Preliminary Investigations of Fuel Cloud Formation in Fuel Tank Ullage

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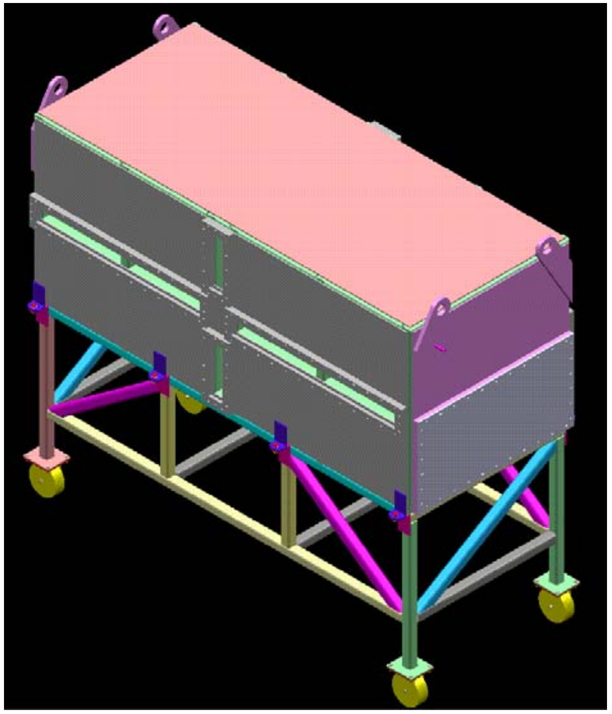


Fuel Tank Test Cell

Third Triennial International Fire & Cabin Safety Research Conference

October 22-25, 2001

Taj Mahal, Atlantic City, NJ

Description of Project:

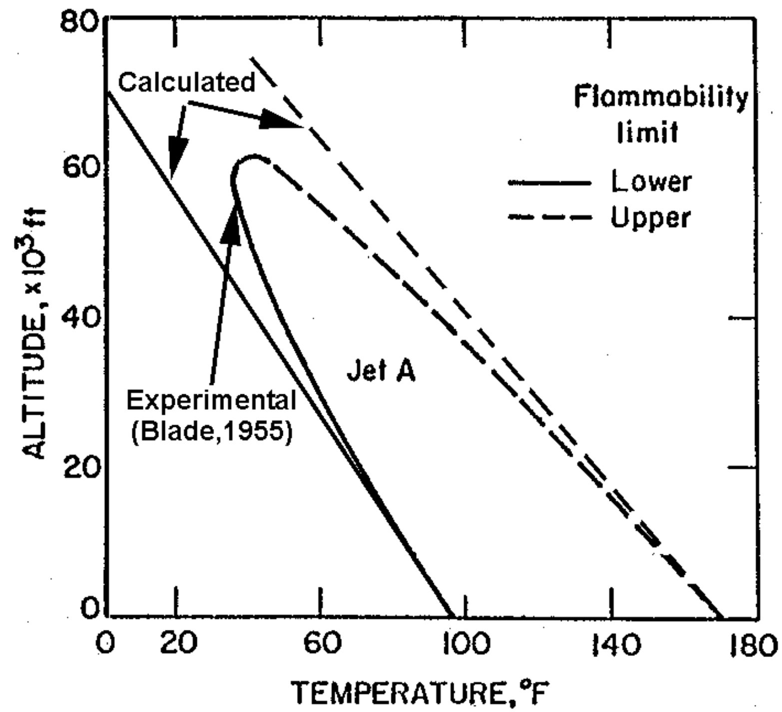
- Simulate realistic tank dynamics in fuel tank cloud chamber:
  - Preflight scenario - fuel tank is heated on bottom and cooled on top.
  - Takeoff scenario - fuel tank is heated before take-off and then cooled while climbing
- Identify conditions that promote droplet formation in fuel tanks
- Understand vapor dynamics to prevent/minimize explosive conditions

Benefit:

- Supplement to FAA tank inerting program
  - Identify “dynamic” flammability limits
  - Improve reliability of fuel tank explosion risk analysis

Background: Static (Equilibrium) Flammability

- **Flammability envelope of fuel tank ullage depends on ignition limits, [Jet A] and [O_2]**
  - [O_2] depends on altitude and temp.
    - Air composition invariant in troposphere and stratosphere
    - Air density varies with altitude
  - [Jet A] depends on temp. and loading
    - Saturation pressure limits the concentration
    - Loading influences Psat(T)

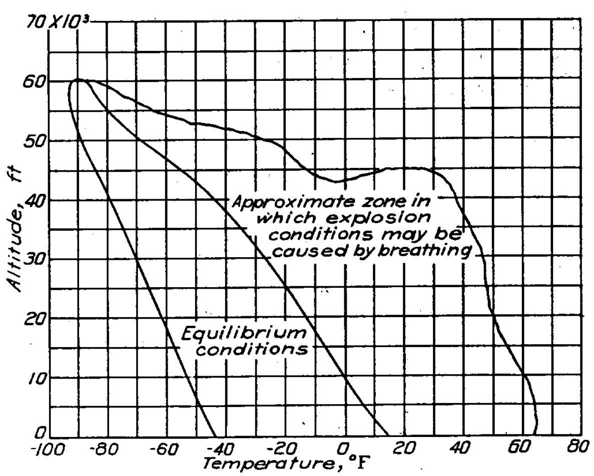


Background: Dynamic (Non-Equilibrium) Flammability

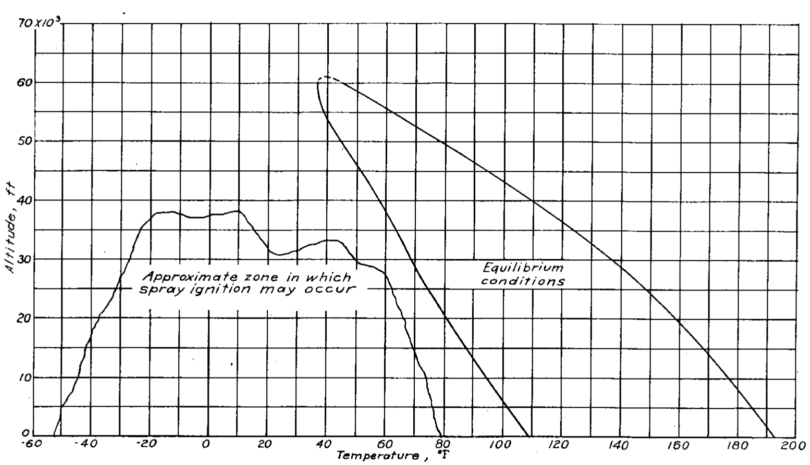
- Flammability outside the static flammability envelope

  CASE 1: High-volatility fuels may be flammable beyond the rich limit because of aspiration

  CASE 2: Low-volatility fuels may be flammable below the lean limit if suspended droplets are present in the ullage



(a) Fuel, 100-octane gasoline.



(b) Fuel, kerosene.

Zones of Inflammability of Fuel in Aircraft Fuel Tanks [Scull, 1951]

Background: Dynamic Flammability (Cont.)

When droplets of sufficient size and number density are present, fuel tank ullage at any lean fuel-vapor/air ratio can be flammable, even in an atmosphere without any premixed fuel vapor (Burgoyne and Cohen, 1954; Ott, 1970)

Two distinct dynamic conditions occurring in aircraft fuel systems can result in the formation of fuel mists (Ott, 1970):

- **sloshing and vibration (agitation)**
- **pressure changes (homogeneous, gas-phase condensation)**

Nester (1967) and Ott (1970) investigated agitation

- **While fuel droplets can significantly lower the lean limit, aircraft just don't get that agitated**

No one has investigated homogeneous, gas-phase condensation

Progress to Date:

- ✓ Reconciled Discrepancies
- ✓ **Construction of the Fuel Tank Test Cell**
- ✓ **Installation of the Test Facility**
- ✓ **Shakedown Runs**
- ❑ **Acquisition of Droplet Diagnostic Equipment**
- ❑ **Program of Experimental Investigation**

Progress to Date (cont.): Test Cell Construction

✓Preliminary drawings (L. Morton – 10/10/00)

✓Boeing-Seattle funding, $30,000

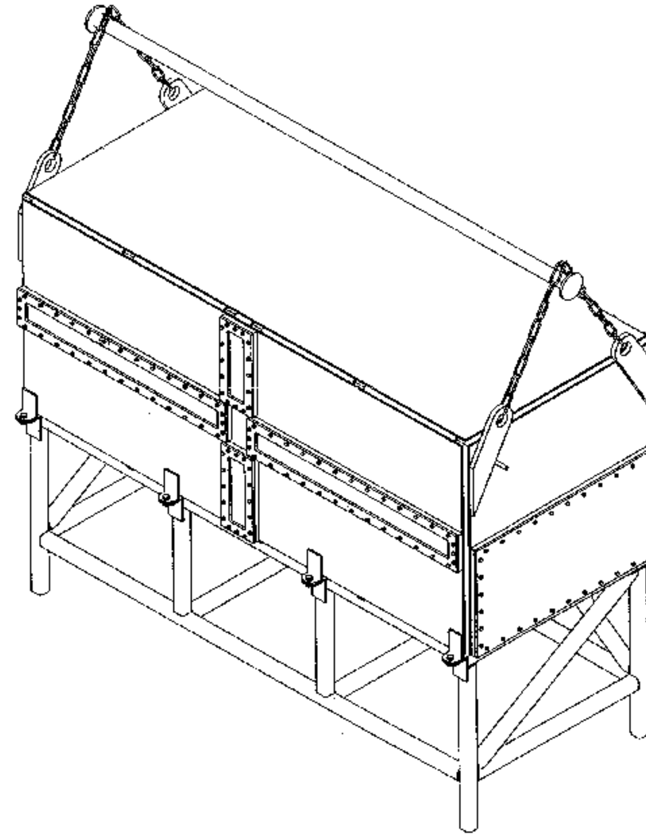
✓FEM/Design review (T. Briscoe – 11/3/00)

- Design Pressure of 10 psi vac
- Structural design per OSHA Standard 29 CFR, part 1926.152 (API Std. No. 620)
- Finite Element Model to determine loads in stiffener tubing around windows

✓Blueprints (Boeing – 11/15/00)

✓Test cell fabrication (Boeing – 2/28/01)

✓Test cell delivery (3/15/01)



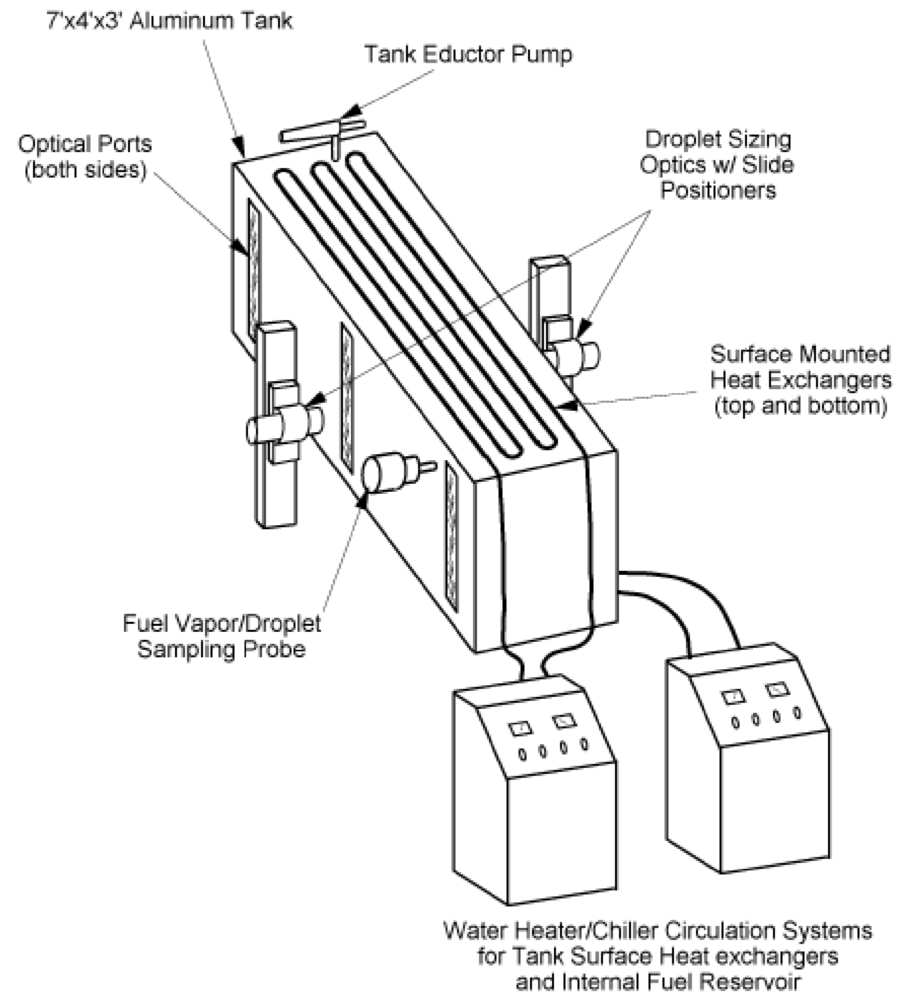
Test Cell Design

-Optical access via LEXAN windows

-7’ x 3.5’ x 3.5’ (~ 85 cu. ft. or 640 gal.)

Progress to Date (Cont.): Test Facility Installation

- ✓Laboratory facilities modifications
- ✓Eductor pump system
- ✓Heating-cooling system
- ✓Design computer control system
- ✓Installation/calibration



Progress to Date (Cont.): Test Facility Installation (Cont.)

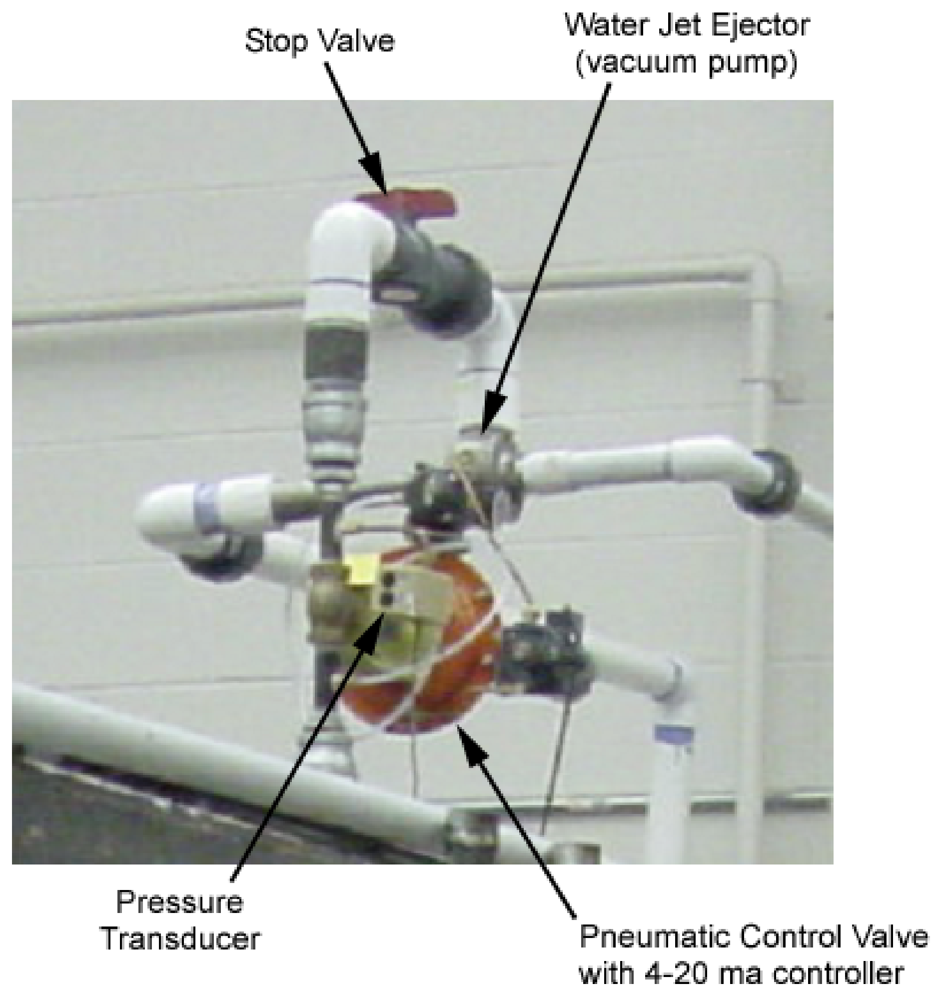
- **Laboratory facilities**
  - Electrical
  - Ventilation
- **Eductor pump system**
  - Water-Jet w/control valve
  - dP/dt max., 5 psi/min
  - Design → 1000 ft/min climb
  - Problems with reservoir temp
- **Computer control system**
  - Tank pressure control
  - Surface temperature control
  - Data logging

Progress to Date (Cont.): Test Facility Installation (Cont.)

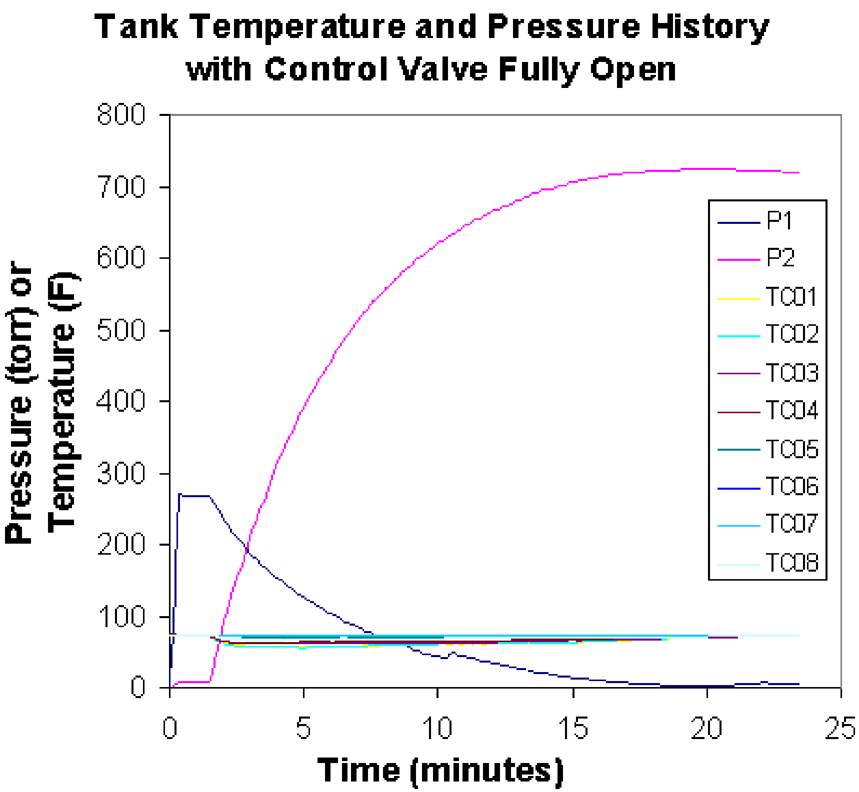
- **Heating-Cooling system**
  - Two 18 kW/3 ton heater/chillers
  - Design → 1000 ft/min climb
  - Manufacturer shipped with wrong PID temp. controllers
  - Heat exchanger problems

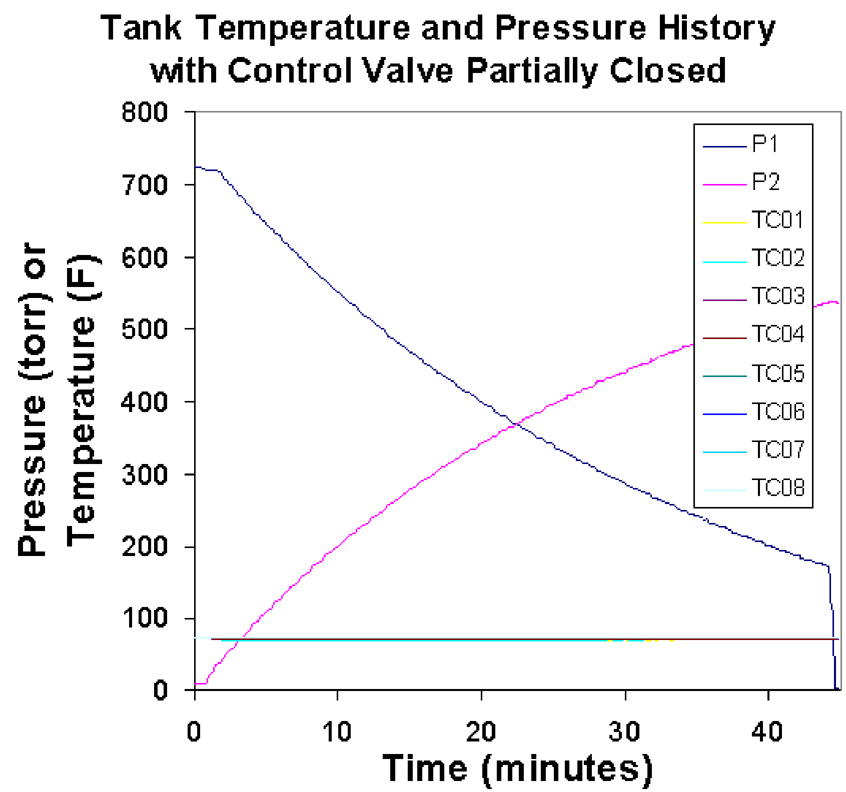
Progress to Date (Cont.): Shakedown Runs

- **Pressure Control System**
  - Water circulated through jet ejector (constant vacuum, $P_{sat@Twater}$)
  - dP/dt in tank regulated by control valve
  - 4 to 20ma controller adjusts control valve set point
  - Pressure transducers and 4 to 20ma controller connected to PC
  - Closed loop control
- **Results of Calibration/Shakedown**



Progress to Date (Cont.): Shakedown Results

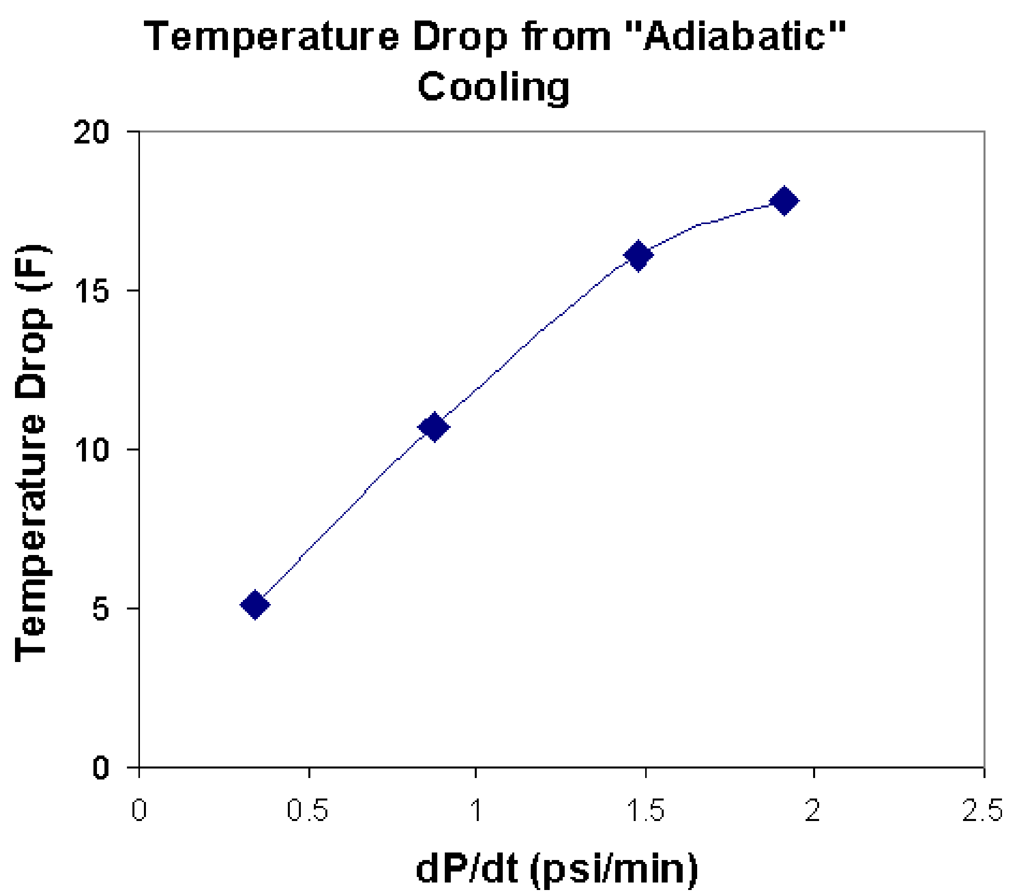




Progress to Date (Cont.): Shakedown Results

Control Valve Calibrations →

- Temperature drop during tank decompression due to adiabatic cooling
- ΔT correlates with dP/dt (control valve setting)



Progress to Date (Cont.): Shakedown Results

- **Droplet formation via thermal diffusion configuration (1st Exp.)**
  - Tank bottom heated, top cooled
  - Thermal diffusion cloud chamber
  - Conditions:
    - Argon atmosphere
    - 10 gal. Jet A (1.6% mass loading)
    - Tank top 50 F
    - Fuel 90 – 110 F
  - Droplets 1st observed at 90 F (fuel)

Progress to Date (Cont.): Shakedown Results

P1: tank pressure (vac torr)

P2: tank pressure (torr)

TC01: internal tank temp. (-28 in.)

TC02: internal tank temp. (-20 in.)

TC03: internal tank temp. (-12 in.)

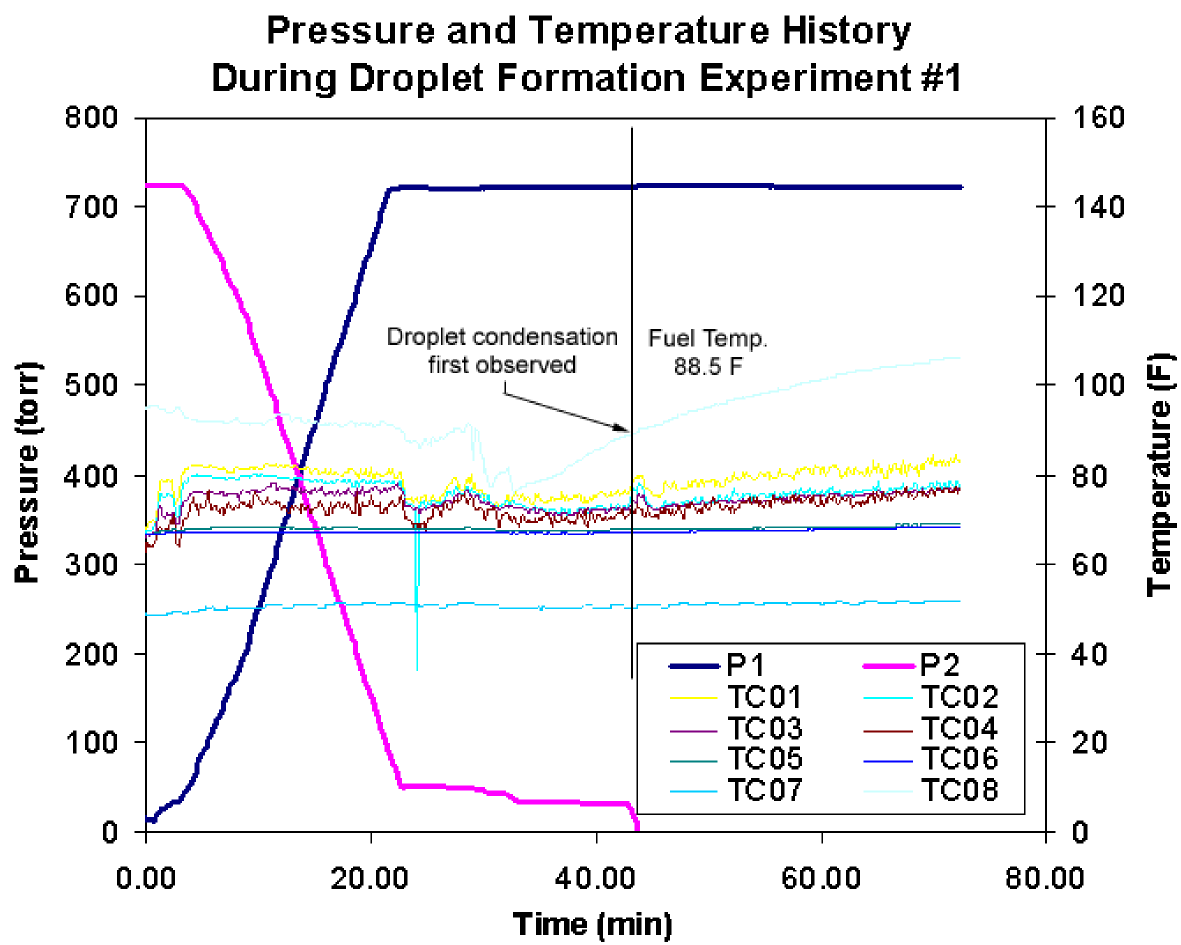
TC04: internal tank temp. (-4 in.)

TC05: tank side surface temp.

TC06: tank side surface temp.

TC07: tank top surface temp.

TC08: fuel pan temp.



Progress to Date (Cont.): Shakedown Results

Progress to Date (Cont.): Acquisition of Droplet Diagnostic Equipment

- ✓ Additional Funding via 2nd FAA Grant
  - Droplet sizing interferometry (2-D PDPA)
- ❑ Bring in Vendors to demonstrate
  - Video-based microscopic imaging
    - Theoretically capable of droplet characterization and velocity measurement
    - Long range microscopy is iffy
  - Mie scattering theory-based Fruaenhofer diffraction technique (Malvern analyzer)
    - Relatively inexpensive
    - Line of sight averages on droplet size only

Progress to Date (Cont.): Program of Experimental Investigation

- Homogeneous condensation during tank decompression
  - Diabatic decompression during ascent
  - Experiments matching flight profile T, P-data
- Homogeneous condensation through thermal diffusion
  - Tank bottom heated, tank top cooled to match ground operations
  - Thermal diffusion cloud chamber
- Chemical composition of fuel, fuel vapor and droplets
- Competitive processes due to tank dynamics
  - Convective flow due to venting
  - Buoyant flow due to non-uniform wall temperatures

Concluding Remarks

- **Working Test Facility**
- **Some facility enhancements needed**
  - Heater/chillers and heat exchangers
  - Data acquisition hardware
  - PDPA
- **Investigation of homogeneous condensation underway**
  - Limit identification
  - Simulation of realistic preflight and in-flight conditions