Factors Affecting the Limiting Oxygen Concentration Required for Ignition in an Aircraft Fuel Tank

Presented by
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Background

• LOC = Limiting Oxygen Concentration required for ignition during nitrogen inverting
• Military used 9% as design criterion based on Bureau of Mines suggestion of 20% safety margin
• Recently changed by FAA to 12% based on:
  – Recent FAA LOC tests
  – Review of prior test data
  – More cost effective inverting technology
  – Probabilistic argument on what is a sufficient level of safety improvement for the entire fleet
• This talk addresses factors affecting LOC test data
  – Review of test data on LOC
  – Calculation of LOC from modeling
Historical Data on LOC (Zinn)

FIG. 9 COMPOSITE CHART OF INERTING REQUIREMENTS AS PLOTTED FROM LITERATURE SEARCH
Experimental Ranges

Altitude

Ullage Temperature

Source Strength

Ignition Criteria

Vibration, Slosh, and Mist

Fuel Composition

- Experimental Ranges

- Vibration, Slosh, and Mist

- Ullage Temperature

- Source Strength

- Ignition Criteria

- Altitude

- Fuel Composition

- FAA 2004
- Bu. Mines Kerosene 1965
- Ott WPAFB 1971
- Bu. Mines JP-4 1956
- U. CA 1955
- Boeing 1951
- Anderson WPAFB 1978
- Tyson NWC 1991
Example of Determining LOC, JP-8, Ott

Sea Level, Static

Sea Level, Slosh

Oxygen Percent

Fuel Vapor Percent By Volume

- Ott Sea Level Static Fire
- Ott Sea Level Static No Fire
- Ott Sea Level Static Boundary

Ott Sea Level Slosh Fire
Ott Sea Level Slosh No Fire
Ott Sea Level Slosh Boundary
Limiting Oxygen Concentration, JP-8/Jet A, All data

Oxygen Percentage vs. Fuel Vapor Percentage graph with various conditions and altitudes:
- Kerosene 50 kft Stewart
- Dynamic Conditions Disimile
- AN-F-32 Gunfire Stewart
- Static Sea Level
- Slosh Sea Level
- Sea Level
- Ott
- Summer

Conditions: 20 kft, 30 kft, 38 kft
Limiting Oxygen Concentration, JP-4, All Data

Y-axis: Oxygen Percentage
X-axis: Fuel Vapor Percentage

Legend:
- Zabetakis
- Starkman No Fan
- Starkman Fan
- SeaLevel
- 10kft
- 20kft
- 30kft
- 40kft
- 50kft
- 60kft
General Observations

- General agreement on effect of altitude
- LOC lower for JP-4 than JP-8/Jet A
- Uncertainty in LOC data is +/- 0.5% for a given set of conditions with most experimental setups
- Effect of ullage temp. important but little data
- BlazeTech model predicts correct dependence of LOC on ullage temperature
- Some reports we could not obtain
- Many factors can decrease LOC below 12%
Reported Drops in LOC below 12%

1. Source Strength/Ignition Criteria:
   - Effect: WPAFB ≈ 0%, Bu.Mines 0.5%, U.CA 1.5% (inc source)
   - Well covered by FAA study: ~ 1%
2. Ullage Temperature:
   - ≈ 0.5% if ullage at 200°F
   - 1.5% from 125 to 140°F
3. Vibration and slosh:
   - Boeing used hexane vapor and mist. Effect 1%±0.5%
   - WPAFB: no effect 1971; 2% 2008 at 130°F
   - U.CA 0.5% with fan that aids mixing
   - O₂ enters tank near vent
5. Variations in Jet A composition depending on grade:
   - Based on results for JP-4 vs. JP-8/Jet A

Combined Effect is neither obvious nor additive
Model of Ullage Flammability – Overall Architecture

**Model Inputs**

**Fuel Conditions:** type, amount & temperature  
**Tank Geometry and dimensions**  
**Ignition Characterization:** Source location, type and strength  
**Flight Profile:** Altitude versus time, Fuel extraction rate to engine, and Fuel and tank wall temperatures  
**Inerting:** ground vs. in-flight and percent concentration

**BlazeTank**

**Output**

**Temp. and concentration vs. height and time**  
**Flammable volume inside fuel tank**  
**Ignition and Propagation**  
**If ignition occurs,** Temp., burn rate and Overpressure vs. time  
**Limiting Oxygen Concentration**
Deflagration Module in BlazeTank

- Key assumptions
  - Ullage consists of 2 zones: premixed unburned gases and burned gases separated by a flame sheet
  - Unburned gases are pressurized by expanding burnt zone
  - Pressure in ullage remains spatially uniform because it equilibrates at acoustic speed $>>$ deflagration speed

- BlazeTank solves the coupled equations of:
  - Continuity
  - Energy conservation
  - Species conservation
  - Experimental burn rate (fuel, stoichiometry, T and P)
Burning Velocity Model

\[ S_L = \left[ B_m + B_2 (\phi - \phi_m)^2 \right] \cdot \left( \frac{T}{T_{ref}} \right)^{2.18-0.8(\phi-1)} \cdot \left( \frac{p}{p_{ref}} \right)^{-0.16+0.22(\phi-1)} \]

where

- \( \phi \) = equivalence ratio
- \( T \) = temperature
- \( p \) = pressure
- \( B \) = fitting constants for laminar burning velocity calculation

Subscripts

- \( m \) = condition at which the burning velocity is maximum
- \( ref \) = reference conditions

Comparison of BlazeTank Model Predictions with Quarter Scale Test Data

J. E. Shepherd et al, “Results of 1/4-scale experiments, vapor simulant and liquid Jet A tests”
Explosion Dynamics Laboratory Report FM 98-6, July 1998
Comparison of BlazeTank Model Predictions with HYJET Test Data

J. E. Shepherd et al, “Results of 1/4-scale experiments, vapor simulant and liquid Jet A tests” Explosion Dynamics Laboratory Report FM98-6, July 1998
Equilibrium Calculation

- Several codes available
  - NASA Equilibrium code
  - CANTERA
- Calculates temperature and product composition
- Issues
  - Combustion at constant pressure or constant volume
  - Differences in how unburnt carbon is treated
  - Lean versus rich
Equilibrium Products Composition
Adiabatic Flame Temperature for Alkanes
(No inerting)
LOC Predictions by BlazeTank

First Approach: Flame Temperature Cut-off

Adiabatic Flame Temperature of Jet-A Vapors

Jet-A Vapor ($\approx$C$_9$H$_{18}$)
$T_0 = 298.15$ K
$P_0 = 101325$ Pa $= 1$ atm

Oxygen Percentage (at LOC)

20.7
18.6
16.5
14.5
12.4
10.3
8.3

Does not know the cut-off temperature a priori
Inerting of JP-4

25°C, 1 atm

Doesn’t match both LFL, UFL and LOC

Experimental Data
(Zabetakis WADC TR52-35 Sup 4, 1956)
BlazeTank Model for N2 inerting:
- Matching LOC
- Matching Flammability Limits in Air
Conclusions

• Recent FAA tests generated good data on LOC over a range of conditions
• Additional conditions that can lower LOC:
  – Ullage temperature, slosh and vibration, variations in fuel composition and gradient effects
• Their combined effect is not obvious nor additive
• Effect can be quantified by testing or modeling (BlazeTank)
• Modeling can be used to optimize:
  – The design of inerting systems
  – Their operation (when and how much to inert) so as to minimize system size and load on engine
References

- Summer, “Limiting Oxygen Concentration Required to Inert Jet Fuel Vapors Existing at Reduced Fuel Tank Pressures”, DOT/FAA/AR-04/8, 2004