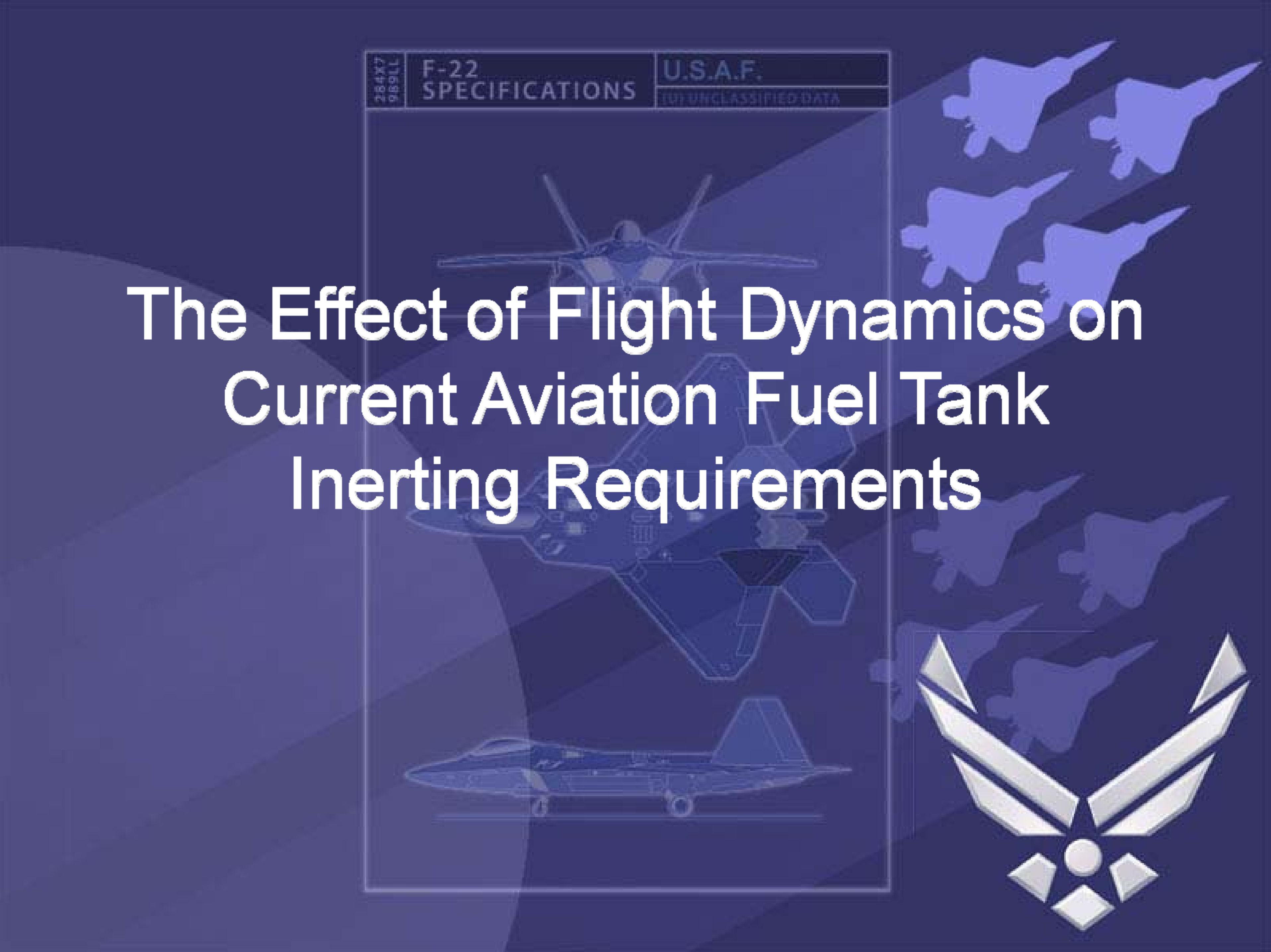

The Effect of Flight Dynamics on Current Aviation Fuel Tank Inerting Requirements

The Effect of Flight Dynamics on Current Aviation Fuel Tank Inerting Requirements

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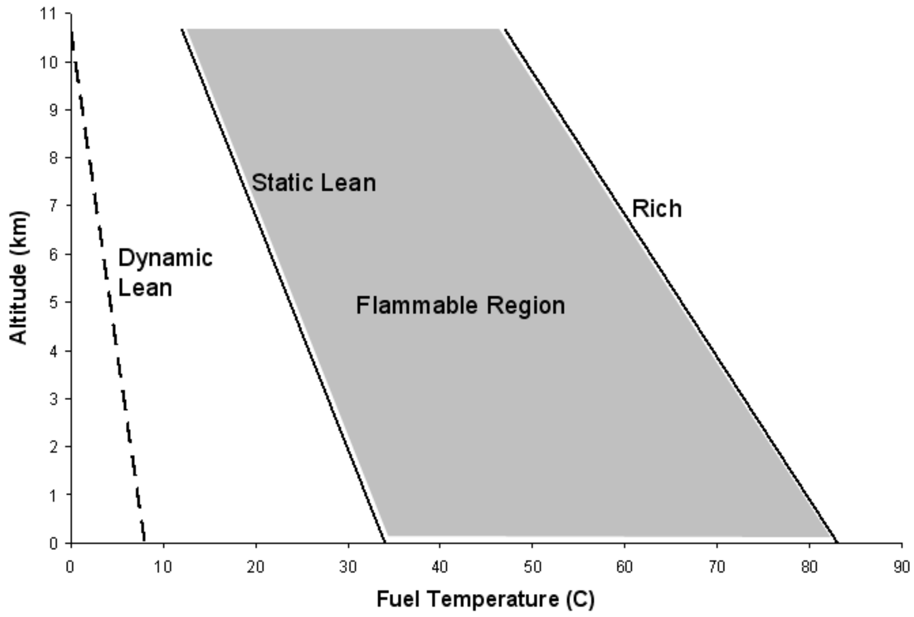
Overview

- Fuel Tank Vulnerability
- Fuel Tank Sloshing Background
- Motivation
- Sloshing Test Facility
- Experimental Slosh Characterization
- Stationary Tank Test Results
- Enhanced Fuel Tank Ignition Results
- Summary

Fuel Tank Vulnerability

- The dynamic motion of liquid in a container experiencing external forces is called slosh.
- Slosh poses a risk to dynamic, nonstationary fuel containers because of the violent mixing and droplet separation produced, leading to enhanced flammability effects.
- Past research has shown expanded flammability limits under dynamic conditions
- They noted the formation of fluid discontinuities along the surface of the sloshing fuel and attributed the enhanced limits to added mixing and spray production.
- Little is understood on the effect of slosh on the limiting oxygen concentration (LOC).

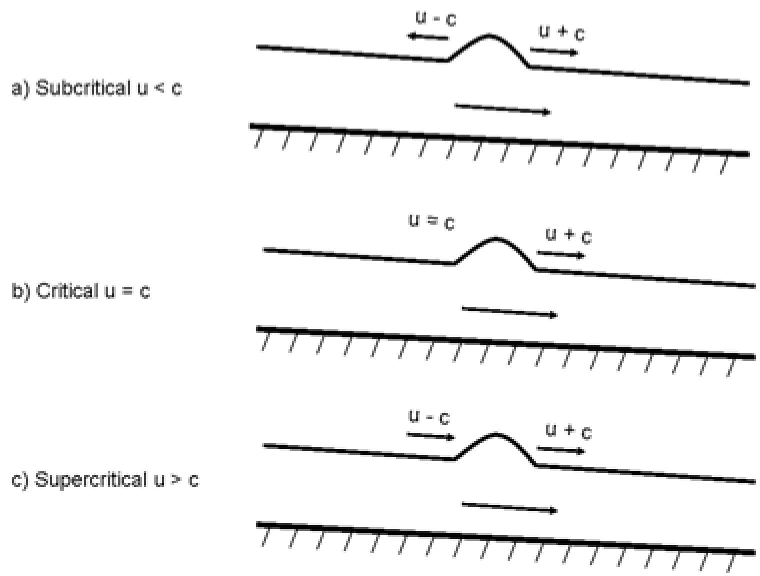


Flammability Limits from Nestor

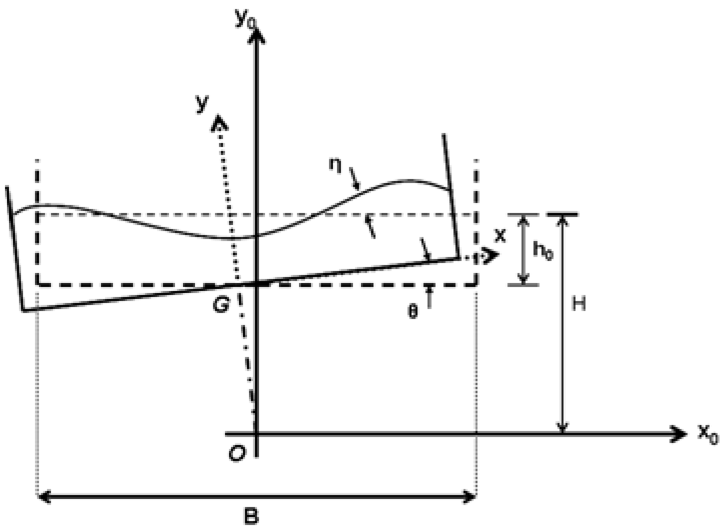
Fuel Slosh Theory

- Fuel slosh can be characterized as one of two conditions: Subcritical or Supercritical
- A partially filled tank has a characteristic resonance frequency based on the liquid depth. If the frequency of the tank oscillation meets or exceeds the resonance frequency, the sloshing state moves from subcritical to supercritical. Resonance frequency:

$$\omega_0 = \left[\frac{g\pi}{B} \tanh\left(\frac{\pi h_0}{B} \right) \right]^{1/2}$$



- The conditions that produce wave/wave interactions and hydraulic jumps represent the difference between subcritical and supercritical conditions.
  - Waves travel in opposite directions in subcritical conditions.
  - Waves travel in a single direction in supercritical conditions



Motivation

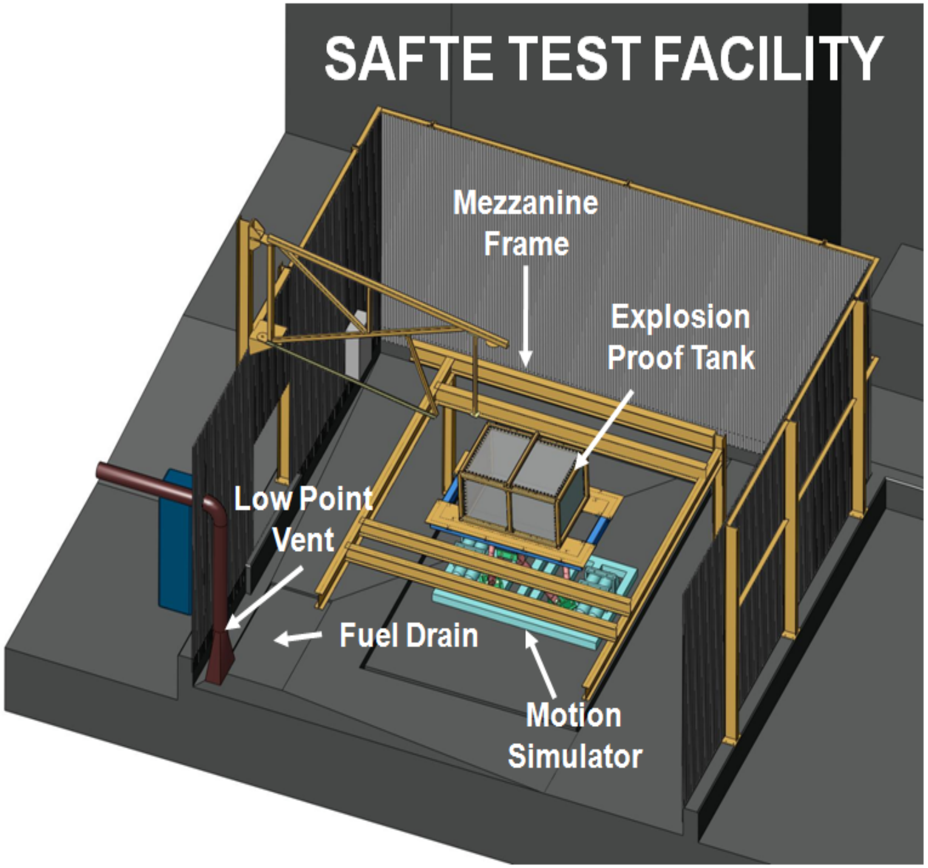
- Slosh enhanced flammability limits have been well documented for military and commercial aviation fuels.
- The effect of slosh on fuel tank inerting and the limiting oxygen concentration (LOC) requirements is not well documented. Past research has established a LOC of 12% O_2 by volume; however, these results have all been demonstrated under **stationary** conditions.
- The FAA has issued a fuel tank flammability reduction rule that suggests a 12% LOC for commercial aviation applications. Likewise, the military has instituted a 9% LOC requirement based on stationary testing and a 20% safety margin.
- The added safety margin requires increased use of onboard resources and thus, required experimental evaluation of the current military and commercial LOC under simulated flight conditions.

Program Requirements

- A Department of Defense funded three year program was conducted in three phases with the following objectives:
  - **Phase I:** Characterize the liquid dynamics believed to enhance fuel tank flammability in a dynamic tank.
  - **Phase II:** Establish LOC baseline for a stationary tank and compare to existing data.
  - **Phase III:** Couple observed liquid dynamics in Phase I with ignition study and determine the dynamic LOC.

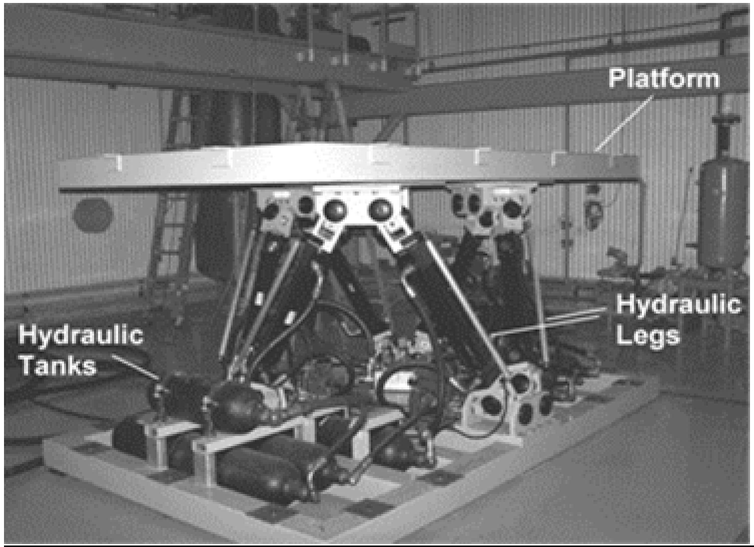
USAF SAFTE Facility

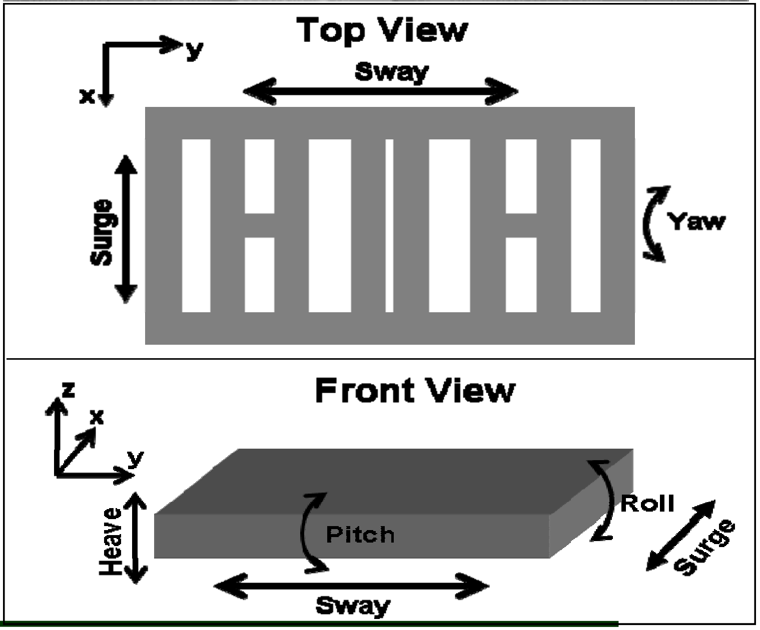
- Testing was conducted at the USAF 46th Aerospace Safety & Survivability Test Group's Simulated Aircraft Fuel Tank Environment (SAFTE) Facility at Wright Patterson AFB.
- This facility is equipped with:
  - Six-degree of freedom motion simulator
  - Explosion proof tank
  - Optically conducive tank
  - Environmental tank conditioning system (thermal, pressure, and inert gas systems).
  - Fire Suppression Systems
- Measurement capabilities include:
  - Simultaneous MHz sampling LabView system.
  - FID Hydrocarbon Analyzer
  - Oxygen Analyzer for Combustibles
  - Ignition Threat Characterization
  - Temperature and Pressure
  - ASTM Combustion Test Methods (Flash point, Autoignition, Heat of Combustion)



Motion Simulator

- The SAFTE Facility motion simulator and hydraulic unitis a custom fabricated test fixture for replicating aircraft maneuvers for test & evaluation purposes.
- The simulator is controlled through custom software that can implement a series of maneuvers or flight plan for a range of commercial or military aircraft.
- Supports a maximum payload of 11,300 kg (25,000 lbs).
- All angular and spatial movements are replicated at a rates up to 250 deg/s and 1.5 m/s respectively.
- Max/Min Movements:

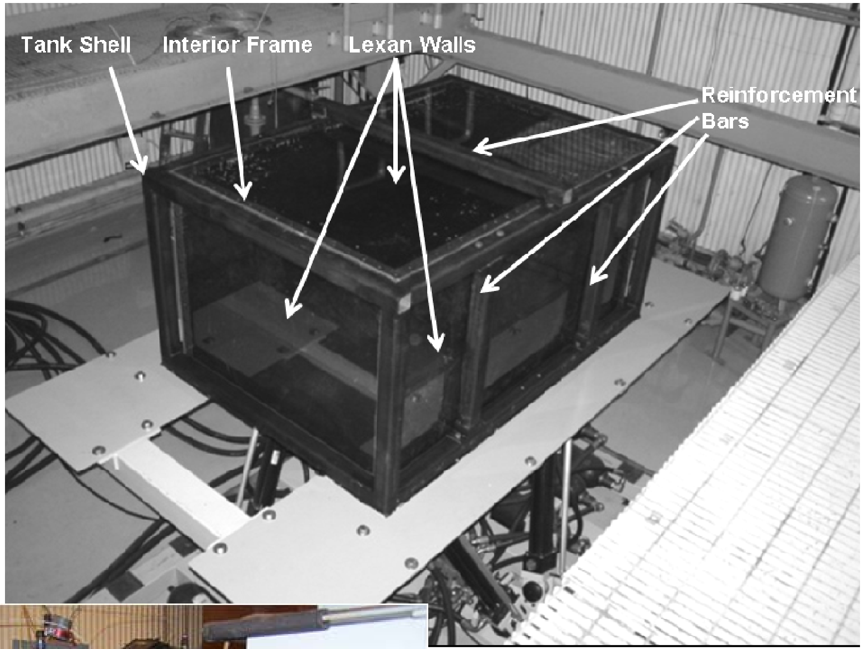


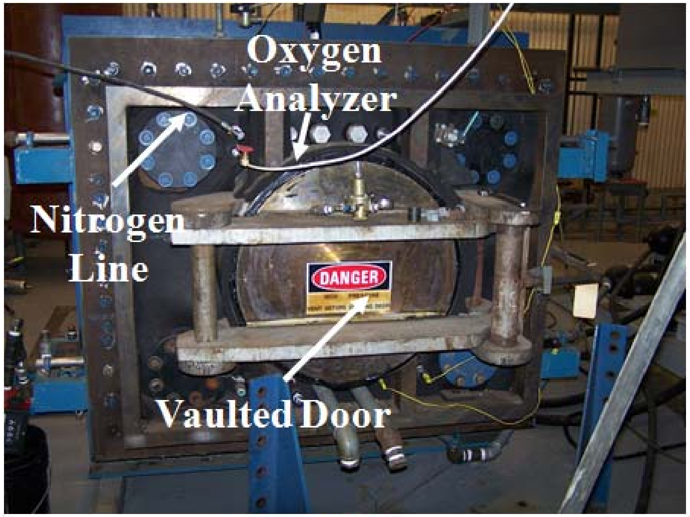


Motion	Maximum	Minimum
Roll	+25.0° ± 0.1°	-24.6° ± 0.1°
Pitch	+24.7° ± 0.1°	-23.5° ± 0.1°
Yaw	+20.0° ± 0.1°	-20.0° ± 0.1°
Surge	+61.0 cm ± 0.5 cm	-61.0 cm ± 0.5 cm
Sway	+50.8 cm ± 0.5 cm	-50.8 cm ± 0.5 cm
Heave	+30.5 cm ± 0.5 cm	-30.5 cm ± 0.5 cm

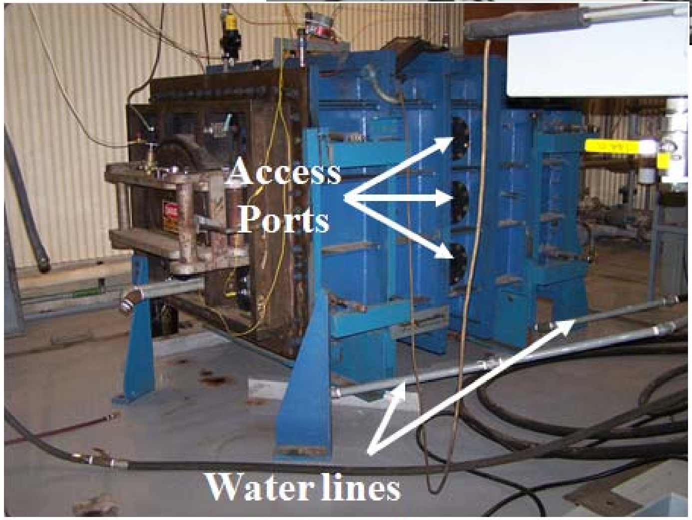
Fuel Testing Tanks

- For Phase I, an optically conducive tank (upper right) was used to characterize the liquid dynamics for a two-dimensional roll oscillation. Using high-speed digital imagery and analysis software.
- Combustion tests were conducted in a dimensionally similar explosion proof tank (shown below). Optical access ports allowed for visual confirmation of an ignition event.
- Each tank has a total volume of 2.29 m^3 (586 gallons).





Front View



Corner View

Dynamic Tank Conditions

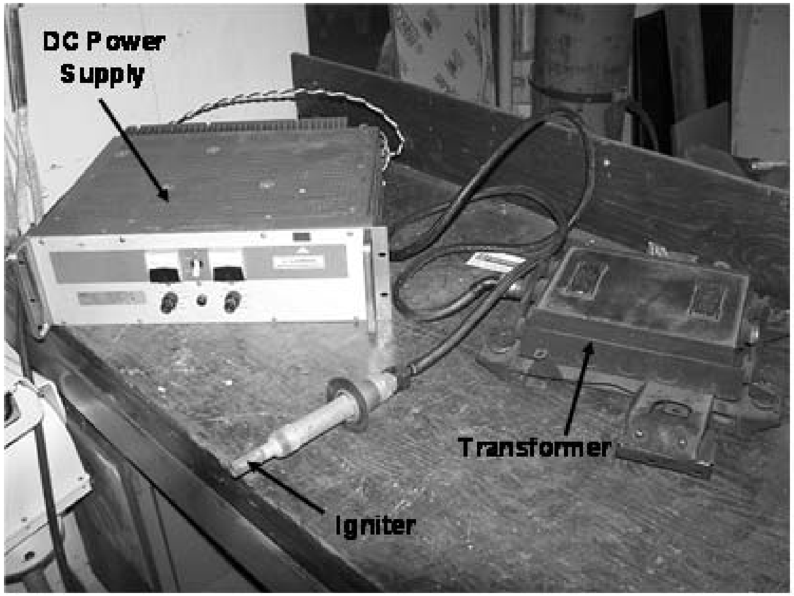
- Three different liquid depths were tested and the fluid mechanics characterized: 0.265 m, 0.371 m, and 0.530 m.
- For this test series, a simple, two-dimensional roll oscillation was implemented to minimize complex 3D sloshing motions. The criteria was to simulate low frequencies and small angles that could be experienced by an aircraft.
- The time-varying angle of the motion simulator is expressed below. The given test conditions are also presented.
  - Note: A slight offset 'A' had to be introduced to the equation because of the asymmetry in the simulator.

Amplitude (%)	θ_0 (deg)	Frequency Range (Hz)
10	2.42°	0.25 – 0.50
15	3.50°	0.20 – 0.45
20	4.72°	0.20 – 0.45

$$\theta(t) = \theta_0 \sin(\omega t - \lambda) + A$$

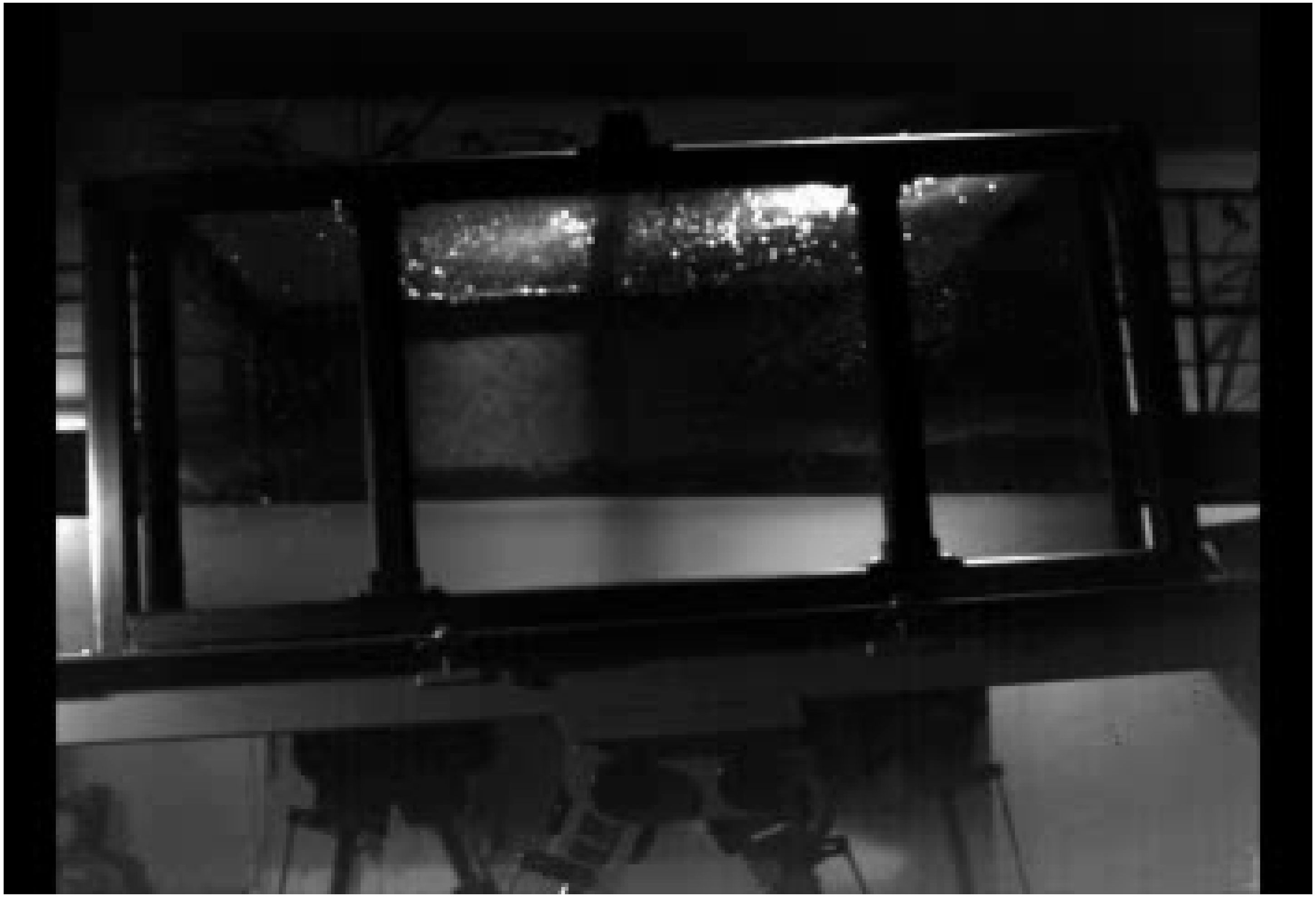
Fuel Tank/Ignition Test Conditions

- For the Phase II + III ignition study, only a single fuel depth, 0.265 m (125 gallons), was examined.
- Phase III dynamic tests only involved testing of dynamic conditions that resulted in the formation of a hydraulic jump.
- Two separate ignition threats were evaluated for this study:
  - A Jacob's Ladder (~ mJ spark energy)
  - Aircraft Igniter (4 J spark energy)
- Nitrogen used as inertant species.
- Flash Point: 51 °C (125 °F)
- Fuel temperatures tested:
  - 51 °C (125 °F)
  - 54 °C (130 °F)
  - 60 °C (140 °F)



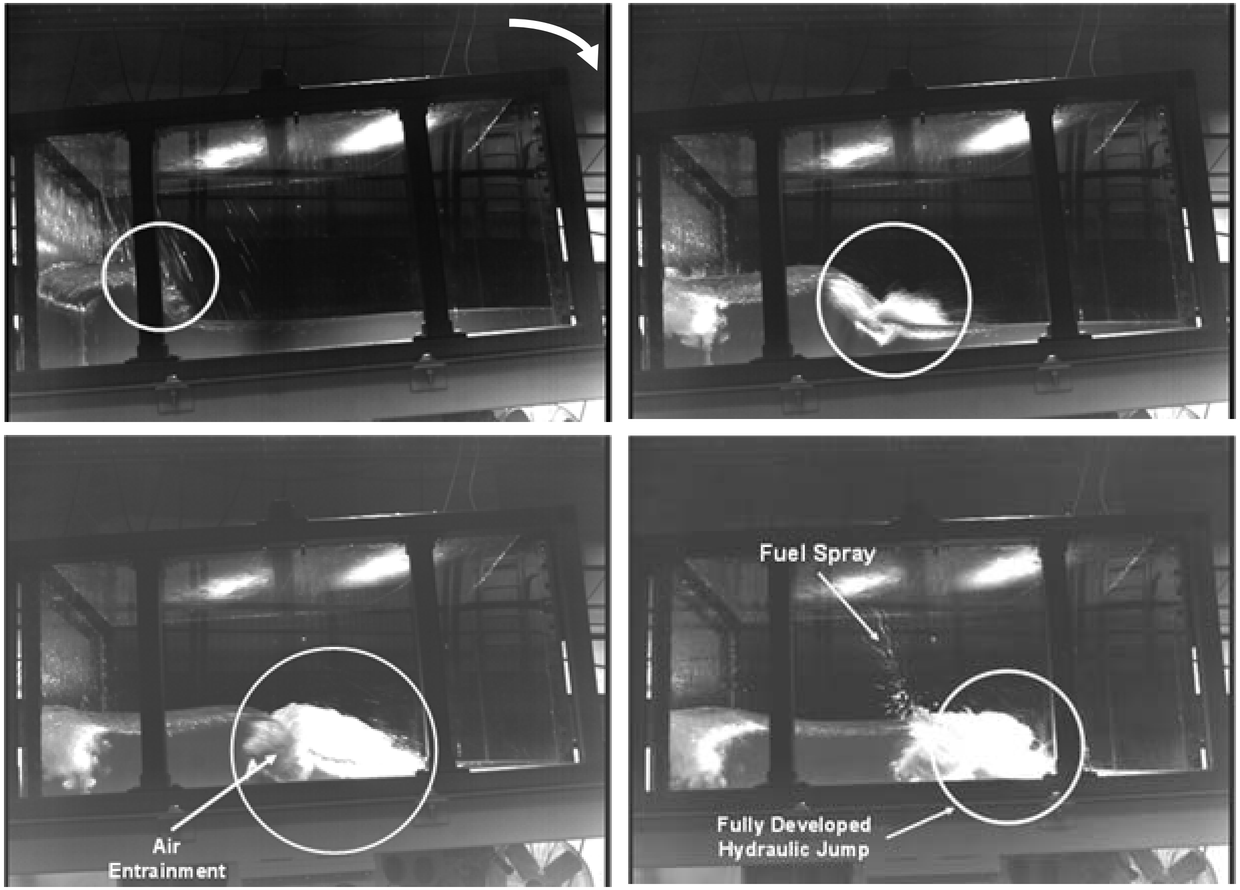
Test Results

Phase I Sloshing Video



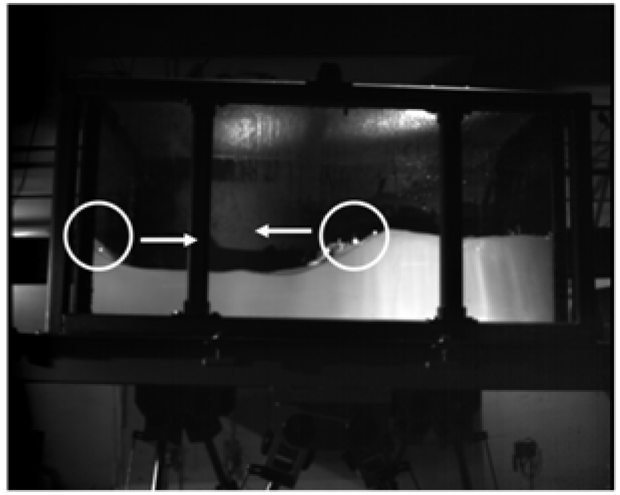
Phase I Sloshing Results

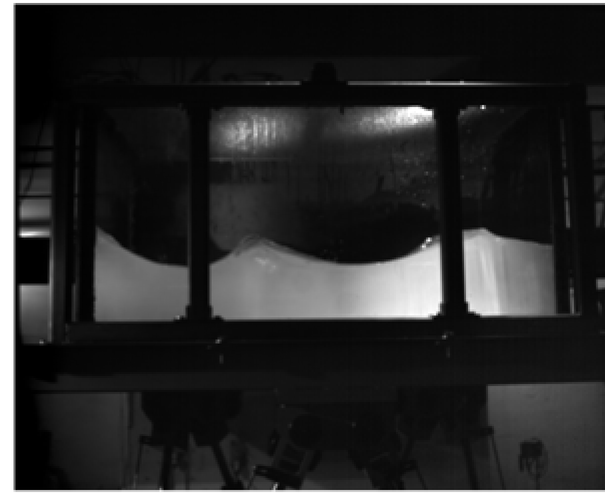
- Test Conditions:
  - 0.265 m depth
  - Frequency = 0.30 Hz
  - 5° incline angle
- This is a supercritical oscillation frequency for this liquid depth.
- The images show the formation of a solitary 2D wave that traverses across the tank. The speed of the wave exceeds the wave celerity of the upstream fuel depth, causing the wave to break.
- This fluid discontinuity known as a hydraulic jump creates a localized fuel spray and fuel/air mixing region at the center of the tank.

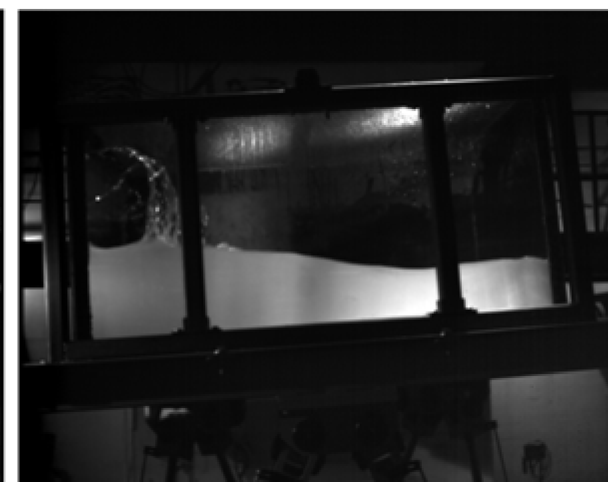


Phase I Sloshing Results

- Test Conditions:
  - 0.371 m depth
  - Frequency = 0.40 Hz
  - 5° incline angle
- This is a subcritical condition and demonstrates the interaction of multiple waves to produce fuel spray.

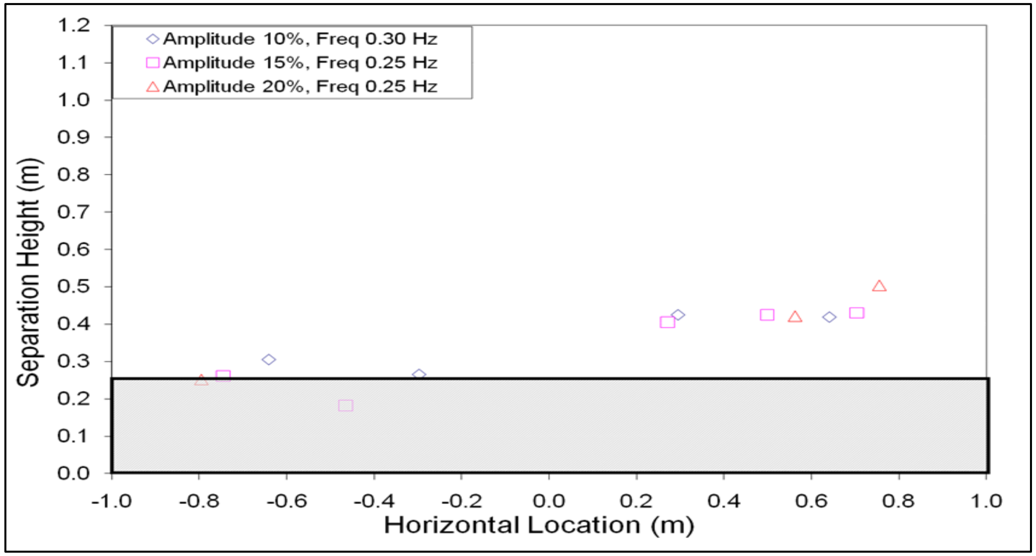


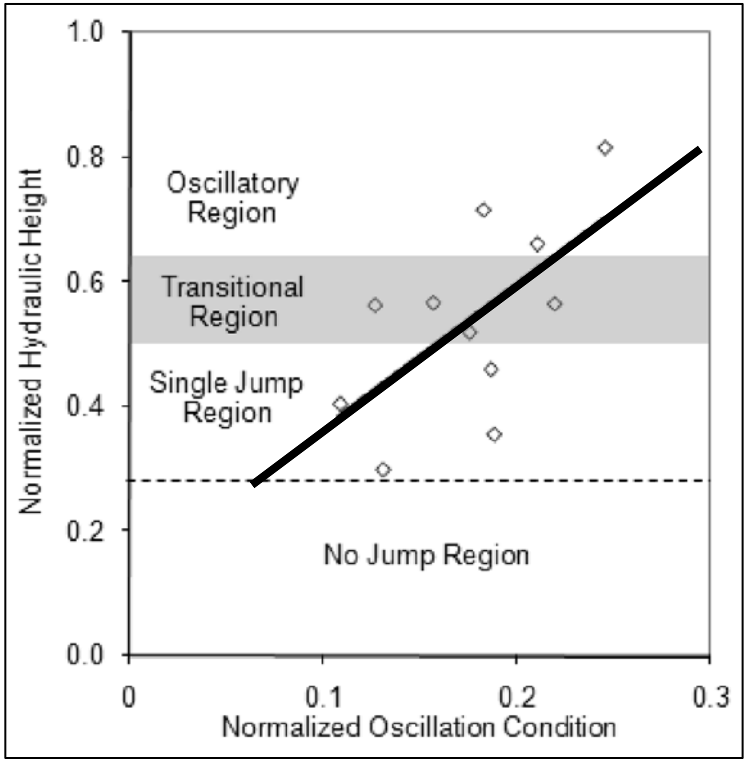




Phase I Sloshing Results

- The conditions tested clearly demonstrated the transitional region from subcritical to supercrical wave propagation and liquid/air interactions believed to enhance fuel tank flammability.
- Graph below shows the locations at which wave interactions were observed and the height of the constructive interference of the two waves. Symmetrical interference locations are observed, however, asymmetry in the resulting wave height is due to the offset of the motion simulator.



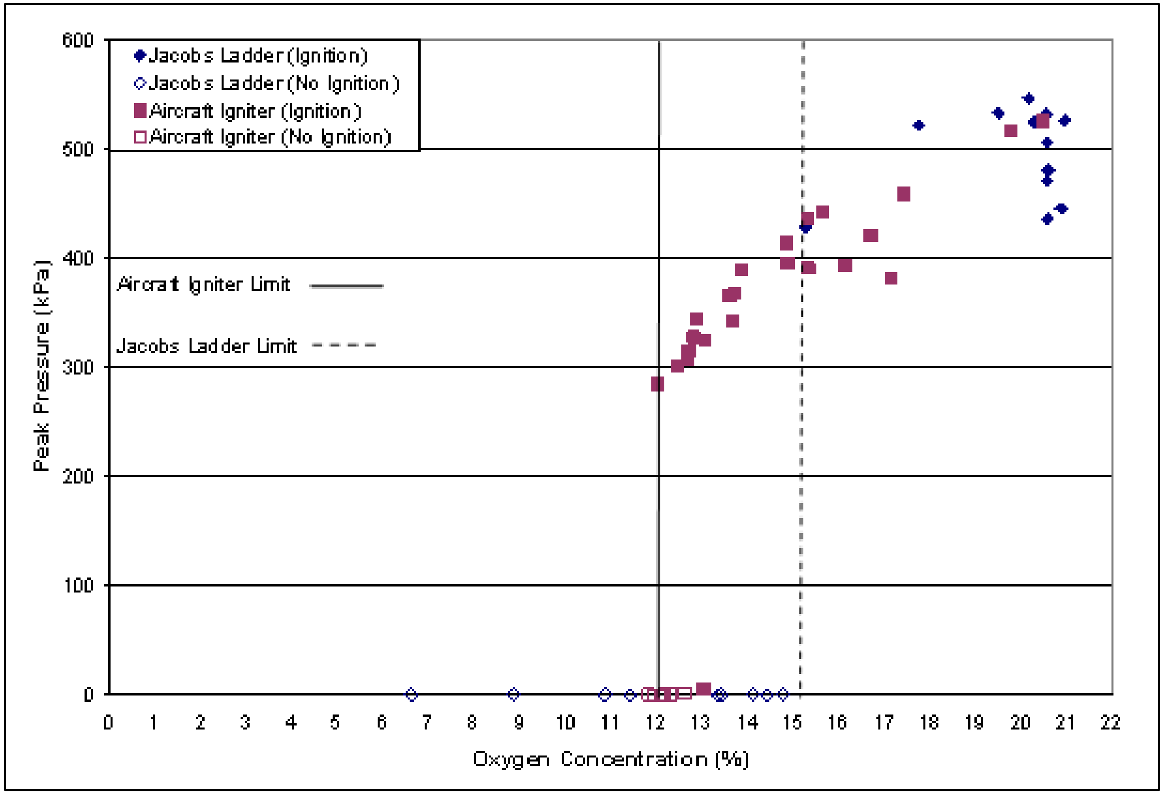


$$Normalized\,Oscillation\,Condition = \frac{y_{max}}{h_0} * \frac{f}{f_0}$$

- Likewise, a correlation relating the oscillation condition to the size and formation rate of hydraulic jumps in the fuel tanks was developed.

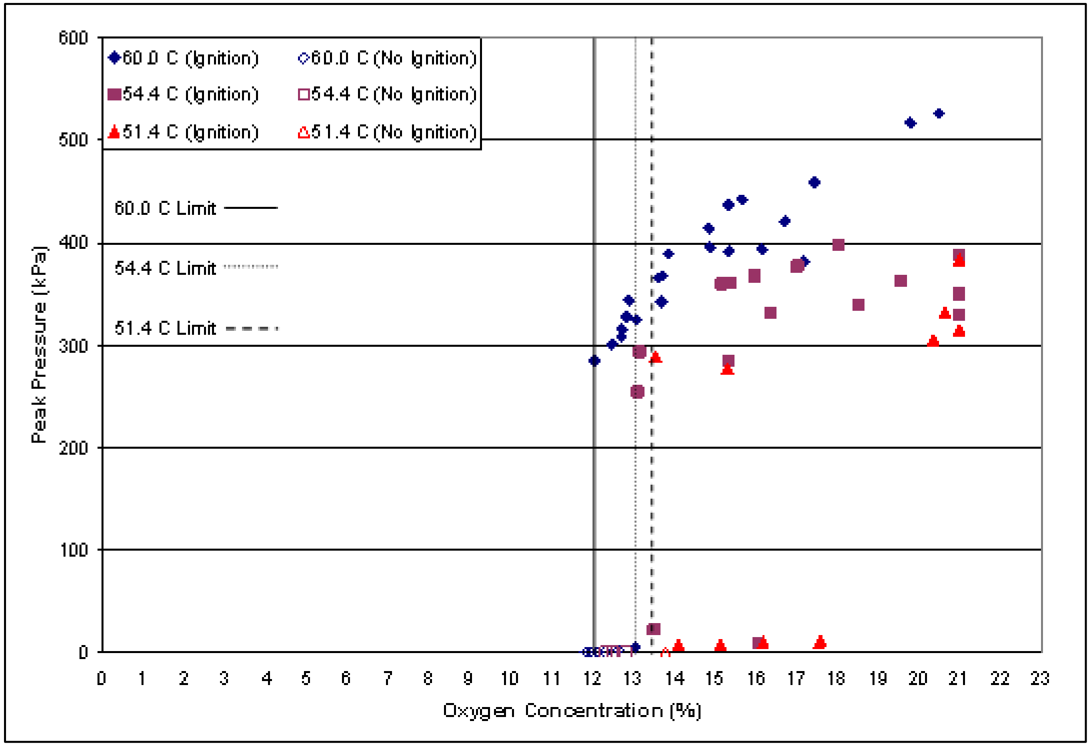
Phase II: Igniter Comparison

- Compared two separate ignition sources to determine ignition repeatability:
  - Jacob's Ladder similar to that used by Ott
  - Aircraft Igniter
- The Jacob's ladder was found to provide inconsistent results, even at noninerting test conditions. Only an LOC of 15% was observed for the tested fuel temperatures with this igniter.
- The higher energy aircraft igniter was tested and found to provide repeatable results and matched the current LOC of 12% for stationary testing.



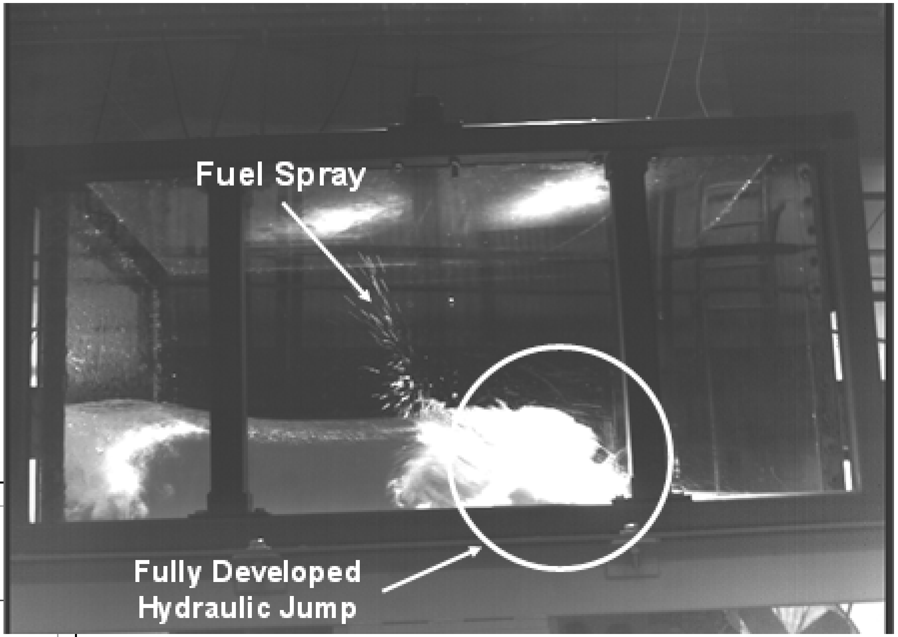
Phase II Testing Results

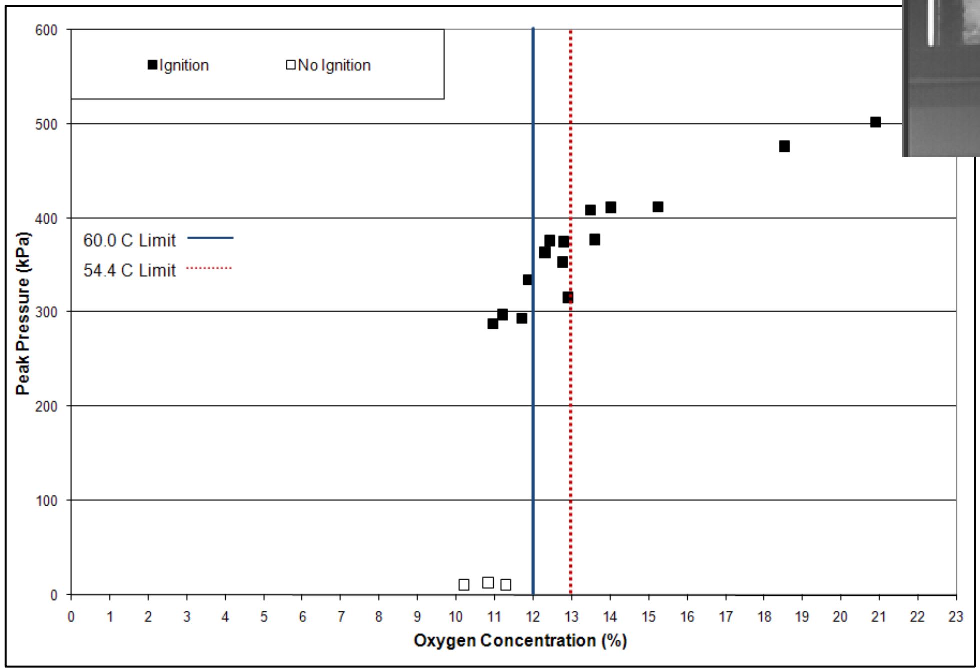
- The graph to the right shows the peak reaction pressure measured for various oxygen concentrations at three different fuel temperatures and provided a baseline for Phase III dynamic ignition comparison.
- This demonstrated that the LOC is temperature dependent.
- The 60 °C fuel temperature matches FAA data suggesting a 12% limit under stationary conditions.



Phase III Dynamic Tank Test Results

- Test Conditions:
  - Fuel temperature: 55 °C
  - Supercritical sloshing condition.
  - Aircraft Igniter (4 J)





- **Critical: Ignition observed below the 12% LOC limit at 11% Oxygen Concentration**

Summary

- This test program examined the effect of sloshing from aircraft motion has on the limiting oxygen concentration for fuel tanks.
- **Phase I**: Range of subcritical frequencies that produced wave separation:
  - 0.265 m: 0.25 Hz – 0.30 Hz
  - 0.371 m: 0.30 Hz – 0.40 Hz
  - 0.530 m: 0.35 Hz – 0.40 Hz
  - **Note:** Frequencies above the listed yielded a supercritical condition. Frequencies below did produce wave interactions but not droplet separation.
- **Phase II**: USAF SAFTE Facility provided baseline results of aviation fuel combustion properties. Measured LOC of 12% observed and matched currently available stationary tank data.
- **Phase III**: The addition of dynamic tank maneuvers and enhanced mixing lowered the measured LOC of 12% in the stationary testing to 11% in the dynamic testing.
- **The recommendation provided to the military that the current 9% LOC limit is advisable and a move to the 12% commercial requirement is not advisable.**

Acknowledgements

- The presenters would like to extend their gratitude to the Joint Aircraft Survivability Program Office for funding this research.