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

Presented

by

N. Albert Moussa and Venkat Devarakonda

BlazeTech Corporation

29 B Montvale Ave., MA 01890

Phone: 781-759-0700   Fax: 781-759-0703 www.blazetech.com

at

6th Triennial International Aircraft Fire & Cabin Safety Research Conf.

Atlantic City, NJ

October 25-28, 2010

BlazeTech

Background

- LOC = Limiting Oxygen Concentration required for ignition during nitrogen inerting
- Military used 9% as design criterion based on Bureau of Mines suggestion of 20% safety margin
- Recently changed by FAA to12% based on:
  - Recent FAA LOC tests
  - Review of prior test data
  - More cost effective inerting 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

BlazeTech

Historical Data on LOC (Zinn)

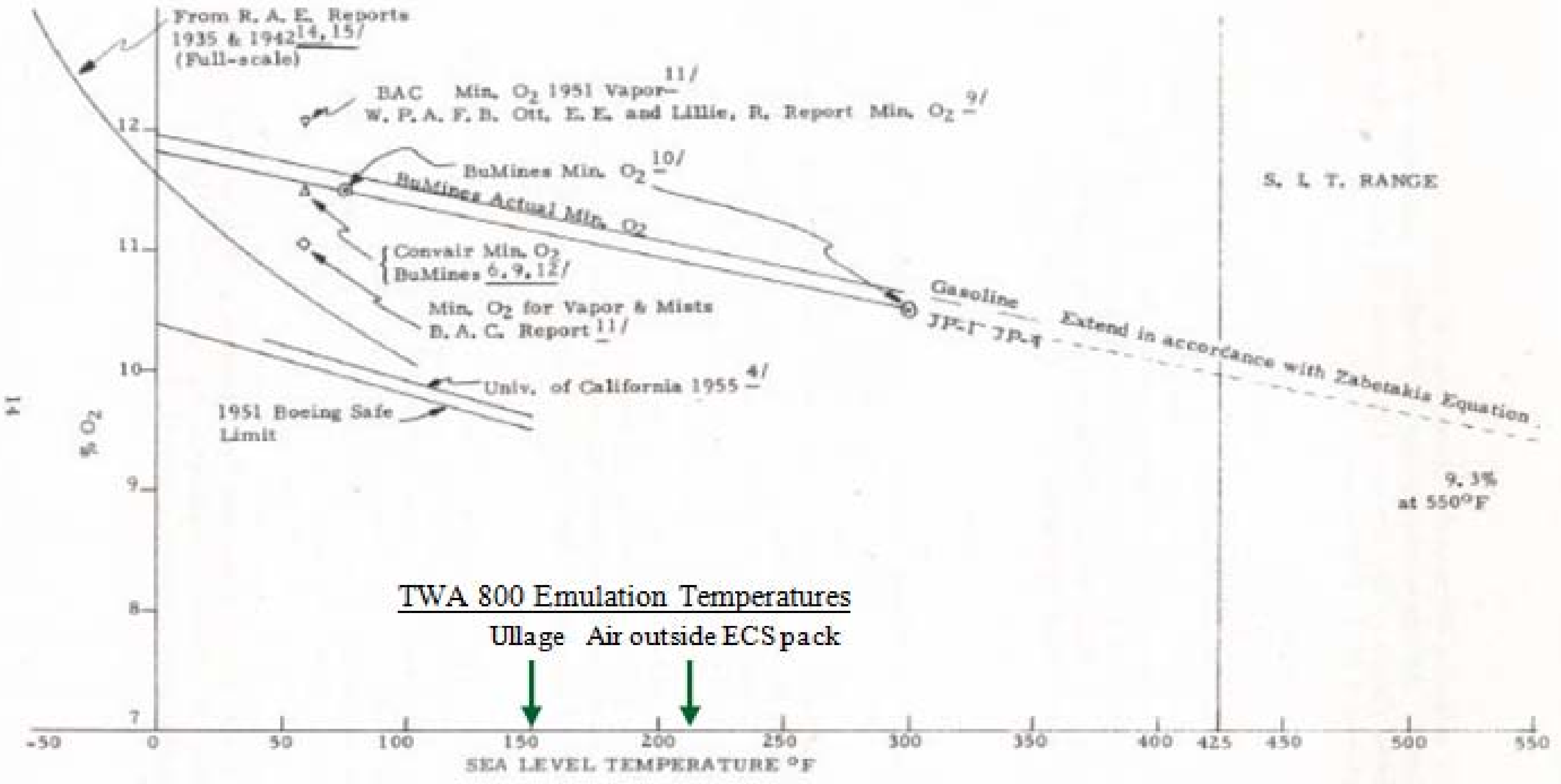
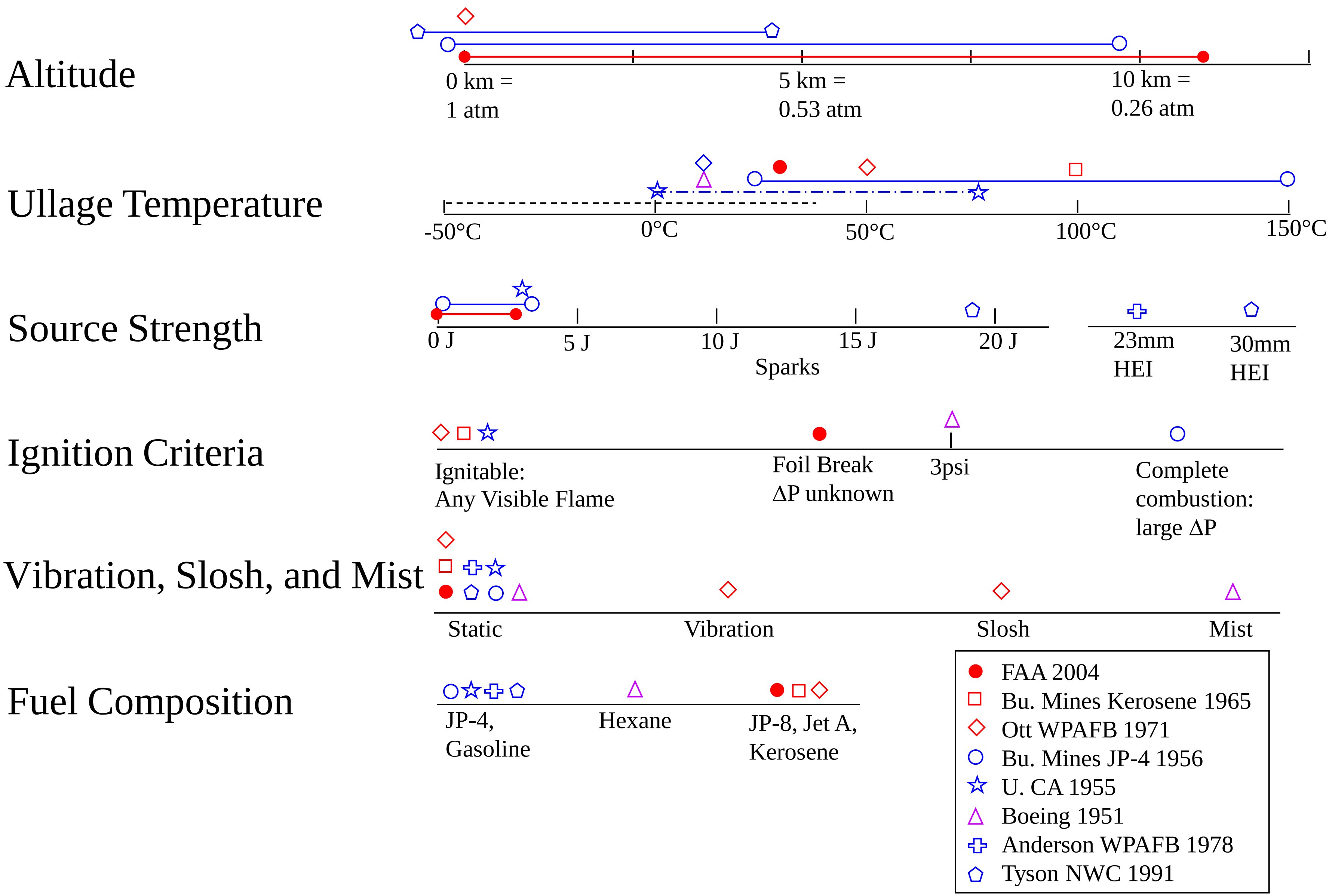
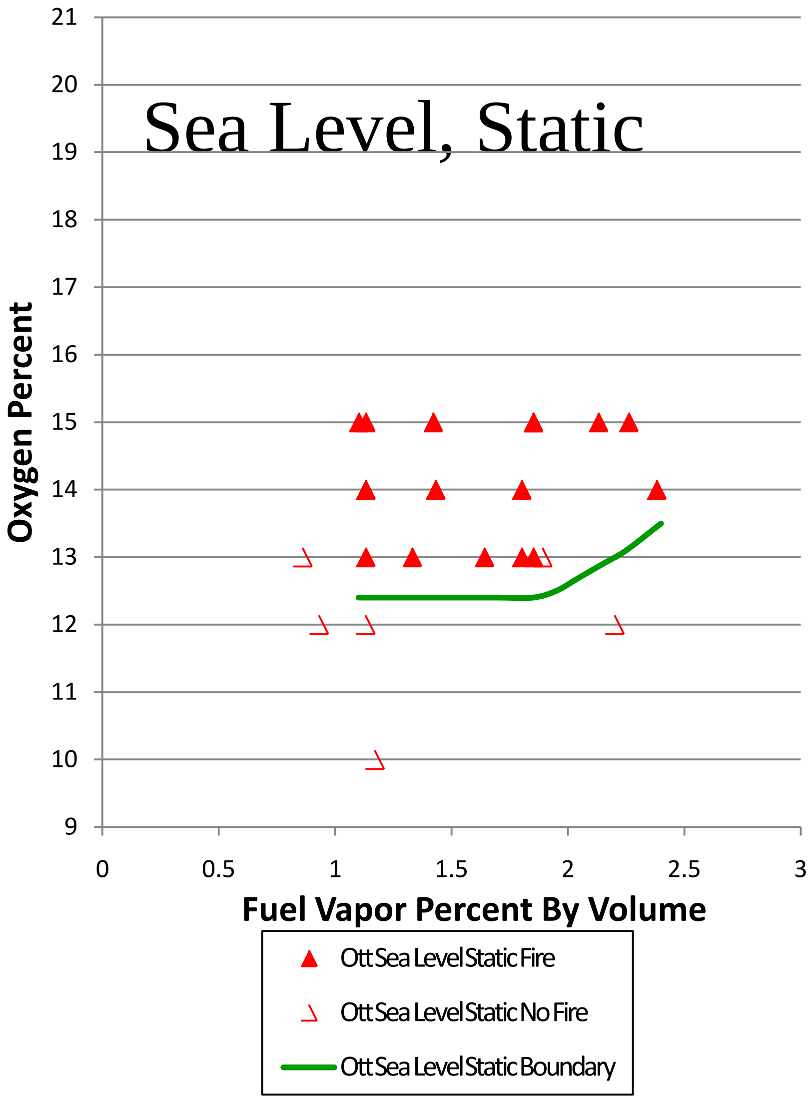


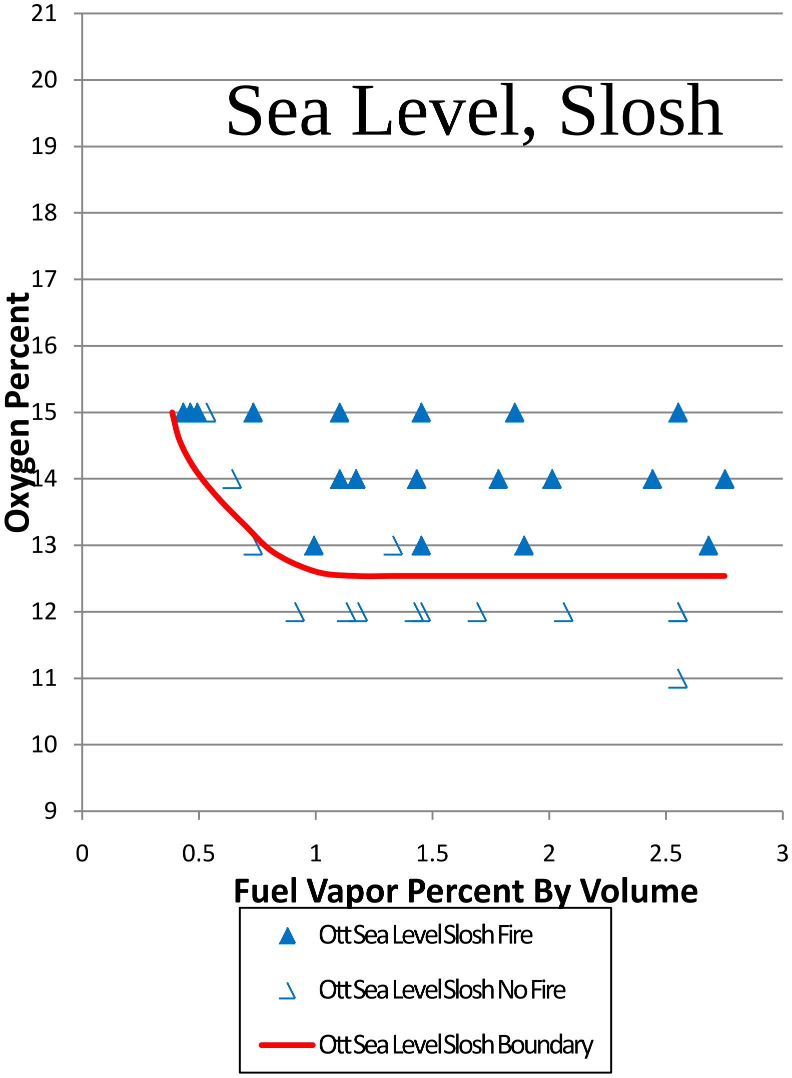
FIG. 9 COMPOSITE CHART OF INERTING REQUIREMENTS AS PLOTTED FROM LITERATURE SEARCH

Experimental Ranges



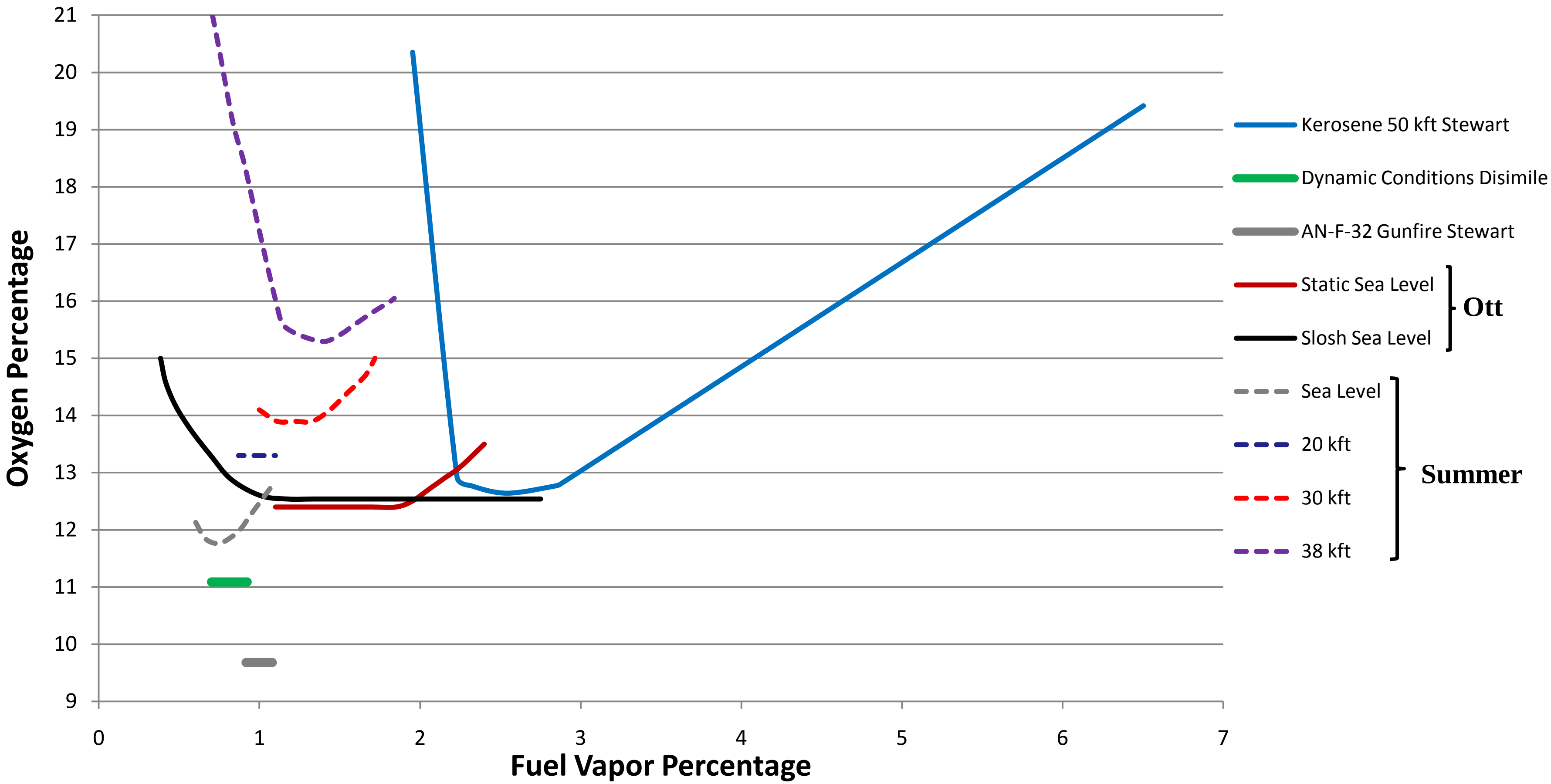
Example of Determining LOC, JP-8, Ott



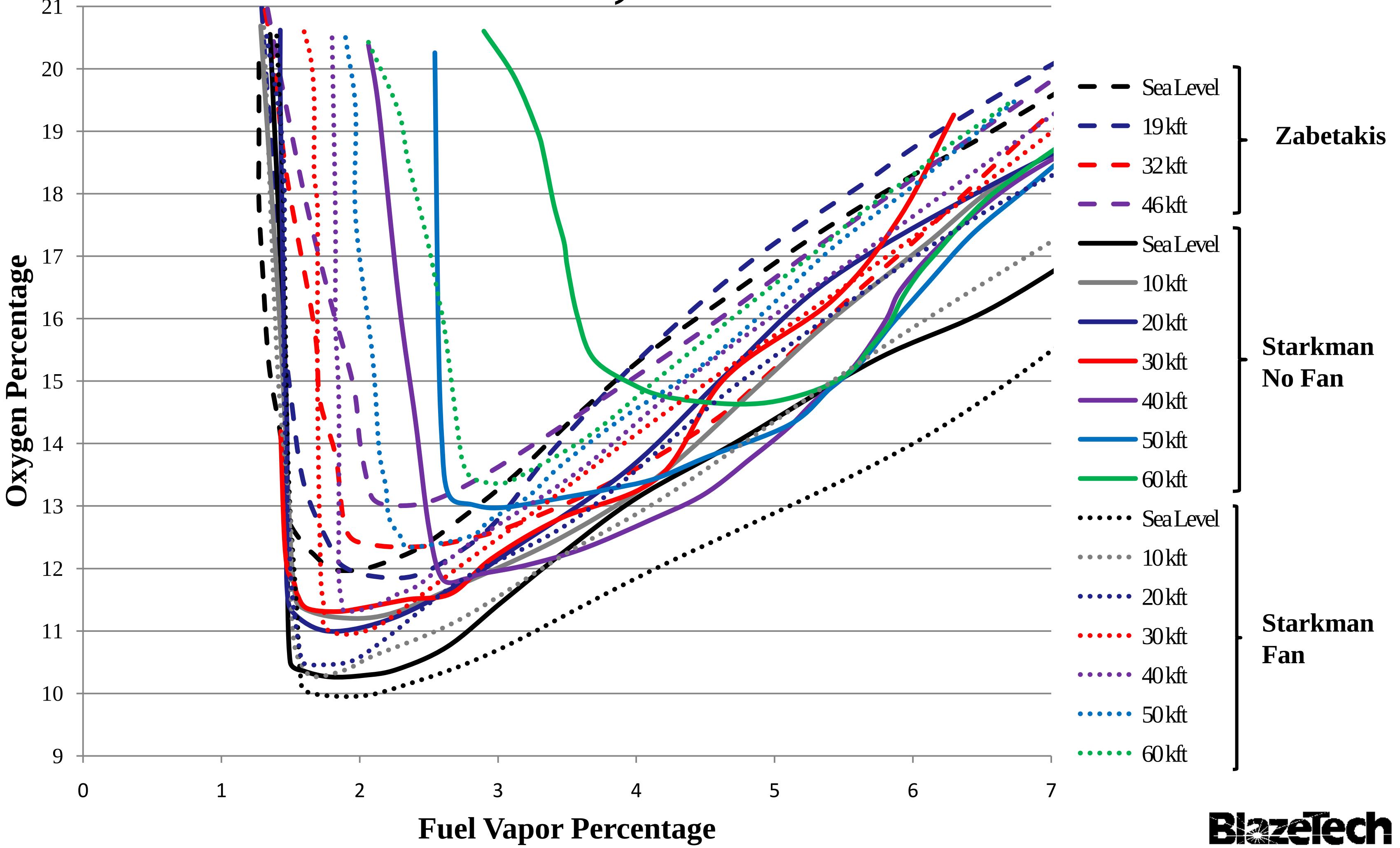


BlazeTech

Limiting Oxygen Concentration, JP-8/Jet A, All data



Limiting Oxygen Concentration, JP-4, All Data



BlazeTech

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
4. Gradients in Concentration: Depends on mixing.
   - U.CA 0.5% with fan that aids mixing
   - O_2 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

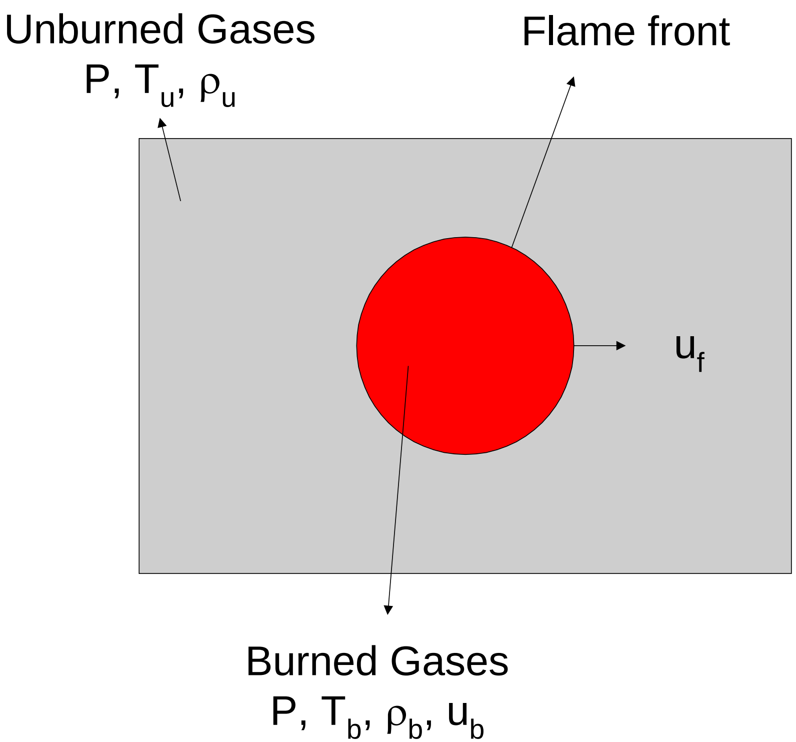
Ignition and Propagation

If ignition occurs, Temp., burn rate and Overpressure vs. time

Limiting Oxygen Concentration

BlazeTech

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)

BlazeTech

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

ϕ = equivalence ratio

T = temperature

p = pressure

B = fitting constants for laminar burning velocity calculation

Subscripts

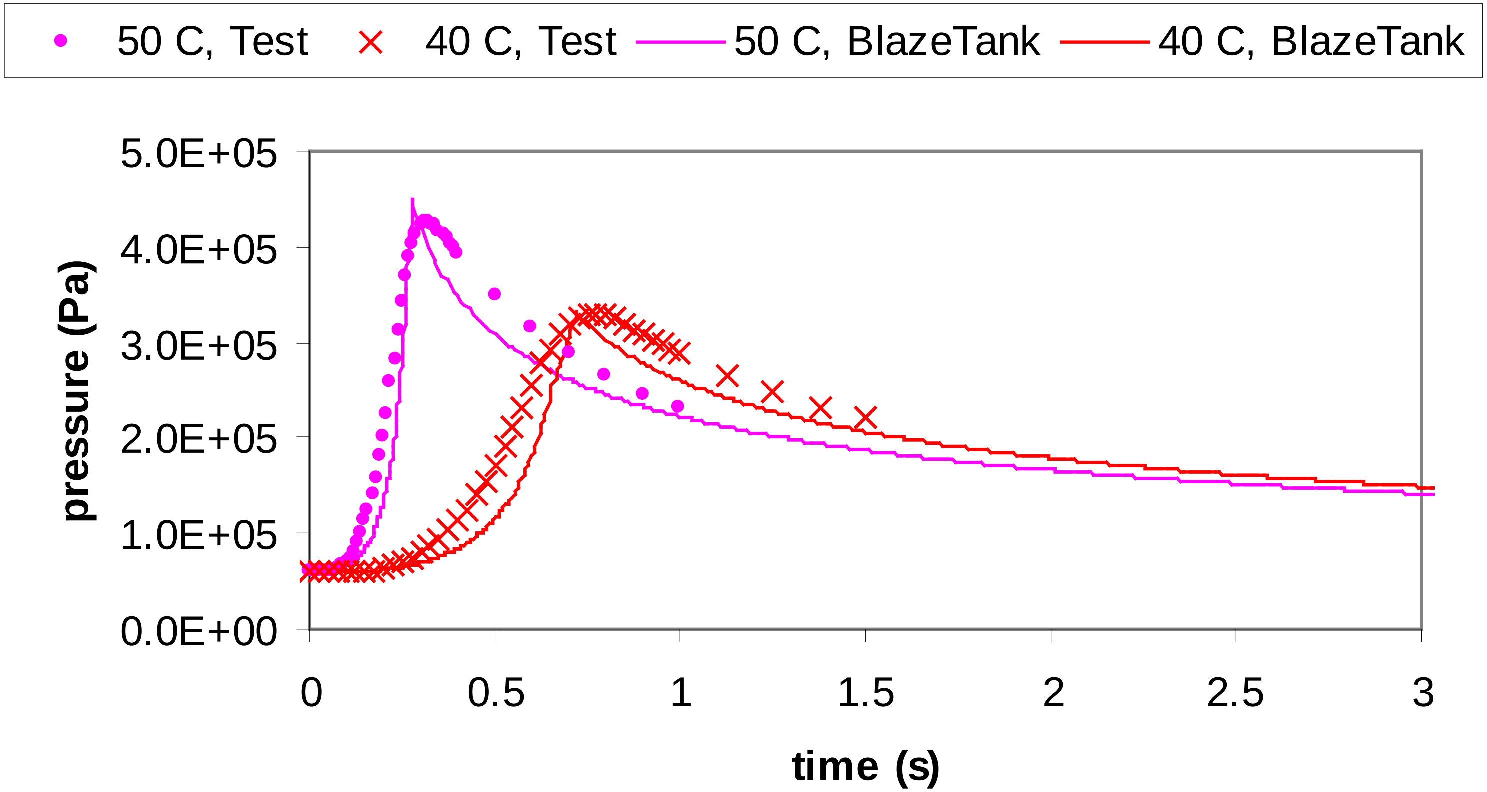
m = condition at which the burning velocity is maximum

ref = reference conditions

Source: Metghalchi, M. and Keck, J.C., Combustion and Flame 48:191 – 210 (1982)

BlazeTech

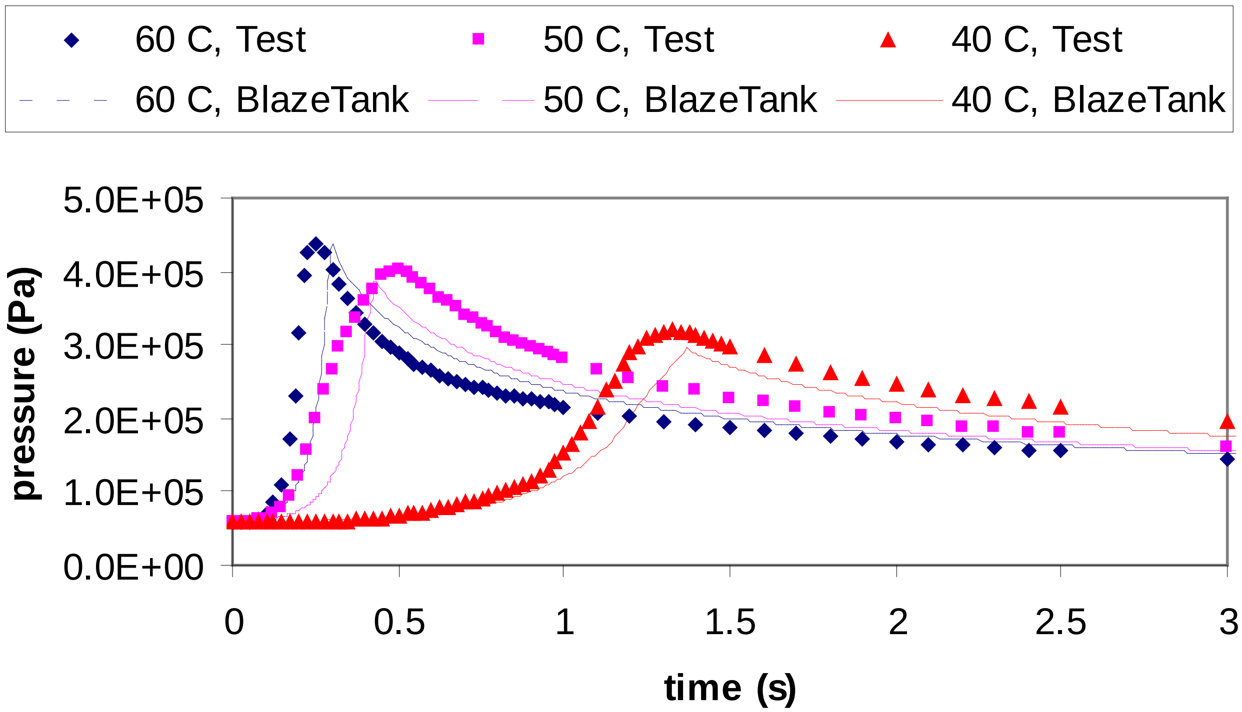
Comparison of BlazeTank Model Predictions with Quarter Scale Test Data



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

BlazeTech

Comparison of BlazeTank Model Predictions with HYJET Test Data



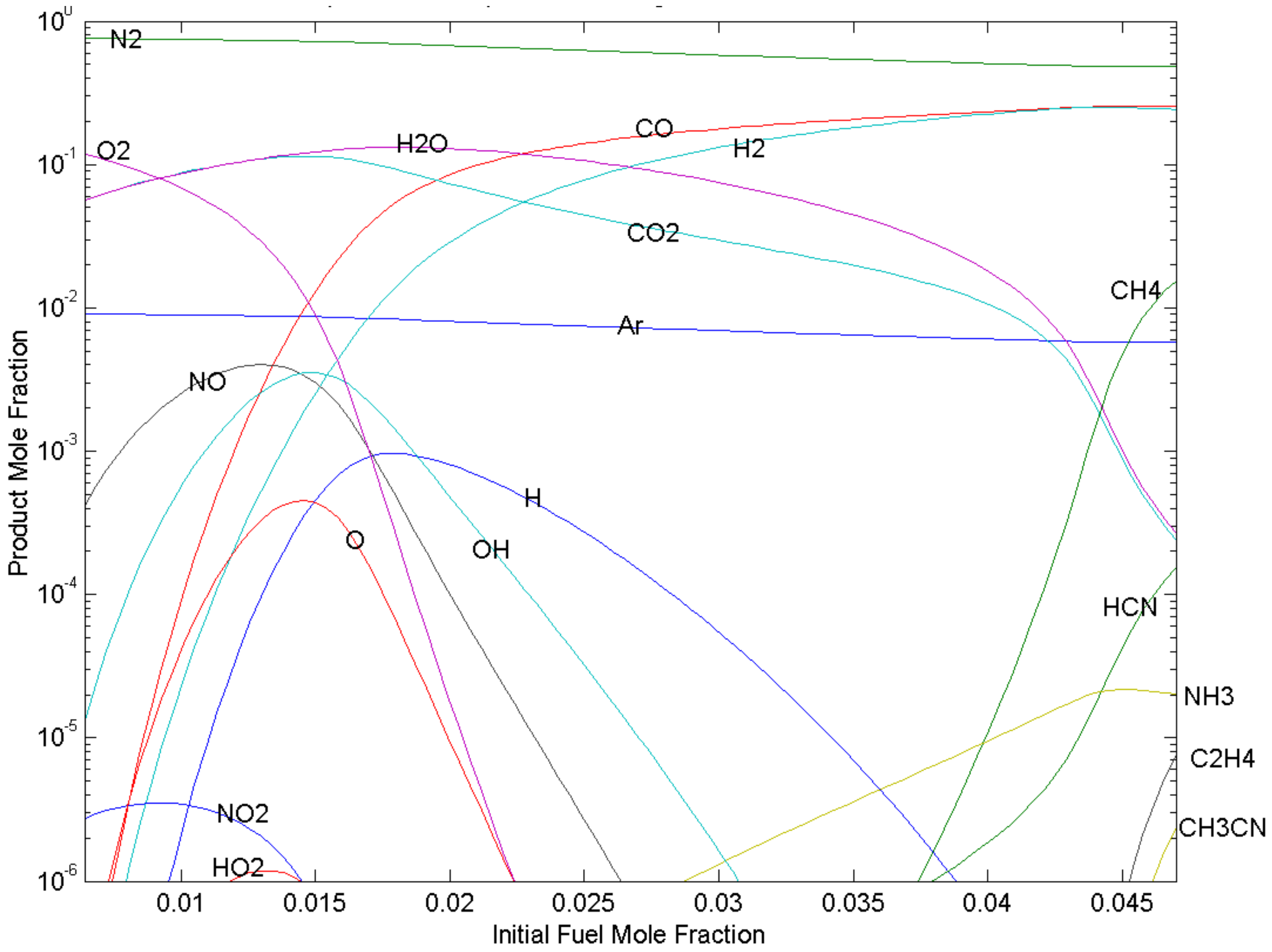
J. E. Shepherd et al, "Results of 1/4-scale experiments, vapor simulant and liquid Jet A tests" Explosion Dynamics Laboratory Report FM98-6, July 1998

BlazeTech

Equilibrium Calculation

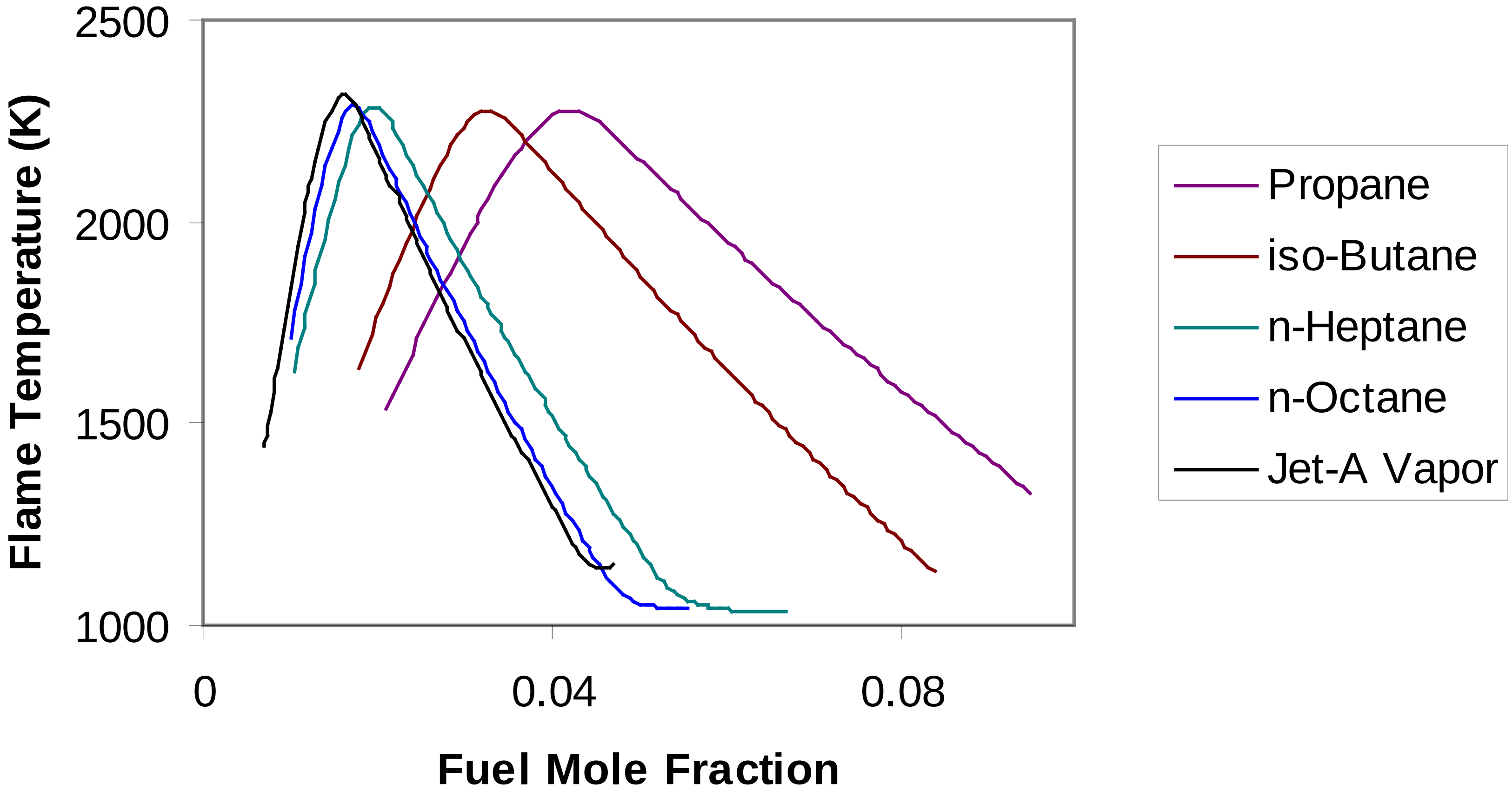
- Several codes available
  - NASA Equilibrium code
  - CANTERA
- Calculates temperature and product composition
- Issues
  - Combustion at constant pressure or constant volume
  - Differences in how unburnt carbon is treated
  - Lean versus rich

Equilibrium Products Composition



BlazeTech

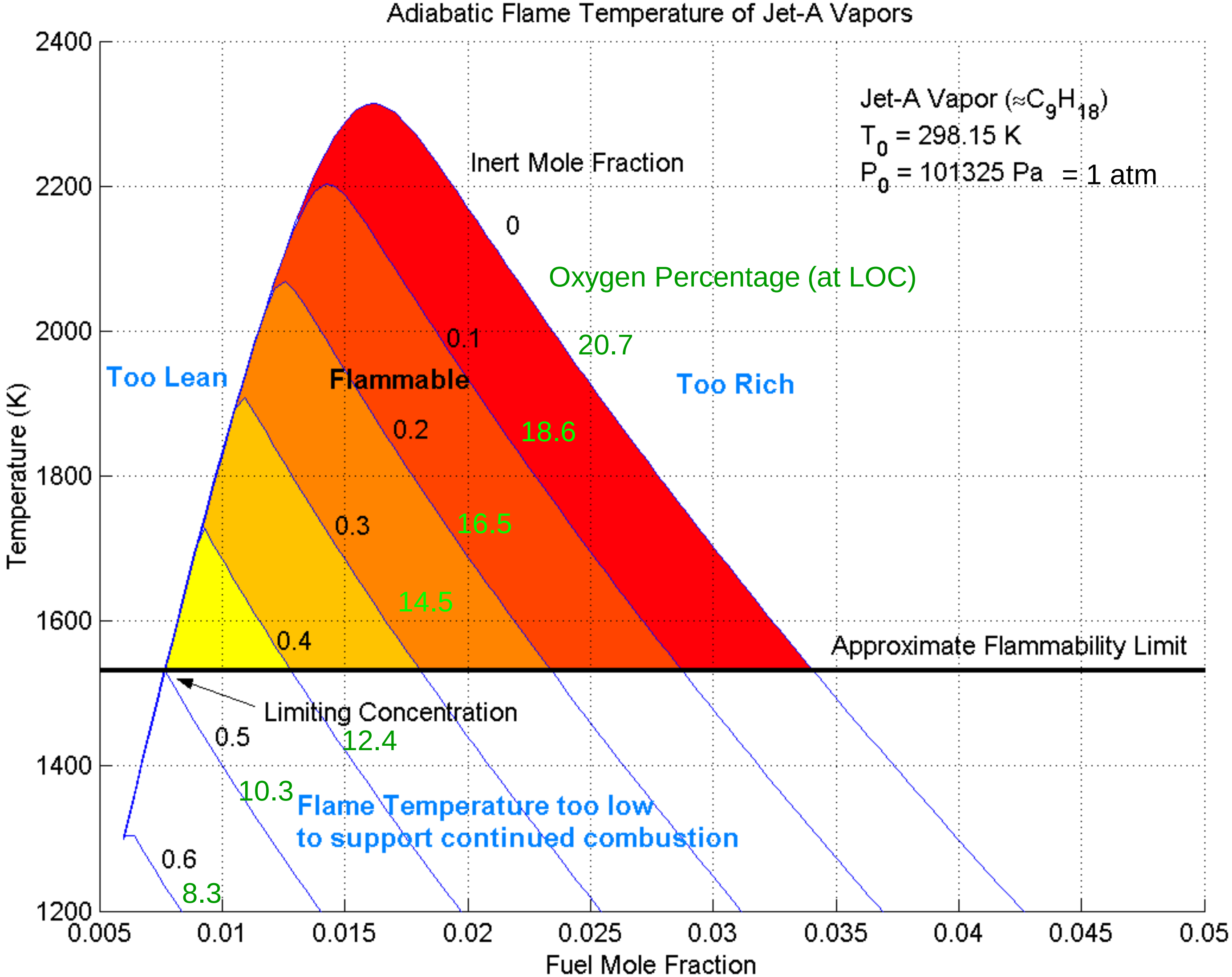
Adiabatic Flame Temperature for Alkanes
(No inerting)



BlazeTech

LOC Predictions by BlazeTank

First Approach: Flame Temperature Cut-off

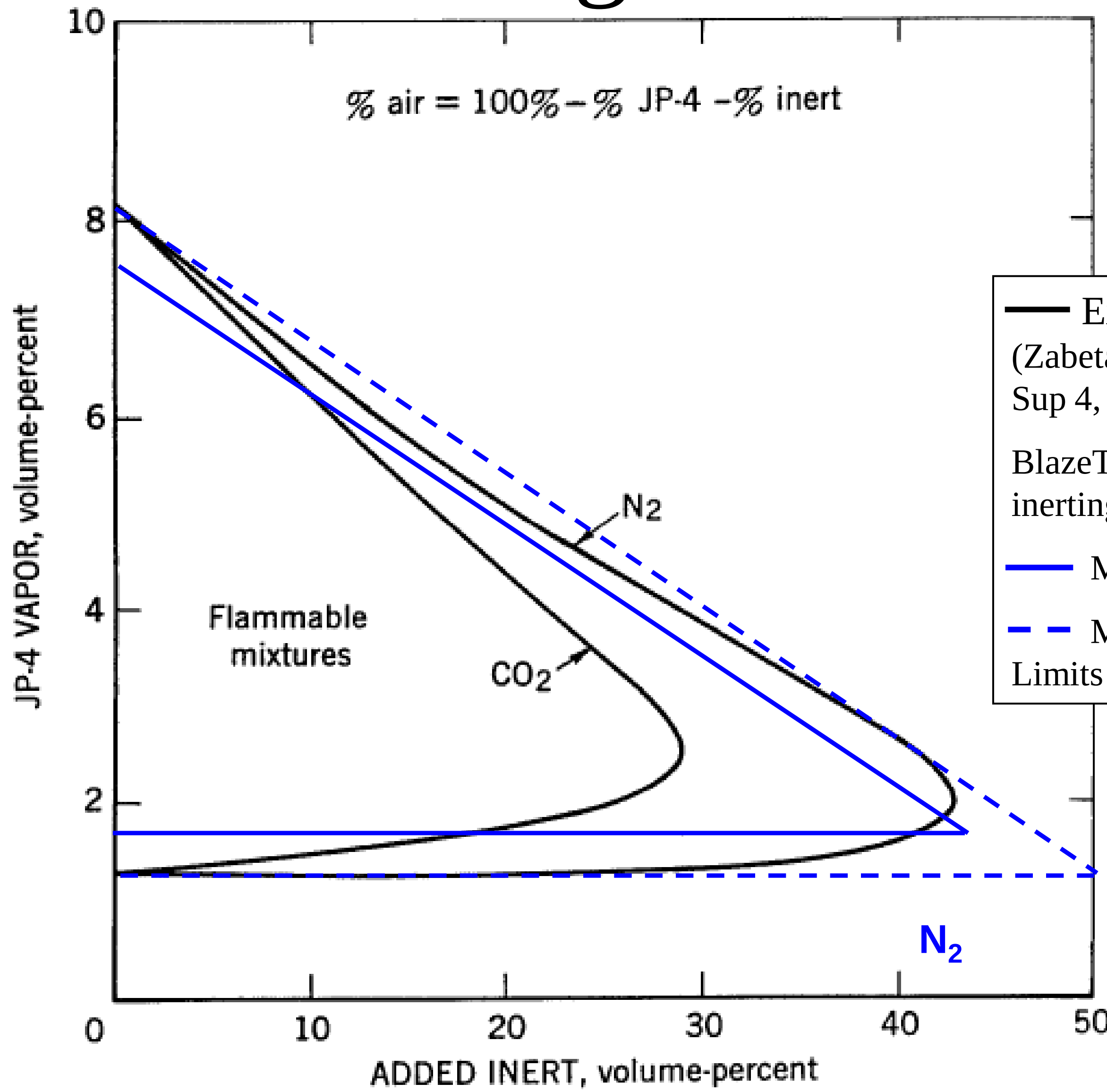


Does not know the cut-off temperature a priori

BlazeTech

Inerting of JP-4

25°C, 1 atm



Experimental Data (Zabetakis WADC TR52-35 Sup 4, 1956)

BlazeTank Model for N2 inerting:

Matching LOC

Matching Flammability Limits in Air

Doesn't match both LFL,UFL and LOC

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
- Ott, E. and Lillie, R., “Influence of Fuel Slosh Upon the Effectiveness of Nitrogen Inerting for Aircraft Fuel Tanks”, AFAPL-TR-70-82, 1971
- Zabetakis, M. G. , Jones, G. W. , Scott, G. S. , and Furno, A. L., “Research on the Flammability Characteristics of Aircraft Fuels”, WADC Technical Report No.52-35, Supplement 4, January 1956.
- Zabetakis, M. G. , "Flammability Characteristics of Combustible Gases and Vapors, " U. S. Bureau of Mines Bulletin 627, 1965.
- Starkman, E. S., Stewart, P. B., Gott, R. E., and Lichtman, L., “Flammability of AN-F-58 (JP-4) Vapor with Nitrogen Inerting”, Fuel Ignition Studies Technical Report No. 1, Submitted to Air Material Command United States Air Force, Contract No. AF 33(600)-17677, November 1953.
- Stewart, P. B. and Starkman, E. S. , "Inerting Conditions for Aircraft Fuel Tanks, " WADC Technical Report No.55-418, 1955
- Glendinning, B. A. and Parker, W. G., "Note on the Inhibition of Explosions in Fuel Vapour/Air Mixtures by Dilution With Nitrogen, " Royal Aircraft Establishment Chem Note No.515, August 1942.
- Gatward and Wifeth, "The Effect of Air Evolution From Fuel on the Inert Gas Protection of Aircraft Fuel Tanks, II Royal Aircraft Establishment T. N. No. M. E. 96, October 1951.
- Anderson, C.L., Test and Evaluation of Halon 1301 and Nitrogen Inerting Against 23 mm HEI Projectiles," AFFDL-TR-78-66, May 1978.
- Boeing Aircraft Company, "Explosive Limits of Fuel Vapors and Fuel Mists and the Suppression of These Limits With Inert Gases", WCNE MR 524-3079, 1951.
- Zinn Jr., S.V., “Inerted Fuel Tank Oxygen Concentration Requirements,” FAA-RD-71-42, August 1971.
- Disimile, P., Pyles, J. and Toy, N., “Limiting Oxygen Concentration (LOC) for Dynamic Fuel Tank Applications, Aircraft Survivability, Spring 2008.
- Tyson, J.H. and Barnes, J.F., “The Effectiveness of Ullage Nitrogen-Inerting Systems Against 30-mm High-Explosive Incendiary Projectiles-Final Report,” NWC TP 7129, May 1991.

BlazeTech