2nd NASA Alternative Aviation Fuel Experiment

AAFEX-II
Background and Overview

Bruce Anderson, LaRC

Sponsored by NASA Subsonic Fixed-Wing Program, Clean Energy and Emissions Project

Why Do We Care About Aircraft Emissions?

- Aircraft emit reactive gases and large numbers of black carbon and volatile aerosol particles; aircraft traffic expected to double over next 20 years
- Particle and gas emissions can effect climate (clouds, ozone) and local air quality
- Airports located in EPA non-attainment areas must assess environmental impacts before expanding
- New certification standards being considered by SAE—detailed observations needed to guide method development
- Europeans considering placing tighter controls on emissions including limits on number of particles emitted
- Better understanding of AC emissions needed for assessing environmental effects of current and future fleets

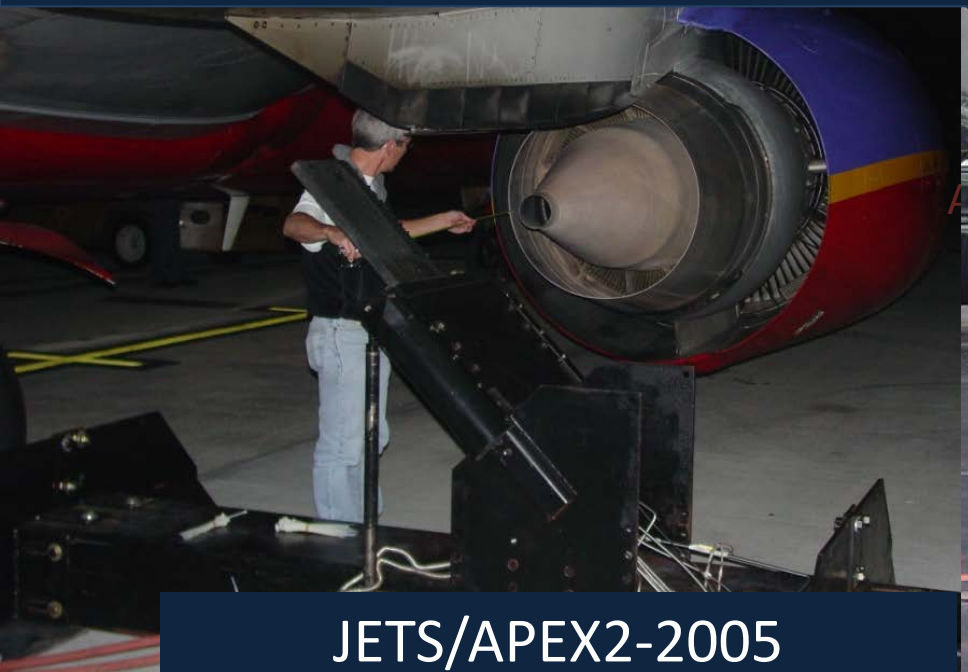
Certification Data of Limited Value for Assessing Effects

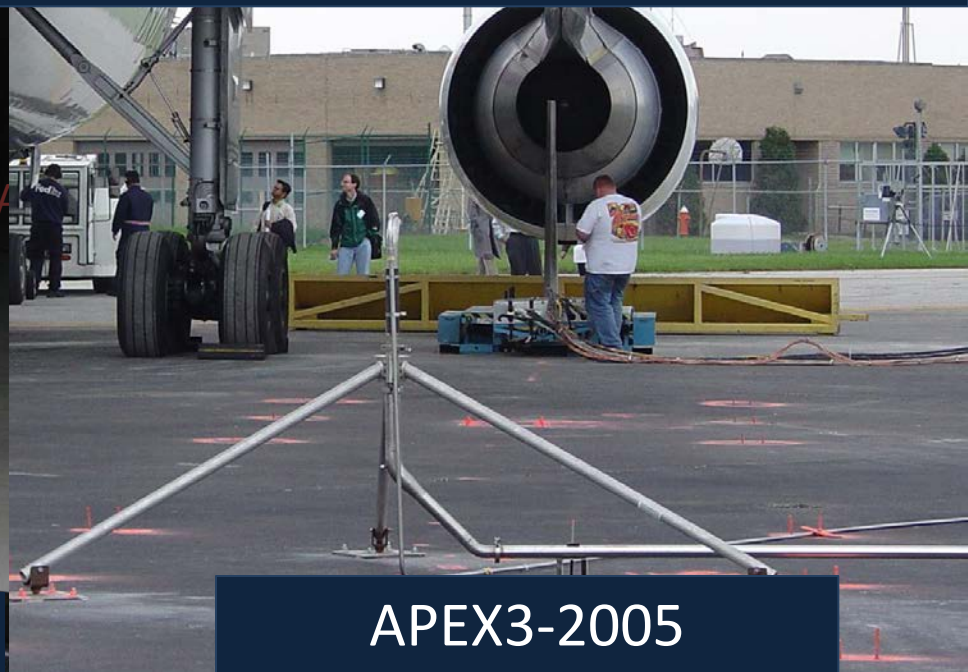
ICAO Archive Data for Typical Engine Cycle

Mode	Power Setting	Time minutes	Fuel flow kg/s	THC g/kg	CO g/kg	NOx g/kg	Smoke Number
Take-off	100%	0.7	0.38	0.22	0.77	19.6	1
Climb Out	85%	2.2	0.31	0.26	0.97	16.6	0.01
Approach	30%	4	0.11	0.66	3.93	7.1	0.01
Idle	7%	26	0.05	3.85	23.8	3.5	0.01

- Total Hydrocarbons (THC) can be dominated by background methane
- Smoke Number not representative of anything physical
- Measurements from exit plane—ignores plume chemistry/condensation
- **Speciated hydrocarbon and detailed particle data needed for broad range of engines, power settings, and ambient conditions to enable chemical and climate model assessments**

NASA-sponsored experiments produced an extensive emissions data base, but many questions regarding sampling, measurements and plume chemistry remain





Growing Impetus to develop Alternative Fuels

- Almost 60% of US oil is imported—will increase to 70% by 2025
- Large fraction of imported oil comes from unfriendly/unstable nations—leaves us vulnerable to embargoes and terrorist threats
- Worldwide demand is increasing—fuel prices have doubled in two years, causing large increases in transportation costs
- Increasing domestic oil production may come at a high environmental price (ANWAR, offshore, etc.)
- Fossil fuels are non-renewable, cause increases in atmospheric greenhouse gas concentrations

Fuel costs are now the largest expense in civil aviation—increasing and fluctuating prices are causing an economic crisis in the industry

US Federal Agencies Coordinating Efforts to Develop Fuels

Economic and environmental sustainability analysis across entire supply chain

	Feedstock Production	Feedstock Logistics	Fuel Conversion	Conversion Process Scale-up/Integration	Fuel Testing/Approval: Fuel Performance	Fuel Testing/Approval: Environment Assmt	Enable Production	End User/ Buyer
USDA	✓	✓	✓	✓	---	---	✓	---
DOC	---	---	---	---	---	---	✓	---
DOE	✓	✓	✓	✓	---	✓	✓	---
DoD	✓	---	✓	✓	✓	✓	---	✓
EPA	---	---	---	---	---	✓	✓	---
FAA	---	---	---	---	✓	✓	---	✓
NASA	---	---	---	---	✓	✓	---	---

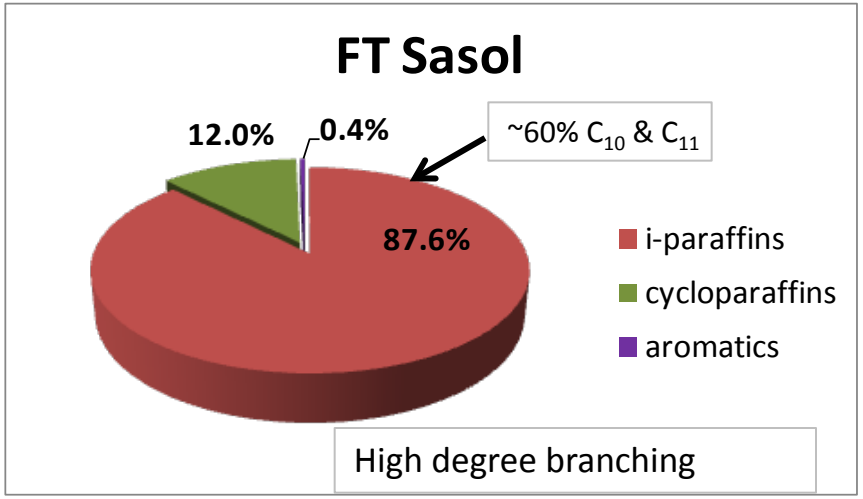
NASA Alternative Fuels Research

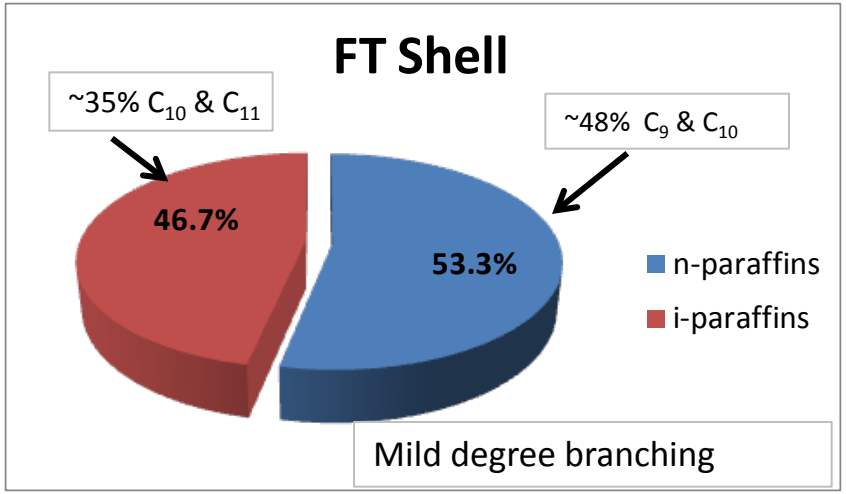
SFW Alternative Fuel Characterization Work

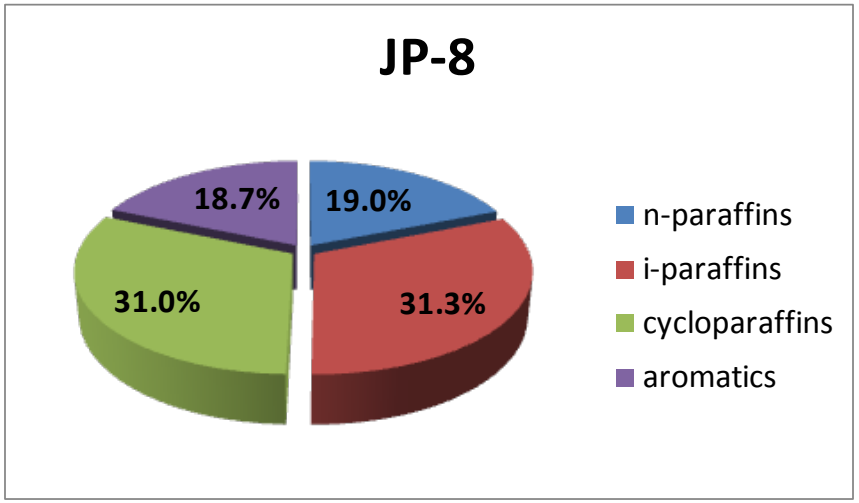
- **Laboratory tests** to determine alternative fuel combustion and emissions characteristics
  - ✓CE-5 flame-tube experiments on LDI fuel injectors--ongoing
  - ✓ASCR tests of GE & PW sector rig combustors—2013
- **Ground-based engine tests** to evaluate alternative fuel effects on performance and emissions under real-world conditions
  - ✓PW308 test stand experiment—March 2008
  - ✓AAFEX-I—January 2009
  - ✓AAFEX-II—March 2011
- **Cloud chamber tests** to examine PM effects on contrail formation
  - ✓ACCRI/SFW Tests—October 2010--?
- **Airborne experiments** to evaluate fuel effects on PM emissions and contrail formation
  - ✓Chase plane modifications and test flights—2012-2013
  - ✓Emissions and contrail survey flights—2013-2014

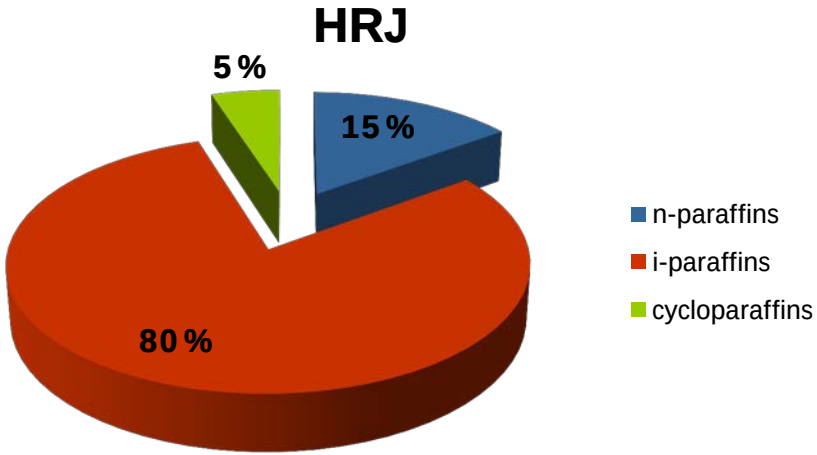
Available Alternative Fuel Composition

Alternative Fuels contain < 0.5% Aeromatics and < 20 ppm Sulfur





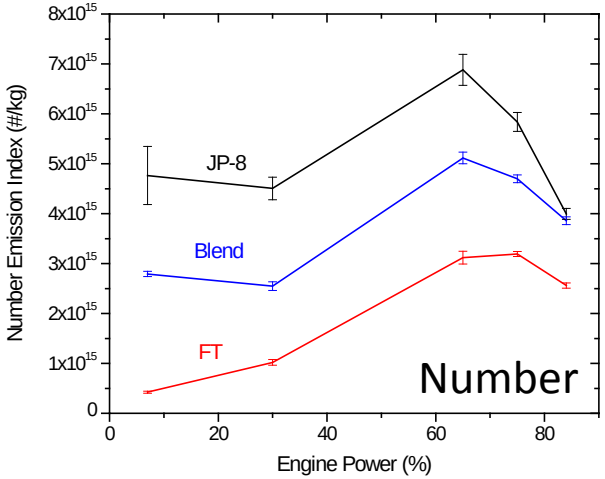


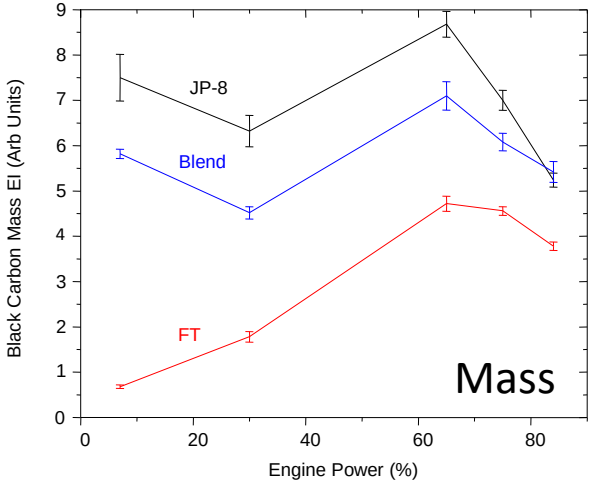


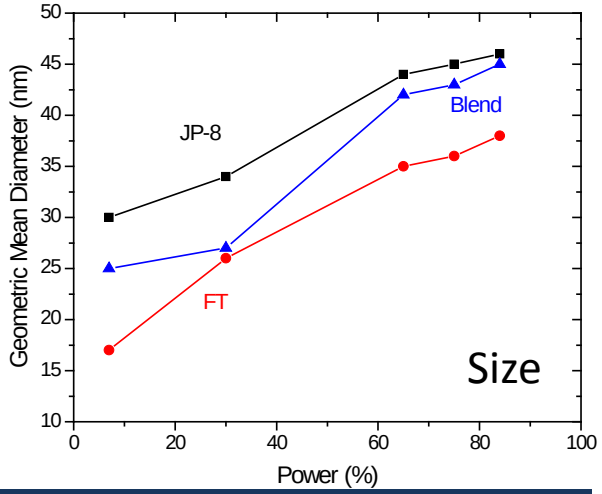
Fuels Vary Considerably in Hydrocarbon Composition

Shell FT tested in PW308 at West Palm Beach

Property	JP-8	Blend	Synthetic
Viscosity (cSt)	1.38	1.14	0.96
Specific Gravity	0.8050	0.7734	0.7377
Net Heat of Combustion (Btu/lb)	18,533	18,735	18,960
Hydrogen % mass	13.95	14.78	15.71
Particulate contamination (mg/L)	0.71	0.21	0.11
Sulphur content (%)	0.123	0.065	0.003
Aromatic content (%)	19	10.1	0.17

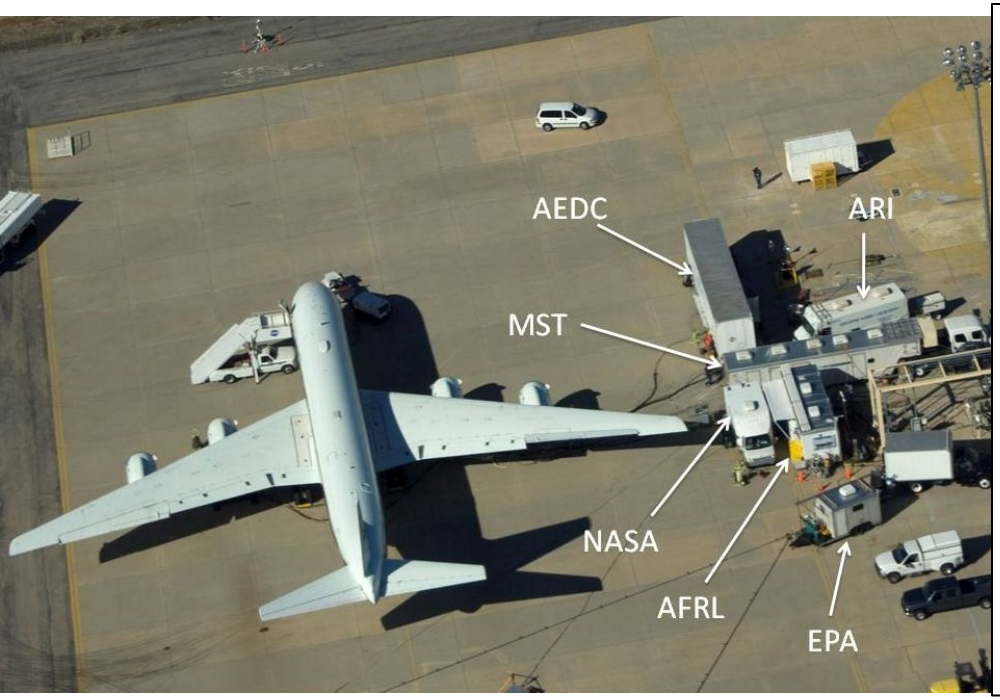






- Tests were a collaboration between NASA, AFRL, Aerodyne and Pratt and Whitney
- PW308 is modern high-bypass engine suitable for use on executive jets
- Saw significant reductions in Number and Mass EI and particle size when burning FT or FT blends
- Fuels had little impact on NOx, CO or hydrocarbon production

AAFEX-I: Shell, Sasol FT Emission Characterization



Objectives

- Create gaseous and particulate emission profiles as a function of fuel-type and engine power;
- Investigate the factors that control volatile aerosol formation and growth
- Establish aircraft APU emission characteristics and examine their dependence on fuel composition
- Evaluate new instruments and sampling techniques
- Inter-compare measurements from different groups to establish expected range of variation between test venues

- Inlet probes at 1- and 30-m behind each engine and at 143-m behind engine #3
- Downwind plume sampled with ARI mobile lab
- Burned JP-8, coal/natural gas FT, + 50/50 JP-8 blends
- FT fuels contained 0 aromatics and 0 sulfur
- Made extensive gas phase and PM measurements
- Examined emissions at 4, 7, 30, 45, 65, 85, and 100%
- Recorded over 35-hours data
- Engine runs over wide range of ambient temperature

AAFEX-II: HRJ Emission Characterization

Location:	**NASA Dryden Aircraft Operations Facility (DAOF) Palmdale, California**
POCs:	**Dan Bulzan, GRC, Project Manager Bruce Anderson, LaRC, Project Scientist Robert Howard, AEDC, Project Engineer Frank Cutler, DFRC, Mission Manager**
Dates:	**March 21 – April 2, 2011**
Aircraft:	**NASA DFRC DC-8, CFM-56-2C engines**
Fuels:	***Standard JP-8 *Tallow-based HRJ & 50% Blend w/JP-8 *Coal-based FT & Coal-based FT w/1000ppm S added**
Runtime:	**11 separate Emissions Tests, 30.5 hrs total run time**
Duration:	**~6 days setup/teardown, 5 days testing**
Measurement:	**Certification gases, smoke, HAPS, PM number, size, mass, composition, black-carbon content, and morphology**

AAFEX-II Project Objectives

1) Evaluate HRJ fuel effects on engine performance and fuel-handling equipment
2) Determine the effects of HRJ on engine particle and gas phase emissions
3) Investigate the role of sulfur in regulating volatile aerosol formation in engine exhaust plumes
4) Examine the effects of sample line chemistry and particle losses on emission measurements
5) Conduct tests to support SAE E-31 development of standard exhaust sampling methods

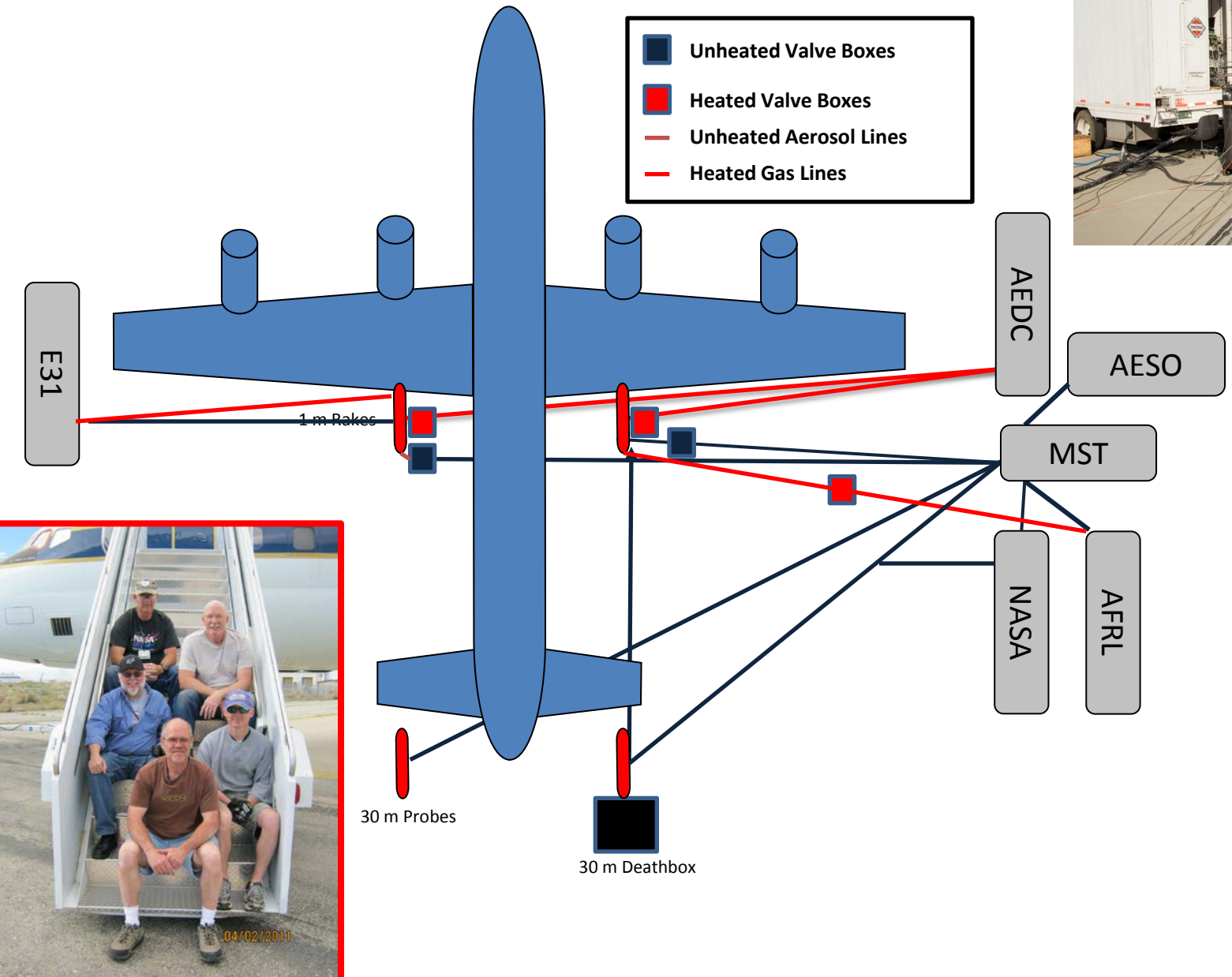
AAFEX-II Investigators

Organization	POC	Measurements
AEDC	Robert Howard	Smoke Number
AESO	Xu Li-Jones, Triet	Aerosols
AFRL	Edwin Corporan	Aerosols and Gases
ARI	Rick Miake-Lye Scott Herndon	Aerosols and Gases
Missouri S&T	Phil Whitefield Don Hagen	Aerosols
MIT	Eben Cross	Aerosol Comp
Montana State	Berk Knighton	Hydrocarbons, HAPS
NASA GRC	Dan Bulzan	Aircraft Parameters
NASA GRC	Changlie Wey	Certification Gases + FTIR
NASA LaRC	Bruce Anderson	Aerosols
Penn State	Randy Vander Wal	Soot Morphology

E-31 Team

Member	Organization	Role
David Liscinsky	**UTRC**	**Team Lead, Number Lead**
John Kinsey	**EPA**	**Assistant Lead, Mass Lead**
Robert Howard	**AEDC**	**Engineering Lead**
Mark Johnson	Rolls Royce	Sampling Lead, Manufacturer Rep
Greg Smallwood	NRC-Canada	Mass Team
Russ Arey	GEAE	Manufacturer Rep
Anuj Bhargava	P & W	Manufacturer Rep
Dave Christie	Honeywell	Manufacturer Rep
Steve Baughcum	Boeing	Industry Rep
Carl Ma	FAA	RAT Rep
Will Bachalo	Artium	Instrument Rep
Tim Johnson	TSI	Instrument Rep
Bill Silvas	AVL	Instrument Rep

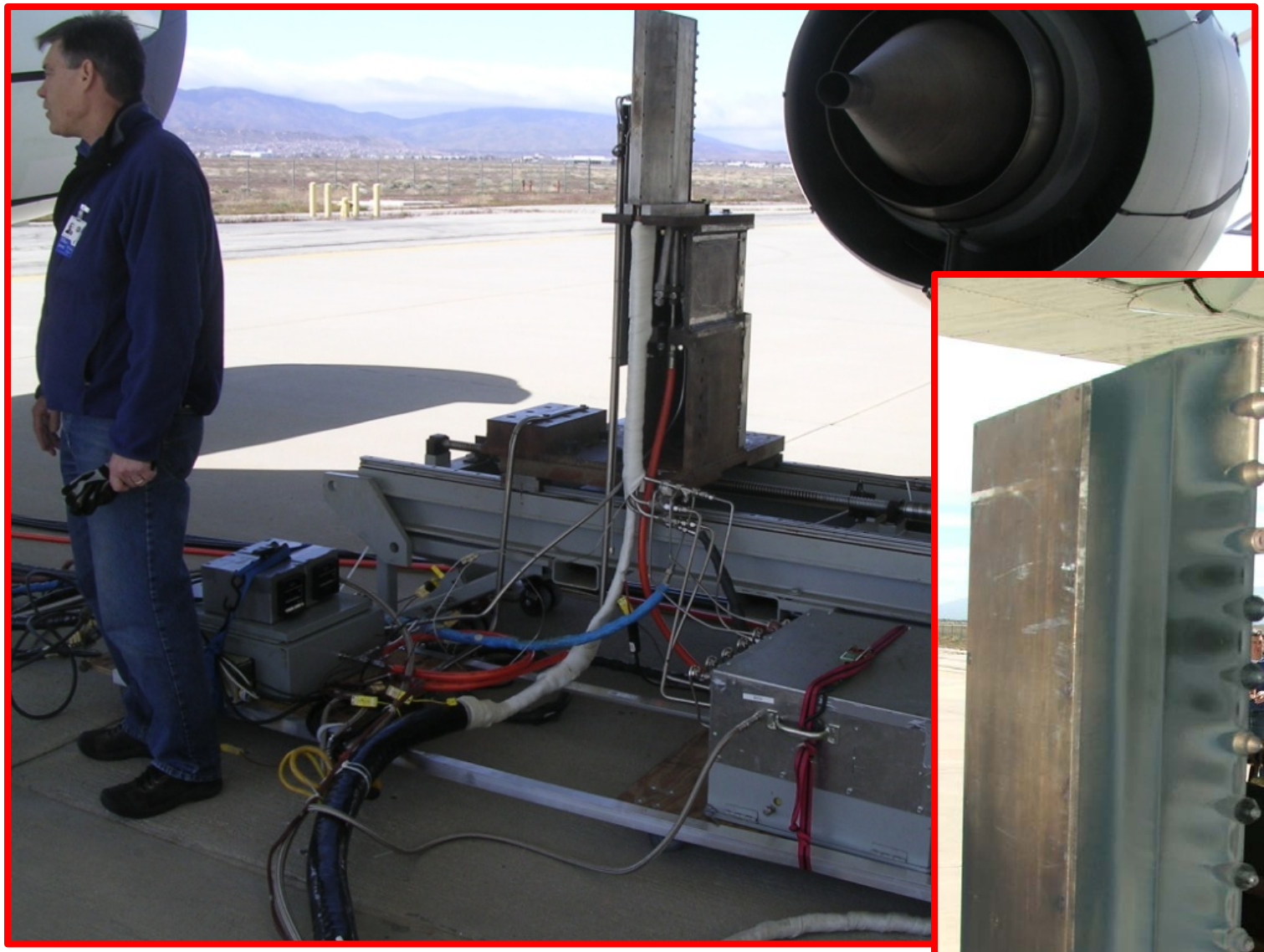
Near-Field Sampling System Layout



Sampling Systems: Right 1-meter Rake

"Tinker" Rake mounted on translation stage

Sampling Systems: Left 1-m Rake

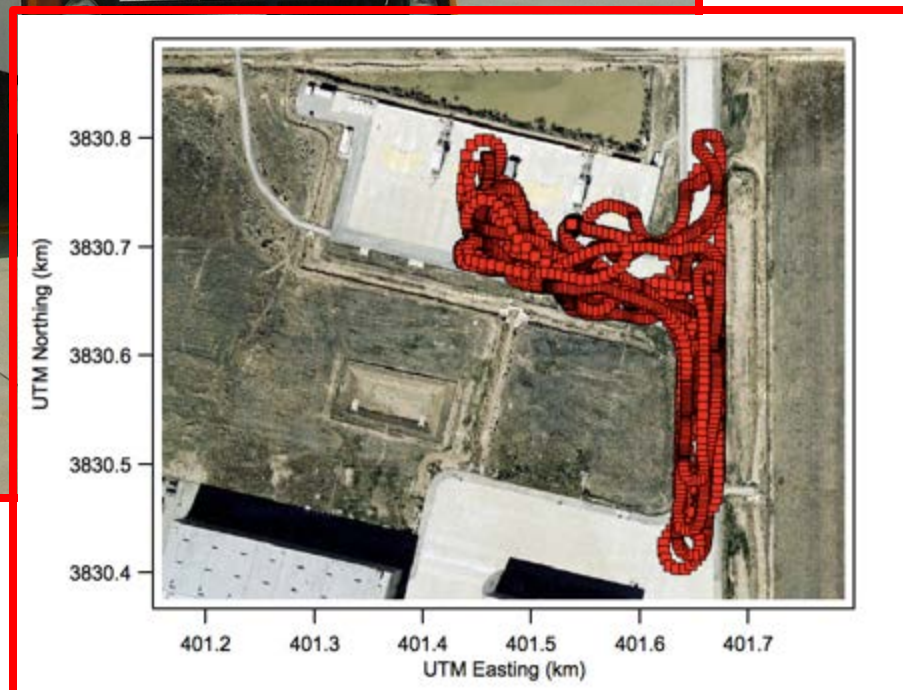


E31 inlets mounted adjacent to rake

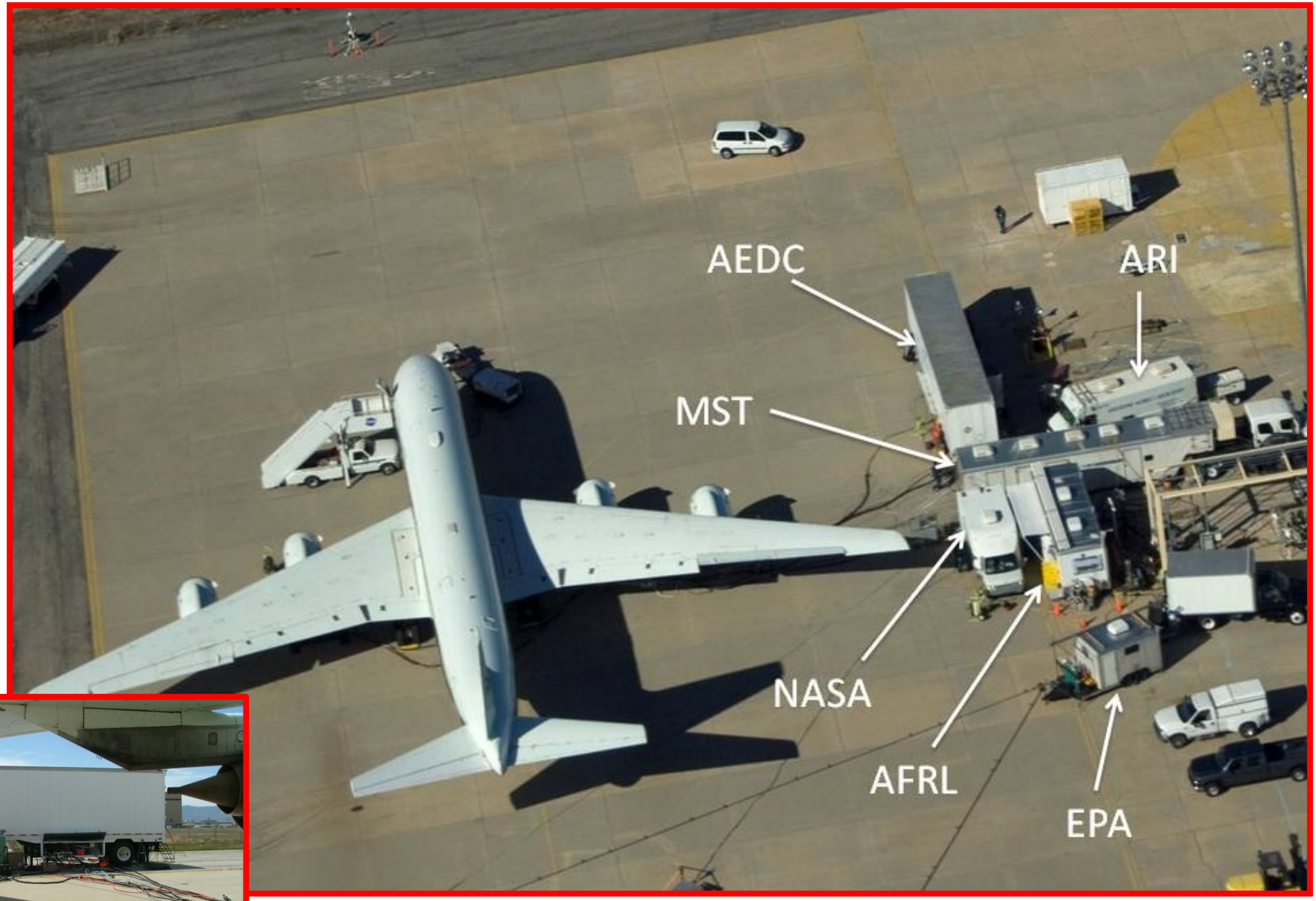
30-m Inlets and Death-Box

Sampling Systems: 143-m Trailers

AERODYNE MOBILE LABORATORY
HAWS


3830.8
3830.7
3830.6
3830.5
3830.4
UTM Northing (km)
401.2
401.3
401.4
401.5
401.6
401.7
UTM Easting (km)

Site Layout Nearly Same as AAFEX-I



Primary Emissions Measurements

AEDC—*Certification gases: CO_2, CO, THC, NOx and Smoke Number*

AESO—*Aerosol number and size*

Aerodyne—*Aerosol number, size, Size-resolved aerosol and soot composition, NOx, CO, Ethene, Formaldehyde, etc.*

AFRL—*PM number, size, black carbon mass, EC/OC, and PAH content; FTIR Certification gases; HAPS; and Smoke Number*

MIT—*Aerosol and condensable gas composition*

MS&T—*PM number and size*

MSU—*HAPS and speciated hydrocarbons*

NASA GRC—*Certification gases, FTIR speciated hydrocarbons and SO_2*

NASA LaRC—*PM number, size, mass, black carbon content, composition, EC/OC, black carbon size, speciated hydrocarbons*

PSU—*Soot composition and morphology*

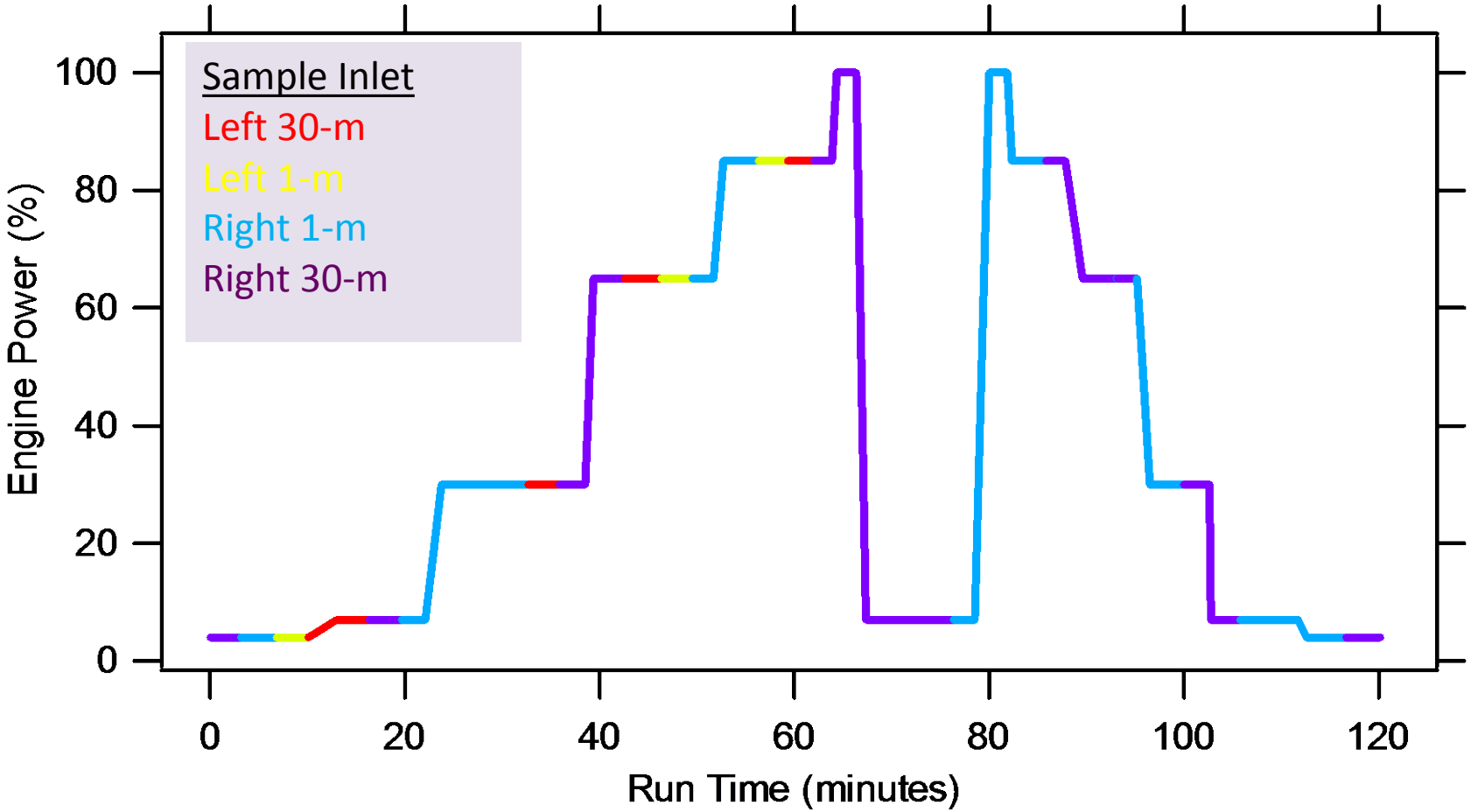
Fuel Characteristics

Test	JP8	HRJ	Blend	FT	FTS
Sulfur Content (ppm Mass)	100	0	200	0	1000
Parafins (% mass)	44	95	69	88	88
Cyclo Paraffins (% mass)	33	5	21	11	11
Normal Paraffins (% mass)	15	15	11	<.2	<.2
Aromatics (% vol)	21.8	0.4	9.8	1.7	2.1
End Point (°C) 300	268	254	264	225	224
Flash Point (deg C)	46	52	46	43	43.5
Density (kg/L)	0.811	0.759	0.783	0.761	0.761
Freezing Point (deg C)	-53	-49	-54	-78.5	-76.5
Hydrogen Content (% mass)	13.5	15.3	14.4	15.0	15.0
Smoke Point	22.0	28.3	29.0	31.5	29.3

Summary of AAFEX-II Test Runs

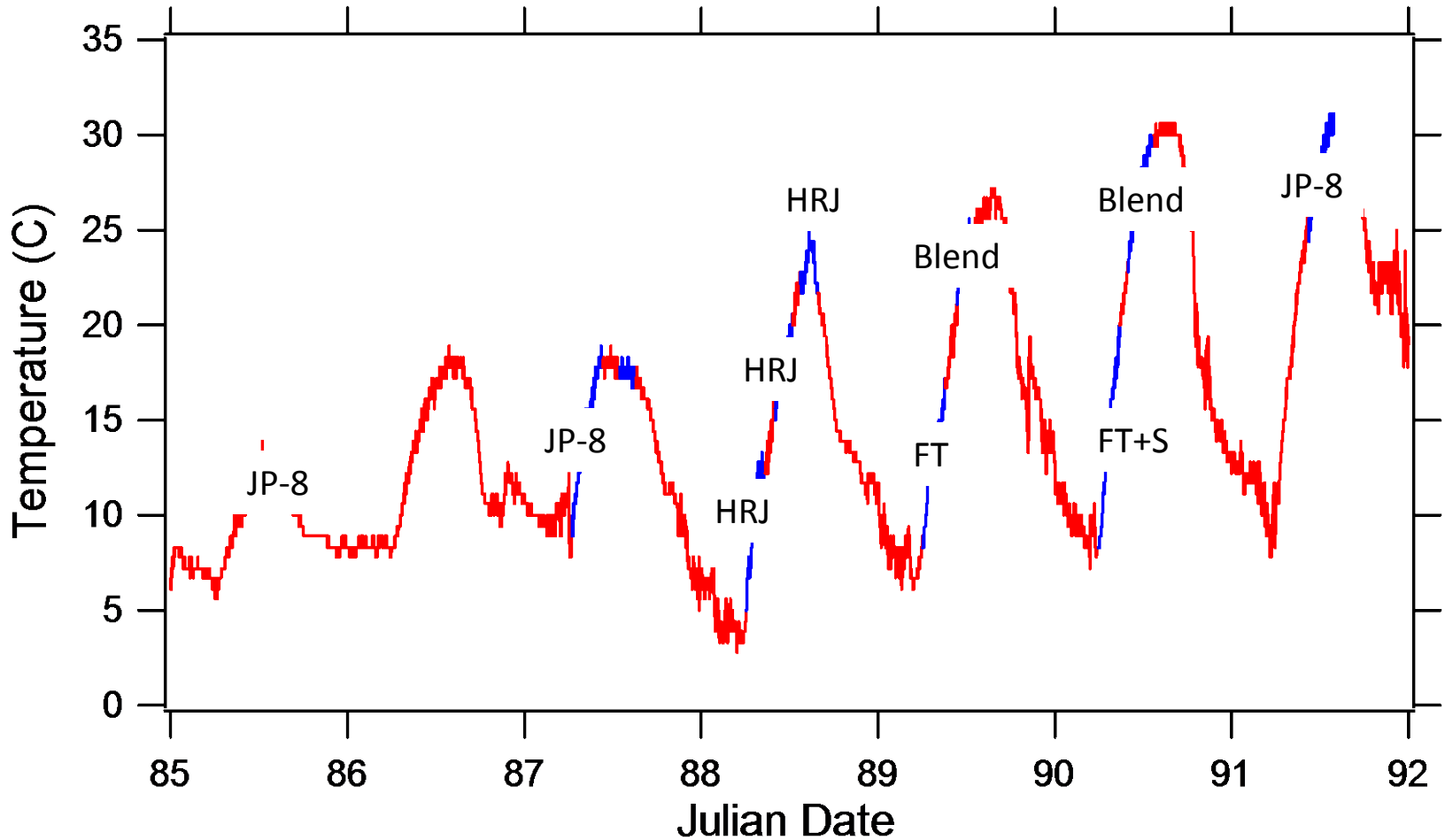
Test Number	Test Date	Times		Test Duration	Engine Fuel		Objective
		Start	End		Left	Right	
1	26-Mar	1420	1530	1.1	JP-8	JP-8	Shakedown
2	28-Mar	0630	1040	4.1	JP-8	JP-8	JP-8 Characterization-Cold
3	28-Mar	1300	1507	2.1	JP-8	JP-8	JP-8 Characterization-Warm
4	29-Mar	0605	0840	2.5	JP-8	HRJ	HRJ Characterization-Cold
5	29-Mar	1004	1225	2.4	JP-8	HRJ	HRJ Characterization
6	29-Mar	1331	1550	2.4	JP-8	HRJ	HRJ Characterization-Warm
7	30-Mar	0605	0910	3.1	JP-8	FT	Fuel S--FT Characterization- Cold
8	30-Mar	1045	1250	2.1	JP-8	Blend	HRJ/JP-8 Blend Characterization
9	31-Mar	0555	0850	3	JP-8/FT+S	FT+S	Fuel S--FT + S Characterization- Cold
10	31-Mar	1000	1330	3.5	JP-8	Blend	HRJ/JP-8 Blend Characterization/E-31
11	1-Apr	1030	1445	4	JP8 & Blend	JP8 & Blend	JP-8 Characterization/E-31 Tests

Example Engine Test Sequence



Left inboard engine typically burned JP-8, right engine burned test fuel

Temperature Context for Test Runs

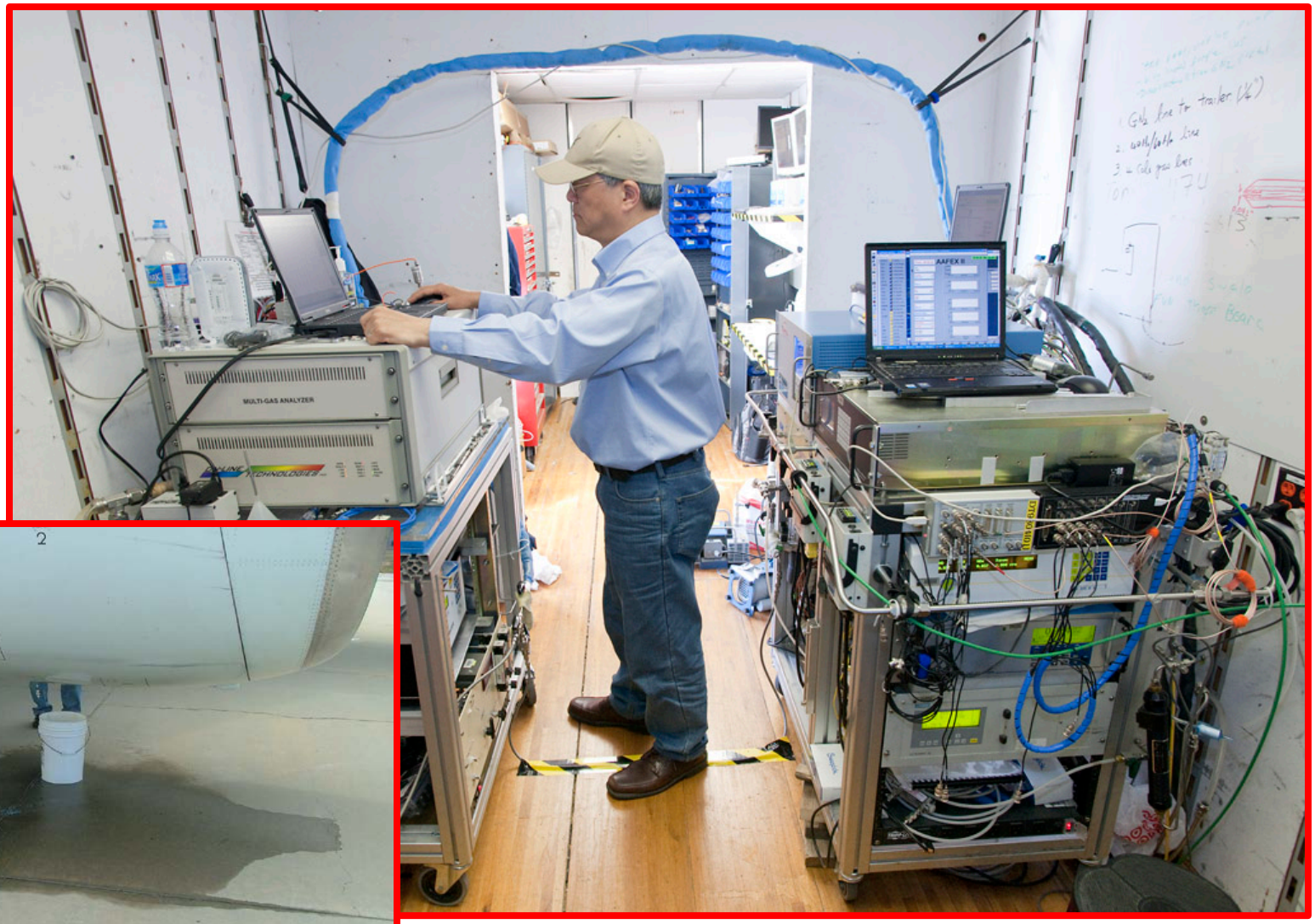


Temperatures 5 to 10 C warmer than during AAFEX-II, less volatile aerosol formation

More than 60 individuals participated, representing 22 public and private institutions

Today's Agenda

8:45—Fuel Effects on Performance and Certification Gas Emissions—Dan Bulzan



9:15—Gas Phase Emissions I: Criteria Pollutants and HAPS—Berk Knighton/Rick

9:45—Gas Phase Emissions II: Chemical Evolution in the Exhaust Plume—Scott Herndon/Rick

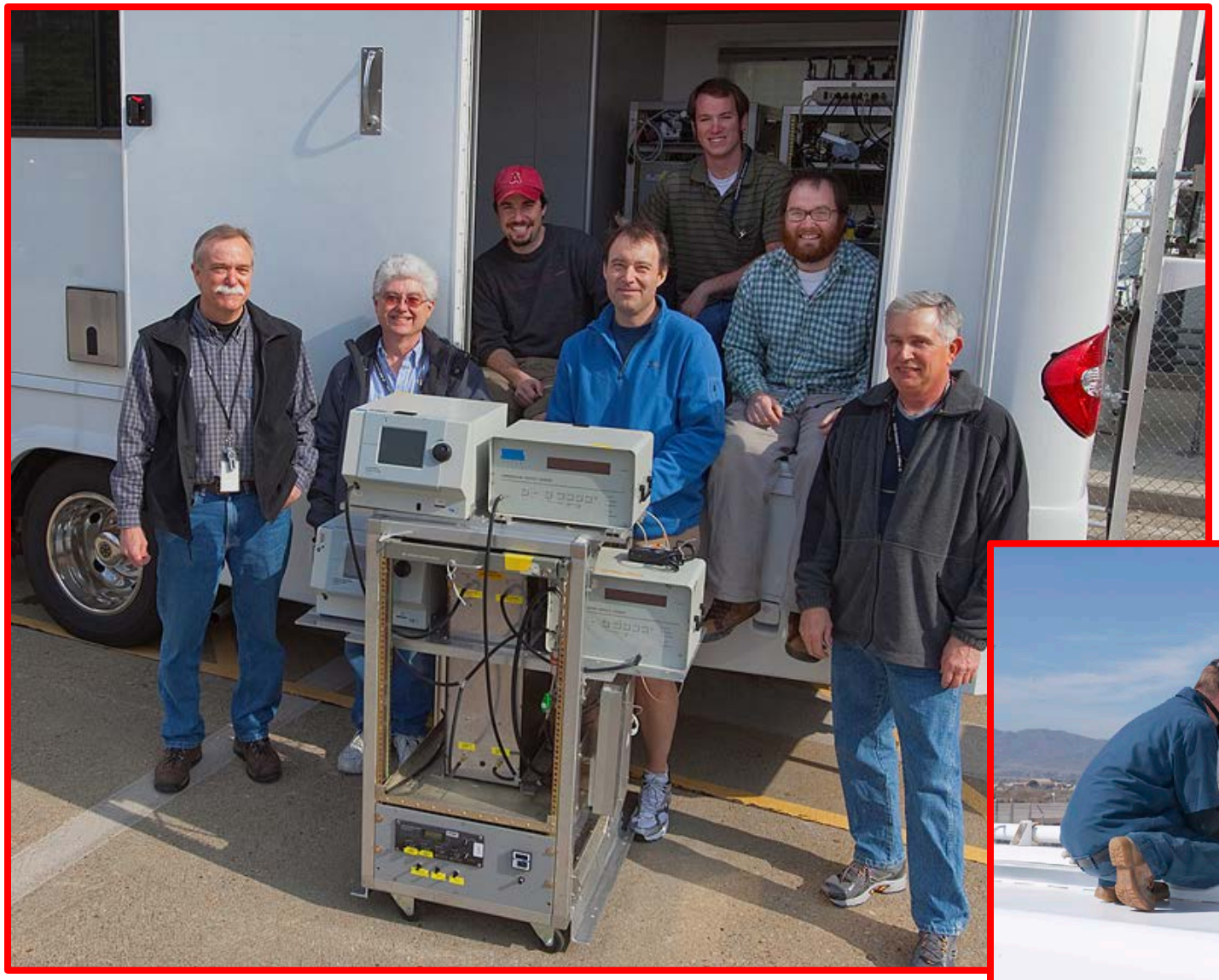
10:30—Particle Emissions I: Fuel Effects on Nonvolatile Particle Emissions—Edwin Corporan

11:00—Particle Emissions II: Volatile Particle Composition—Team Aerodyne/Rick

11:20—Particle Emissions III: Volatile Particle Formation/Growth/Microphysics—Luke Ziemba

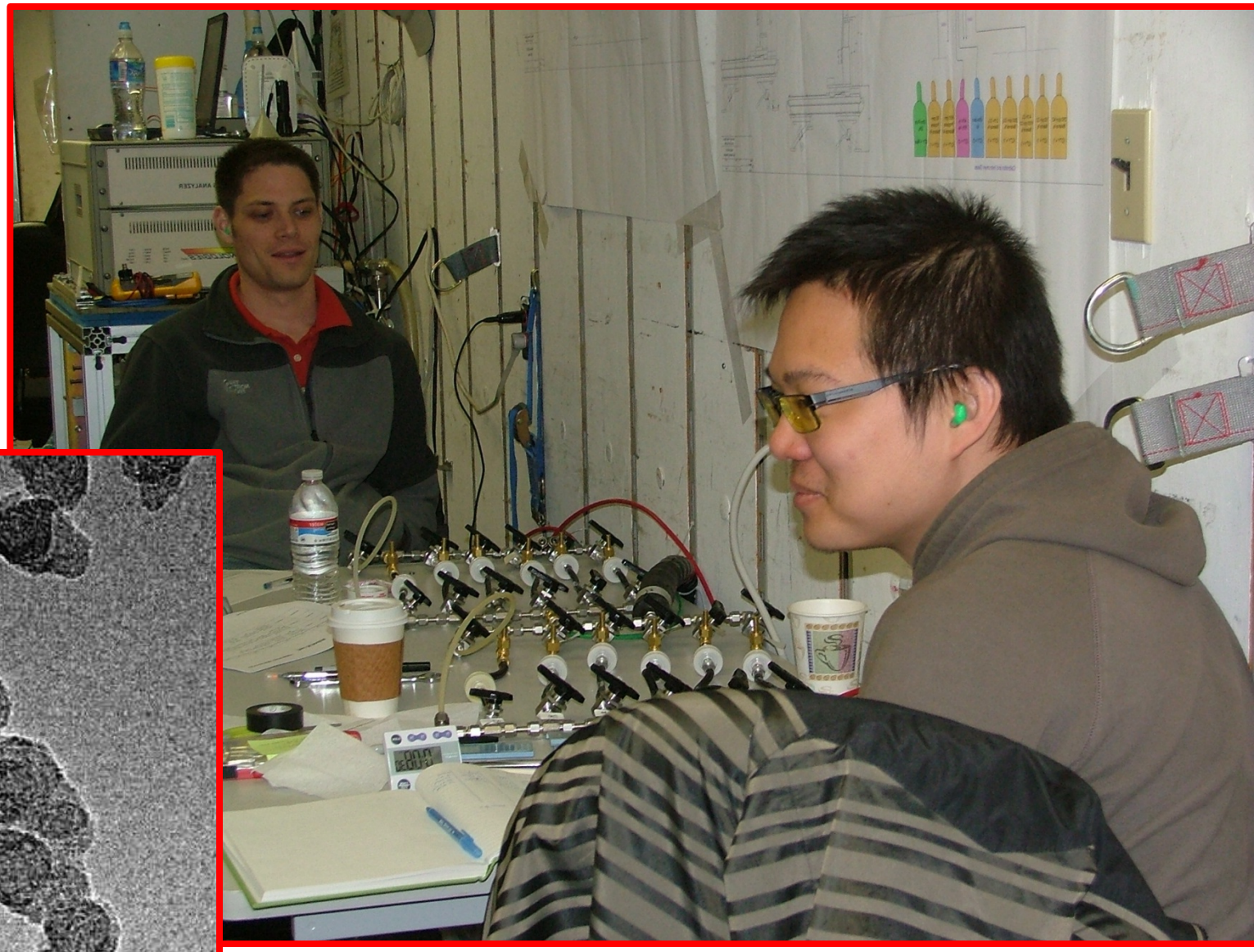
11:40—Particle Emissions IV: Evolution of Black Carbon Properties—Don Hagen

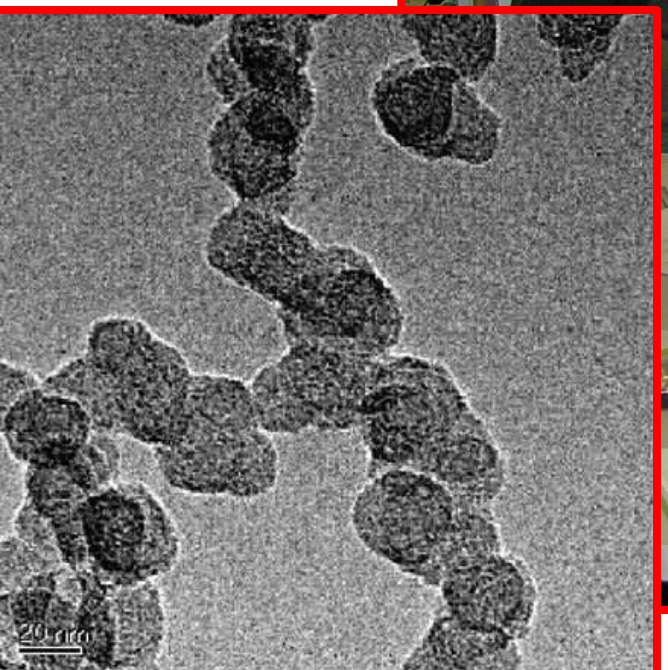
13:00—Sulfur Experiment and AAFEX-I/II Comparisons—Bruce Anderson

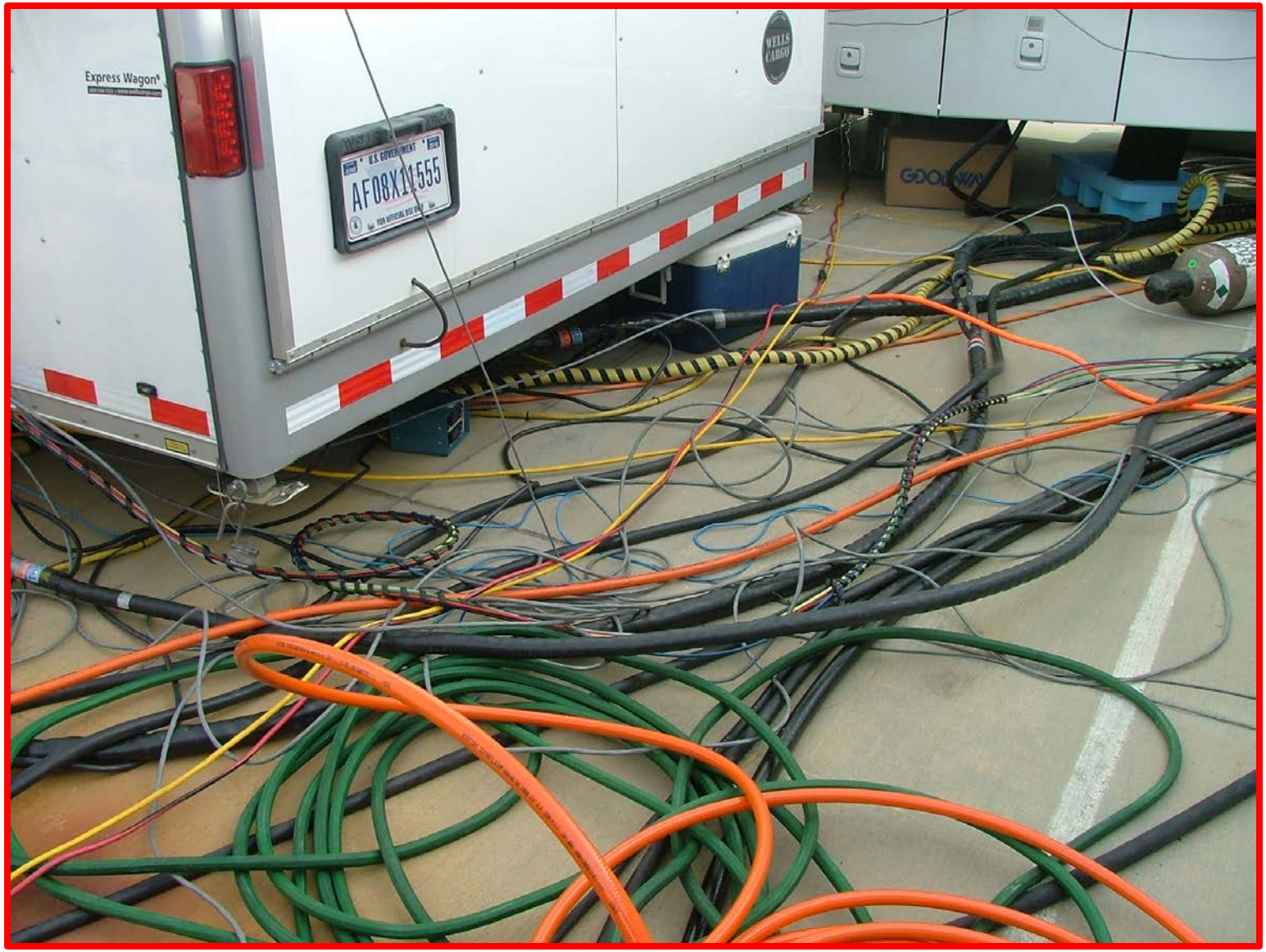


13:20—Sampling System Effects on PM Measurements—Xu Li-Jones/Robert Howard

13:20—Black Carbon Composition and Morphology—Randy Vander Wal





14:00—E31 Sampling System Evaluation—David Liscinsky

14:30—Untangling the Data: Summary and Questions—Rick Miake-Lye