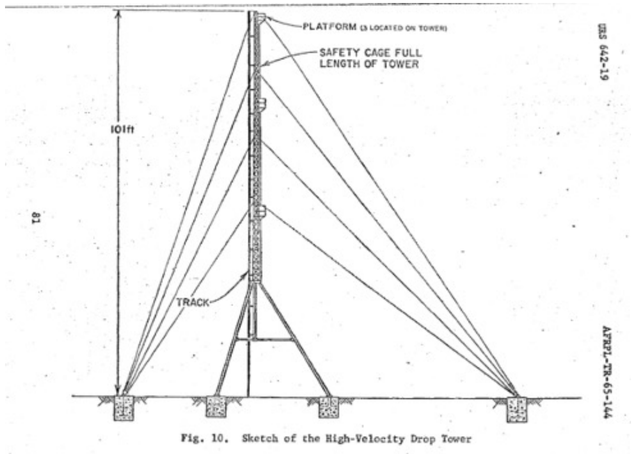
Between NASA, USSF, FAA and The US Department of Energy (DOE), there are at lease 12 different hazard and risk analysis models used to protect national assets, our workforce and the public. Each analysis is applied to unique operational scenarios, and all require experimental input data to work with new propellants.

Historic Launch Vehicle Propellant Testing

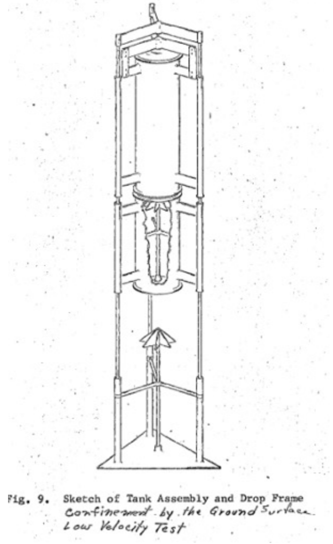
Basis for LO2/LH2 and LO2/RP-1 Hazzard Assessment

- Tests were conducted over six decades with large projects in the 1960s and 1990s
- Around 350 total data points including
  - 17 over 45,000 Kg
  - 21 over 30 m/s impact velocity
- Estimates of explosive energy from several real vehicle accidents are also included in the data base

For LO2/LNG the currently available dataset is very small with just a couple tests at ~9000 kg

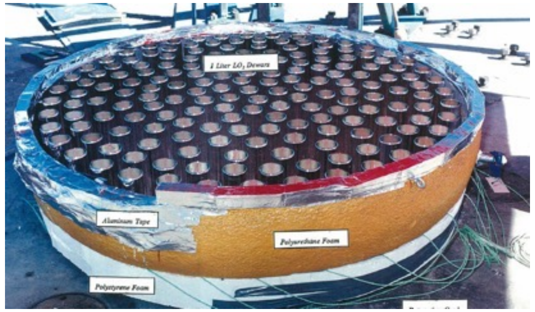


Project Pyro



Project Pyro

*HOVI 250 ft Drop Tower**



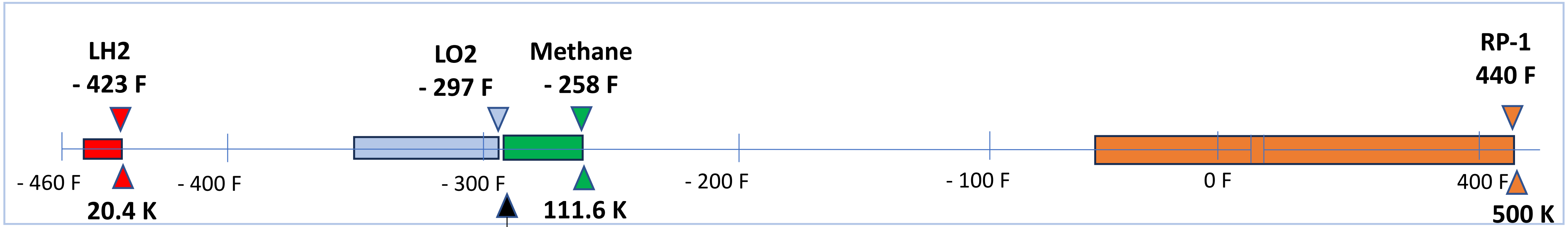
Distributed Mixing Test

* HOVI = Hydrogen Oxygen Vertical Impact

What makes LOX/methane different?

Why can't we simply leverage the hydrogen and RP-1 data?

Normal Boiling Point Temps and range of liquid phases



Observed Temperature of liquid MOX*

- The miscibility of LOX with LNG creates:
  - The risk of condensed phase detonation, resulting in significantly higher overpressures than LOX/LH2 and LOX/RP-1.
  - Unique risks when used in launch vehicles that have common bulkhead tank designs, common-walled downcomers, or transfer tubes
- Little data are available on LOX/LNG behavior in Launch Vehicle (LV) accident scenarios

When intentionally mixed, small-scale, unconfined mixtures of LOX/LNG have shown a broad detonable range with yields greater than that of TNT.

Appx. 255g of liquid MOX being stirred

Caution – this is a sensitive high explosive and should be treated as such.

* *MOX – Homogenous mixture of liquid methane (~ LNG) and LO2*

The LOX/Methane Explosive Hazard Assessment

A Tri-Agency Coordinated Effort to Collect Data on LO2/LNG

- Coordinates testing and analysis funded by the Federal Aviation Administration (FAA), United States Space Force (USSF), and NASA to efficiently and quickly collect data sufficient to develop explosive hazard guidance and tools to assess the hazard with confidence.
    - Numerous other government organizations are engaged as well as critical industry partners
    - 72 - 100 planned tests
- Periodic “sync points” to assess progress and whether test plans need to be adjusted

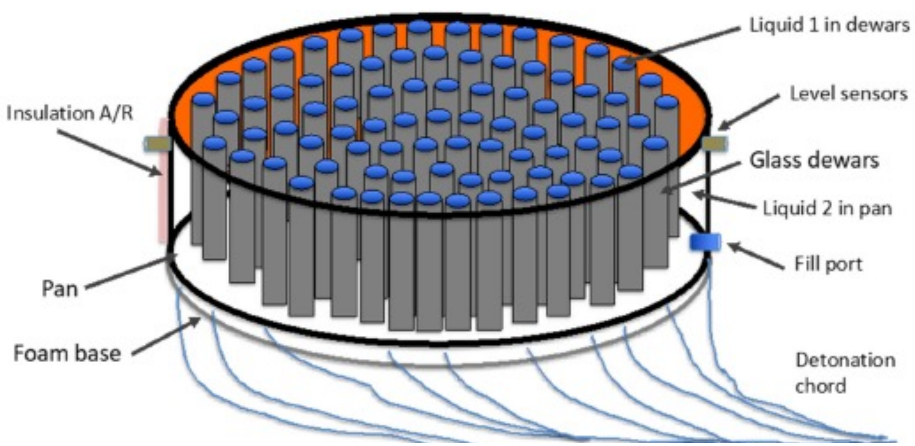
Leverages the lessons from past propellant testing to maximize effectiveness of tests

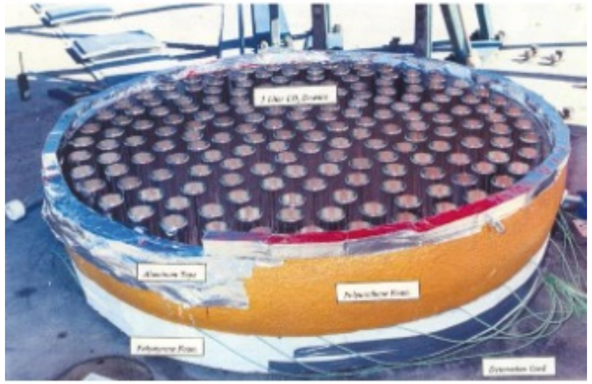
- Three major test categories
    - Static and dynamic tests that will inform assessment of accident scenarios
- Characterizes the influence of critical parameters (including propellant quantity, mass ratio, impact velocity, pressure, temperature...)
- Additional laboratory experiments to study fundamental processes that cannot be observed in larger scale tests
- Builds on limited existing data
- *Incorporates an Integrated Data Analysis and Modeling team to guide the various test activities and integrate results.*

Data collection will begin this year for all three major tests

- Some preliminary and laboratory testing has already begun

Propellant Reactivity Characterization Test
(Also Known as a Distributed Mixing Test)





1990s Test Article
LO2/LH2

Test Procedure:

- Propellant quantity: 70 to 225 kg
- Glass Dewars (nominally 1 liter) are filled with one propellant.
- Pan (~ 1 ft deep) is filled with the other propellant (Dewar and pan fluid can be reversed).
- Det. cord under the pan floor sends shock to Dewars, shattering them and creating a large mixing interface area.
- Autoignition occurs or igniter is activated.

Small-scale and large mixing interface area enables “rapid” test cadence and improved mixing control to characterize multiple parameters.

Earliest tests prioritize ignition delay (mixing time), mixture ratio, and fuel composition.

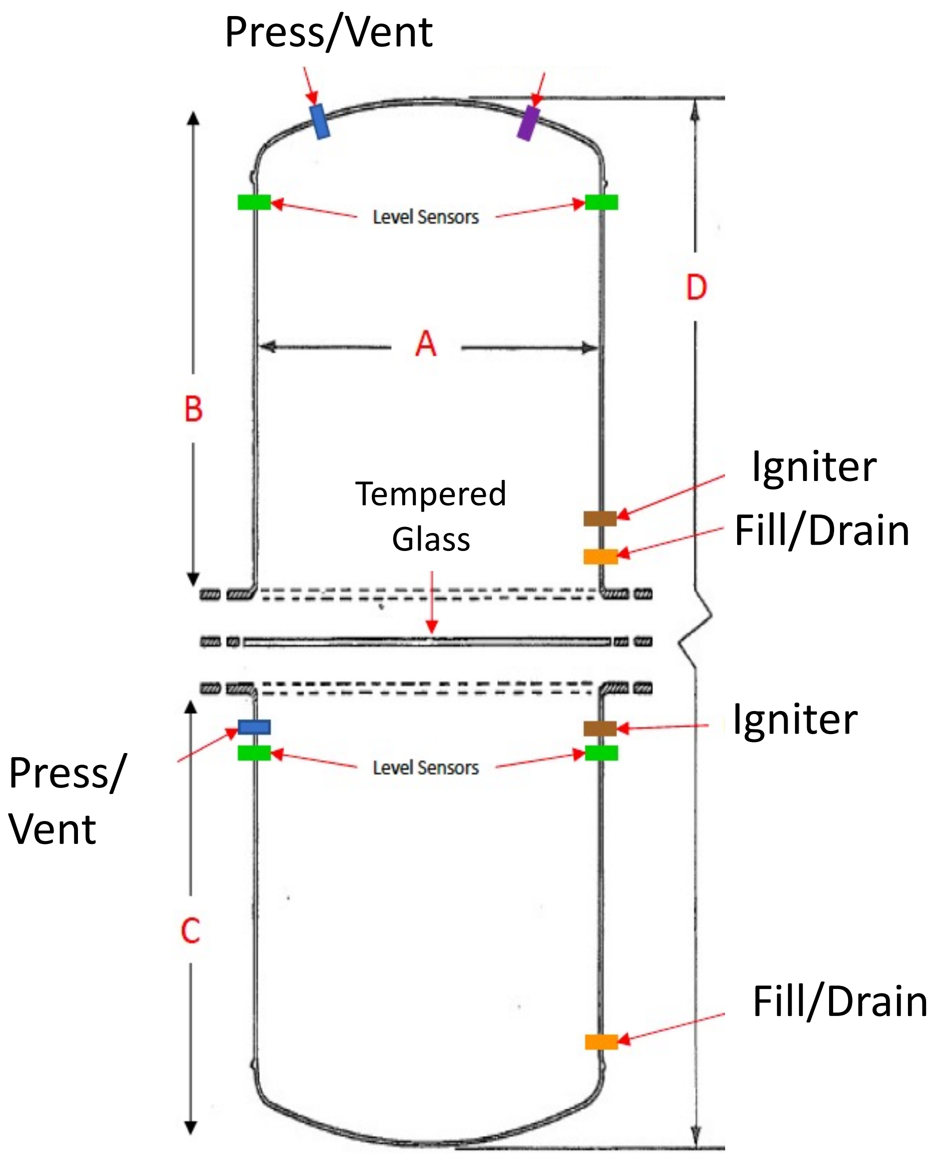
LAB Scale Tests (academia or other): e.g., Mixing characterization, ignition phenomena,
MOX equations of state, detonation limits and velocity

Propellant Reactivity Characterization Pathfinder Tests

LMA PRC Pathfinder Test Article
(30 Kg of propellant)

White Sands Test Facility

Confined By Missile(CBM) Test



Test Procedure:

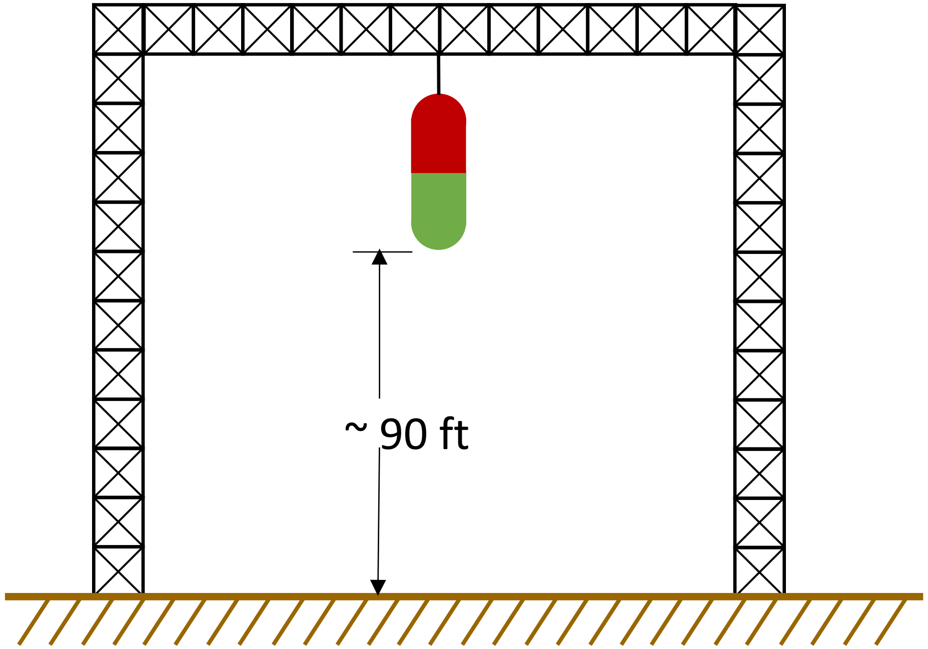
- Propellant quantity: 45 to 70,000 kg
- Bottom and top tank are filled and pressurized to test conditions.
- Tempered glass barrier is shattered, allowing mixing within the confines of the two tanks.
  - Diameter of glass barrier is a variable.
- Autoignition occurs or igniter is activated.
- Tank configuration details are still under consideration

Represents common bulkhead or transfer tube failure in a controlled experiment.

Phase 1 focuses on ignition delay (mixing time) and propellant mass effects.

Phase 2 focuses on additional factors including tank orientation, LNG purity, propellant temperature, contact area, and tank pressure.

Impact Test
(Also Known as Confined By Ground Surface)



Phase 1 Test Configuration: Not Drawn to Scale

C-4 Calibration test occurred on May 10th.

Test Procedure:

- Propellant Quantity: 225 to 9000 kg; TBD up to 70,000 kg
- Bottom and top tank are filled and pressurized to test conditions, raised by winch to planned drop height
- Tanks are dropped and impact a cutter on the ground surface; glass common bulkhead and glass downcomer shatter, and tank walls rupture
- Propellants spill on ground surface and mix
- Either autoignition occurs or a timed igniter is activated

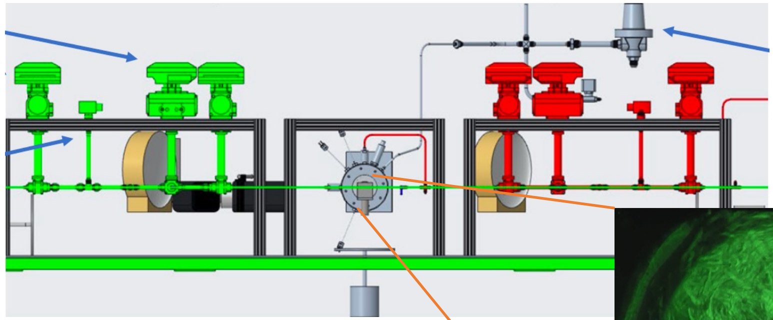
Represents vehicle fallback type failure to support Flight Safety Analyses; energy of impact can enhance mixing and may promote autoignition.

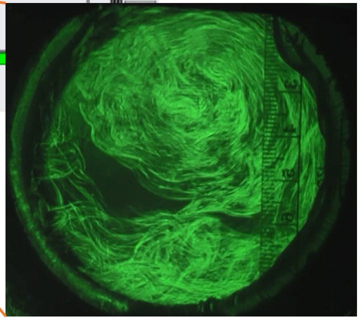
Phase 1 will emphasize ~90 ft/sec impact and slower and propellant mass scaling.

Phase 2 will emphasize higher impact velocity (acceleration device added) and parameters determined by PRC and CBM to be important to explosive energy.

Laboratory Scale Testing

Characterization of MOX – Advanced





WSTF, NASA White Sands Test Facility

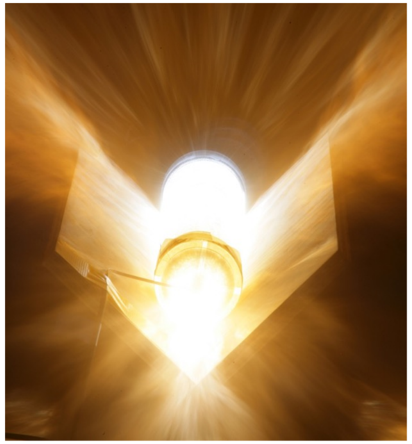
40 liter mixing tests: LNG into surrogate cryogens and LO2

JPL, Jet Propulsion Lab

MOX-E

- Pre-mixed MOX
- Detonation overpressure vs. mixture ratio
- Detonation limits
- Yield versus ignition source

NASA Marshall/N2L



MOX Explosion Experiment

- Pre-mixed MOX
- Detonation velocity vs. mixture ratio
- Multiple Ignition sources
- Detonation energy

Texas A&M University

Summary

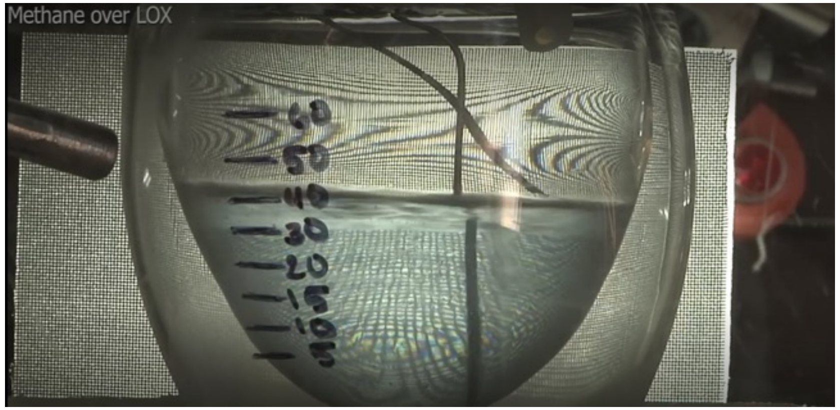
- LO2/LNG will be an important launch vehicle propellant for the future as multiple vehicles are currently under development.
  - *Safely and efficiently launch rockets requires understanding and mitigation of the risks they pose.*
- The explosive hazard data from hydrogen and RP-1 with LO2 are not directly applicable to understanding the hazards of LO2/LNG.
  - *Very little explosive data is currently available for LO2/LNG.*
- A multi-Agency effort is underway to collect data that will provide data for industry and the government Safety and Mission Assurance community to determine the hazards and risks with increased confidence.
- Preliminary testing has already begun and major test data collection will begin soon.

Backup

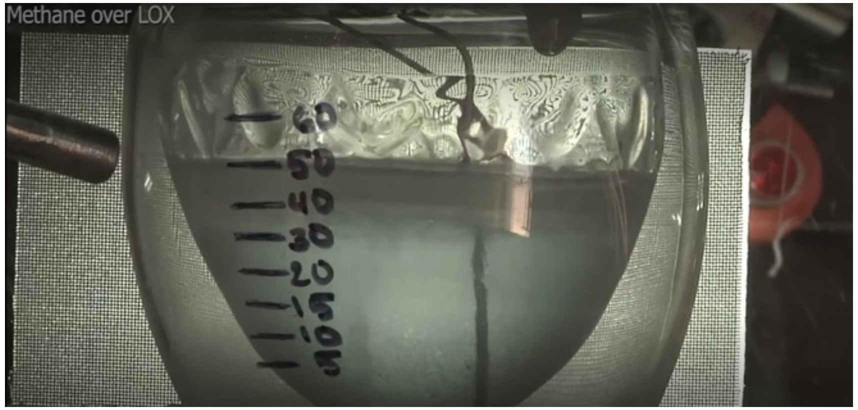
Laboratory Scale Testing
Example Preliminary Mixing Result

CMOX Basic Mixing Experiment

LO2 Pool, Sidewall LNG Injection

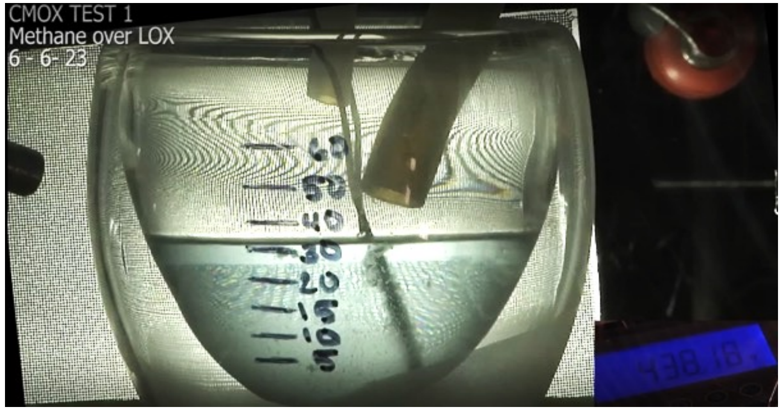


LOX before addition of LNG

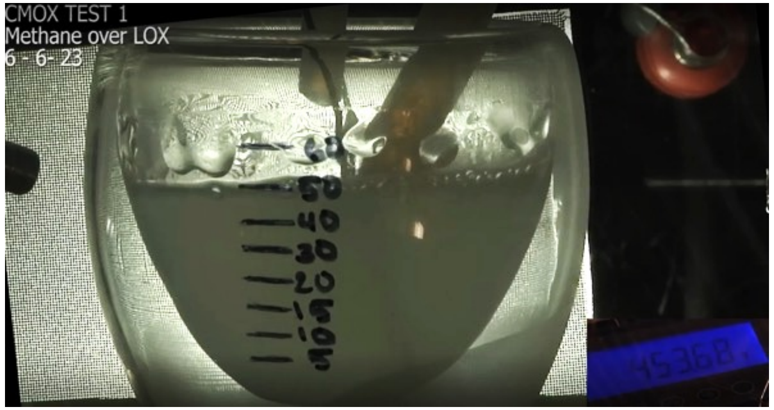


LOX mixed with LNG; some stratification noted; incomplete mixing

LO2 Pool, Centerline LNG Injection



LOX before addition of LNG



LOX mixed with LNG; complete mixing