Federal Aviation Administration

Modeling Flammability Exposure in a Commercial Transport Fuel Tank with Inerting

Steve Summer
William Cavage
Robert Ochs
Federal Aviation Administration
Fire Safety Branch

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Researchers

William M. Cavage
FAA Fire Safety Branch
Wm. J. Hughes Technical Center
William.M.Cavage@faa.gov

Robert I. Ochs
FAA Fire Safety Branch
Wm. J. Hughes Technical Center
Robert.Ochs@faa.gov

Steven M. Summer
FAA Fire Safety Branch
Wm. J. Hughes Technical Center
Steven.Summer@faa.gov

C. E. Polymeropolous
Rutgers University
Dept. of Mechanical & Aerospace Engg.
poly@jove.rutgers.edu

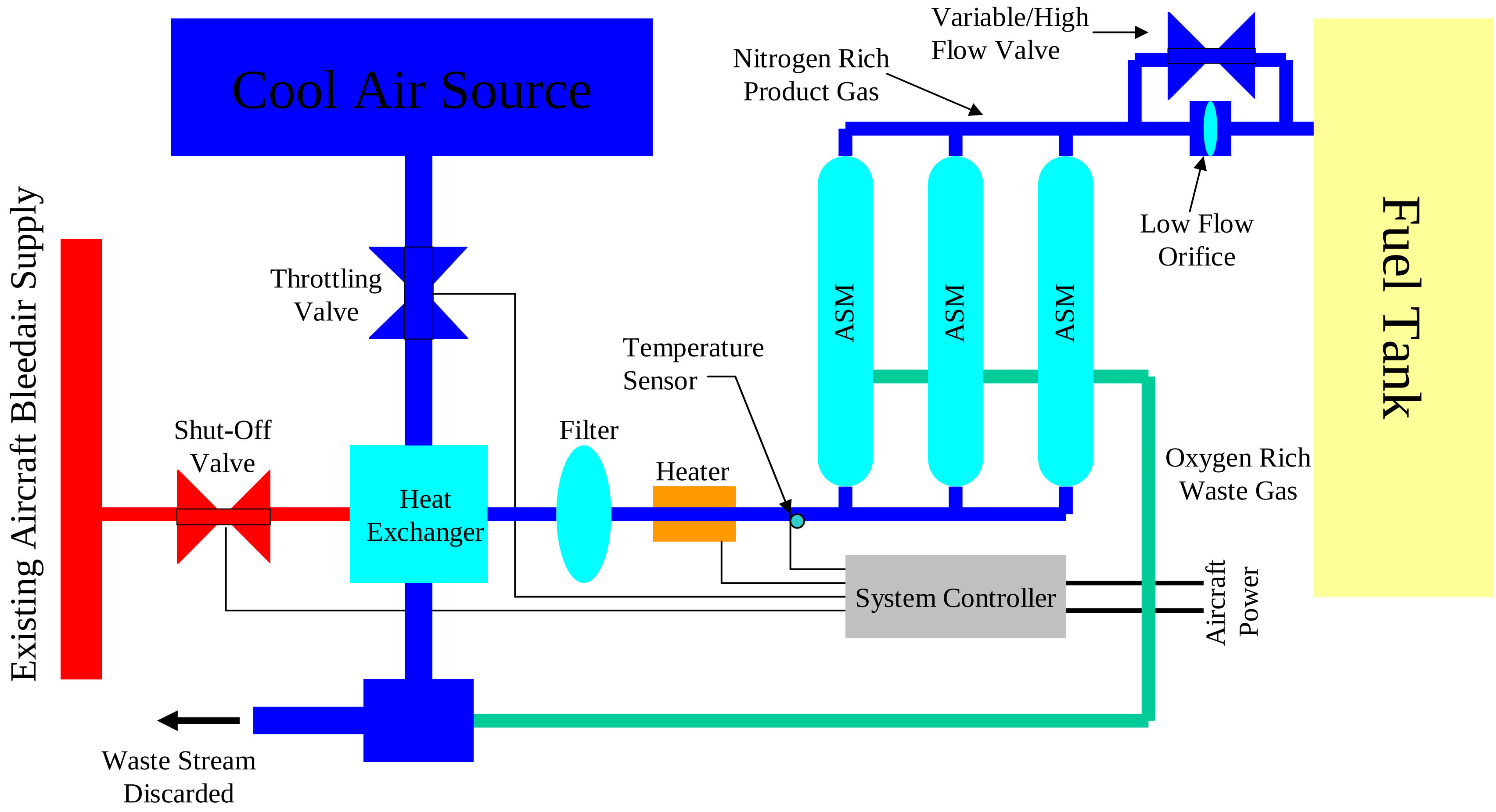
Objectives

- Using the FAA’s current knowledge base and modeling capabilities, develop a representative 747 aircraft flight cycle and predict the flammability exposure of the center wing tank ullage by modeling both inert gas dispersion and hydrocarbon evolution.

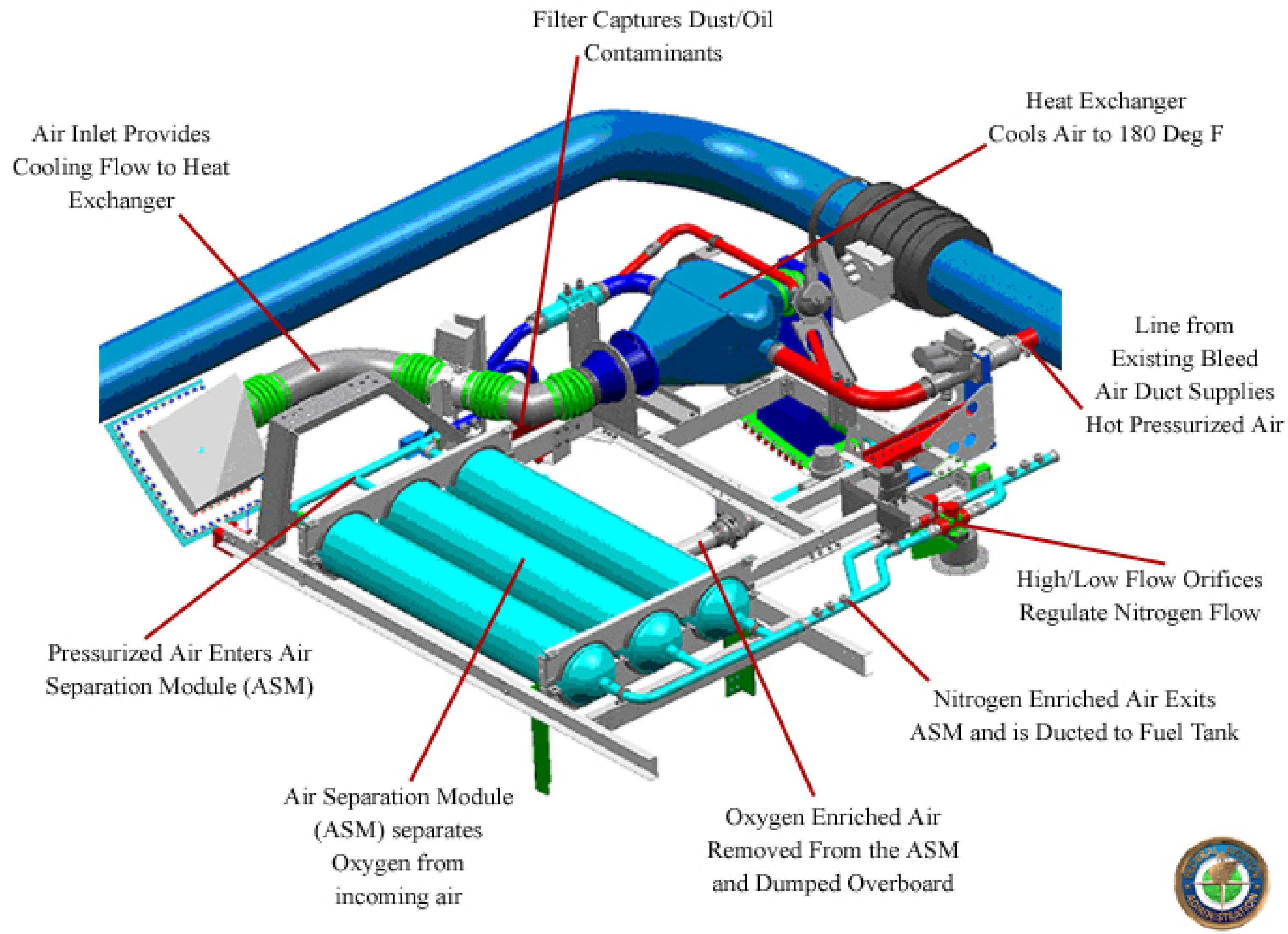
Introduction

- FAA fuel tank protection research has resulted in the development of a proof of concept inerting system designed to inert the CWT of a classic style Boeing model 747
- This proof of concept system has been tested on a ground based 747SP test article and flight tested on an Airbus A320 and NASA 747 Shuttle Carrier Aircraft
- FAA analytical modeling capabilities include:
  - Multiple-bay inerting model
  - Fuel vaporization/flammability model
- Using data from testing of the inerting system, modelling capabilities, and general knowledge of transport aircraft and inerting system operations, it is possible to generate a generic flight profile and examine the flammability exposure of the flight

Proof of Concept Inerting System

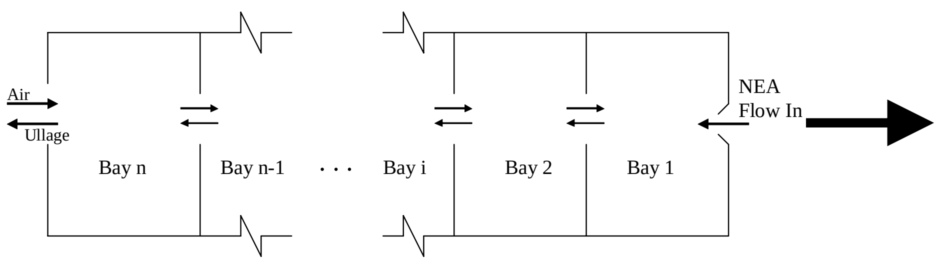


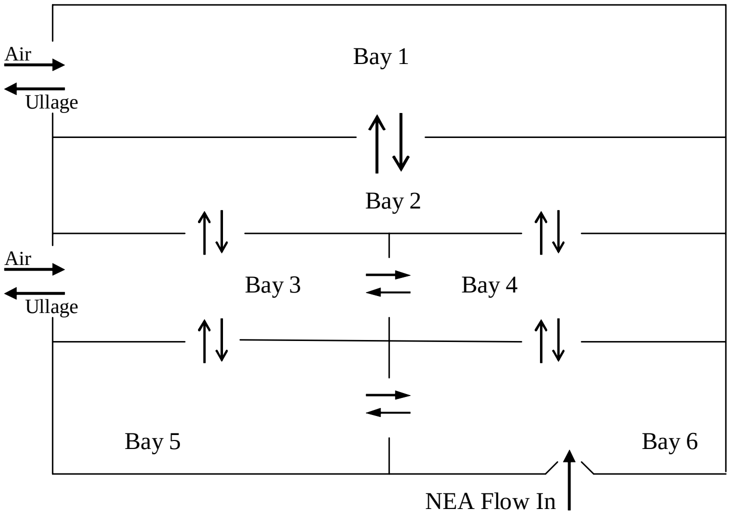
Schematic of On-Board Inert Gas Generation System (OBIGGS)



Multi-Bay Analytical Inerting Model

- Developed analytical model of multi-bay inerting in-flight based on previous ground based inerting model to simulate 747 SCA flight test scenario
  - First developed more simple "cascading" inerting model which has very few assumptions and is more easily validated
  - Model has one inert gas deposit (bay 1) and one vent (bay n)
  - Next, modified model to split flow to several bays and vent flow from several bays using flight test data for ratios





Multi-Bay Analytical Inerting Model

Calculation of Mass of Oxygen in Bay i of a Tank with n Bays

Bay i+1 | Bay i | Bay i-1

Bay Volume = V_i

$$\Delta m = \Delta\rho * V_i$$

$$M_{net_{Bay\ i}} = M_{NEA} + \Delta\rho(V_{Bay\ 1} + V_{Bay\ 2} + \cdots + V_{Bay\ i})$$

IF ⇨ $M_{net_{Bay\ i}} > 0 \quad (i.e.\ \Delta M_{ullage} < M_{NEA})$

Then ⇨ $Mo_{Out_{Bay\ i}} = M_{net_{Bay\ i}} + Fo_{Bay\ i}$

IF ⇨ $M_{net_{Bay\ i}} < 0 \quad (i.e.\ \Delta M_{ullage} > M_{NEA})$

Then ⇨ $Mo_{Out_{Bay\ i}} = M_{net_{Bay\ i}} + Fo_{Bay\ i+1}$

IF i = n, $Fo_{Bay\ i+1} = 0.209$

$$M_{Bay\ i} = M_{Bay\ i}(t-1) + \Delta M_{ullage}$$

$$Mo_{Bay\ i} = Mo_{Bay\ i}(t-1) + Mo_{Out_{Bay\ i}} - Mo_{Out_{Bay\ i-1}}$$

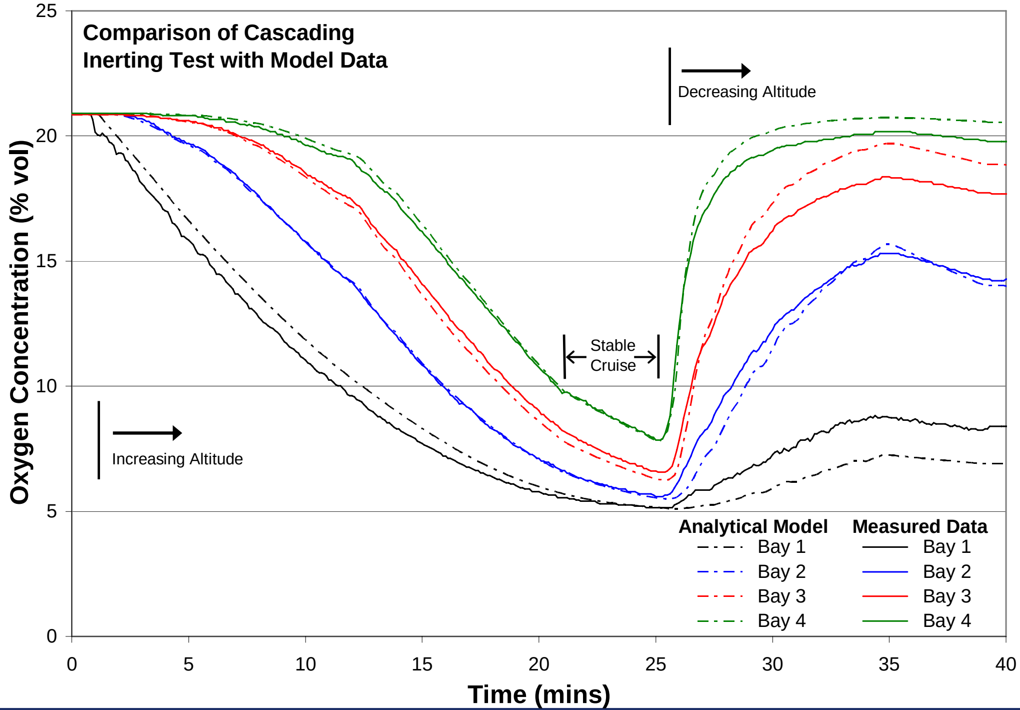
IF i = 1, $Mo_{Out_{Bay\ i-1}} = Mo_{NEA}$

$$Fo_{Bay\ i} = M_{Bay\ i} / Mo_{Bay\ i}$$

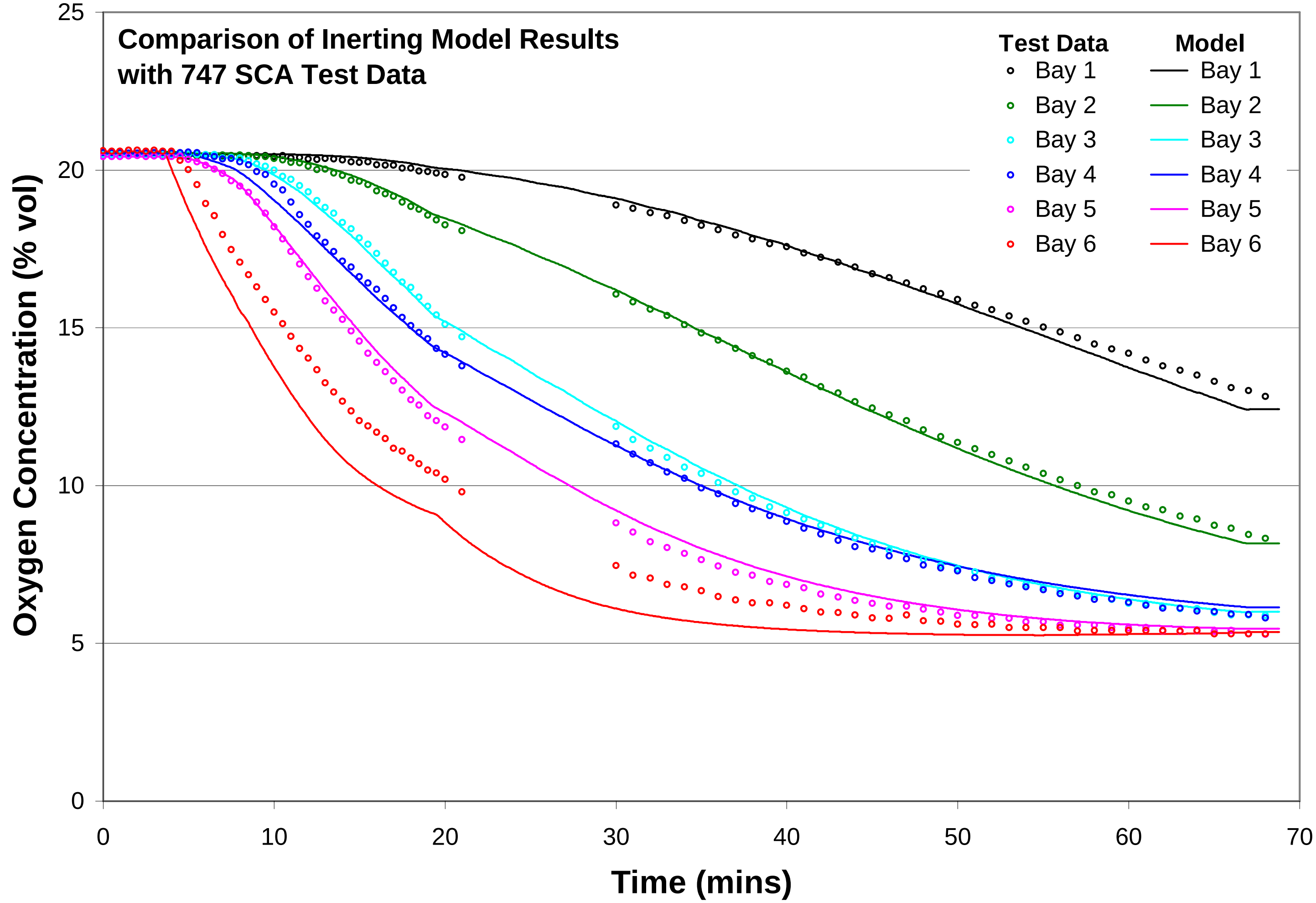
Flow ⇄ | Flow ⇄

Multi-Bay Analytical Inerting Model – Results Compared with Scale Tank Data

- Reconfigured the 747 scale tank to perform cascading inerting tests to compare results of scale tank with analytical model
  - Changed deposit and venting configuration and made holes between bays small to promote mixing
  - Results good but had significant discrepancies during descent
  - Differences contributed to scale tank lid leaking air in due to worn seal
  - Bulk average data matched identically further supporting conclusion



Results – Comparison of Inerting Model Data with NASA 747 SCA Flight Test Data



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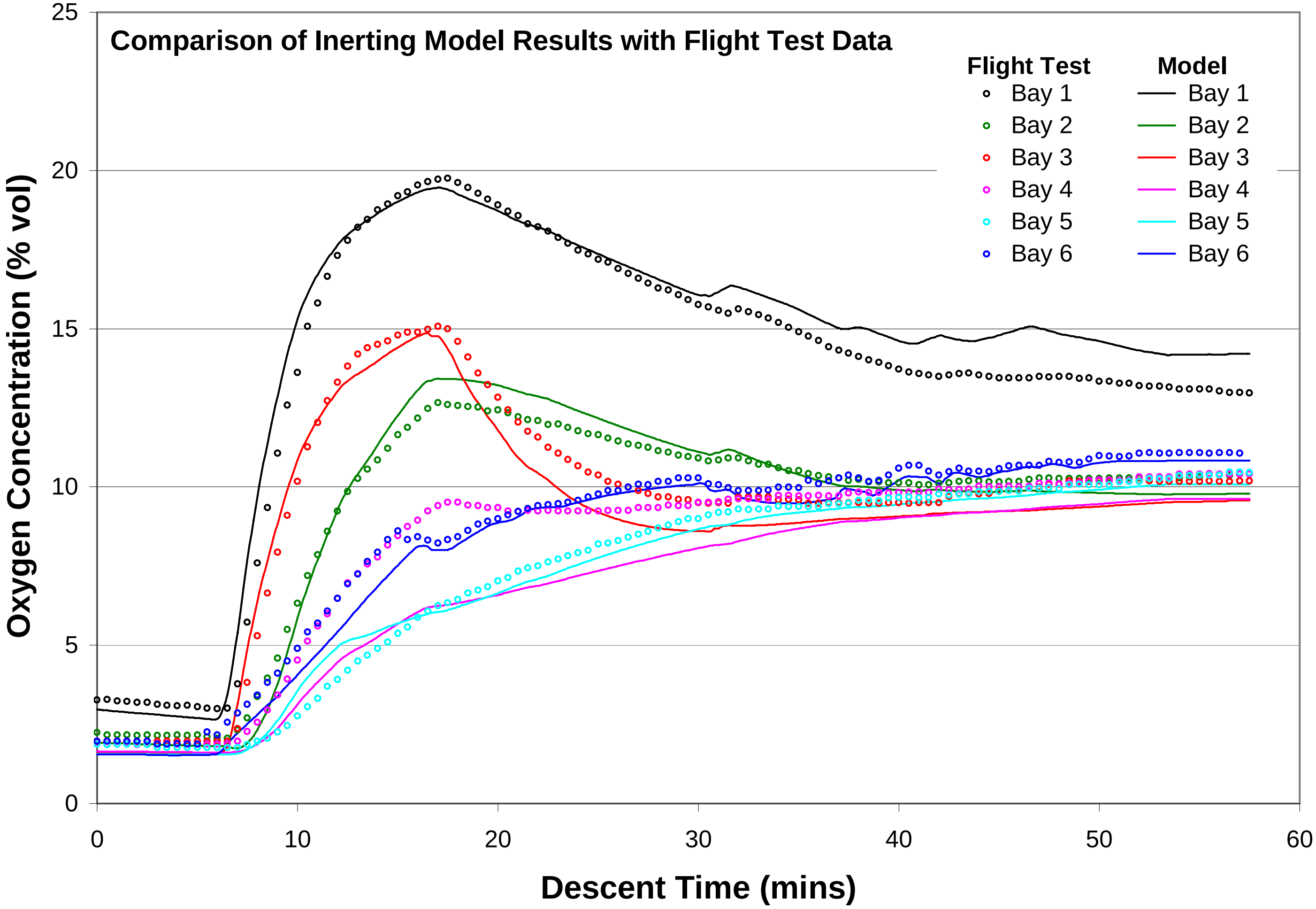
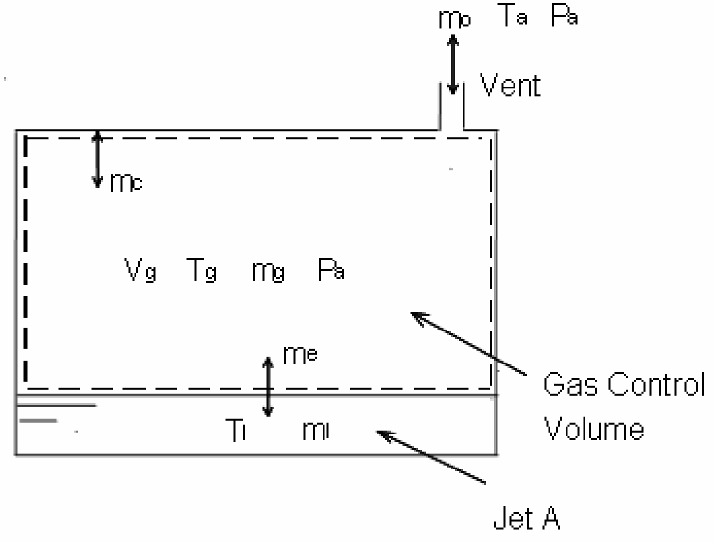
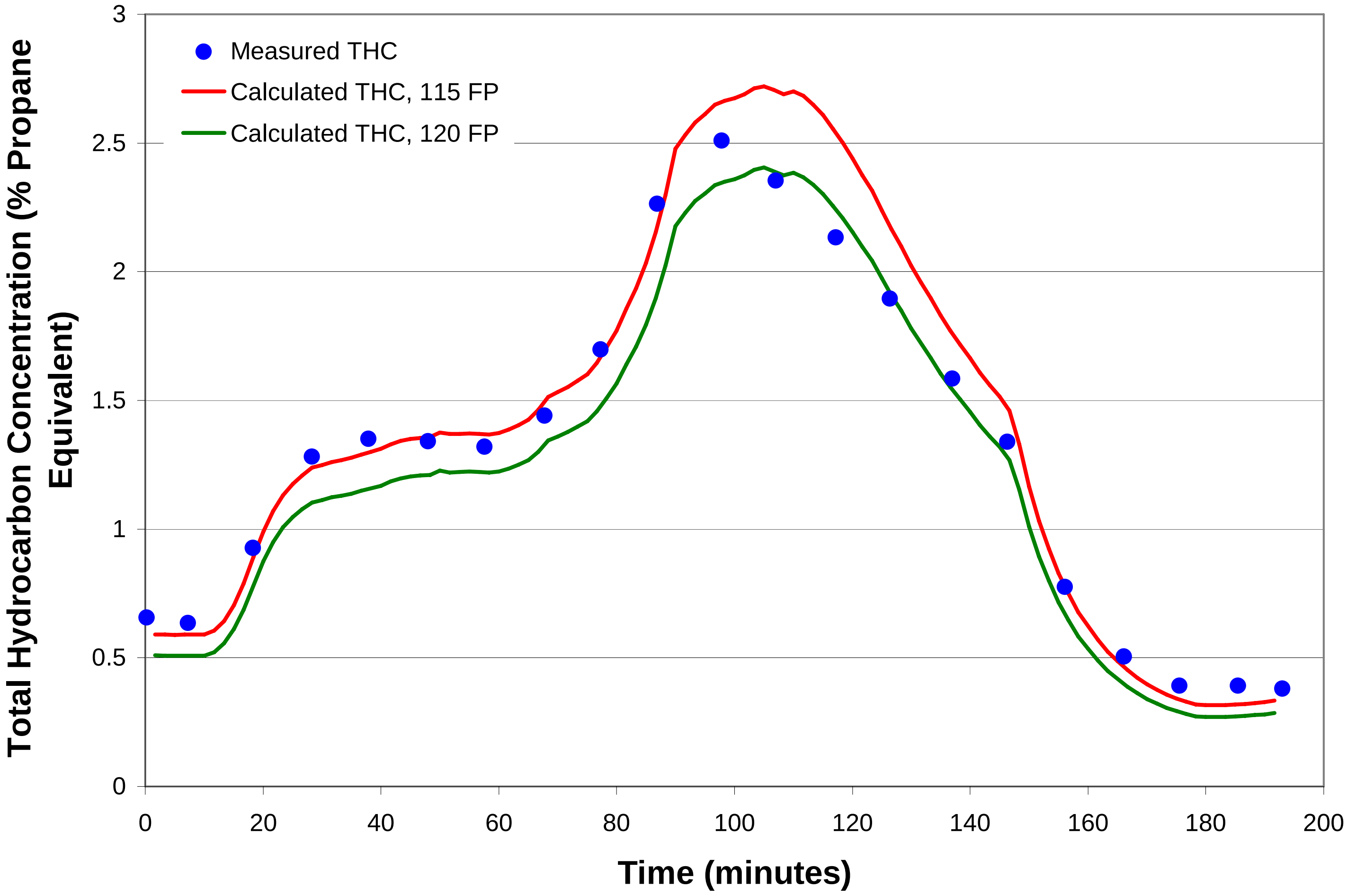


Multi-component Fuel Vaporization Model

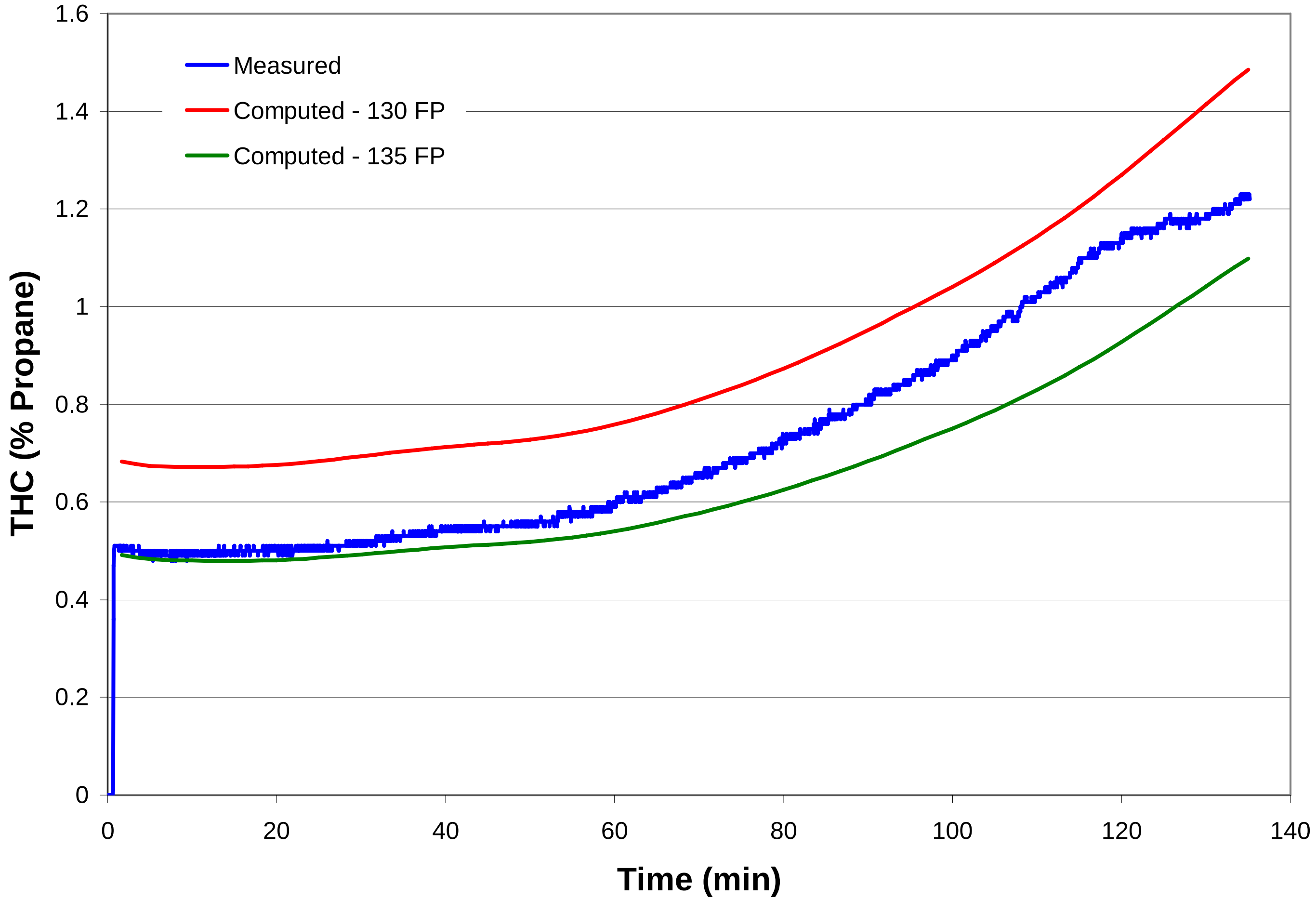
- The model used in this work (Polymeropoulos 2004) is an engineering model that allows for treating the complex natural convection heat and mass transfer processes within the tank using a simplified approach.
- The model assumes:
  - Well mixed gas and liquid phases
  - Uniformity of temperatures and 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)
- These assumptions allow for the use of empirical correlations for the prediction of the temporal variation of the fuel vapor composition within the ullage.
- The analogy between heat and mass transfer was used for estimating mass transfer coefficients for the multicomponent and condensation processes considered.



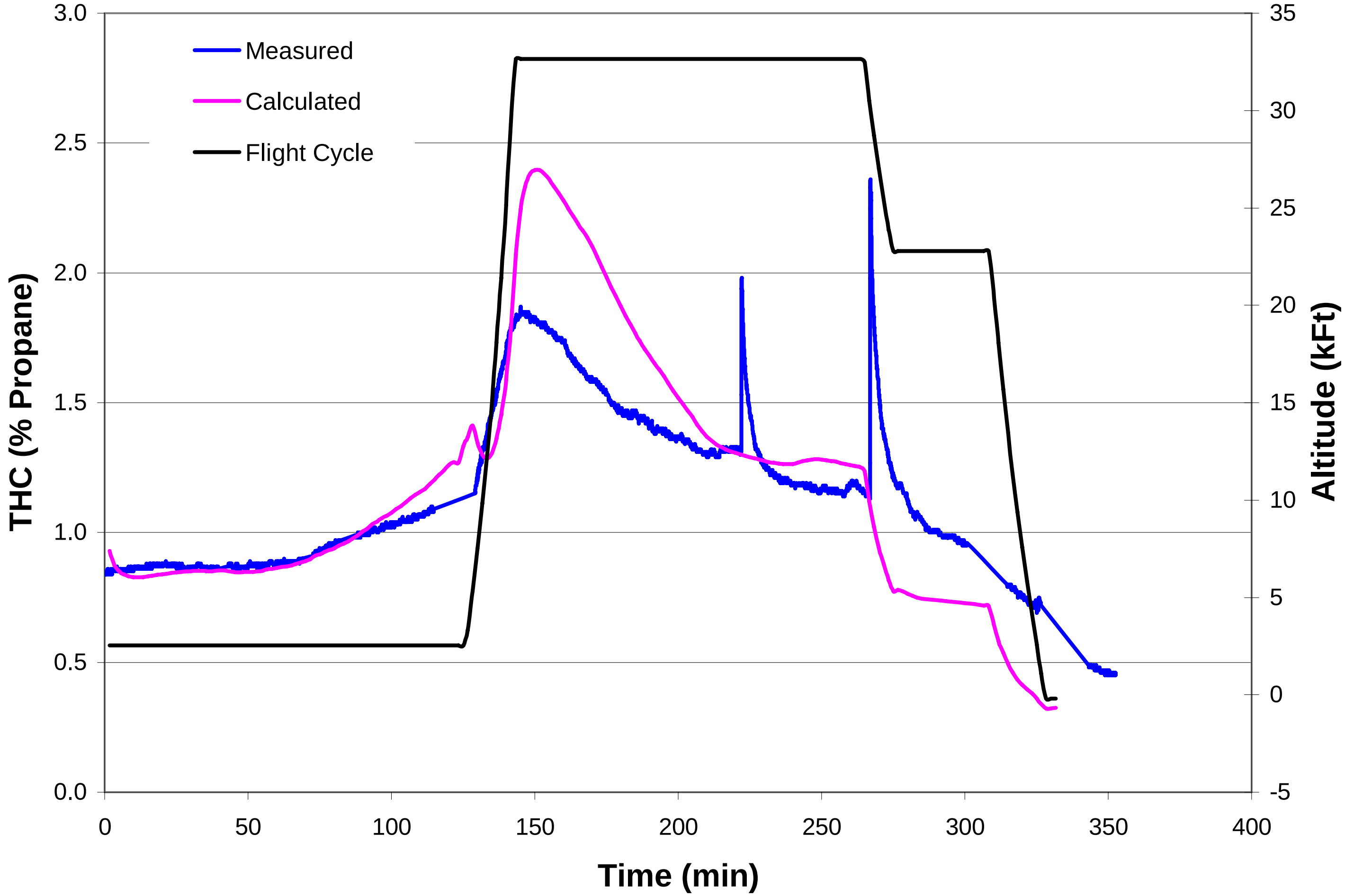
Results – Comparison of Vaporization Model Data with Laboratory Test Data



Results – Comparison of Vaporization Model Data with NASA 747 SCA Flight Test Results



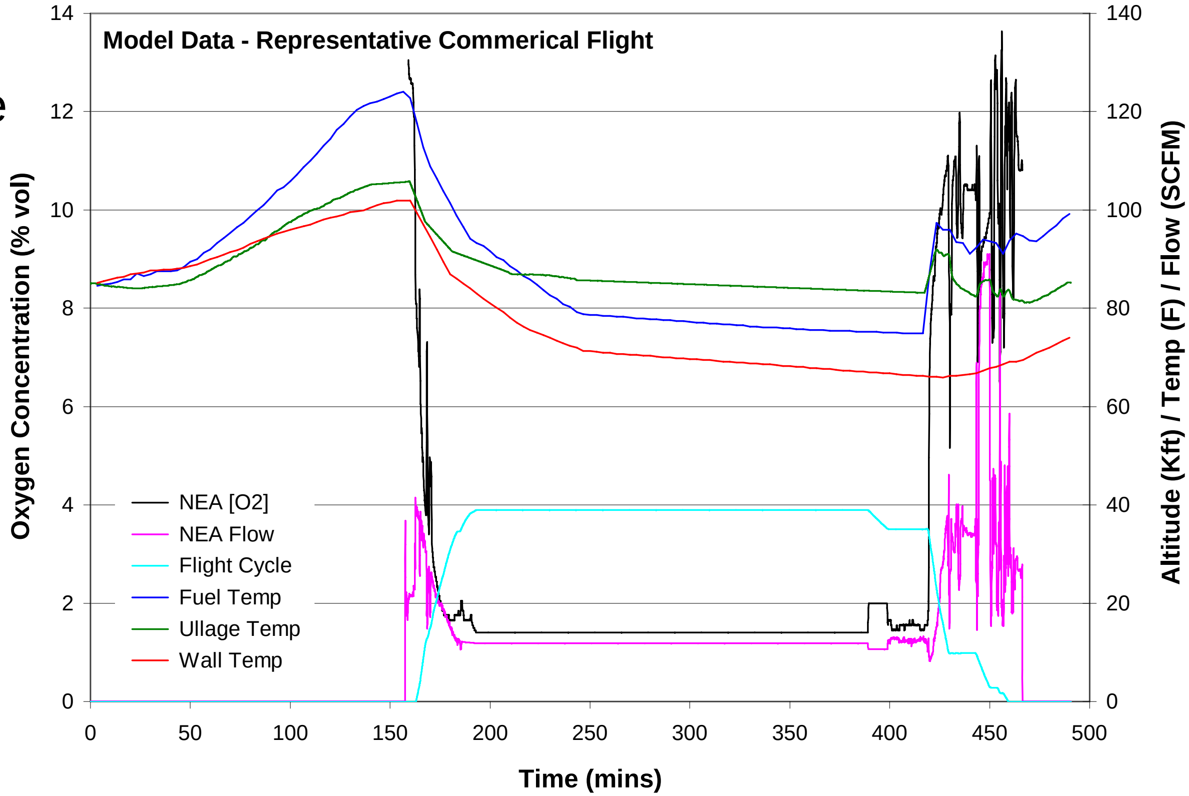
Results – Comparison of Vaporization Model Data with NASA 747 SCA Flight Test Results



Representative Flight Modeling

- Generic flight cycle generated using flight test data and knowledge of transport aircraft operations

- Inerting system modeled in this exercise is larger than the inerting system used in flight test to be more representative of a certified flammability reduction system as currently conceived.



Definition of Flammability

- The lower explosive limit (LEL) of Jet A, in terms of % propane can be calculated by:

$$LEL,\ ppm\,C_3H_8 = FAR_{LEL}\left(\frac{MW_{Air}}{MW_{Vapor}}\right)\times CR \times 10^6$$

where FAR_{LEL} = 0.03

MW_{air} = 28.84 g/mol

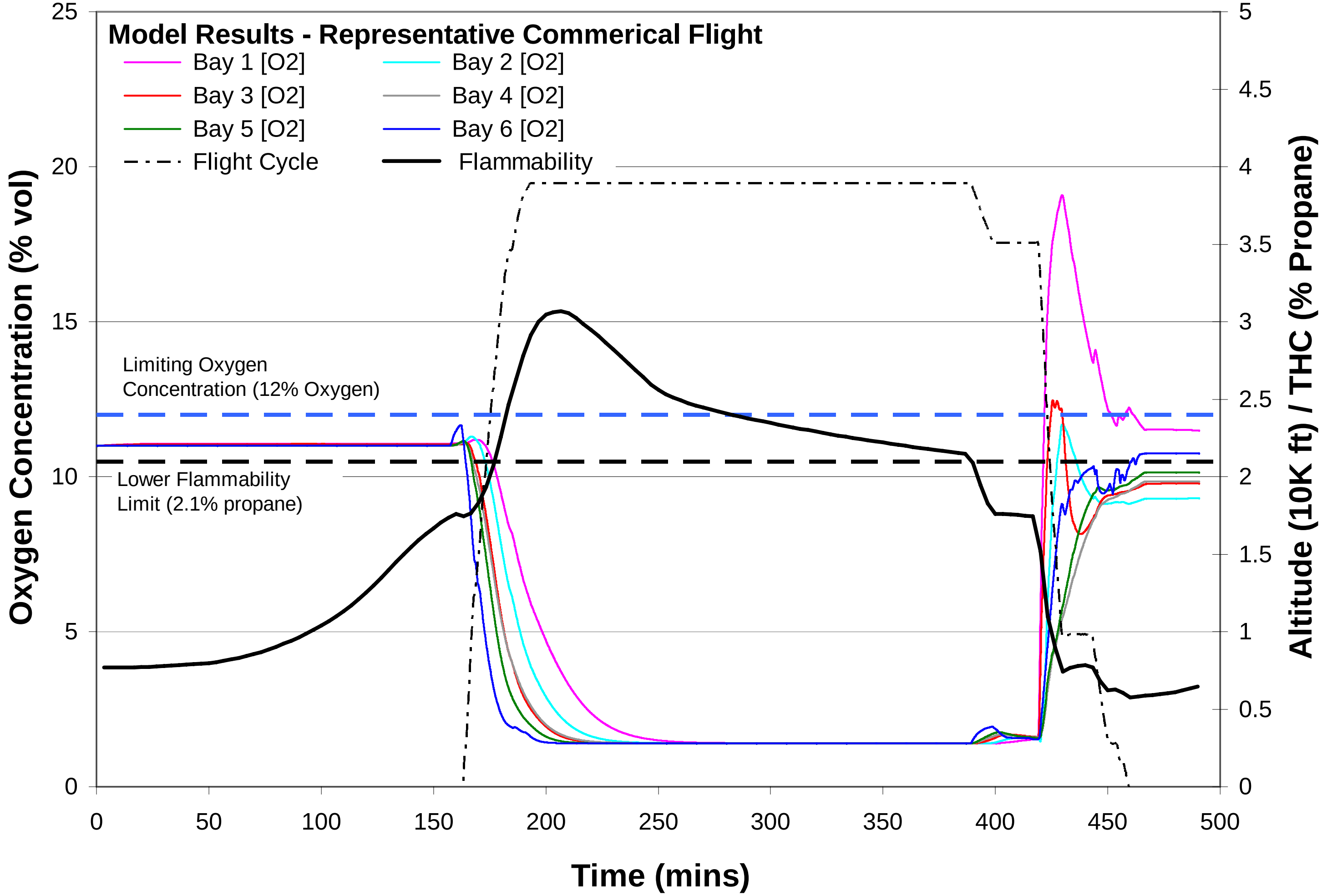
**MW_{vapor} = 132.4 g/mol, using a fuel composition of $C_{9.58}H_{17.2}$*

**CR = 9.58/3, using a fuel composition of $C_{9.58}H_{17.2}$*

- This results in an approximate LEL value of 2.1% C_3H_8
- Coupled with a Limiting Oxygen Concentration of 12% O_2, a flammable vapor environment can be defined as an environment in which the THC is greater than 2.1% C_3H_8 ***and*** in which the oxygen concentration is greater than 12% O_2

**Sagebiel, J. C., "Sampling and Analysis of Vapors from the Center Wing Tank of a Test Boeing 747-100 Aircraft," NTSB Docket No. SA-516, Exhibit No. 20G, 1997*

Representative Flight Modeling - Results



Conclusion

- FAA models used to predict ullage oxygen and THC concentration trend well to acquired flight test data
- Measured THC peak values compare fair with predicted model results
- Additional work is needed to improve upon the predictive capabilities of both the flammability and inerting models
- Results from the representative flight modeling exercise indicated the tank would not be exposed to flammable conditions during the developed flight profile and represented inerting system.