Vaporization of JP-8 Jet Fuel in a Simulated Aircraft Fuel Tank Under Varying Ambient Conditions

Robert I Ochs
Federal Aviation Administration William J. Hughes Technical Center
International Aircraft Systems Working Group Meeting
October 26, 2006

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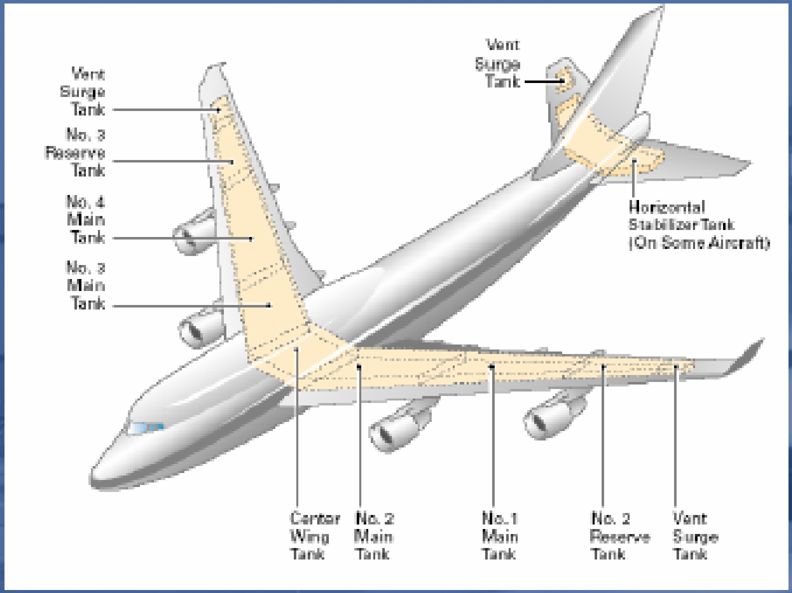
PART ONE: INTRODUCTION

Introduction

- Focus of this work is the study of jet fuel vaporization within a fuel tank

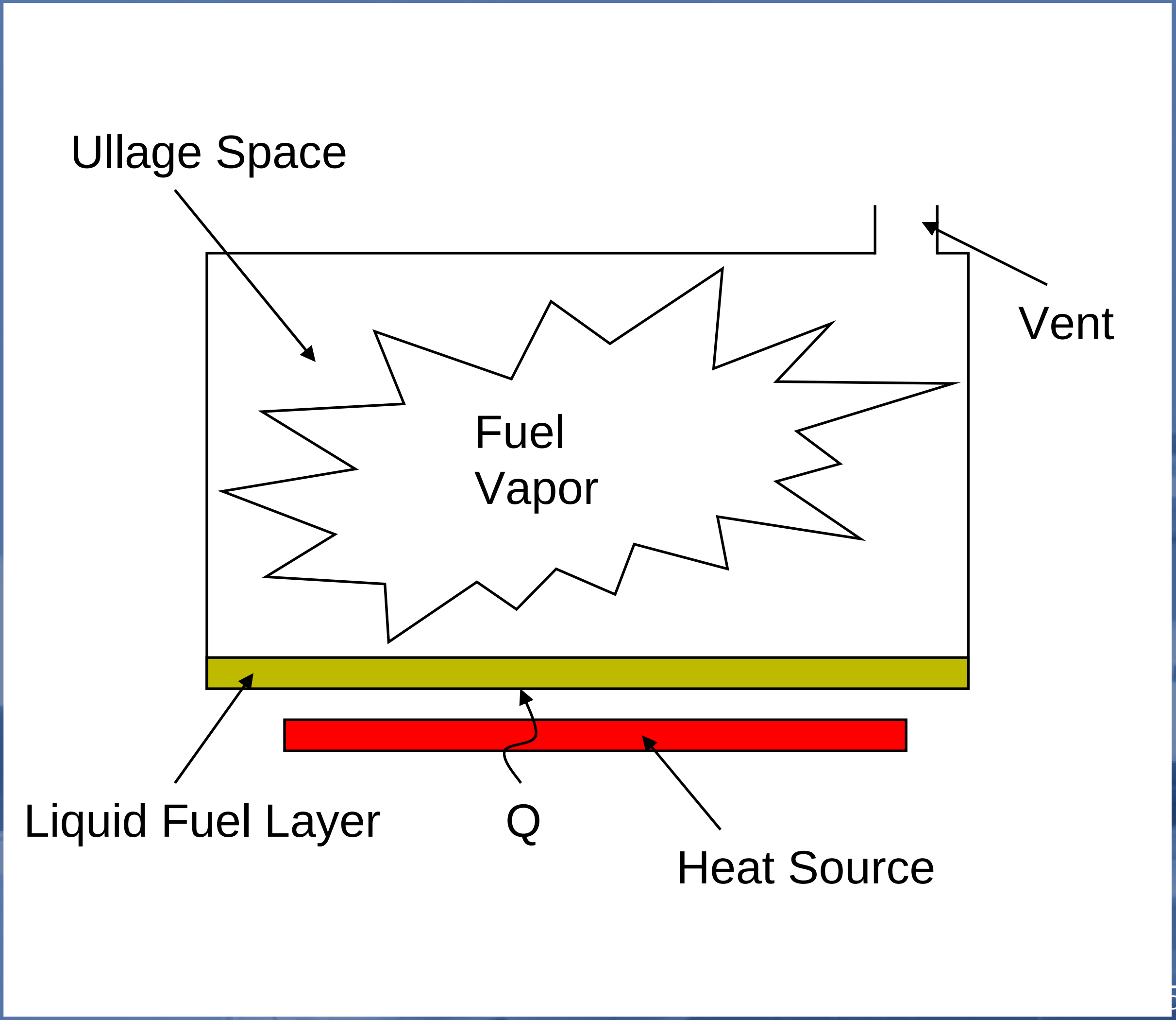
- Primary motivation resulted from the TWA Flight 800 disaster in 1996

- NTSB-led accident investigation determined the cause of the crash was an explosion in a nearly empty center wing fuel tank caused by an unconfirmed ignition source



Fuel Vaporization

- Flammable vapors were said to exist due to the combined effects of bottom surface heating and very low fuel quantity within the tank
- Low fuel quantity results in different compositions between the liquid and the vapor
- Lighter low molecular weight components vaporize first
- These components are known to have a significant effect on vapor flammability



Review of Literature

Fuel Tank Flammability

- Nestor, 1967: *Investigation of Turbine Fuel Flammability Within Aircraft Fuel Tanks*
- Kosvic, et al., 1971: *Analysis of Aircraft Fuel Tank Fire and Explosion Hazards*
- Summer, 1999, 2000, 2004: *Mass Loading, Cold Ambient effects on Fuel Vapor Concentrations, Limiting Ullage Oxygen Concentrations*

Jet Fuel Research

- Shepherd, et al, 1997, 1999: *Jet A composition, flashpoint, and explosion testing*
- Woodrow, 2000: *Characterization of Jet Fuel Vapor and Liquid*

No fuel vaporization data sets including simultaneously varying ambient temperatures and pressures

Objectives

- An experiment was designed to:
  - Simulate in-flight environment around a fuel tank
    - Fuel tank situated in an environmental chamber that could simultaneously vary the ambient chamber temperature and pressure
  - Measure conditions in and around the fuel tank
    - Fuel tank instrumented with thermocouples
    - Ullage fuel vapor concentration measured with a flame ionization detector
- Comprehensive data sets were generated for model validation
- A pre-existing model was used to compare measured and calculated ullage gas temperature and ullage vapor concentration
- The same model was used to make flammability assessments and to discuss the flammability in terms of the overall transport processes occurring within the fuel tank

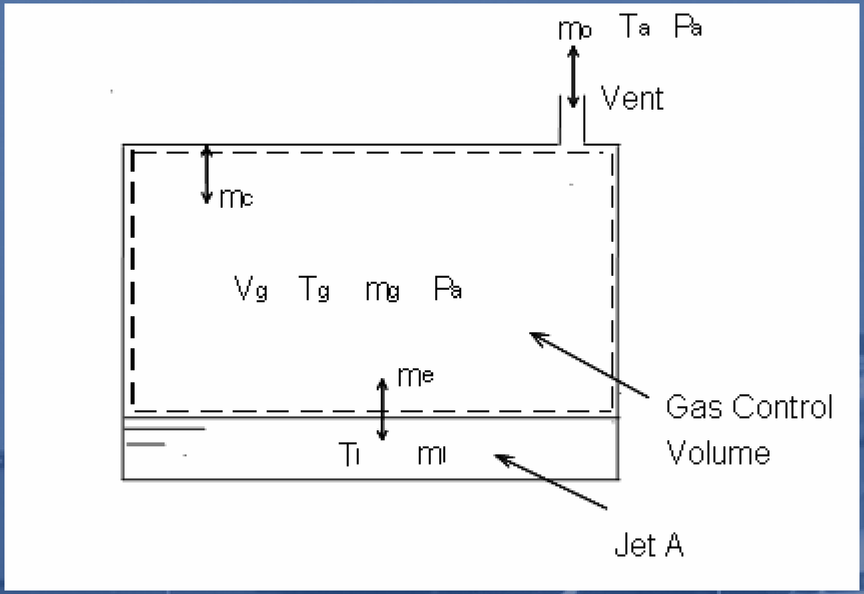
PART TWO: MODEL DESCRIPTION

Modeling Fuel Vaporization

- Calculations can be performed to determine the amount of fuel vapor existing in the ullage space at a given moment
- The model used in this work (Polymeropoulos 2004) employed the flow field that developed as a consequence of natural convection between the heated tank floor and the unheated ceiling and sidewalls
- Combined with flammability limit correlations, the model can give estimates of the duration of time in which the fuel tank can be considered flammable

Physical Considerations

- 3D natural convection heat and mass transfer
  - Liquid vaporization
  - Vapor condensation
- Variable P_a and T_a
- Multicomponent vaporization and condensation
- Well mixed gas and liquid phases
  - $Ra_{ullage} \sim o(10^9)$
  - $Ra_{liquid} \sim o(10^6)$



Principal Assumptions

- Well mixed gas and liquid phases
  - Uniformity of temperatures and species concentrations in the ullage gas and in the evaporating liquid fuel pool
  - Based on the magnitude of the gas and liquid phase Rayleigh numbers (10^9 and 10^5, respectively)

- Use of available experimental liquid fuel and tank wall temperatures

- Quasi-steady transport using heat transfer correlations and the analogy between heat and mass transfer for estimating film coefficients for heat and mass transfer

- Liquid Jet A composition from published data of samples with similar flash points as those tested (Woodrow 2000)

Heat and Mass Transport

- Liquid Surfaces (species evaporation/condensation)
  - Fuel species mass balance
  - Henry's law (liquid/vapor equilibrium)
  - Wagner's equation (species vapor pressures)

- Ullage Control Volume (variable pressure and temperature)
  - Fuel species mass balance
  - Overall mass balance (outflow/inflow)
  - Overall energy balance

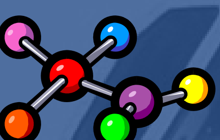
- Heat transfer correlations from natural convection in enclosures

- Heat and mass transfer analogy for the mass transfer coefficients

Characterization of Multicomponent Jet Fuel

- Samples of Jet-A have been characterized by speciation at and near the fuel flash point (Naegeli and Childress 1998)
  - Over 300 hydrocarbon species were found to completely characterize Jet-A and JP-8
- It was found by Woodrow (2000) that the fuel composition could be estimated by characterizing it in terms of a number of *n*-alkane reference hydrocarbons, determined by gas chromatography

- The approach taken by Woodrow effectively reduces the number of components from over 300 down to 16 (C5-C20 alkanes)
- The results from Woodrow's work present liquid compositions of different JP-8 samples with varying flashpoints in terms of the mole fractions of C5-C20 alkanes



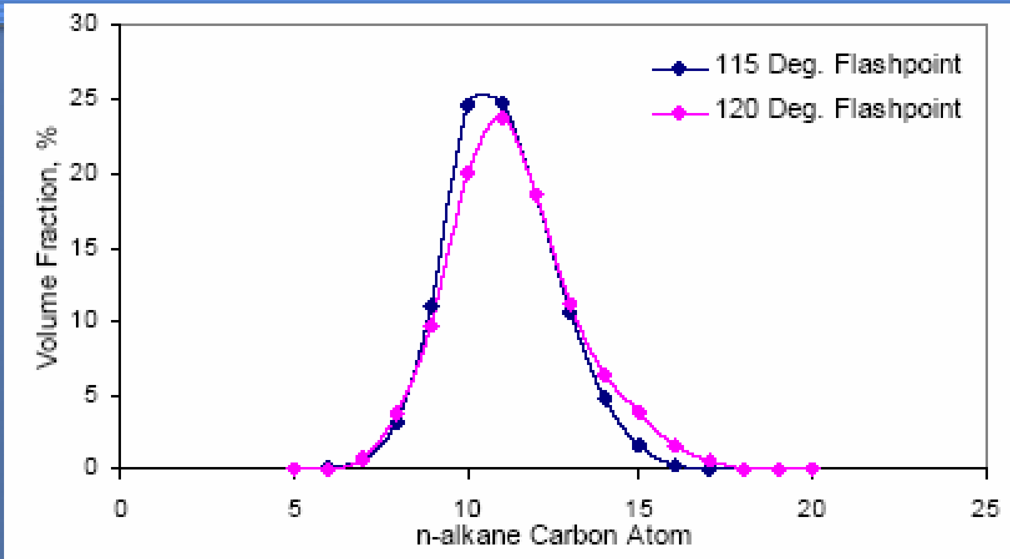
- Since fuels of different composition could be represented by their respective flashpoints, it is evident that the flashpoint is dependent upon the fuel composition

Characterization of Experimental Fuel

- Fuel used in this experimentation was tested twice for flashpoint

- Both tests resulted in a fuel flashpoint of 117°F

- Characterized fuels from Woodrow’s work with similar flashpoints were sought to represent the experimental fuel



- Compositions of two fuels with flashpoints of 115°F and 120°F were used to essentially “bracket” the experimental fuel with flashpoint of 117°F

PART THREE: EXPERIMENTAL

Apparatus, Procedures, and Results

FAA William J. Hughes Technical Center

Airflow Induction Test Facility, Building 204

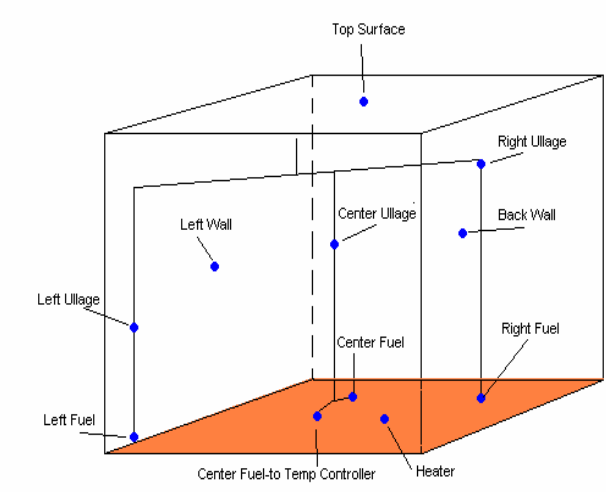
- All experimentation performed at the William J. Hughes Technical Center, Atlantic City Int'l Airport, NJ

Facility houses an environmental chamber designed to simulate the temporal changes in temperature and pressure appropriate to an in-flight aircraft

- Can simulate altitudes from sea level to 100,000 feet
- Can simulate temperatures from -100°F to +250°F

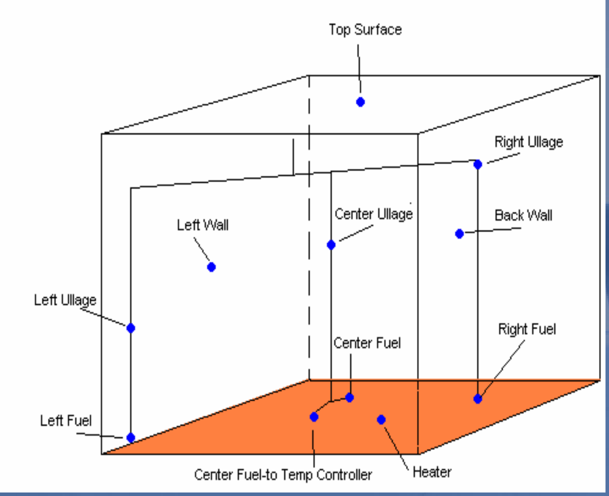
Aluminum fuel tank placed inside environmental chamber

- 36"w x 36" d x 24" h, ¼" Al
- 2 access panels on top surface for thermocouple penetration and ullage sampling
- 2" diameter vent hole, 3" diameter fuel fill



Instrumentation

- Omega® K-type thermocouples
  - 3 bolt-on surface mount
  - 1 adhesive surface mount
  - 8 1/16” flexible stainless steel
  - Measurement error of ±1°F
- Dia-Vac® dual heated head sample pump
- Technical Heaters® heated sample lines
- J.U.M.® model VE7 total hydrocarbon analyzer flame ionization detector (FID)
- Omega® high sensitivity 0-15 psia pressure transducer
- Brisk-Heat® 2,160 watt silicone rubber heating blanket



Experimental Procedure

- Initial Conditions
  - The initial condition was decided to be at the point of equilibrium, typically achieved about 1-2 hours after fuel was loaded and chamber was sealed
  - Initial data indicated that at equilibrium the tank temperatures and ullage vapor concentration varied little with time (quasi-equilibrium)
  - This point was critical to the calculations, as the subsequent time-marching calculations initiated with this point
  - Quasi-equilibrium was said to exist if the ullage vapor concentration varied by less than 1,000 ppm (0.1%) over a period of ten minutes

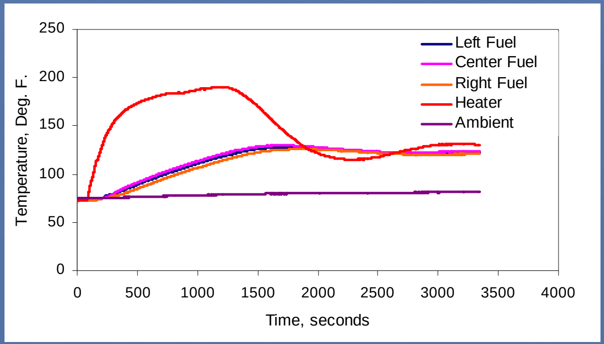
- Test Matrix
  - A quantity of 5 gallons was used for each test
  - An arbitrary fuel temperature setpoint approximately 30°F above the initial temperature was found to create sufficient ullage vapor concentrations within the calibration range
  - Dry tank tests
  - Isooctane
  - Constant ambient pressure
  - Varying ambient temperature and pressure
  - Repeatability

	Altitude			
Test Type:	***0***	***10,000***	***20,000***	***30,000***
Const. P	**X**	**X**	**X**	**X**
Vary T & P	*N/A*	**X**	**X**	**X**
Isooctane	**X**	*N/A*	*N/A*	*N/A*
Dry Tank	**X**	*N/A*	*N/A*	**X**

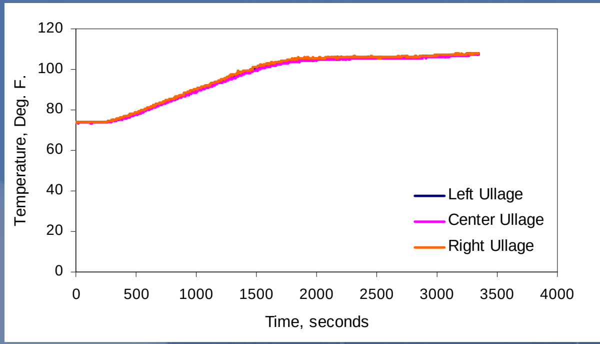
Typical Results: Fuel Tank at Sea Level, Constant Ambient Conditions

- Similar liquid heating profiles were used for tests of same type
- Heating and vaporization trends seen here typical of all other tests
- Note the uniformity in the ullage gas temperature (well-mixed)

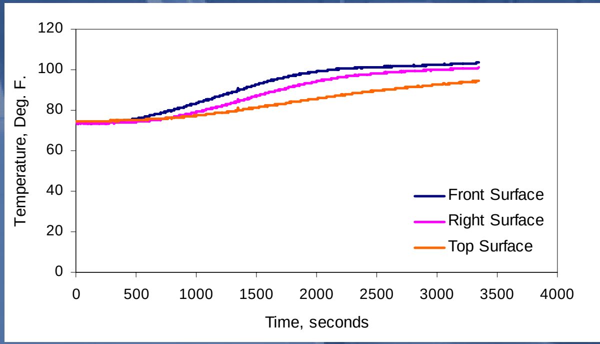
Liquid, Heater, Ambient Temperatures



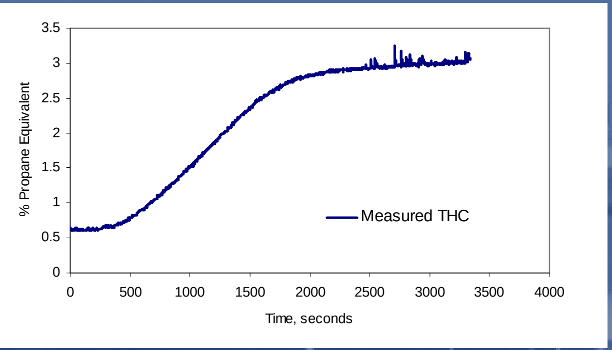
Ullage Temperatures



Surface Temperatures



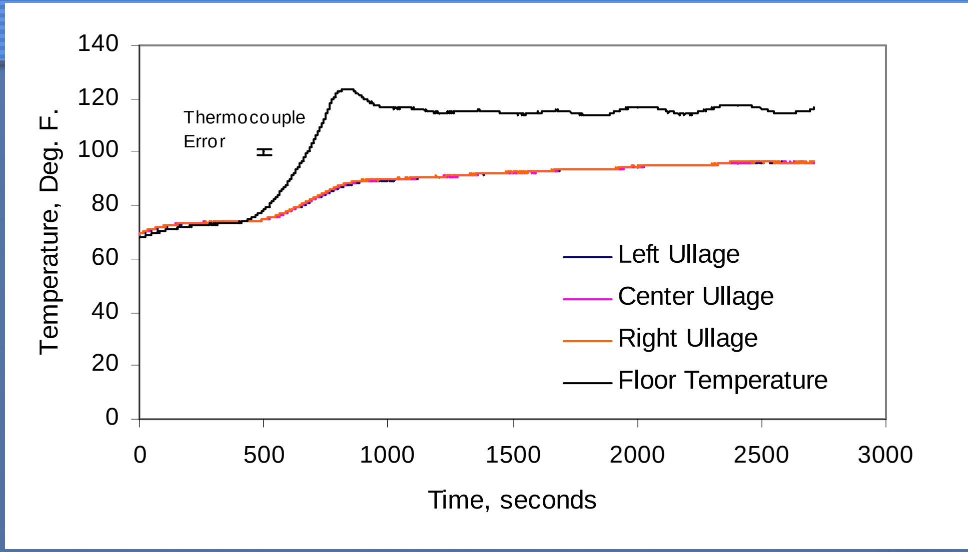
Ullage Vapor Concentration



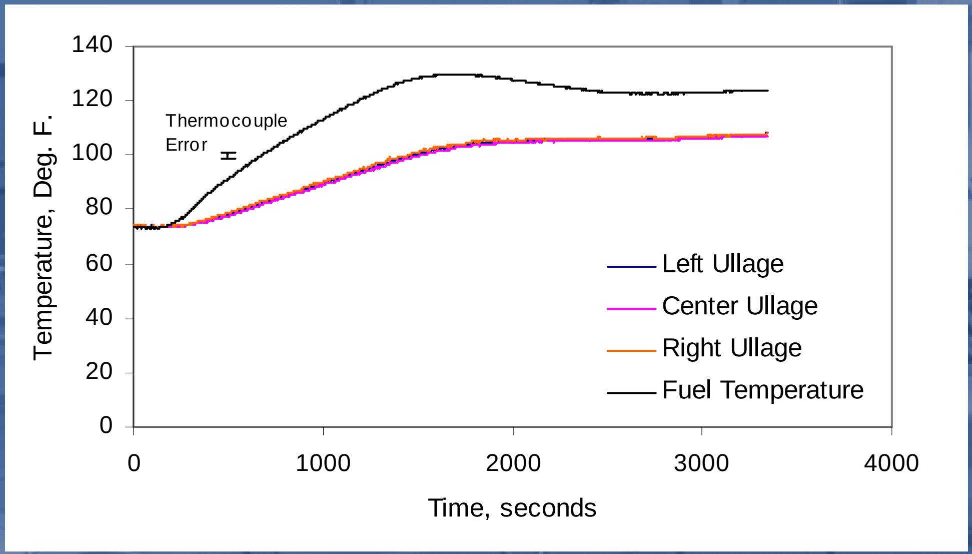
Validation of the Well Mixed Assumption

- Model assumes uniform, well-mixed ullage gas from the magnitude of the Raleigh number, based on the floor to ceiling temperature difference and the distance between them, typically of order 10^9
- This assumption is validated by the experimental data from three ullage thermocouples in various spatial locations within the ullage
  - One test with no fuel in the tank
  - One test with fuel in the tank
- Similar uniformity in ullage gas temperature was found in all other tests as well

Dry tank

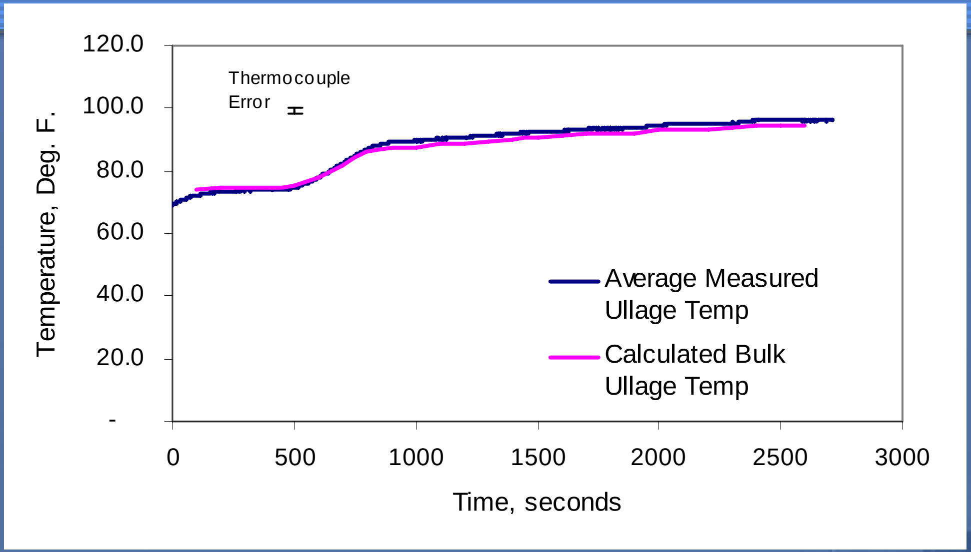


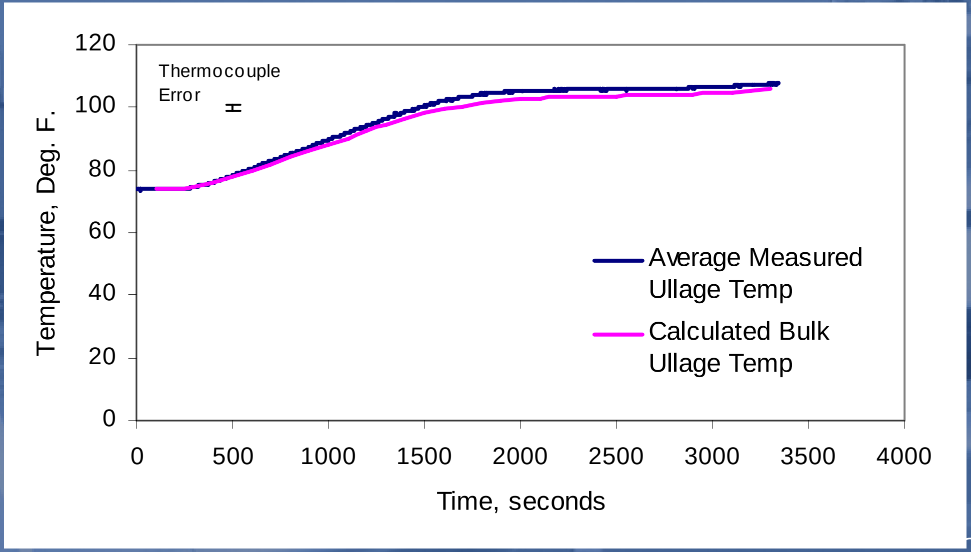
Tank with 5 gal. fuel



Ullage Gas Temperature Predictions

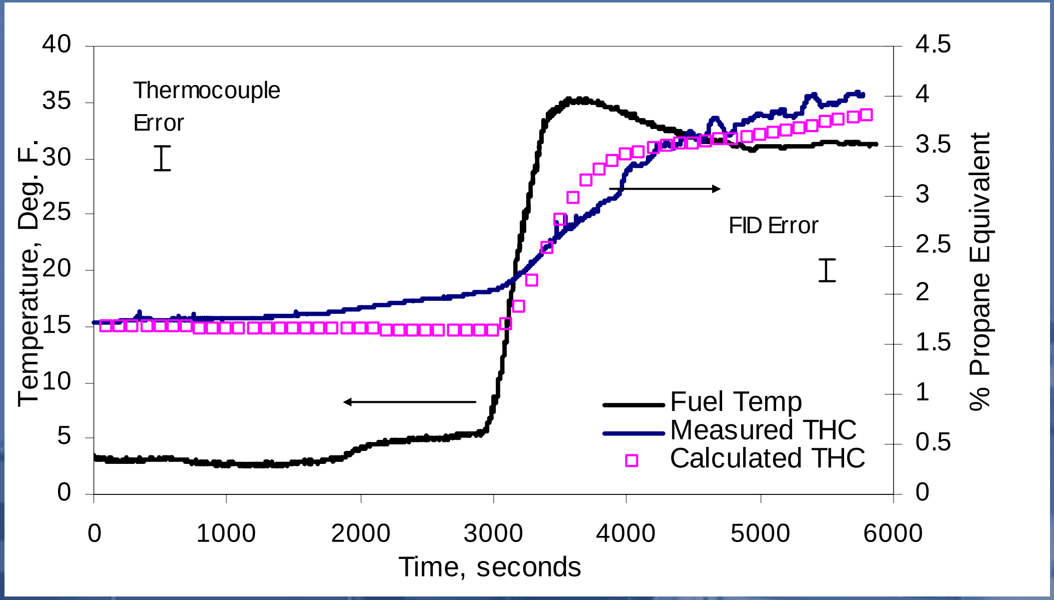
- The data from the same two tests input into the model to calculate the ullage gas temperature
- Ullage gas temperature predictions were within the thermocouple measurement error
- Ullage gas temperature predictions agree well with measured ullage gas temperature





Isooctane Fuel Vaporization

- A pure component fuel of known composition was used to remove the ambiguity of fuel composition from the model calculations
- Isooctane is quite volatile at room temperature, so the fuel had was cooled to near 3°F to obtain fuel vapor concentrations within the FID calibration range of 0-4% propane
- Satisfactory agreement between measured and calculated ullage vapor concentrations was obtained, considering the difficulties involved in using isooctane

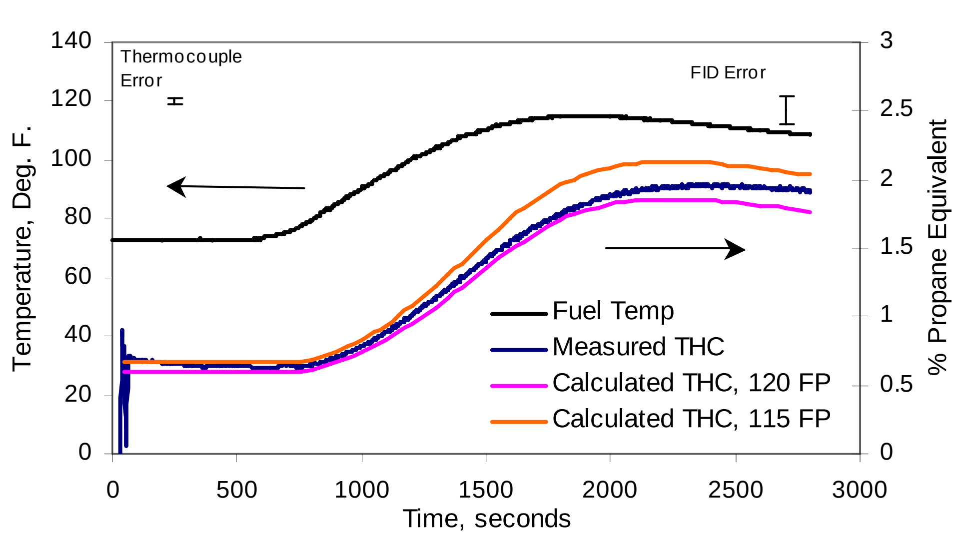


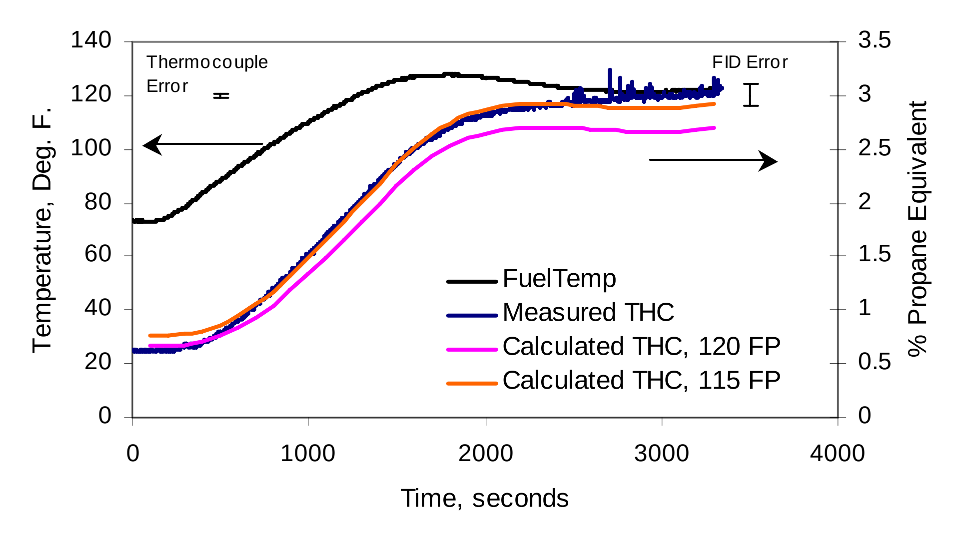
Constant Ambient Pressure at Sea Level

- Two fuel compositions (F.P. = 115 and 120 °F) with flashpoints bracketing the experimental fuel's flashpoint (F.P. = 117°F) were used to calculate the ullage vapor concentrations

- Two tests are shown with similar heating profiles, both with 5 gallons of fuel in a tank at sea level

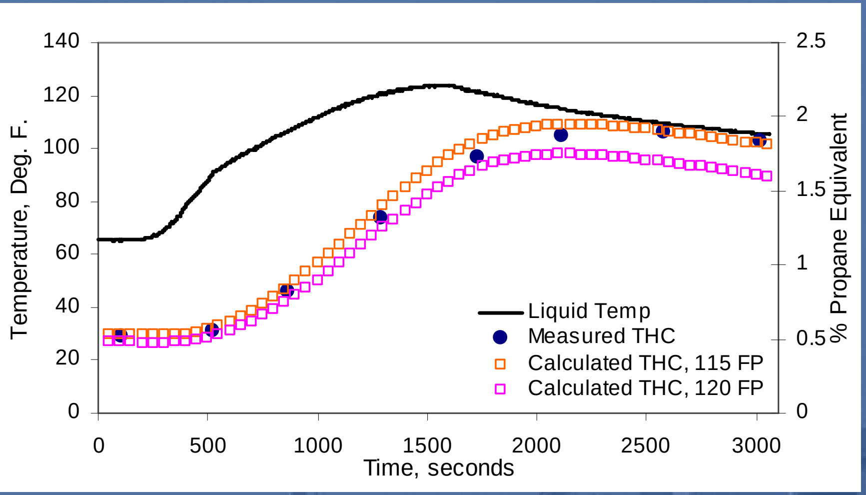
- Calculated results were in good agreement with measured data

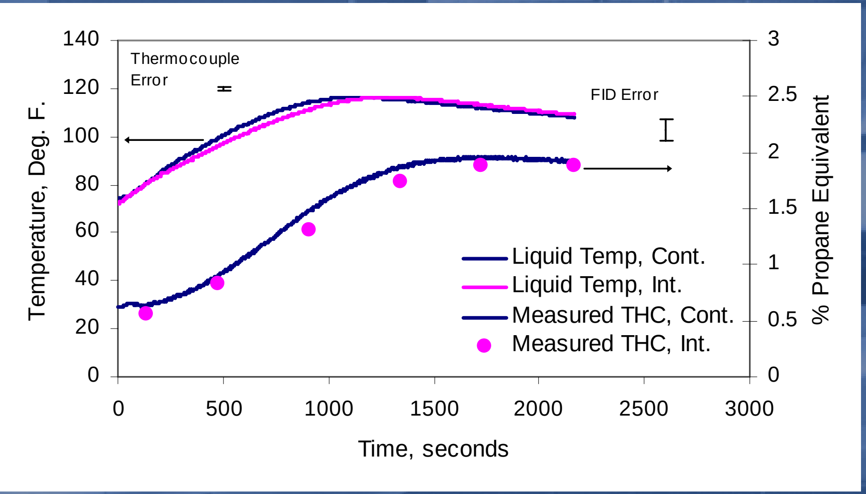




Intermittent Ullage Vapor Sampling

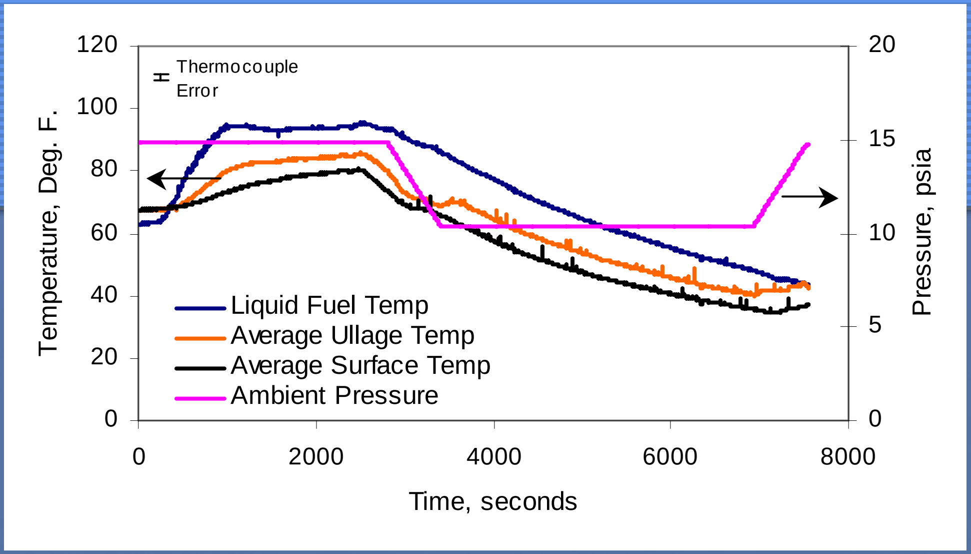
- The F.I.D.'s built-in sample pump could not maintain the required sample pressures when sampling from reduced ambient pressures
- The dual heated head sample pump was used to supplement the built-in pump to maintain the sample pressure
- However, sampling continuously at a high flow rate had the effect of drawing in air through the tank vents, thus diluting the ullage vapor
- It was decided to sample intermittently in order to maintain sample purity
  - Since the F.I.D. had a quick response time, the only sample lag was created by the length of the sample lines
  - A sample time of 30 seconds every ten minutes proved to be sufficient for ullage gas sampling
- Intermittent sampling was compared with continuous sampling at sea level for two tests with similar heating profiles

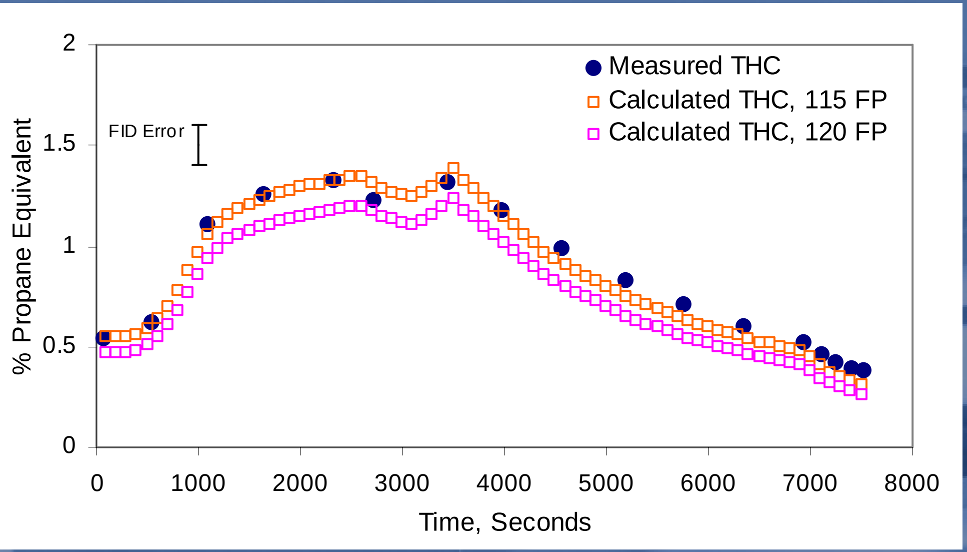




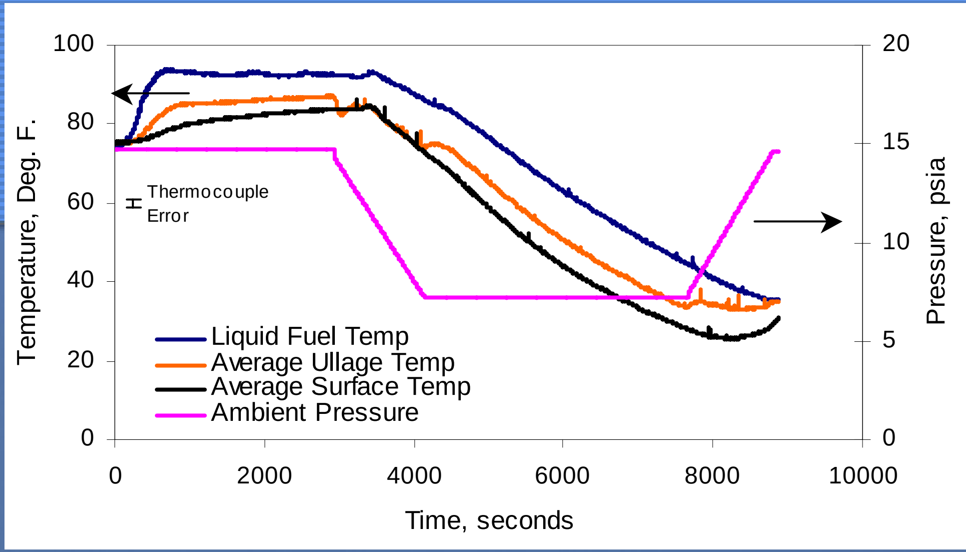
Simulated Flight Conditions 10,000 ft. Cruise

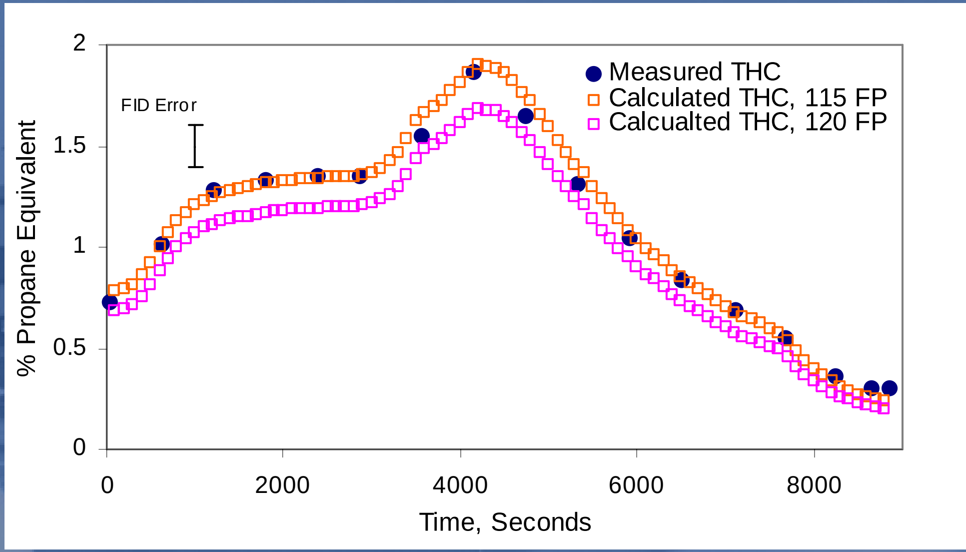
- Simulated Flight Conditions
  - One hour of ground time with bottom surface fuel tank heating
  - Ascend to cruise at 1,000 ft./min.
  - Cruise for one hour
  - Descend to ground at -1,000 ft./min.
- Standard atmosphere pressure



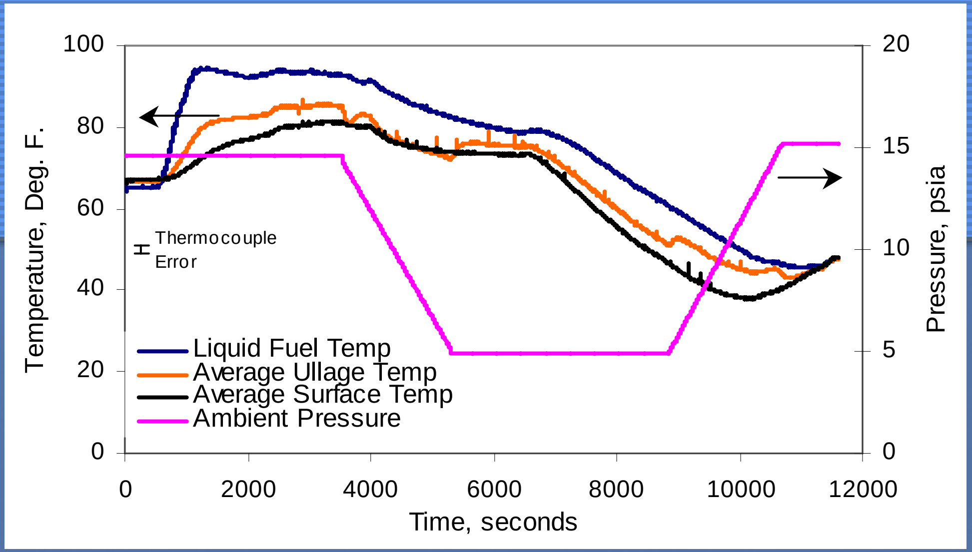


Simulated Flight Conditions 20,000 ft. Cruise

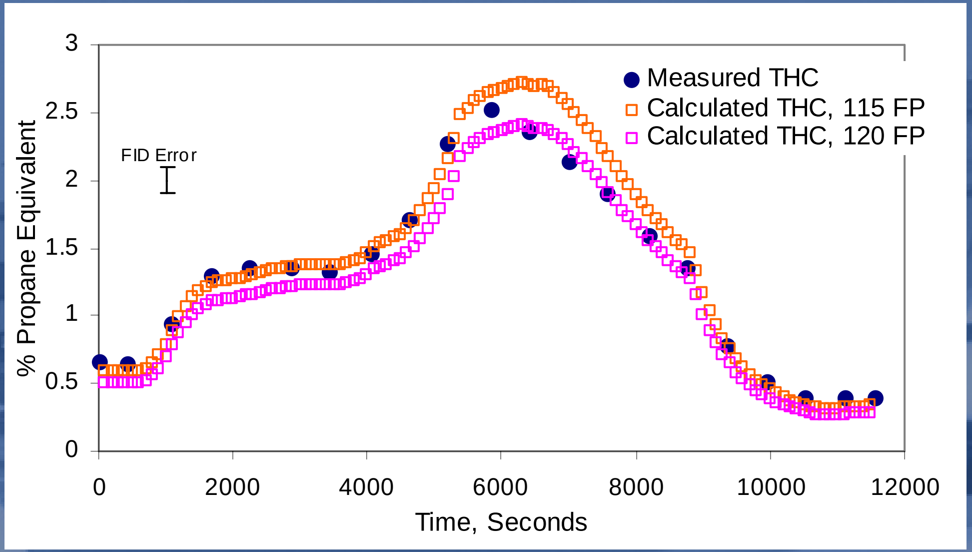




Simulated Flight Conditions 30,000 ft. Cruise



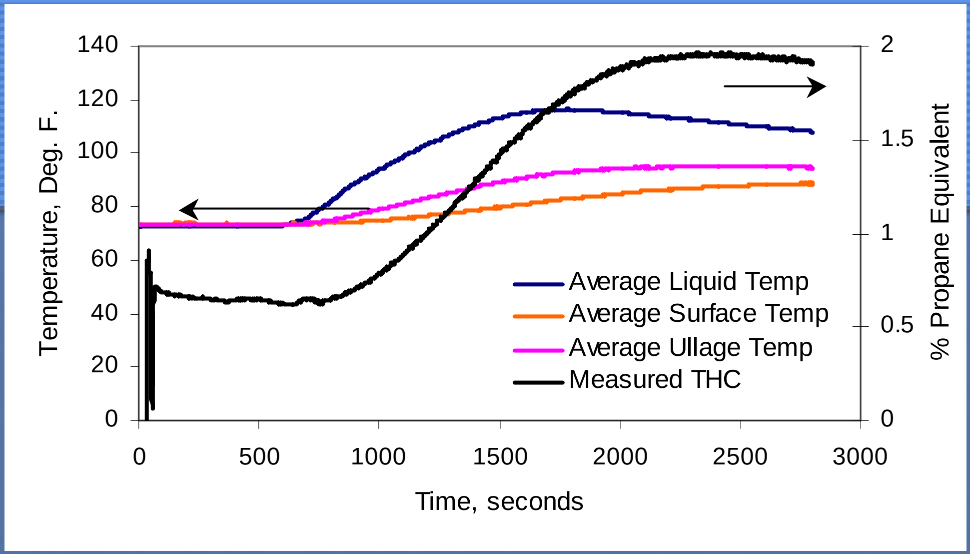
- Good agreement was found between calculated and measured results for varying ambient conditions

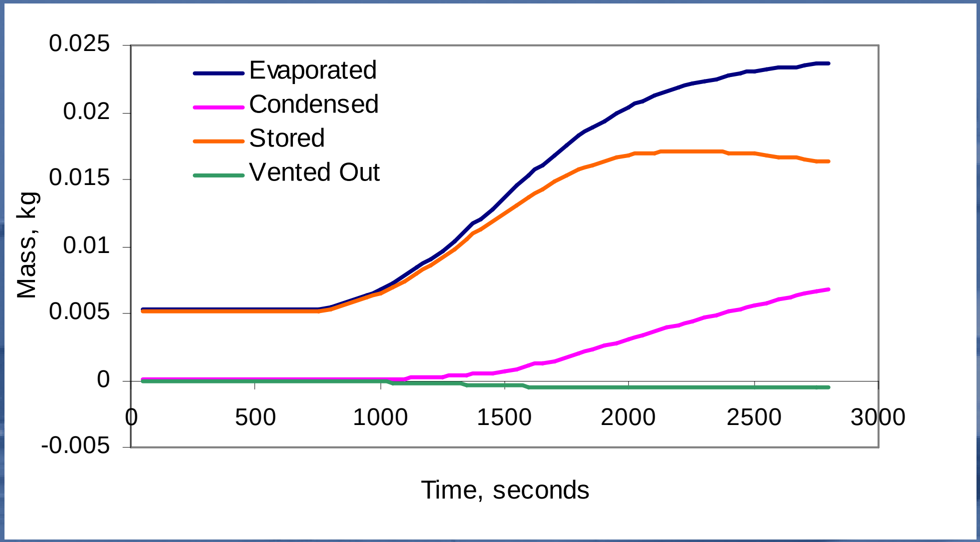


Calculated Mass Transport:

Fuel tank at sea level

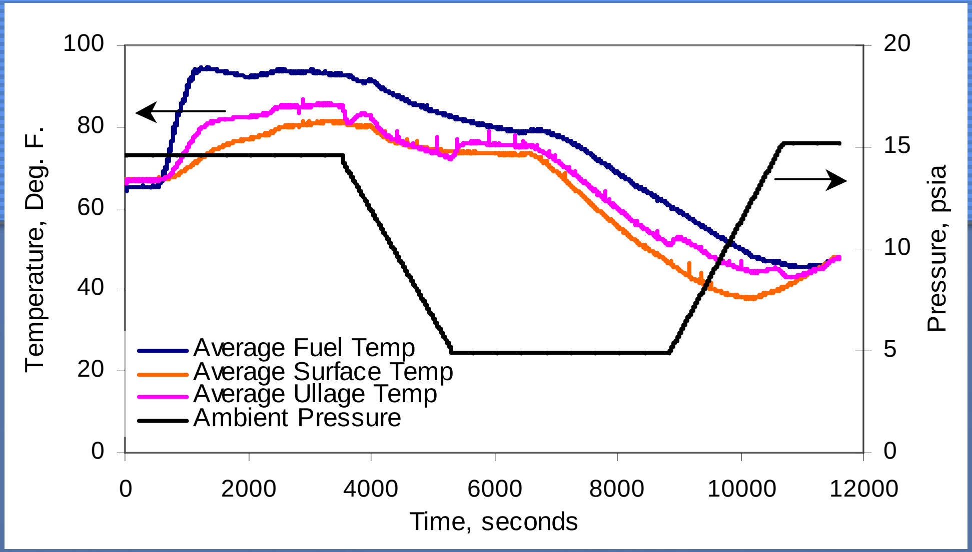
- The good agreement between calculated and measured values gives confidence in the model
- The temporal variation of ullage gas concentration can be explained by the model's calculations of temporal mass transport
- The mass of fuel stored in the ullage gas at a given moment can be calculated when considering
  - Mass of fuel vaporized
  - Mass of fuel condensed on inner surfaces
  - Mass of fuel vented out





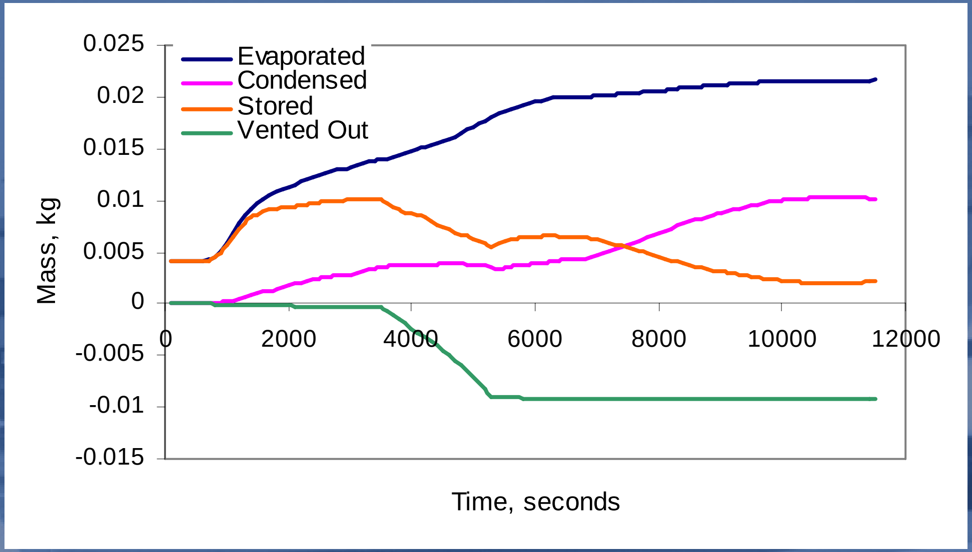
Calculated Mass Transport:

Simulated Flight at 30,000'



- The variation of ullage gas concentration can be explained by the model's calculations of temporal mass transport

- The mass of fuel stored in the ullage gas at a given moment can be calculated when considering
  - Mass of fuel vaporized
  - Mass of fuel condensed on inner surfaces
  - Mass of fuel vented out



Determination of the LFL

- For liquids of known composition, Le Chatelier's rule can be used to estimate the LFL (Affens and McLaren 1972)
  - Empirical formula that correlates flammability limits of multi-component hydrocarbon fuels with the flammability limits of the individual components
  - Accounts for both the concentration and composition of the fuel-air mixture
  - The mixture is considered flammable if $LC>1$

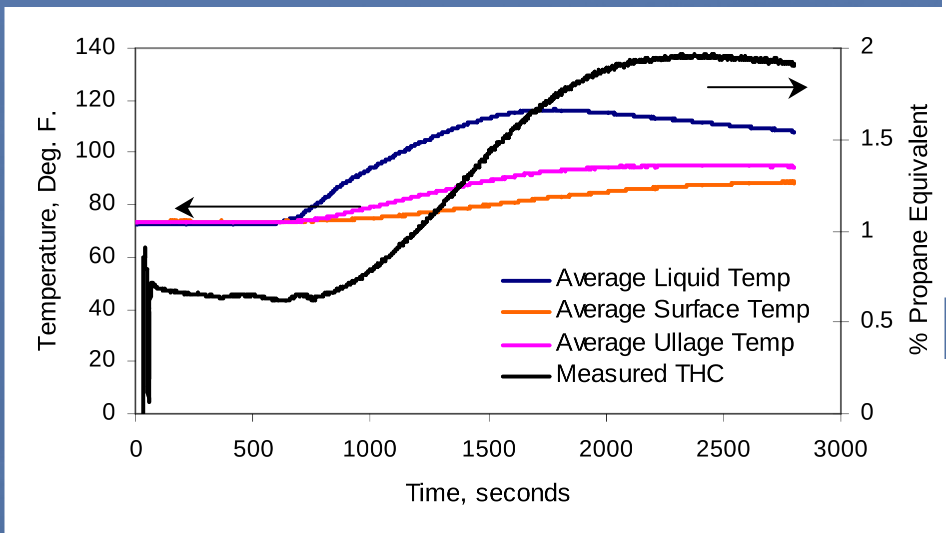
$$LC = \left(1.02 - 0.000721 * T\right)\sum_{I} \frac{x_i}{LFL_i}, i = 1 \rightarrow N$$

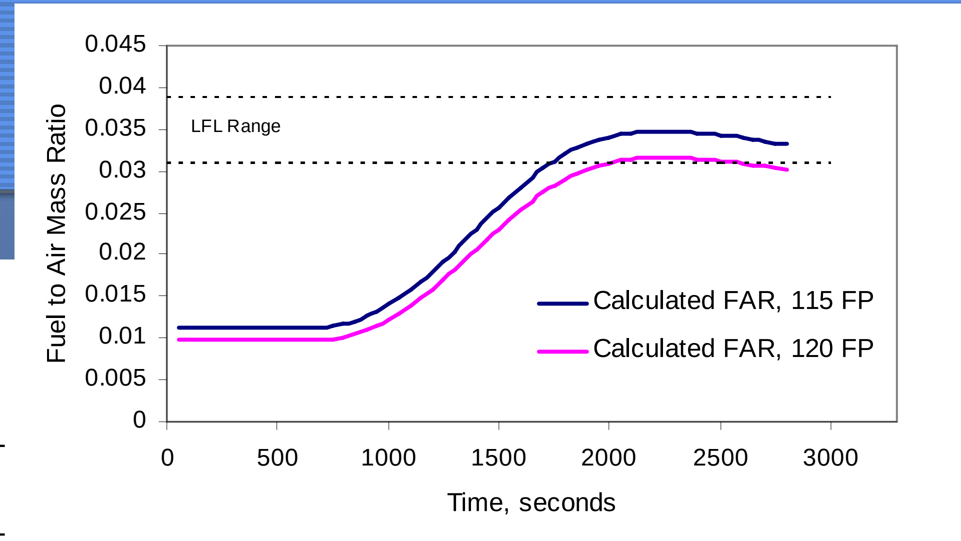
- An empirical criterion for estimating the FAR at the LFL states that at the LFL the FAR on a dry air basis is (*for most saturated hydrocarbons*) (Kuchta 1985)

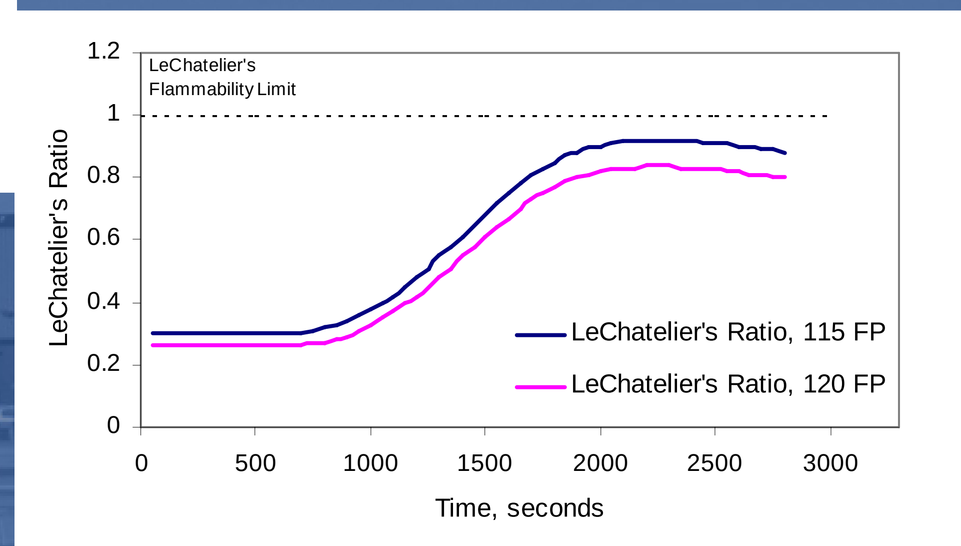
FAR = 0.035±0.004 at 0°C

Flammability Assessment:

Fuel tank at sea level



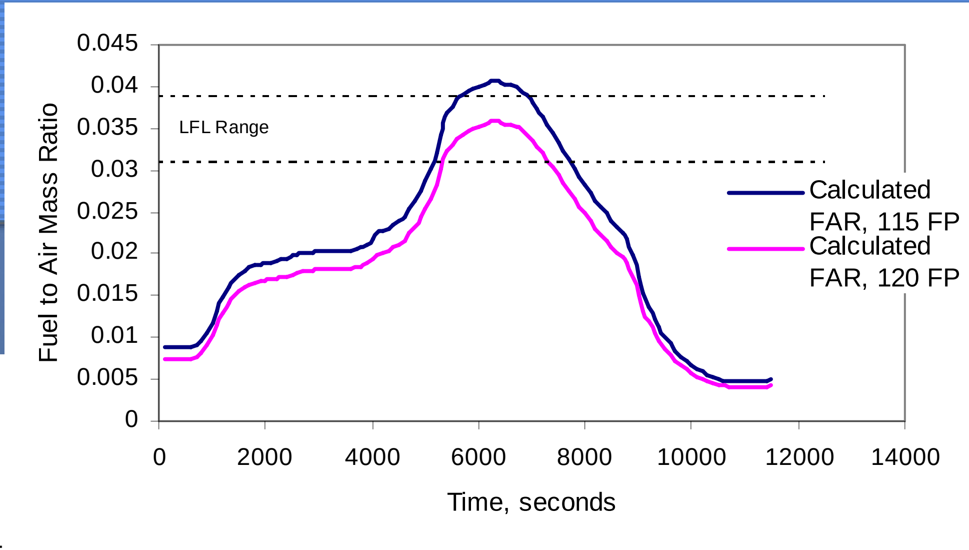


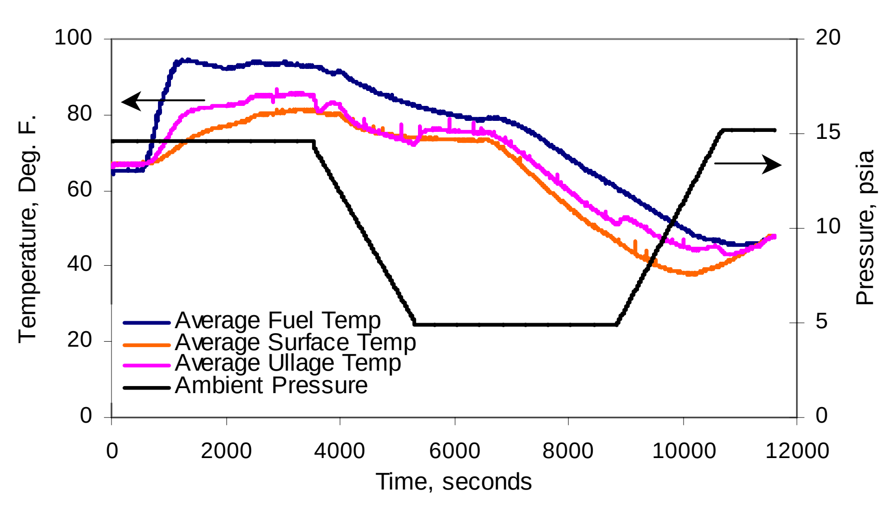


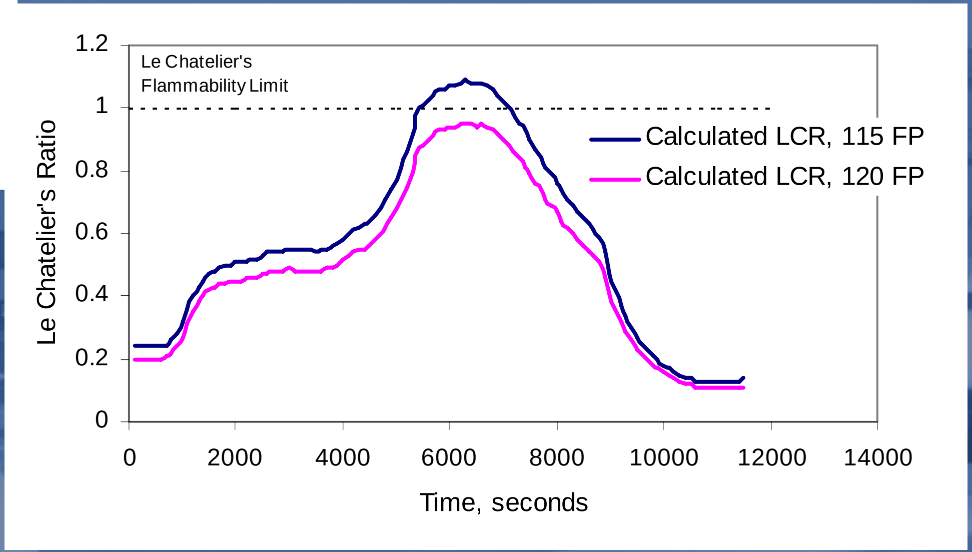
- FAR rule and Le Chatelier's rule were used to assess the flammability using the model calculations
- Fuel compositions with flashpoints bracketing the experimental fuel flashpoint

Flammability Assessment:

Simulated Flight at 30,000'







- FAR rule and Le Chatelier's rule were used to assess the flammability using the model calculations
- Fuel compositions with flashpoints bracketing the experimental fuel flashpoint

Conclusions

- Experimentation was successful in measuring ullage vapor concentration in a simulated fuel tank exposed to varying ambient conditions
- A large data set was generated that can be used for validating fuel vaporization models
- The model used in this work proved to be accurate in it's predictions of ullage gas temperature and ullage gas vapor concentration
- The model was useful in describing the transport processes occurring within the tank and explaining the ullage vapor concentration with a mass balance
- The model was useful in estimating the level of mixture flammability in the ullage utilizing both FAR and Le Chatelier's criterion for the lower flammability limit

Recommendations for Future Research in This Area

- Further detailed experimental data on JP-8 or Jet A flammability limits
- Laboratory testing in scale model partitioned aircraft fuel tanks
- Sampling from a fully instrumented fuel tank on an in-flight aircraft

Thank You…Questions?