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

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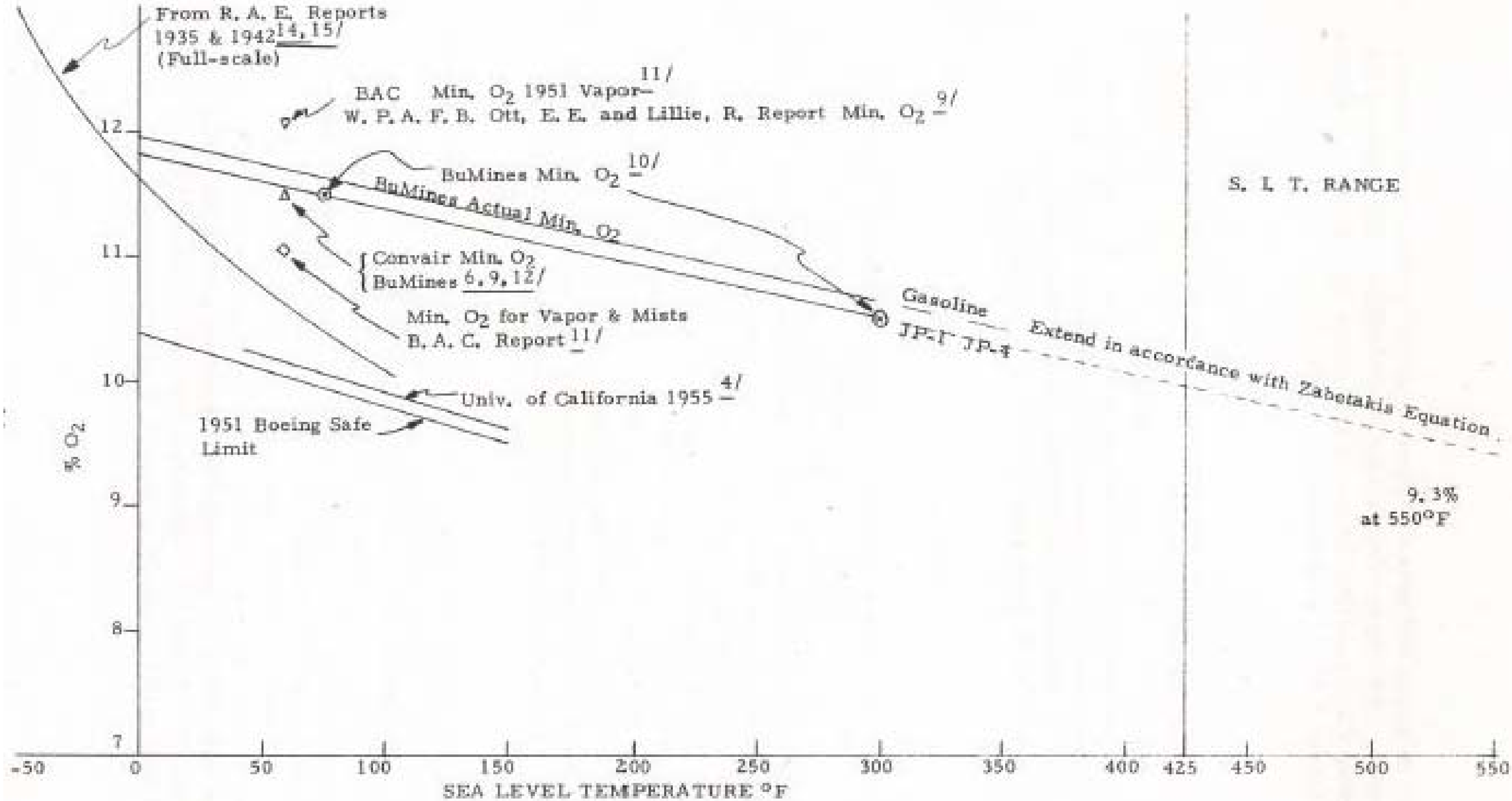
Background

- LOC = Limiting Oxygen Concentration required for ignition with nitrogen inerting
- LOC used to be 9% based on old studies by Bureau of Mines and the military
- Recently changed to 12% based on:
  - Recent FAA LOC test data
  - Available inerting technology
  - Probabilistic argument on what is a sufficient level of safety improvement to the entire fleet
- This talk addresses factors affecting LOC test data
  - Test data
  - Analysis

Historical Data on LOC (from Zinn)



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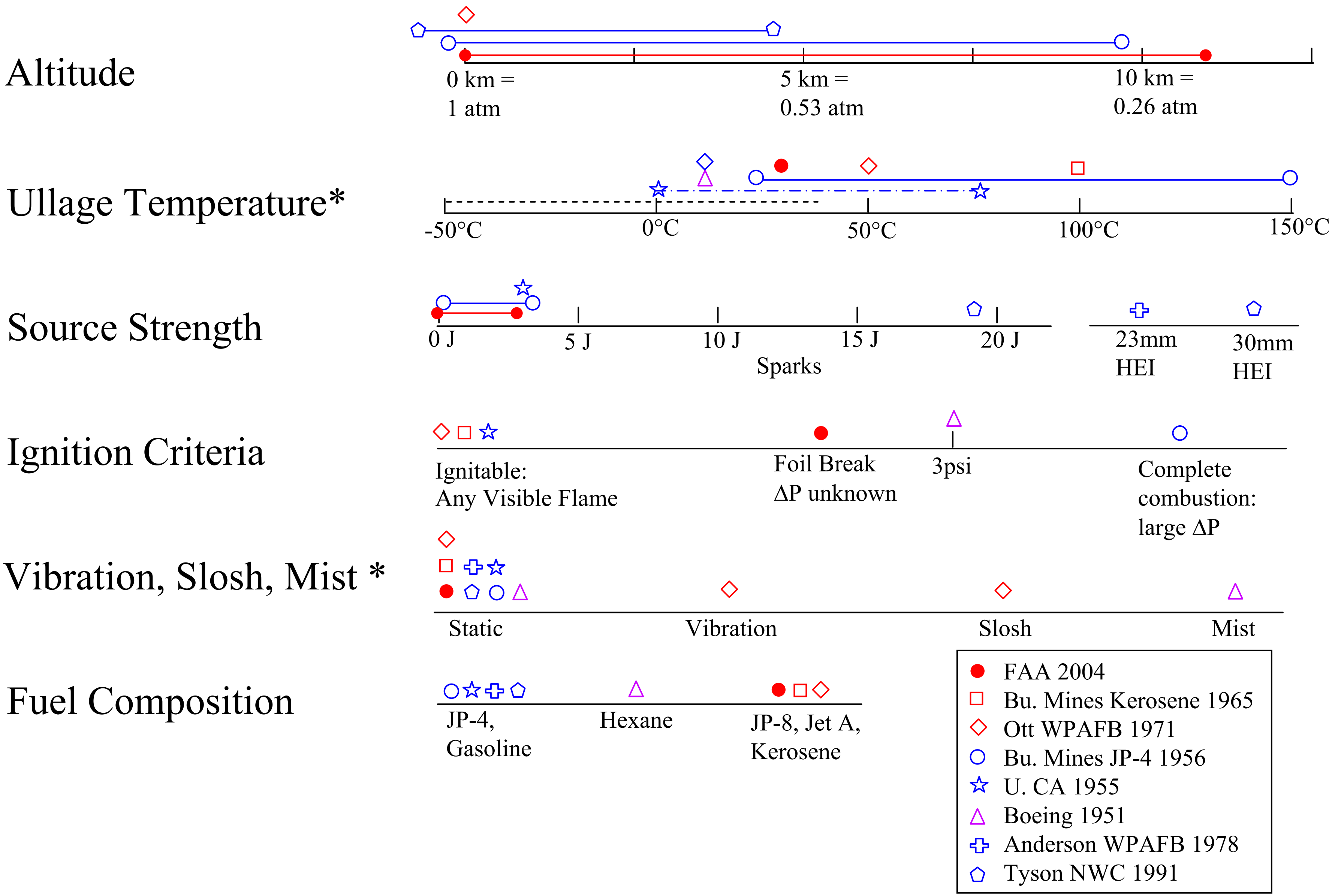
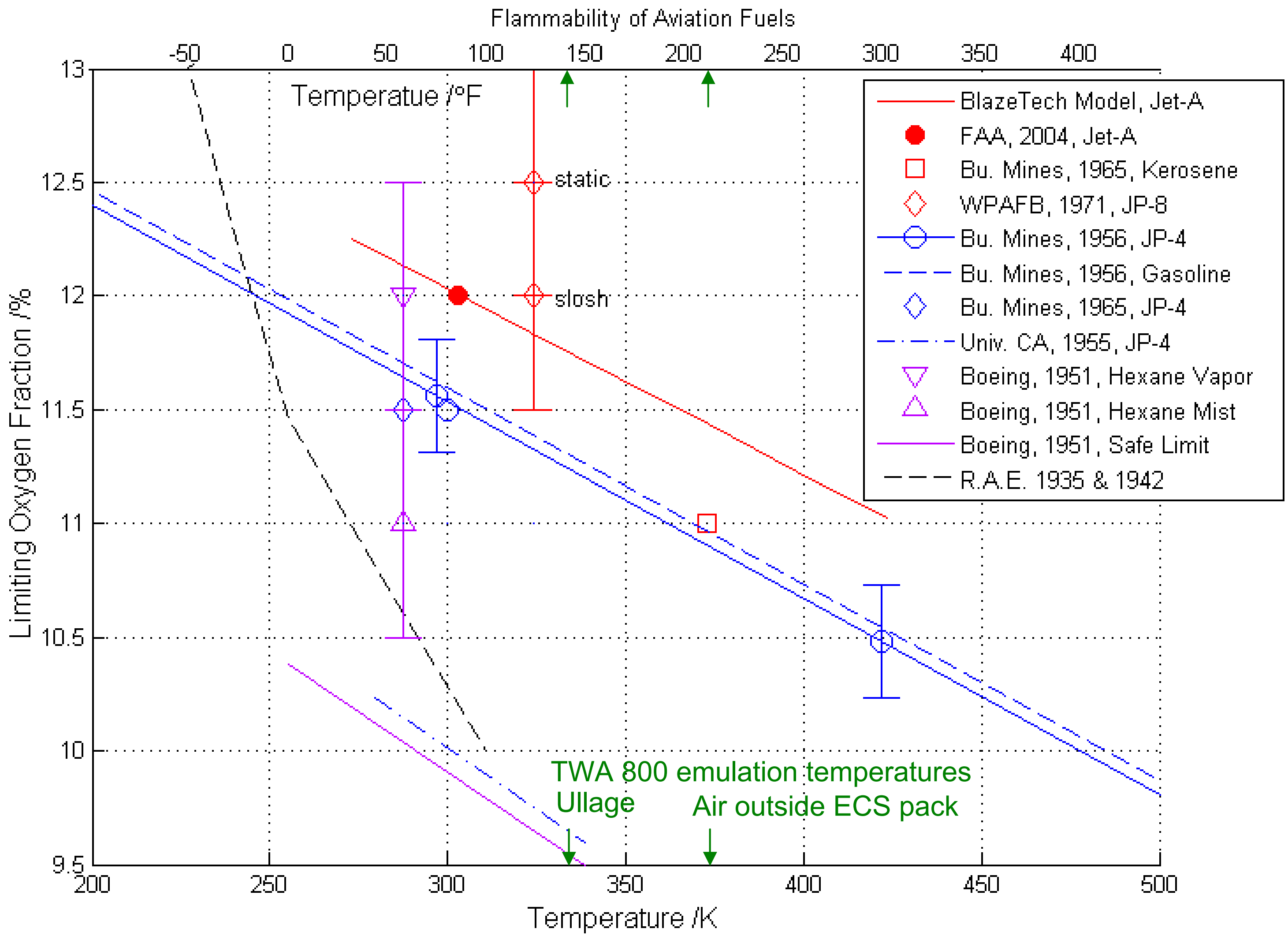
Zinn, "Inerted Fuel Tank Oxygen Concentration Requirements" DOT/FAA-RD-71-42, 1971

Experimental Ranges

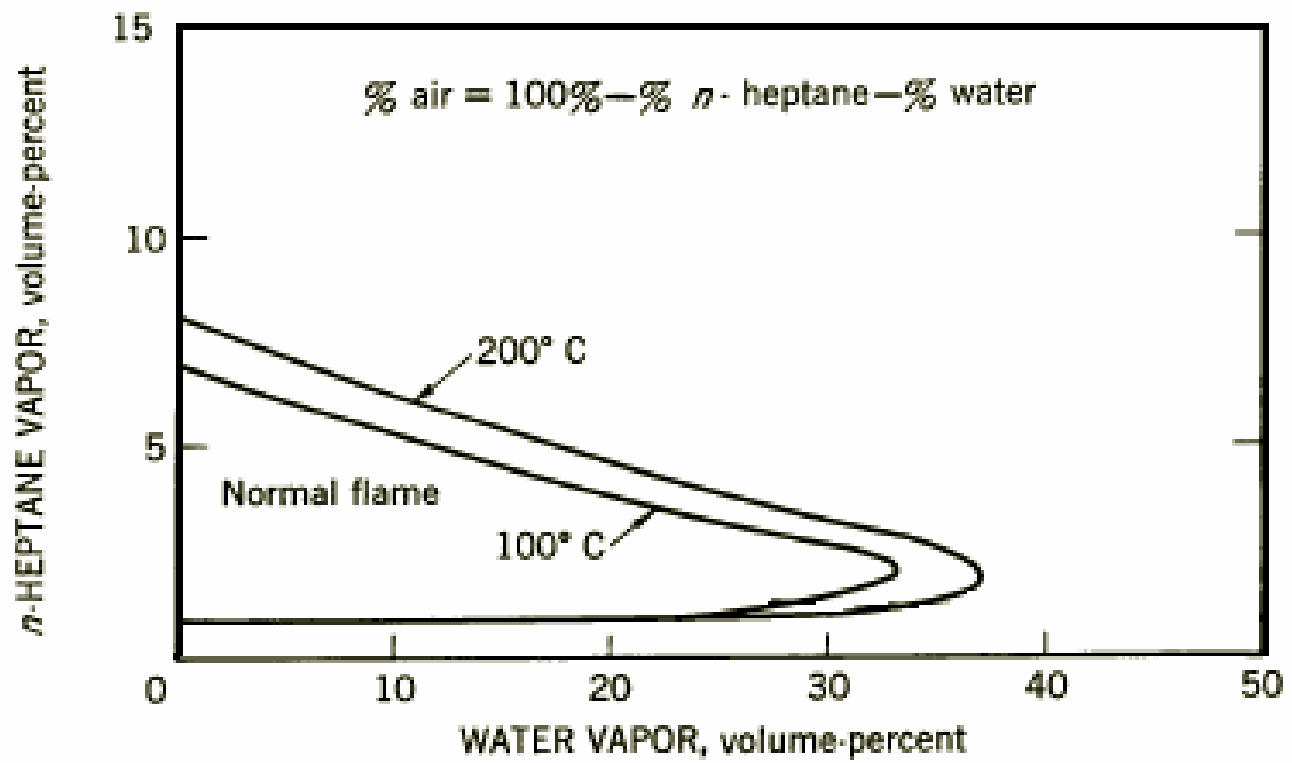


Historical Data on LOC



Revised from a graph compiled by Zinn, DOT/FAA-NA-71-26, 1971

Flammability Limits – Effect of Mixture Temperature



Pressure= 1 atm. From Zabetakis, Bureau of Mines

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General Observations

- Recent FAA data agrees with old data
  - Falls in the middle of tested data
  - Altitude effect is same in both sets of data
- Uncertainty in LOC data is +/- 0.5% for a given set of conditions with most experimental setups
- No comment on R. A. E. since we could not find their report
- Many factors can decrease LOC below 12%

Reported Drops in LOC below 12%

1. Ullage Temperature: ≈ 0.25 to 0.5% depending
2. Vibration and slosh:
   - WPAFB used tank with slosh and vibration. Difference 0.5±0.5%.
   - Boeing used hexane vapor and mist. Effect 1±0.5%
3. Gradients in Concentration/Turbulence (mixing):
   - U.CA 1±0.5% with and without a fan to aid mixing
   - O_2 enters tank near vent
4. Variations in Jet A composition depending on grade:
   - 0.5% between JP-4 and Jet A
   - Expect it to be less across various grades of Jet A

Combined Effect is neither obvious nor additive

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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

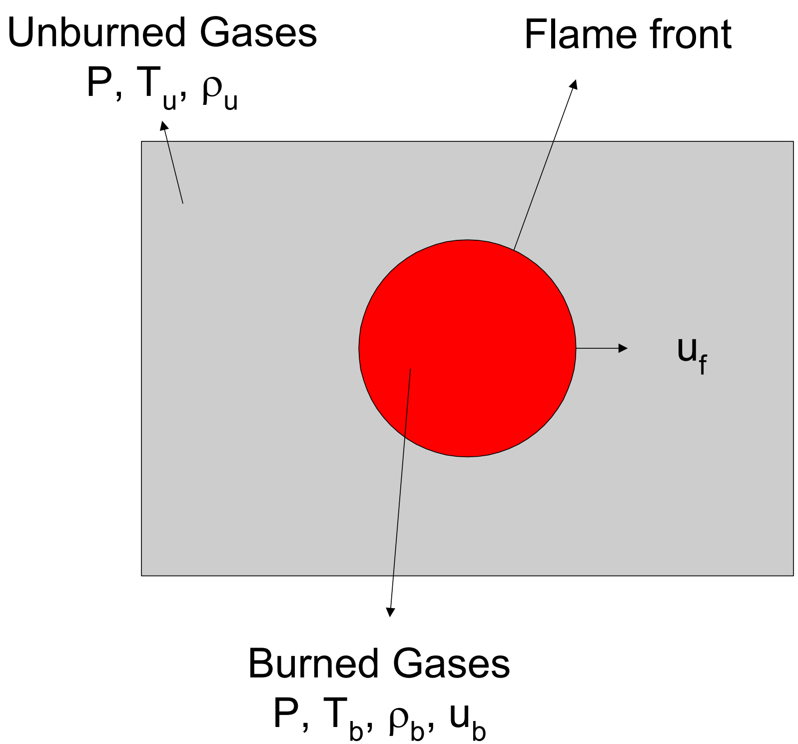
Flammable volume inside fuel tank

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)

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Burning Velocity Model

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

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)

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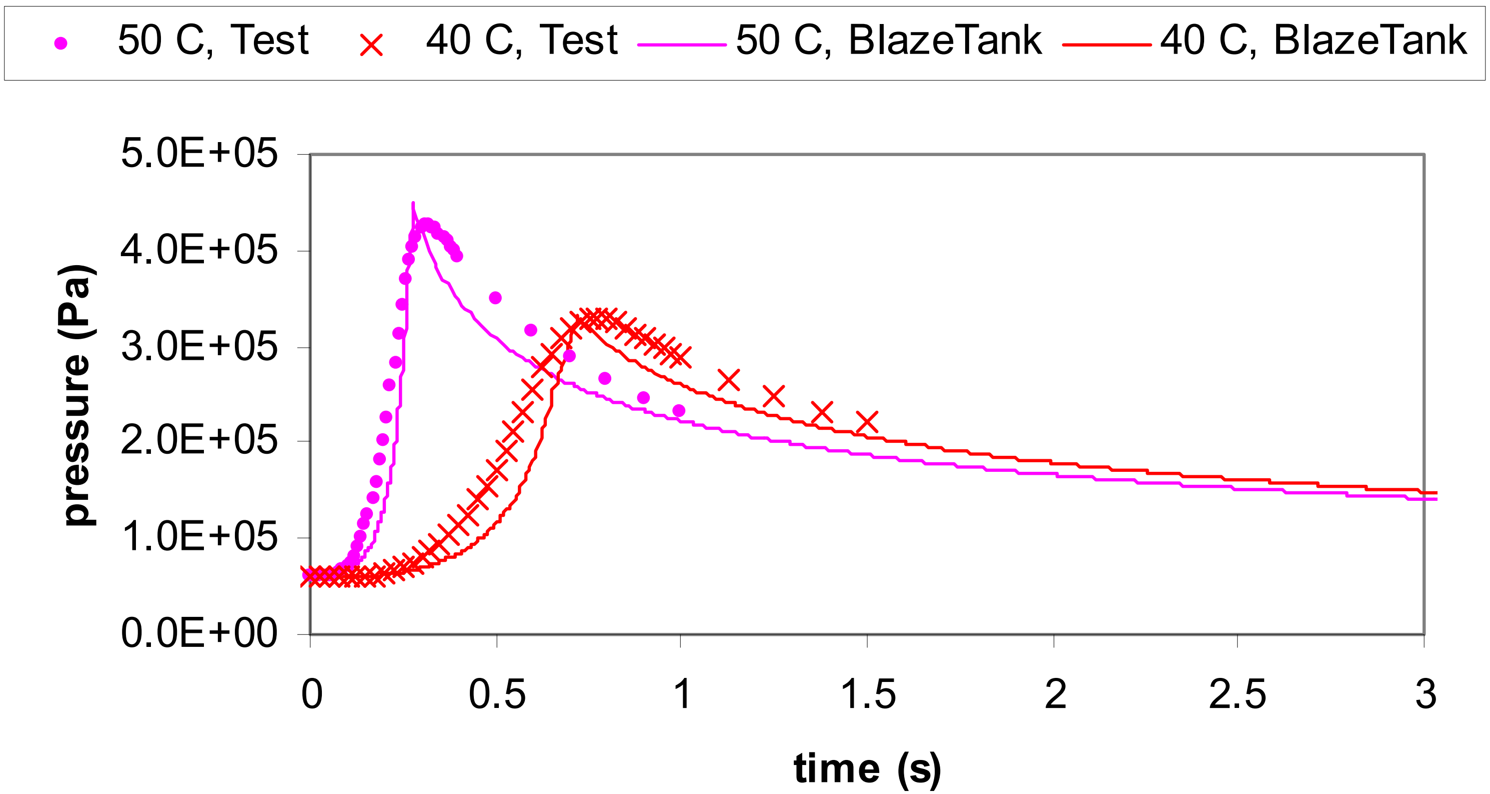
Comparison of BlazeTank Model Predictions with Quarter Scale Test Data



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

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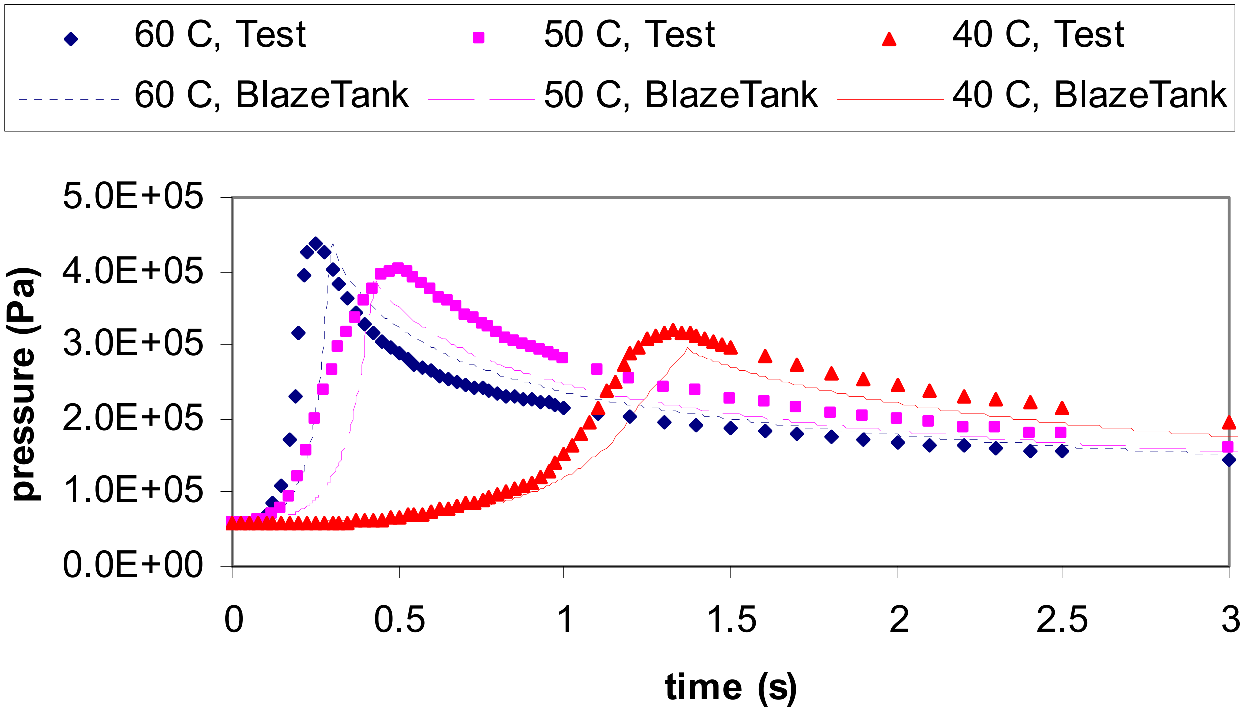
Comparison of BlazeTank Model Predictions with HYJET Test Data



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

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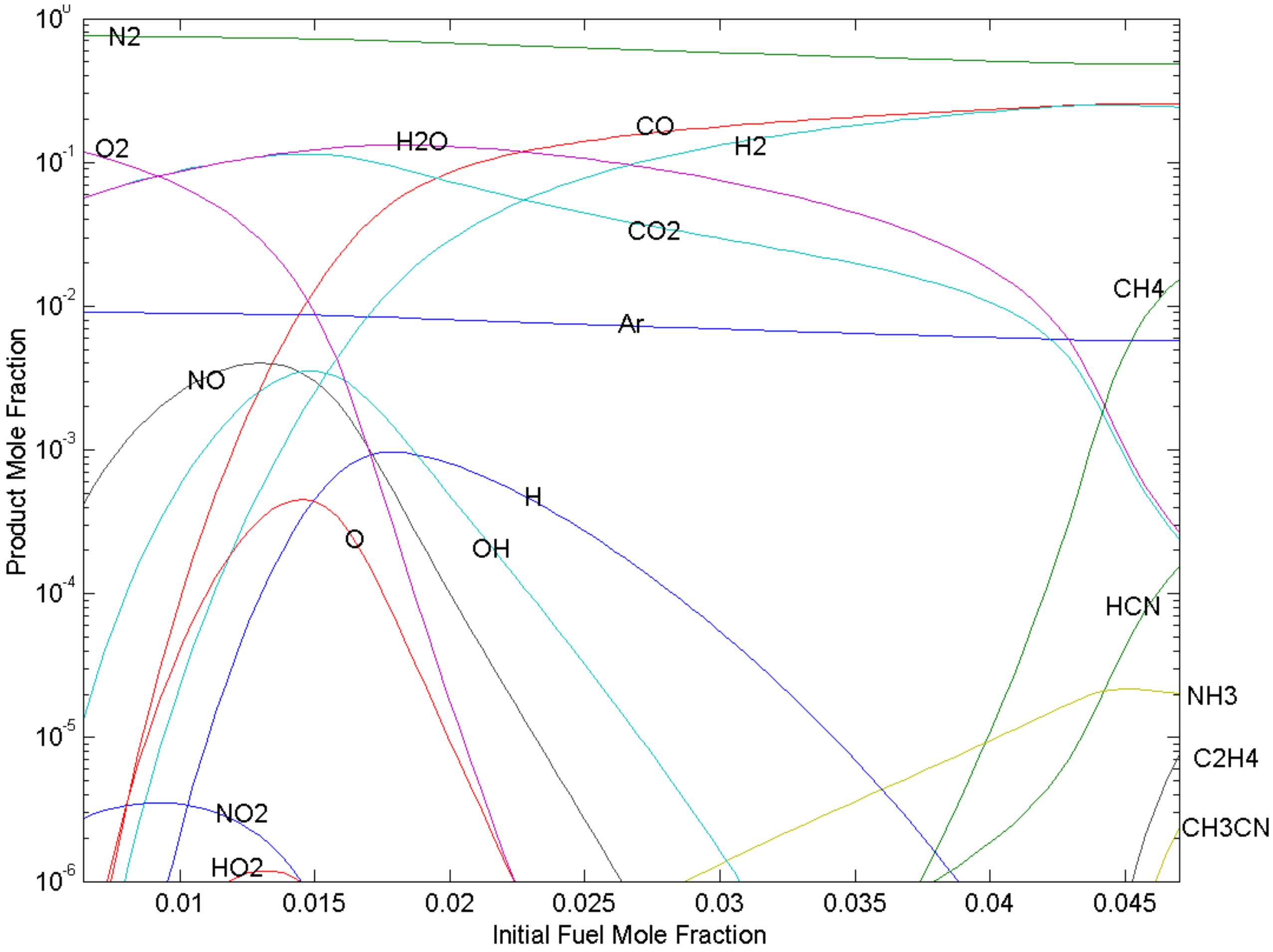
Equilibrium Calculation

- Several codes available
  - NASA Equilibrium code
  - Navy PEP
  - 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



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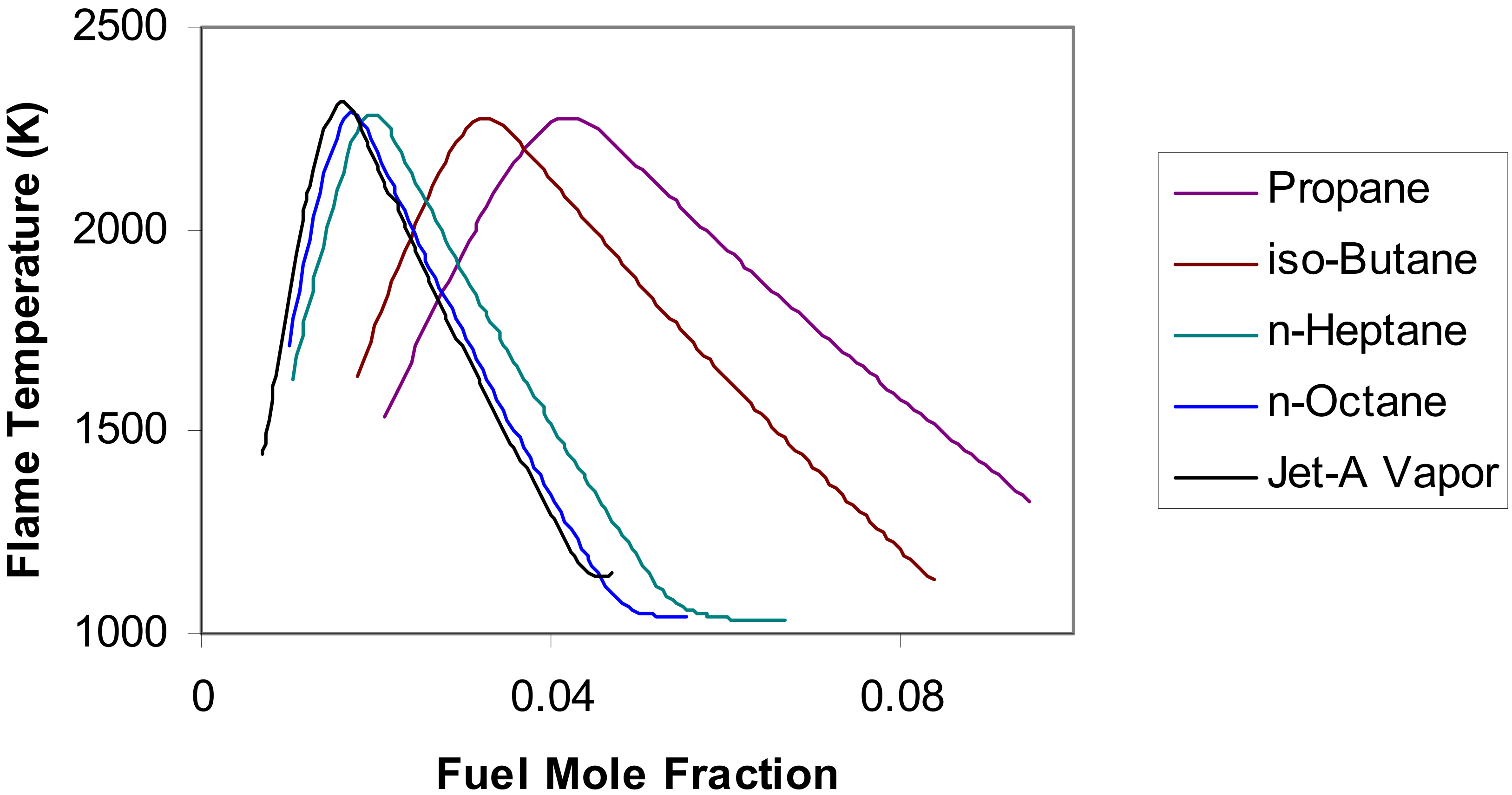
Adiabatic Flame Temperature for Alkanes



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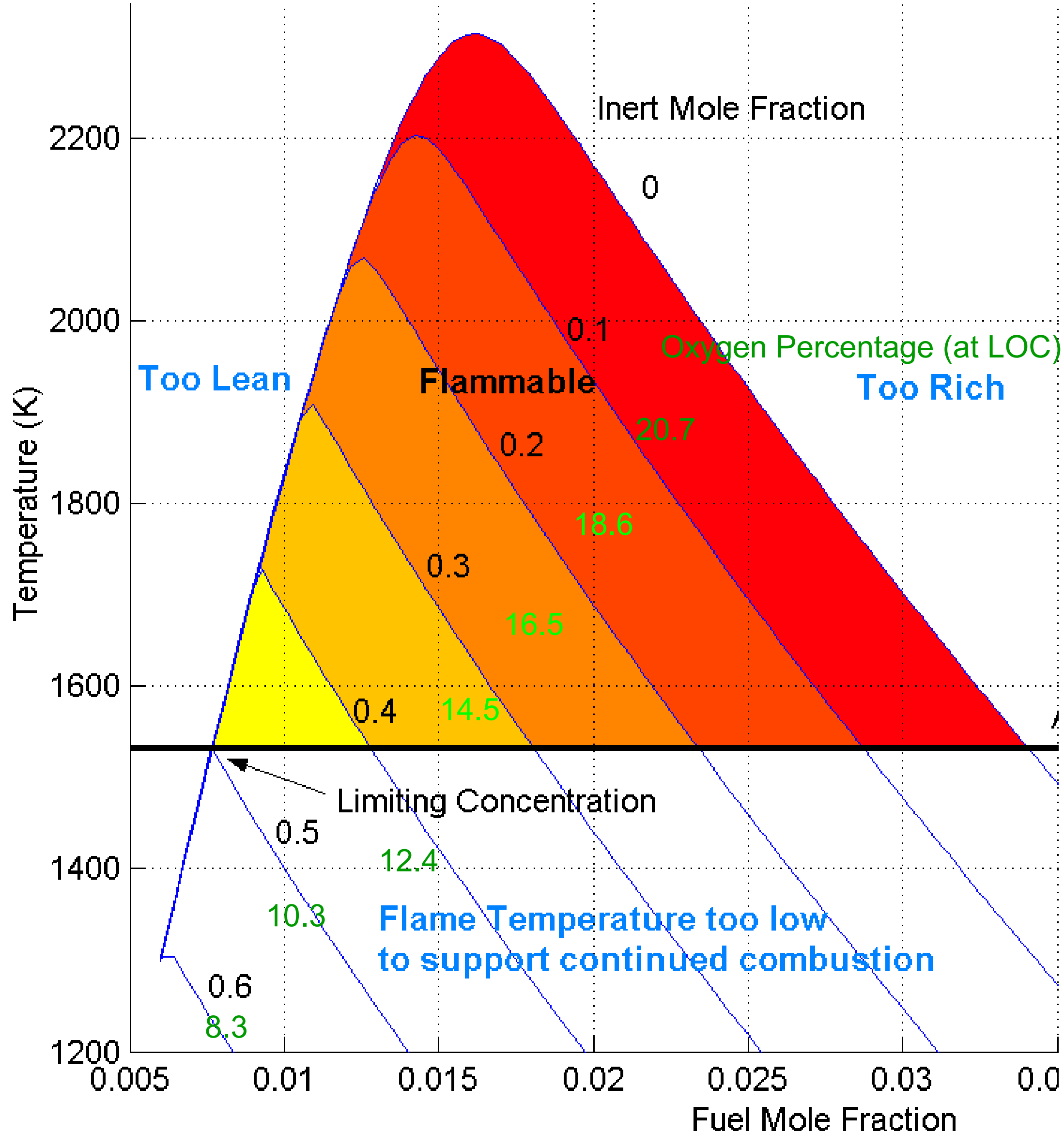
Pictorial Representation of Effect of N2 Inerting



Cut-off Temperature?

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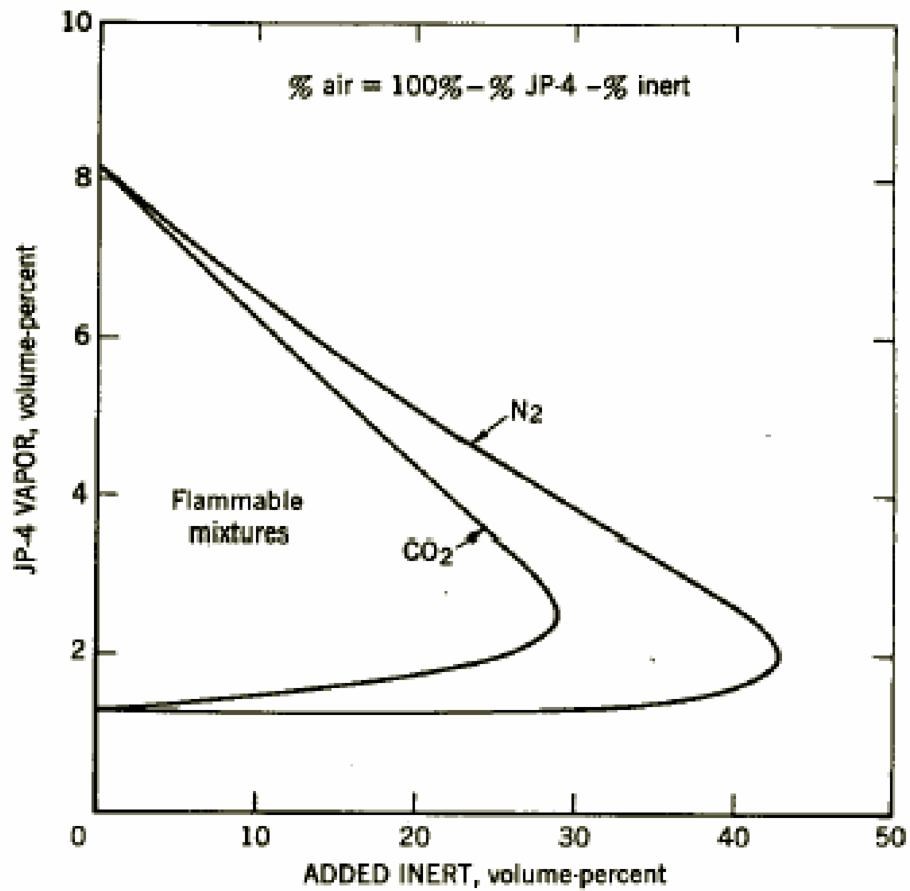
Flammability Limits for JP-4 with Inerting



Flammability limits of JP-4 vapor-CO_2-Air and JP-4 vapor-N_2-Air Mixtures at 27° C and atmospheric pressure. (Zabetakis, 1965)

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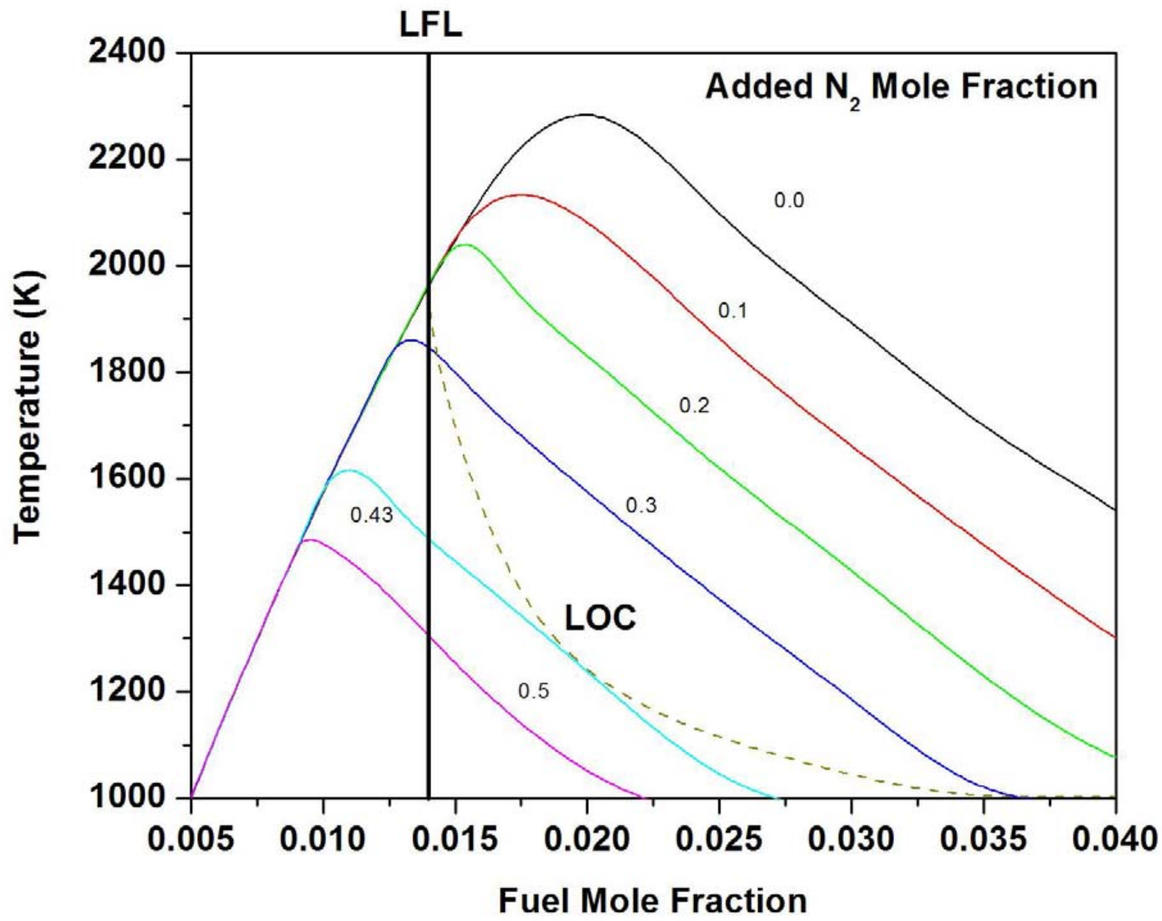
Calculation of Limiting Oxygen Index for JP-4

(n-Heptane at 1 NTP)



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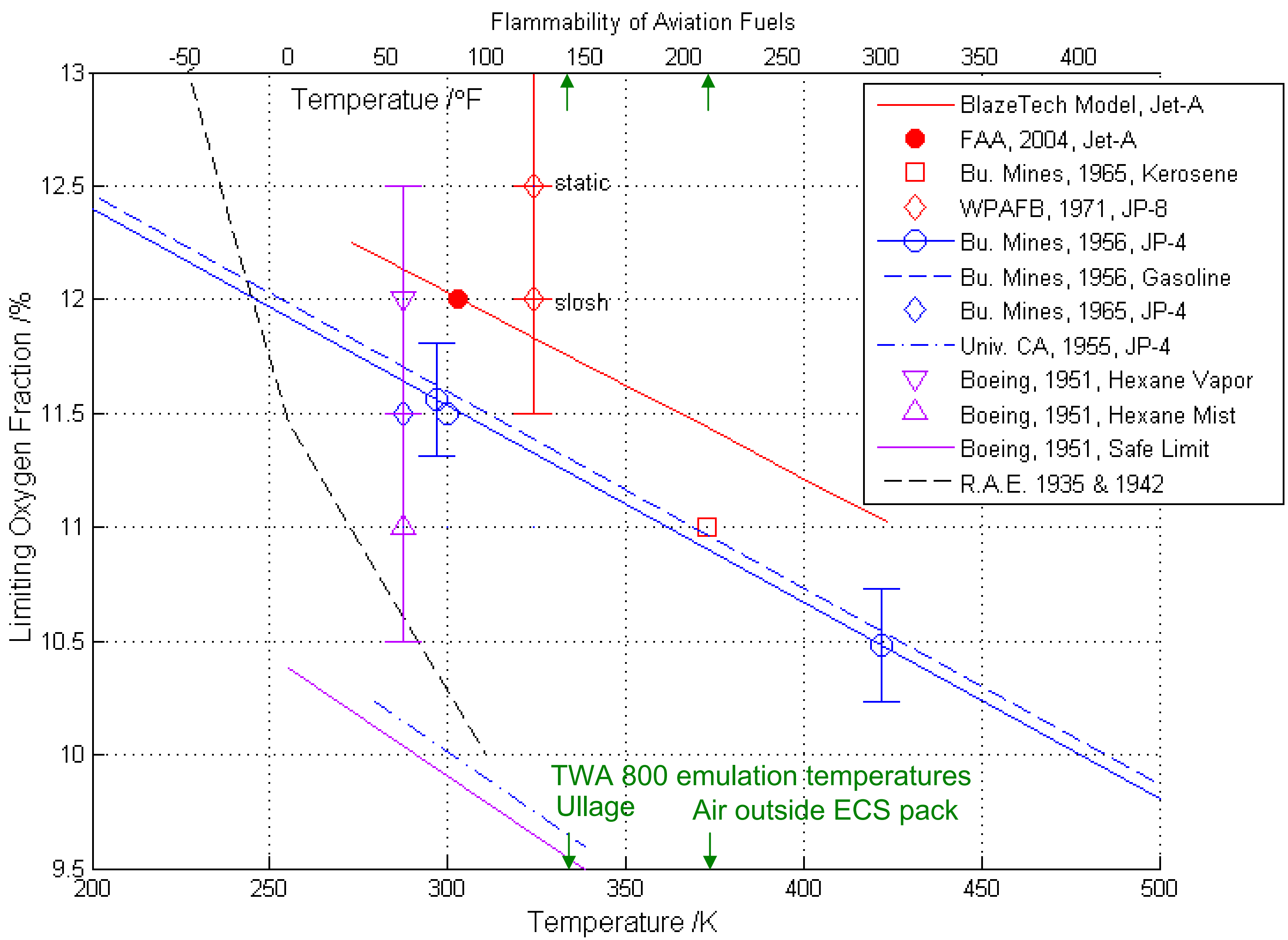
Historical Data on LOC



Revised from a graph compiled by Zinn, DOT/FAA-NA-71-26, 1971

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Conclusions

- Recent FAA tests agree well with previous data
- Recent FAA tests neglect key factors that can lower LOC:
  - Slosh and vibration, ullage temperature, fuel composition
  - Gradient effects in nitrogen or air distribution
- Their combined effect is not obvious and may not be simply additive
- They can be quantified by testing or modeling (such as BlazeTank™)
- Modeling can be used to optimize:
  - The design of inerting systems
  - Their operation (when and how much to inert) so as to minimize load on engine
- Some inerting is better than none but one should err on the conservative side

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Questions?

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