Vaporization of JP8 Jet Fuel in a Simulated Aircraft Fuel Tank Under Varying Ambient Conditions

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Outline

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- Motivation
- Objectives

PART TWO – MODEL DESCRIPTION

- Description of Model
- Discussion of JP-8 and Jet A fuel characterization

PART THREE – EXPERIMENTAL

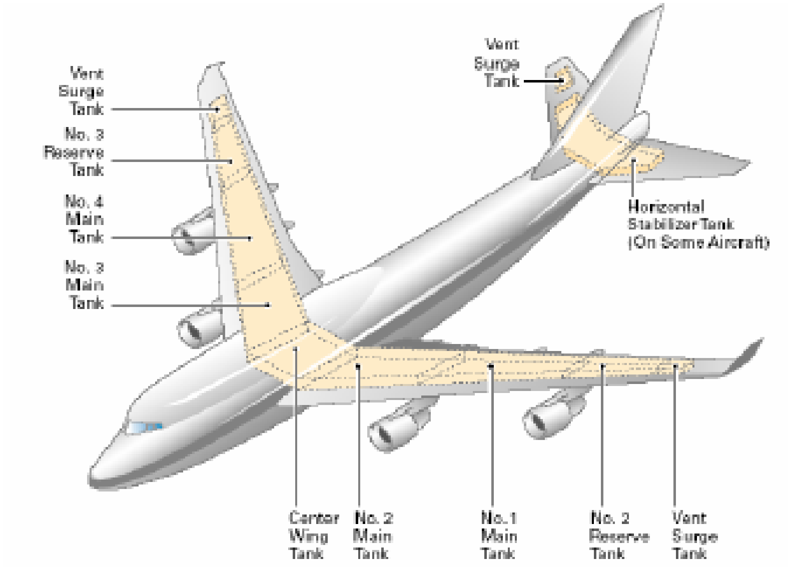
- Description of Experimental Setup and procedures
- Typical fuel vaporization results

Introduction

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

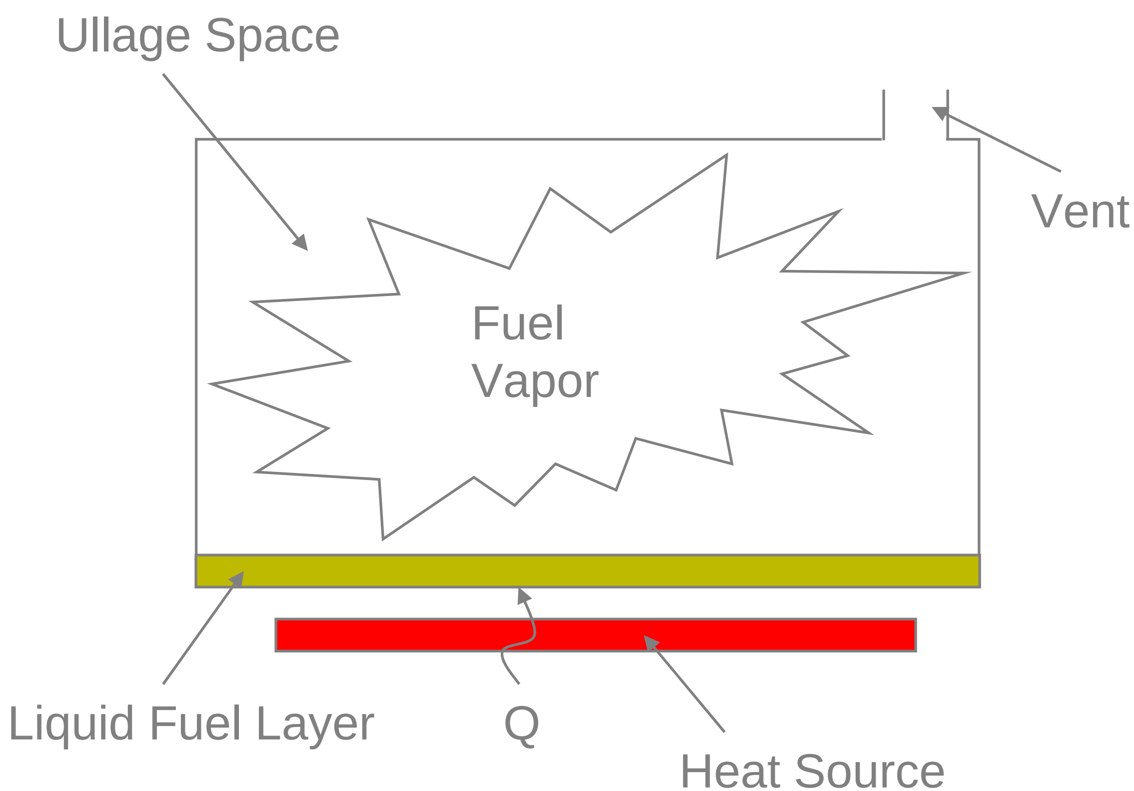
- **Primary motivation resulted from the TWA Flight 800 disaster in 1996**

- **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



Objectives

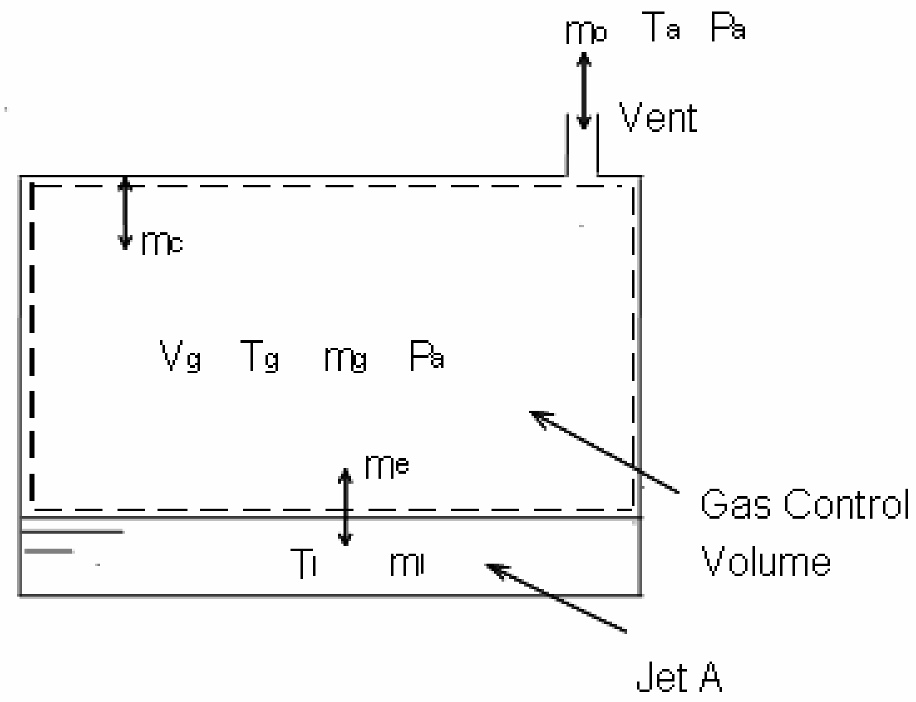
- **An experiment was designed to:**
  - Simulate in-flight environment around a fuel tank
    - Fuel tank situated in an environmental chamber that could simultaneously vary the ambient chamber temperature and pressure
  - Measure conditions in and around the fuel tank
    - Fuel tank instrumented with 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**

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

Modeling: 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
- **Natural convection enclosure heat transfer correlations**
- **Heat and mass transfer analogy for the mass transfer coefficients**

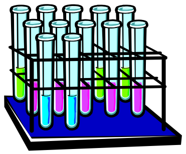
Brief Review of Jet Fuels

Fuel Type	Min. Flash Point (°F)	Max Freeze Point (°F)	Years in Use
JP1	109	-77	1944-47
JP4	0	-77	1951-95
JP5	140	-51	1952-present
JP6	140	-66	1956(XB-70)
JP7	140	-47	1960's(SR-71)
JP8	100	-53	1978-present
Jet A	100	-40	1950's-present
Jet A-1	100	-47	1950's-present

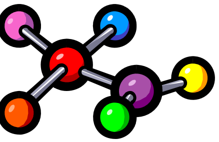
- **ASTM D 1655 is the current standard for Jet-A, Jet –A1, and JP-8**
- **Regulates maximum and minimum limits for stated properties or measurements**
- **Does not require an exact composition of chemical species, and can consist of hundreds of different components**
- **Analysis has revealed over 300 compounds in a batch of Jet-A, and the composition is about 75-85% paraffin compounds**

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**



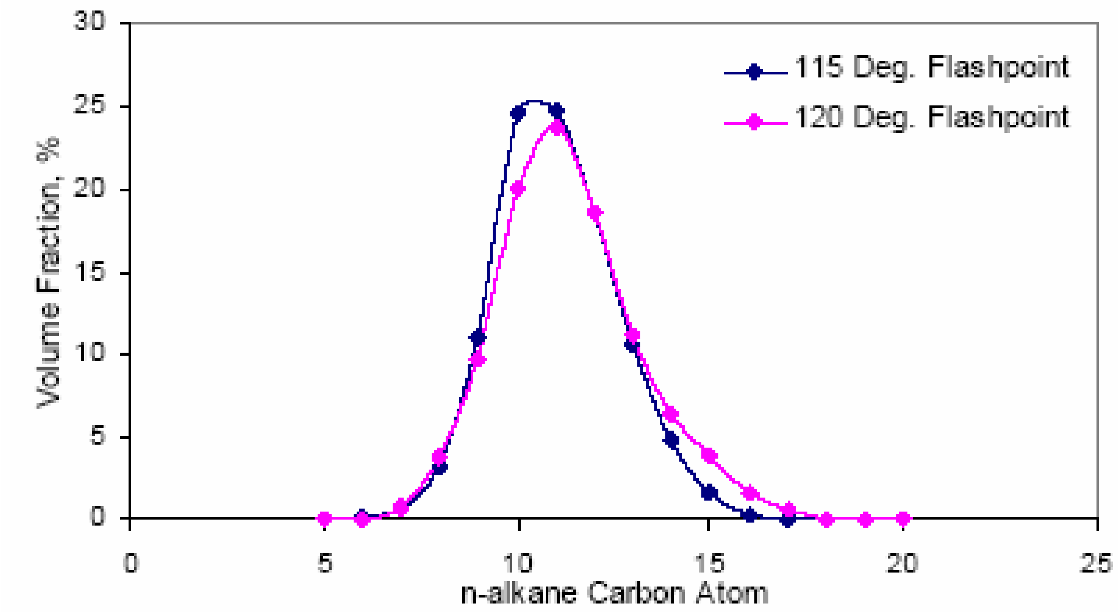
- **The approach taken by Woodrow effectively reduces the number of components from over 300 down to 16 (C5-C20 alkanes)**
- **The results from Woodrow's work present liquid compositions of different JP-8 samples with varying flashpoints in terms of the mole fractions of C5-C20 alkanes**



- **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

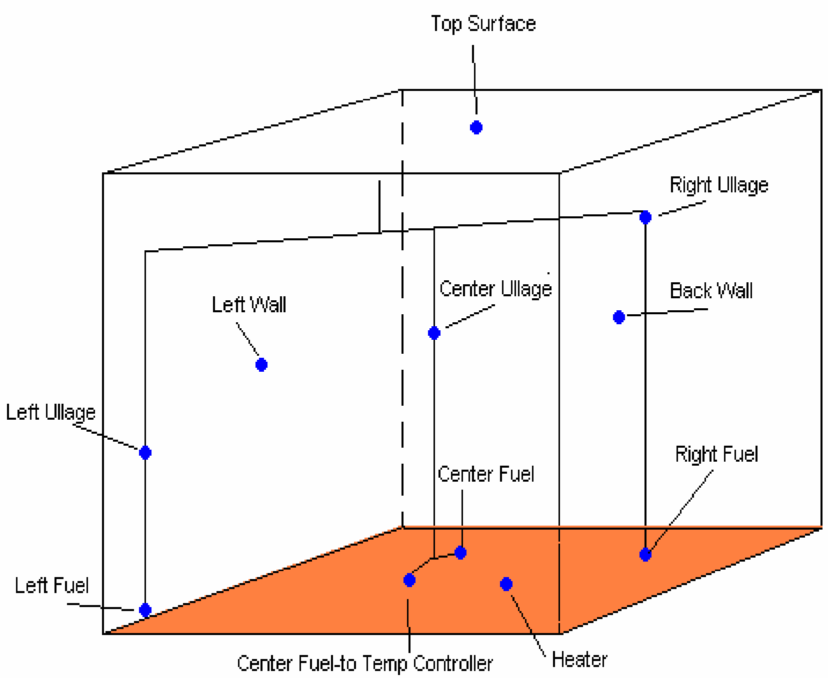


Environmental chamber designed to simulate the temporal changes in temperature and pressure appropriate to an in-flight aircraft

- 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

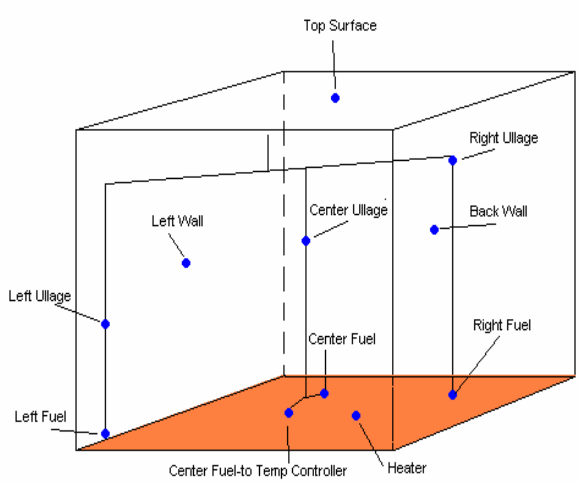
- •36"w x 36" d x 24" h, ¼" Al
- •2 access panels on top surface for thermocouple penetration and ullage sampling
- •2" diameter vent hole, 3" diameter fuel fill



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**

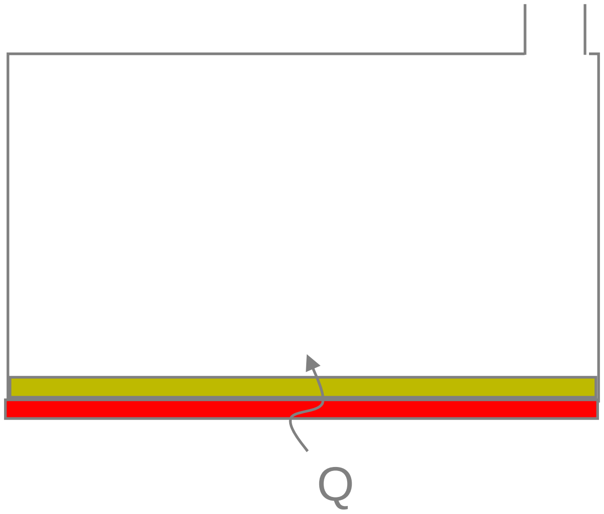
Experimental Procedure

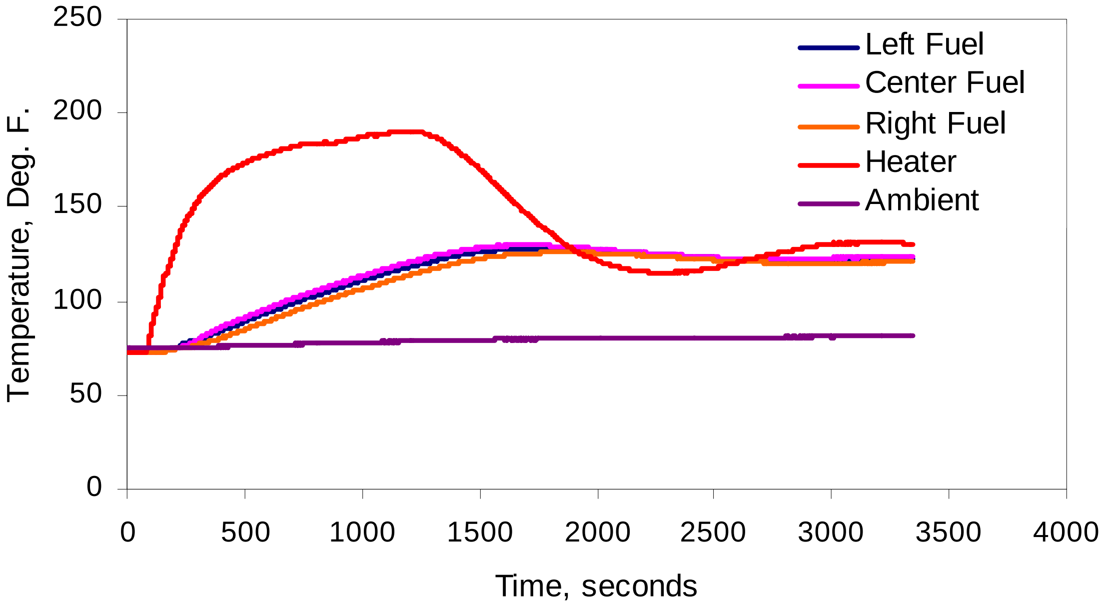
- **Initial Conditions**
  - The initial condition was decided to be at the point of equilibrium, typically achieved about 1-2 hours after fuel was loaded and chamber was sealed
  - Initial data indicated that at equilibrium the tank temperatures and ullage vapor concentration varied little with time (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 set point 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

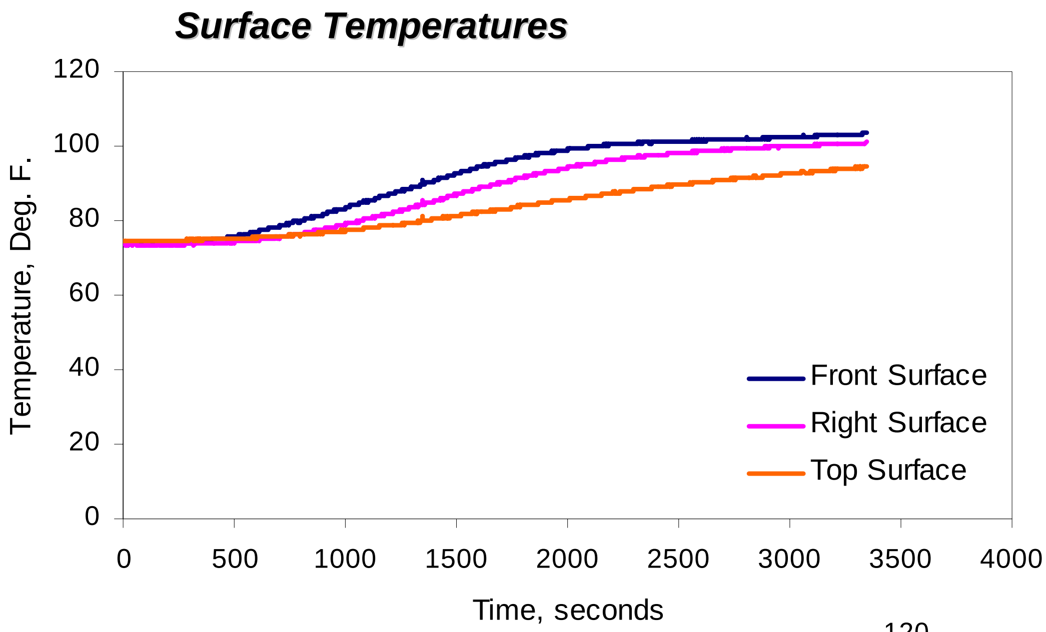
	Altitude			
Test Type:	***0***	***10,000***	***20,000***	***30,000***
Const. P	X	X	X	X
Vary T & P	*N/A*	X	X	X
Isooctane	X	*N/A*	*N/A*	*N/A*
Dry Tank	X	*N/A*	*N/A*	X

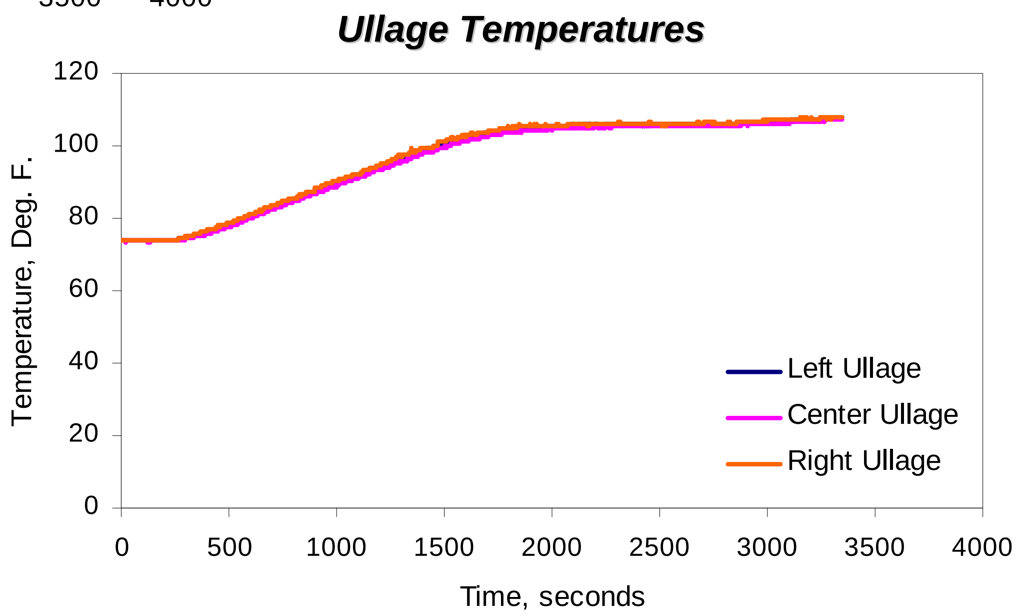
Fuel Tank at Sea Level, Constant Ambient Conditions



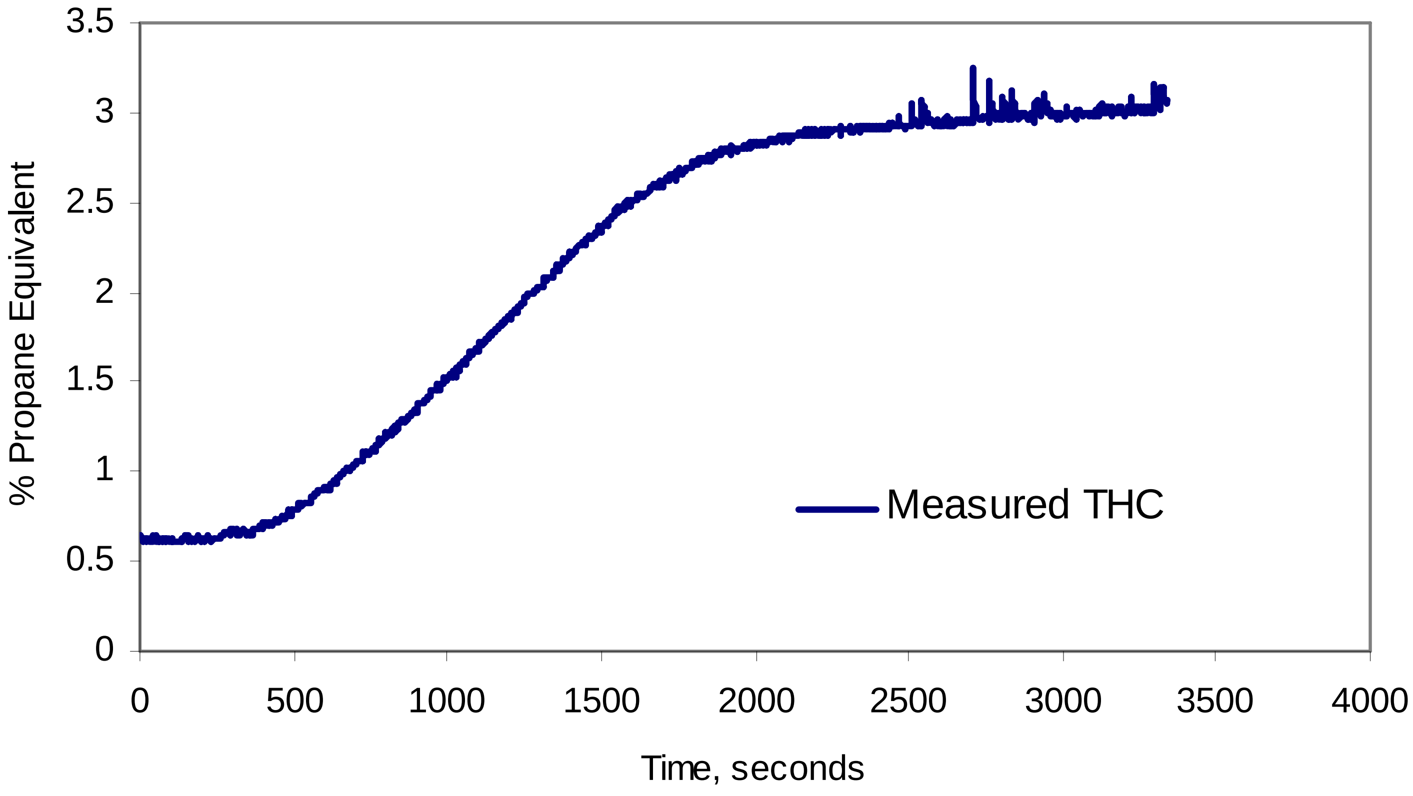


Liquid, Heater, Ambient Temperatures


Surface Temperatures
120
100
80
60
40
20
0
Temperature, Deg. F.
0
500
1000
1500
2000
2500
3000
3500
4000
Time, seconds
Front Surface
Right Surface
Top Surface

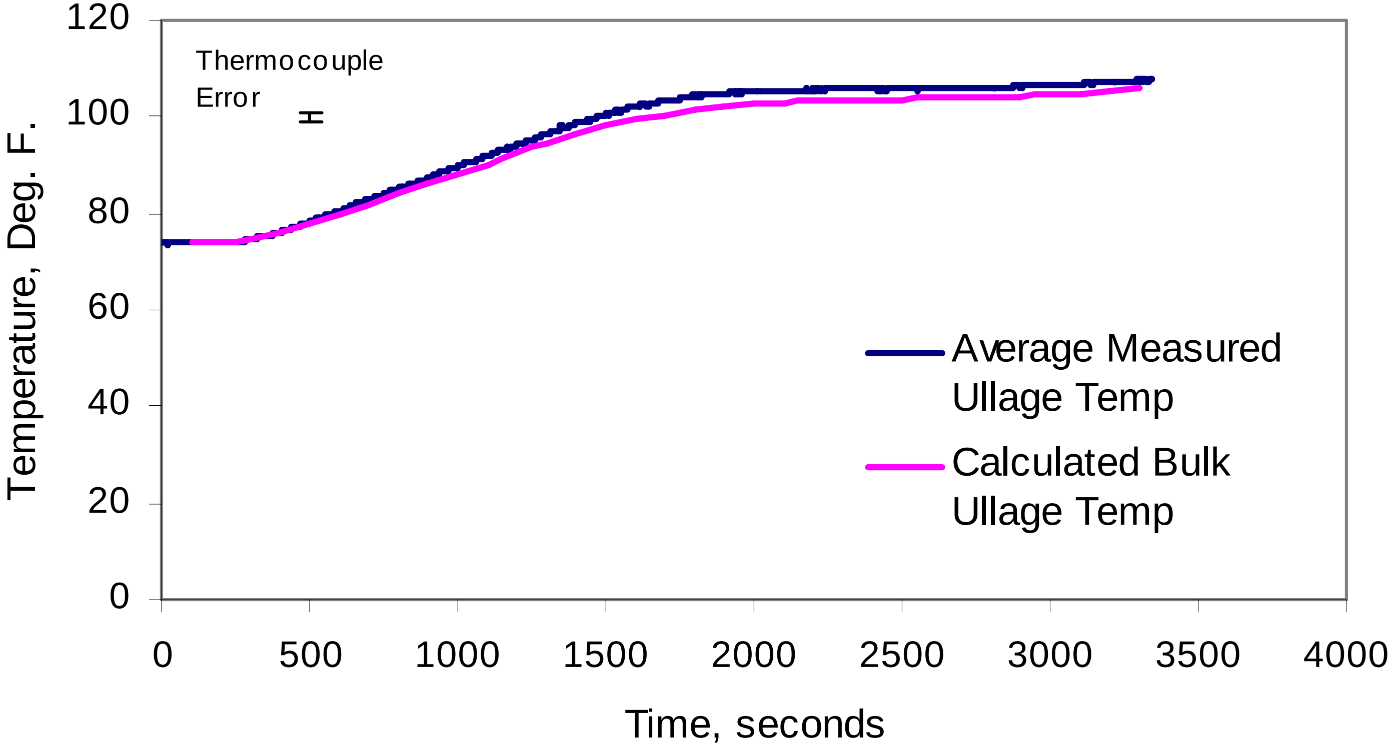

Ullage Temperatures
120
100
80
60
40
20
0
Temperature, Deg. F.
0
500
1000
1500
2000
2500
3000
3500
4000
Time, seconds
Left Ullage
Center Ullage
Right Ullage

Measured Fuel Vapor Concentration



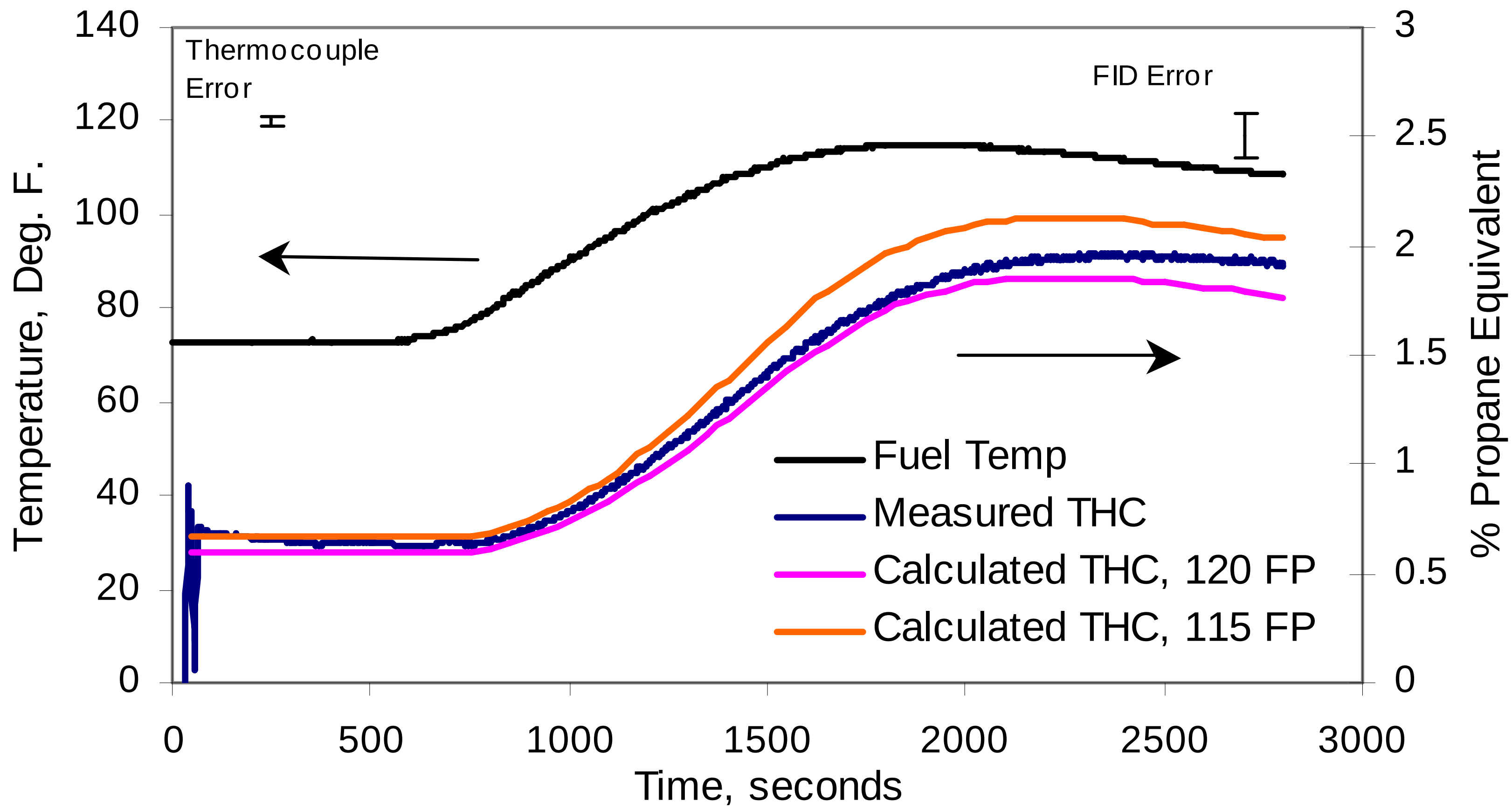
Ullage Vapor Concentration

Calculated Ullage Temperature



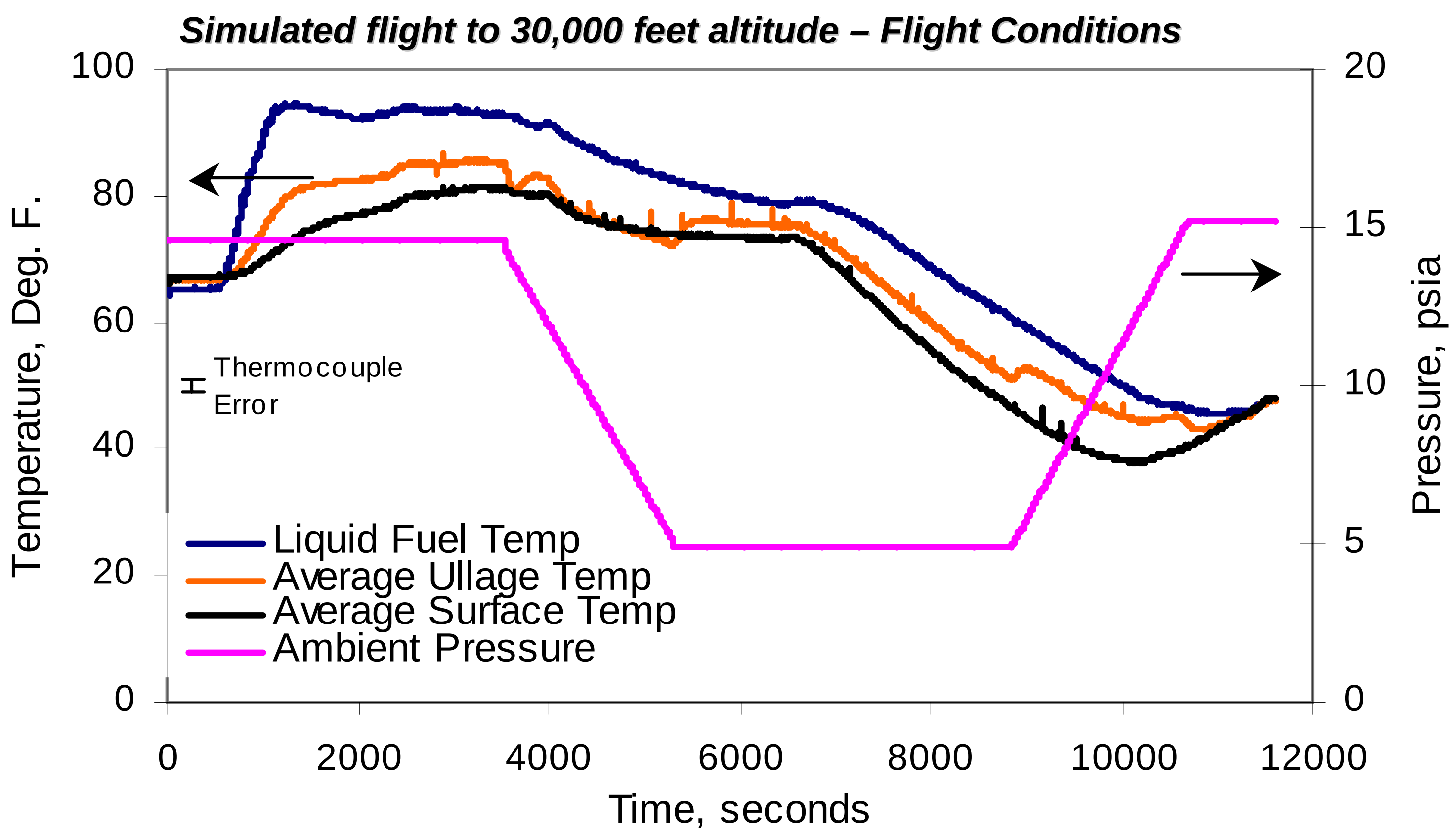
Calculated and Measured Ullage Temperature

Calculated Fuel Vapor Concentration

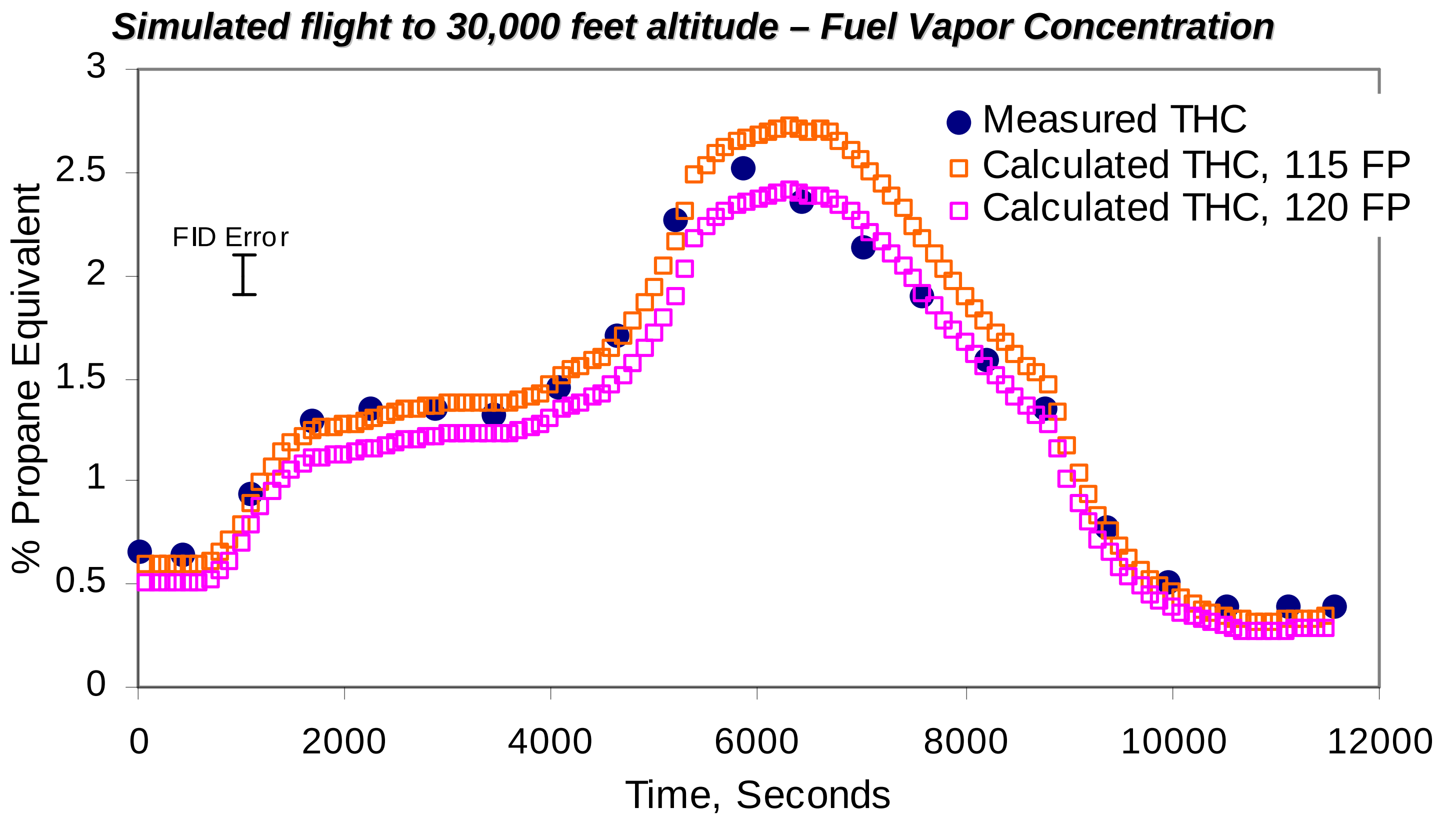


Varying Ambient Conditions

- **Simulated Flight Conditions:**
  - 1 hour of ground time with fuel tank heating from below
  - Increase altitude at a rate of 1,000 feet per minute
  - Cruise at altitude for one hour
  - Decrease altitude at -1,000 feet per minute
  - Return to ground



Varying Ambient Conditions



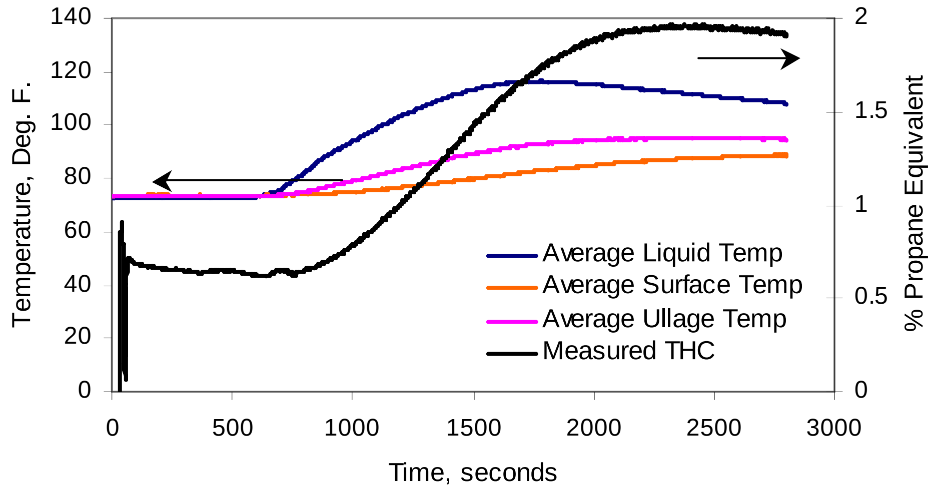
Calculated Mass Transport:

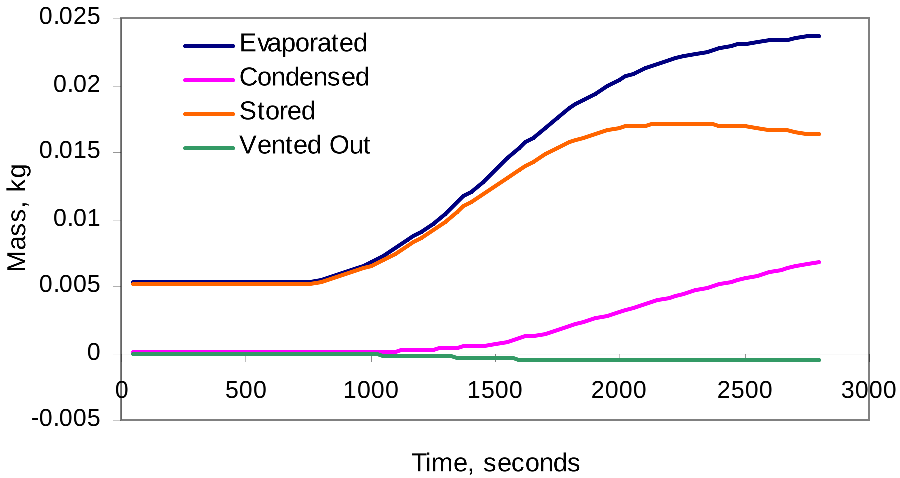
Fuel tank at sea level

- **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**

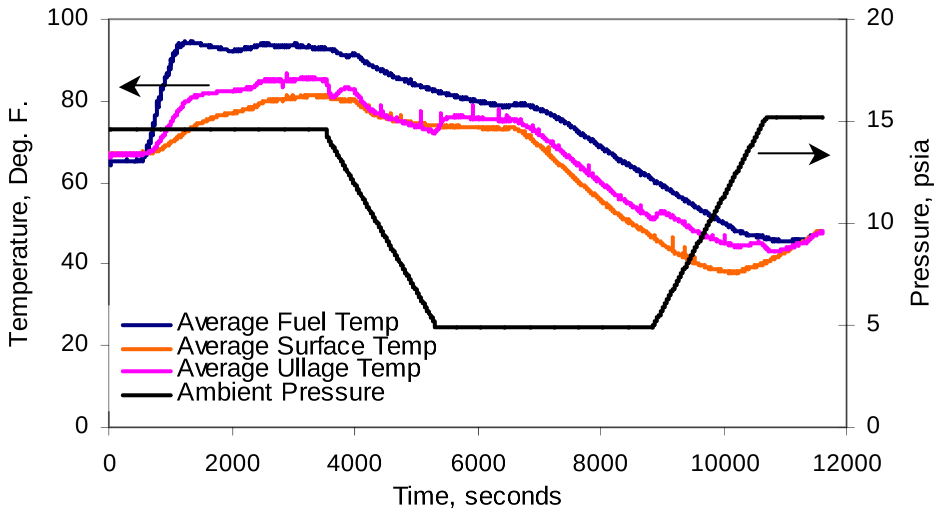
- **The mass of fuel stored in the ullage gas at a given moment can be calculated when considering**
  - Mass of fuel vaporized
  - Mass of fuel condensed on inner tank surfaces
  - Mass of fuel vented out



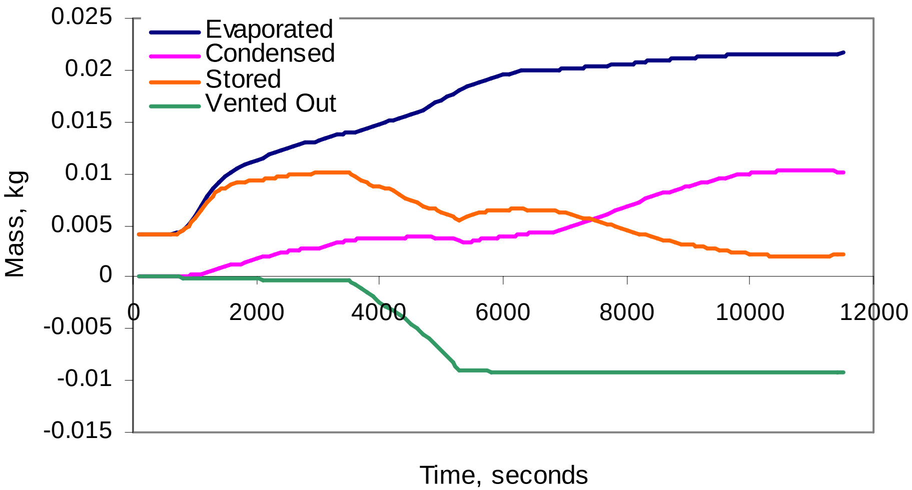


Calculated Mass Transport:

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

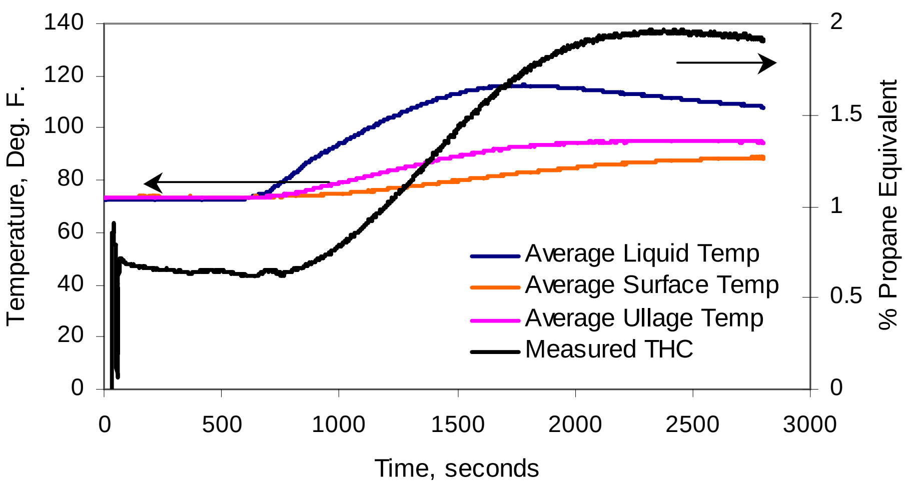
$$LC = (1.02 - 0.000721 * T)\sum_{I} \frac{x_i}{LFL_i}, i = 1 \rightarrow N$$

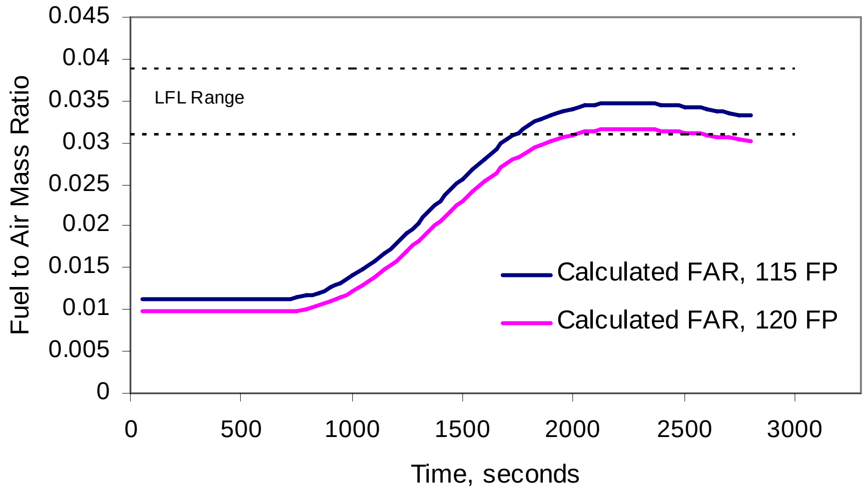
- An empirical criterion for estimating the FAR at the LFL states that at the LFL the FAR on a dry air basis is (*for most saturated hydrocarbons*) (Kuchta 1985)

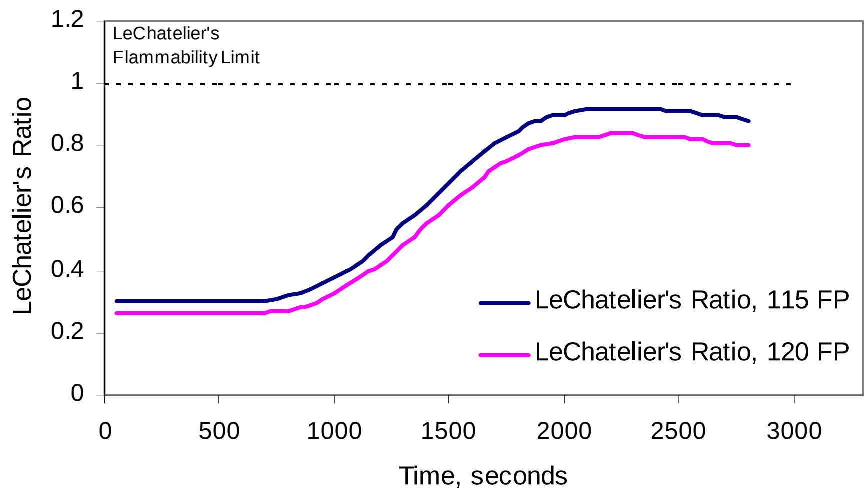
$$FAR = 0.035 \pm 0.004 \text{ at } 0°C$$

Flammability Assessment:

Fuel tank at sea level

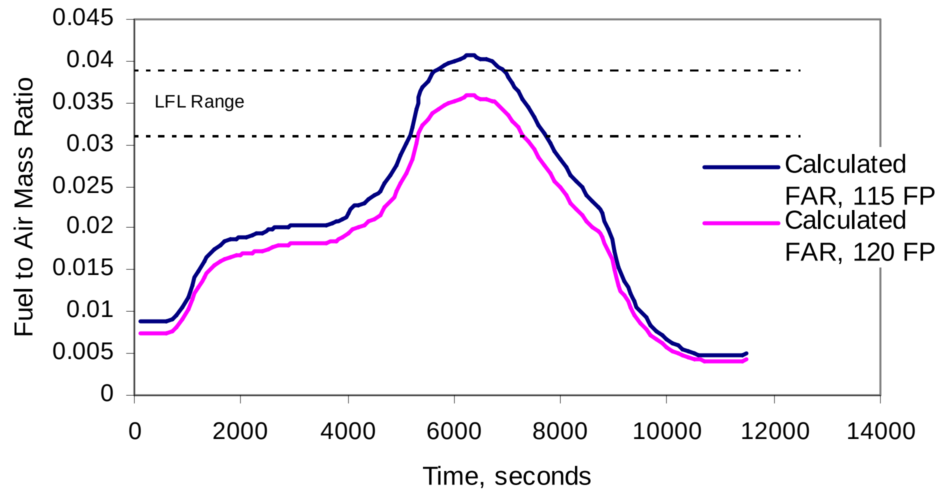


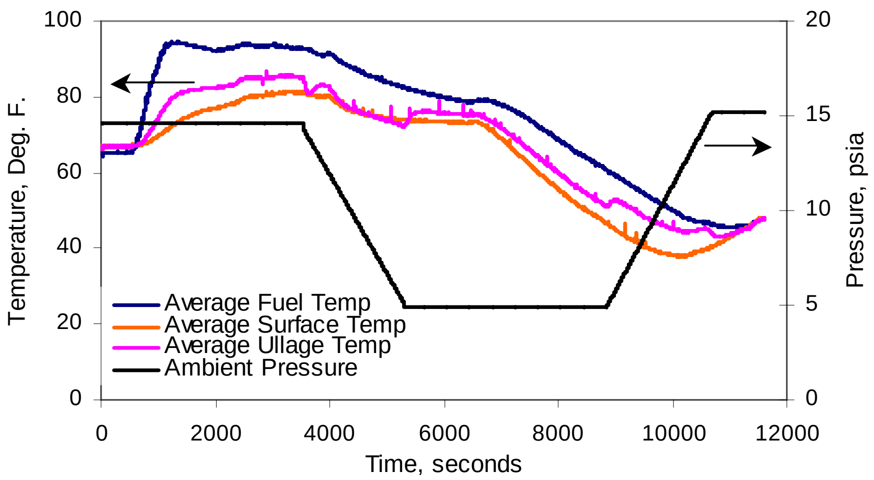


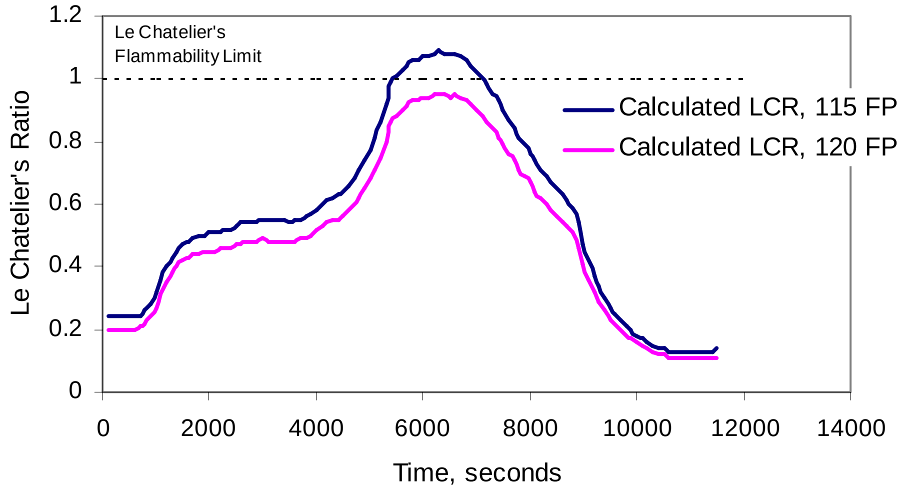


Flammability Assessment:

Simulated Flight at 30,000'







Summary

- 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 (wing and center wing)**
- **Sampling from a fully instrumented fuel tank on an in-flight aircraft**