MISSOURI S&T
University of Science & Technology

Partners: Missouri S&T, MIT, Aerodyne Research Inc.,
AEDC, NASA, FAA, HVL Assoc.

Center of Excellence for Aerospace Particulate Emissions Reduction Research

Aircraft-generated PM Emissions:

(1) APU, Tire Smoke and Brake PM Emissions Generated by In-service Commercial Transports
(2) Comparison of PM emissions from Hydro-treated Renewable Jet Fuel (HRJ), and JP8

Phil Whitefield, Prem Lobo and Don Hagen
Missouri University of Science and Technology

Cambridge Particle Meeting
University of Cambridge, UK.
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ACRP Project 02-17:
Measuring PM Emissions from Aircraft Auxiliary Power Units, Tires and Brakes

Project Team

Missouri S&T
University of Science & Technology

Phil Whitefield, Prem Lobo, Don Hagen

Aerodyne Research, Inc.

Rick Miake-Lye, Scott Herndon, Jon Franklin, Ed Fortner, Mike Timko

Montana State University

Berk Knighton

The Environmental Consulting Group LLC

Sandy Webb

Background

- Currently, there is insufficient information about PM emissions from APUs, Tires and Brakes
- The purpose of this project is to develop sampling and measurement techniques appropriate for these sources and then apply these techniques in a major measurement campaign at an airport
- Data from this project will be used directly in emissions modeling or to supplement airport emission studies
- Providing such data will allow airports to improve the accuracy of their PM emissions inventories and better prioritize their emission mitigation efforts

Project Schedule

	Task	Description	Duration	Status
Phase 1	1	Conduct a Literature Review of PM Emissions Data on APUs, Tires, and Brakes	Sep – Nov 2010	Completed
	2	Develop a Sampling, Measurement, and Analysis Plan for APUs	Sep – Dec 2010	Completed
	3	Develop a Sampling, Measurement, and Analysis Plan for Tires and Brakes	Oct – Dec 2010	Completed
	4	Prepare an Interim Report	Oct – Dec 2010	Completed
Phase 2	5	Implement Pilot Study for Measuring PM Emissions from APUs, Tires, and Brakes	Jan – Mar 2011	Completed
	6	Prepare a Second Interim Report	Apr - Jun 2011	On-going
	7	Implement Measurement Campaign for PM Emissions from APUs, Tires, and Brakes	Aug - Sep 2011	Pending
	8	Prepare a Final Report	Oct 2011 – Aug 2012	Pending

Literature Review – APU Emissions

- APU provides electricity and pre-conditioned air when the aircraft is taxiing or parked at the gate and bleed air for main engine start as well as in-flight power back-up.
- Limited information is currently publicly available on PM emissions from APUs
- The FAA's Emissions and Dispersion Modeling System (EDMS) includes a database of APUs that associates APU model with various commercial aircraft models.

Aircraft Category	***Example Aircraft***	***Representative APU***
Jumbo Wide Body	Boeing 747; Airbus A330	GTCP 331-350; GTCP 660; PW 901
Wide Body	A300; A310; B767; MD11; DC10	GTCP 330-200; GTCP 331-500; TSCP 700;
Narrow Body	A318; A319; A320; A321; B737; B757; MD80; DC8; DC9; EMB170; EMB175	131-9; GTCP 36; GTCP 85; GTCP 331-200; APS2000; APS2300; APS3200
Regional Jet	CRJ100; CRJ200; CRJ700; CRJ900; EMB135; EMB140; EMB145; Cessna Citation III	GTCP36; GTCP85; APS500

Literature Review – Tire Emissions

- Tires contain a wide range of polymer rubbers, fillers, metal (steel), softeners, anti-aging and vulcanizing agents
- Composition data specific to aircraft tires are not available in the open literature
- Abundant literature exists on the tire wear PM emissions of road tires
  - ✓ Understanding aircraft tire wear PM can only be inferred by review of the road tire PM emissions literature
- Tire wear PM mass may be dominated by particles larger than 10 microns, but tire wear PM number may be dominated by particles smaller than 1 micron
- Tire pyrolysis may be an important mechanism for PM formation during braking events for road traffic, similar to the spin up of aircraft tires during landing
  - ✓ Primary products of tire pyrolysis will be styrene, butadiene, and isoprene, and depending on the conditions, additional species including PAHs
- Aircraft tire emissions might be differentiated from exhaust emissions by:
  - ✓ 1) a larger characteristic PM size
  - ✓ 2) the presence of zinc
  - ✓ 3) the presence of benzothiazole
  - ✓ 4) increased concentrations of styrene, butadiene, and PAHs relative to pure exhaust

Literature Review – Brake Emissions

- Information on PM emissions from aircraft brakes is proprietary and not available in the public domain, however there is abundant information on automotive brake emissions and studies on measuring these emissions in the urban environment
- Brakes in general are found to consist of the following five components: fibers, abrasives, lubricants, fillers and reinforcements, and binding materials
- Aircraft brakes can be classified into two categories: steel brakes and carbon brakes
- The presence of Sb, Cu and Ba will be key indicators of break wear, particularly for those smaller aircraft that use steel brakes. For aircraft that use carbon brakes, the most abundant PM is likely to be carbonaceous material.

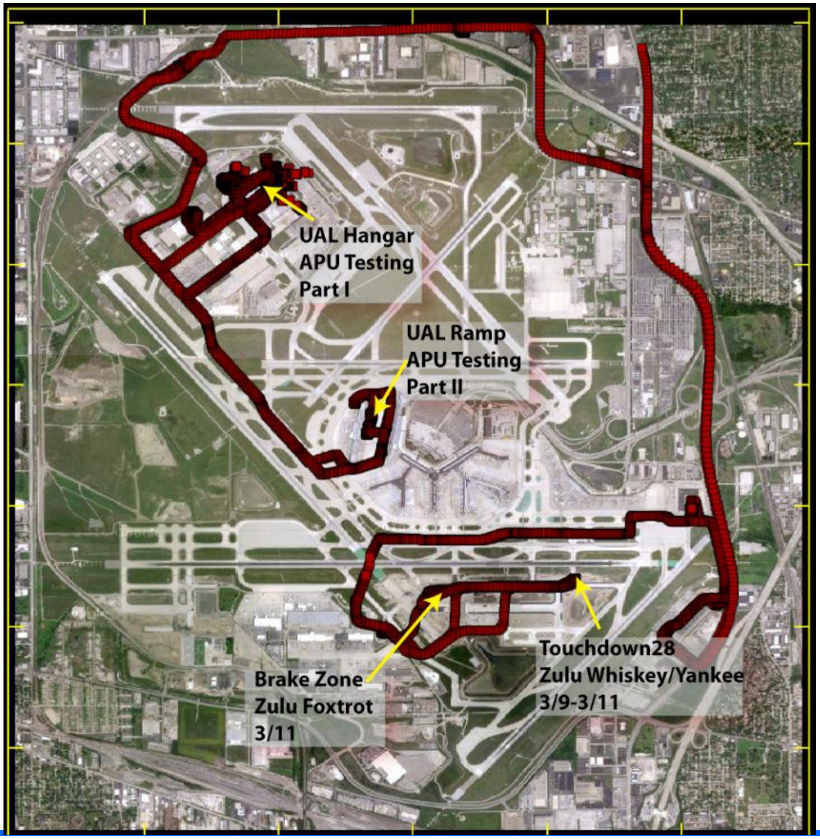
Aircraft Category	*Example Aircraft*	*Brake Material*
Wide Body	A300; A310; A330; A340; A380; B747; B767; B777; MD11	Carbon
	DC10	Steel
Narrow Body	A318; A319; A320; A321; N737NG; B757; CRJ-1000; EMB170/175; EMB 190/195; MD90	Carbon
	B737-600/700/800/900; CRJ100; CRJ200; CRJ700; CRJ900; DC9; MD80;	Steel

Airport Selection Process

- Factors governing the selection of an airport
  - ✓ (1) Fleet mix - access to a variety of aircraft and consequently a variety of APUs, tires, and brakes,
  - ✓ (2) Meteorological conditions - testing in both low and high temperatures,
  - ✓ (3) Airport management supportive of the project and willing to allow the team to travel to several parts of the airport operating area to access equipment and emissions sources, and
  - ✓ (4) Airport layout that will enable ready access to APU exhaust streams and, more importantly, an area sufficiently near an active runway to sample tire emission plumes near the touchdown portion of the runway and brake emission plumes near the deceleration portion of the runway.
- Began with a list of eight airports to screen against these criteria – Atlanta Hartsfield, Boston Logan, Chicago O’Hare, Detroit, Houston Bush, Minneapolis, Oakland, Philadelphia.
- Selected **Chicago O’Hare** as the preferred airport and **United Air Lines** as the preferred airline to work with on this project

Pilot Study

Date	Activity	Location	Temp Range (°F)
March 7, 2011	Setup	UAL Hangar	24-34
March 8, 2011	APU Emissions measurements	UAL Hangar/ Terminal Area	32-45
March 9, 2011	Tire Emissions measurements	Runway	33-44
March 10, 2011	Tire Emissions measurements	Runway	32-37
March 11, 2011	Tire and Brake Emissions measurements	Runway	27-47



APU Emissions Measurements

- Measurements were made on aircraft-mounted, in-service, APU's during non-revenue generating periods
  - ✓ Aircraft was in maintenance facility
  - ✓ Aircraft was RON (remain overnight) at an airport gate

Test Number	Date	Test Start Time	Test Stop Time	Measurement Location	Airframe	APU Model
1	March 8, 2011	12:24:00	12:52:00	Outside UAL Hanger	B767-200	GTCP 331-200
2	March 8, 2011	14:34:00	15:03:00	Outside UAL Hanger	B777-200	GTCP 331-500
3	March 8, 2011	16:32:00	16:52:00	Outside UAL Hanger	A320	GTCP 36-300
4	March 8, 2011	22:28:00	22:43:00	Terminal	A320	GTCP 36-300
5	March 8, 2011	22:56:00	23:09:00	Terminal	A320	GTCP 36-300
6	March 8, 2011	23:35:00	23:50:00	Terminal	A319	GTCP 36-300

- Data was acquired at 3 APU operational conditions

Normal	all locations
Both packs	all locations
Motoring engine	hangar only

APU Emissions Measurements

- Sampling system
  - ✓ Adjustable height probe connected by a flexible line
  - ✓ Designed to provide probe tip dilution

- Instrumentation suite
  - ✓ Housed in the Aerodyne Mobile Laboratory
    - ✓ Cambustion DMS500 (size)
    - ✓ Condensation Particle Counter (number)
    - ✓ Multi Angle Absorption Photometer (mass)
    - ✓ Aerodyne Aerosol Mass Spectrometer (composition)
    - ✓ Concomitant gas phase data, e.g. CO_2 to establish emission indices

APU Emissions Measurements

B767 aircraft with GTCP 331-200 APU

B777 aircraft with GTCP 331-500 APU

APU Emissions Measurements

A320 aircraft with GTCP 36-300 APU

- The sampling system for measurements of PM emissions from APUs worked well.

- The adjustable height probe provided a means to sample exhaust from a wide range of APU models with varying heights above ground.

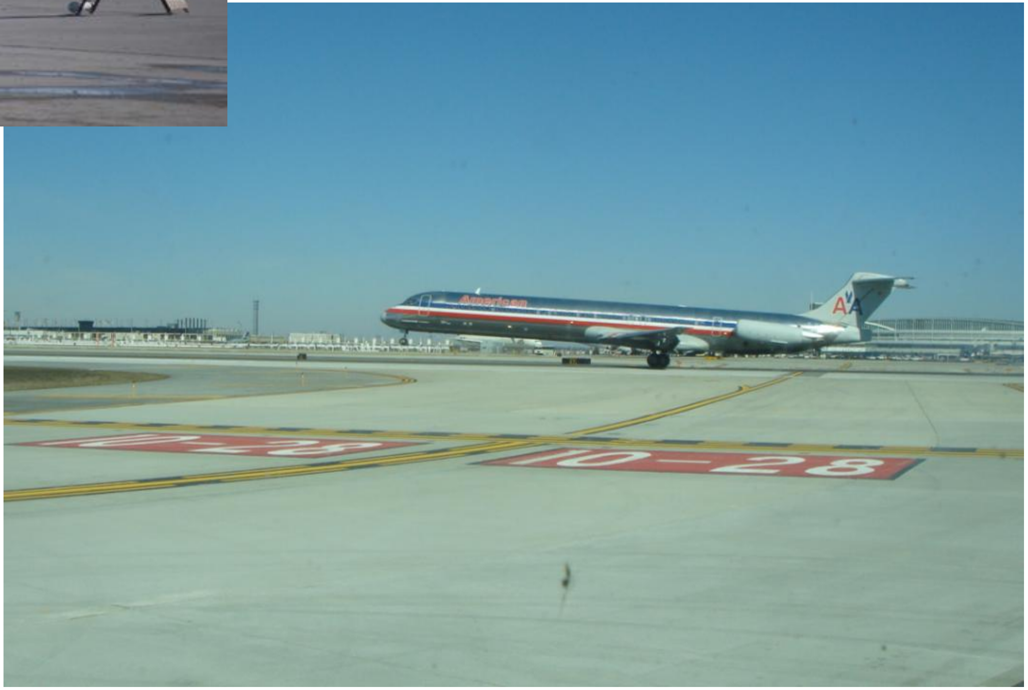
- This sampling system will also be used during the main measurement campaign.

Tire and Brake Emissions Measurements

- Mobile lab was positioned adjacent to runway 10-28, downwind of the main terminal area
  - ✓ Runway was used for take-offs and landings
- Predominant wind direction was W/NW
- The PM instrumentation suite used to measure tire and brake emissions was the same as that used to measure APU emissions.
  - ✓ A TSI Optical Particle Spectrometer (OPS) was used to measure PM size distributions in the 0.3-10µm size range

Tire and Brake Emissions Measurements

B737 aircraft landing with a puff of tire smoke



MD-80 aircraft landing with no visible tire smoke

Tire and Brake Emissions Measurements

- Tire PM emissions
  - Over 30 unique events were recorded
  - Project team is in a position to clearly distinguish engine exhaust PM from tire wear PM

- Brake PM emission
  - Performed on March 11, 2011
  - The winds during the morning were unfavorable to measure brake emissions
  - project team is still analyzing the data to determine if brake PM emissions were sampled

Summary

- Pilot study was successfully executed
- The sampling and measurement plans for PM emissions from APUs and tires and brakes were implemented as planned
- Good data sets for PM emissions from APUs and tires were obtained
- The sampling and measurement plan for brakes will be revised

- Data reduction, analysis and interpretation currently underway

Acknowledgements

- United Air Lines
  - Roger Peterson and colleagues
- Chicago O’Hare International Airport
  - Ray Hoffelt and colleagues

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The opinions and conclusions expressed or implied in the presentation are those of the research team. They are not necessarily those of the Transportation Research Board, the National Academies, or the program sponsor.

Emissions Characteristics of Alternative Aviation Fuels
Project AAFEX 2 March 21 – April 2 2011

This work was funded by the FAA
under FAA Award Nos.: 09-C-NE-MST Amendment No. 003

Objectives

- Long-term
  - Provide comprehensive database on the impact of candidate alternate fuels on PM and HAP emissions from the range of engines currently operating and anticipated to operate in the future in the commercial sector.
- Near term
  - The primary objective of this project is to examine and quantify any changes in PM and HAP emissions from engines burning alternative fuels and blends compared to conventional fuels as these engines are operated in a broad range of atmospheric conditions throughout the world on any given day.

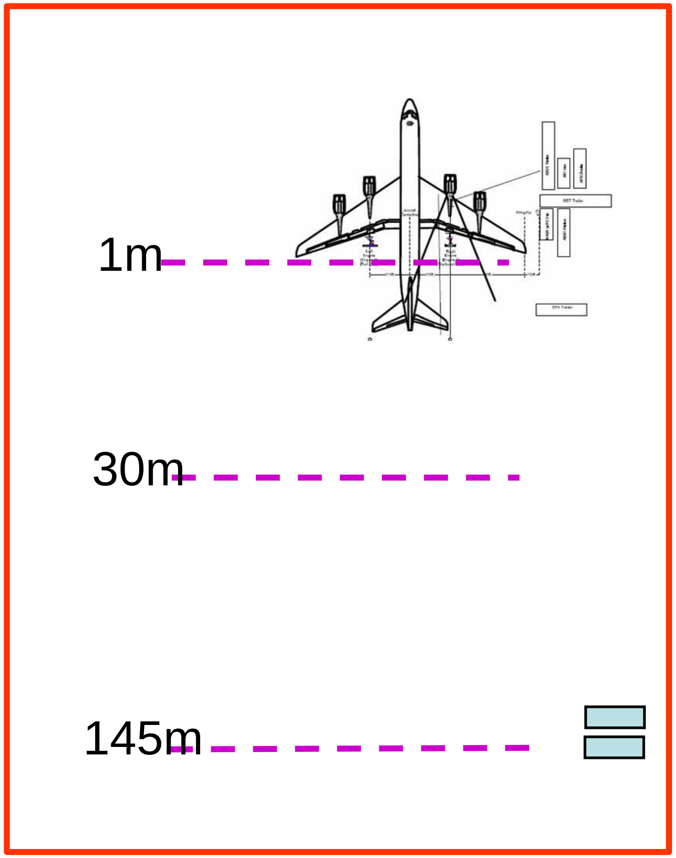
  - Secondary objective: since for the purpose of comparison a conventional fuel will also be studied, it is a secondary objective of this project to obtain PM and HAP emissions data for the engines burning the conventional fuels. This second objective will provide further data for the PM-HAPs emissions database.

Recent Objectives, Accomplishments & Contributions – AAFEX II

Fuels: One biomass-derived (tallow) Hydro-treated Renewable Jet Fuel, One Biomass HRJ blend with JP-8, One F-T fuel (Sasol), One F-T fuel (Sasol) doped with sulfur, JP-8

Objectives

- Examine the effects of alternative fuels – bio-fuel on engine performance and emissions
- Investigate exhaust plume chemistry, including the role of fuel sulfur in regulating volatile aerosol formation in engine exhaust plumes
- Examine the effects of sample line chemistry and particle losses on emission measurements
- Evaluate new instruments and sampling techniques



Accomplishments

1) Test campaign successfully completed by 2 April 2011 and data analysis underway.

Participants: NASA,PARTNER, DOD

News from AAFEX II

- List of preliminary conclusions –
- Similar to FT fuels,
  - ✓ **HRJ dramatically reduces PM soot emissions;**
  - ✓ **HRJ/JP-8 blend produces a disproportionate reduction in PM soot emissions**
  - ✓ Size dependence of reduction in PM soot emissions varies with engine power
  - ✓ Fuel S greatly increases volatile PM number and mass emissions

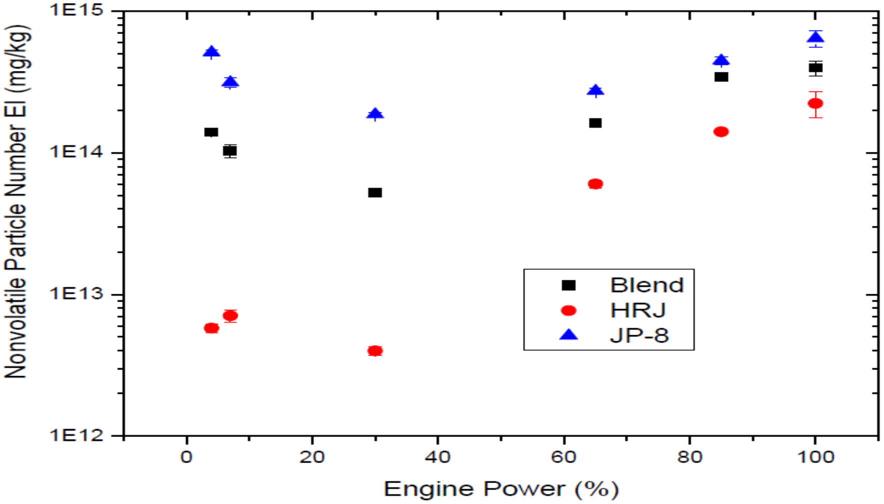
% Reduction Data

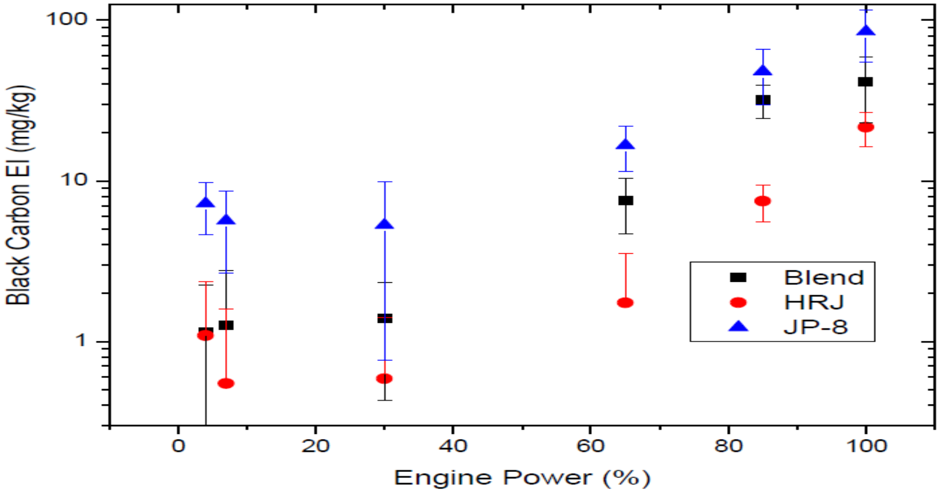
PRELIMINARY DATA – DO NOT CITE

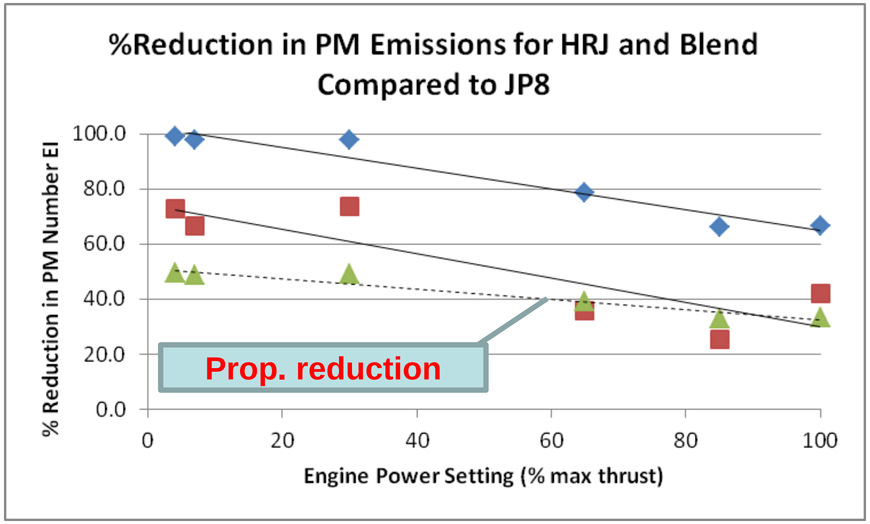
Engine Power	% Reduction with HRJ	% Reduction with 50:50 blend	50% Prop. HRJ % Reduction
Number-based EI			
4	98.9	72.7	49.5
7	97.7	66.7	48.8
30	97.9	73.7	48.9
65	78.6	35.7	39.3
85	66.0	25.5	33.0
100	66.7	42.0	33.3
Black Carbon Mass-based EI			
4	84.7	81.9	42.4
7	94.4	75.4	47.2
30	92.5	71.2	46.3
65	88.8	53.5	44.4
85	84.2	36.0	42.1
100	75.6	52.2	37.8

PM Emission comparisons HRJ,JP8 & 50:50 Blend

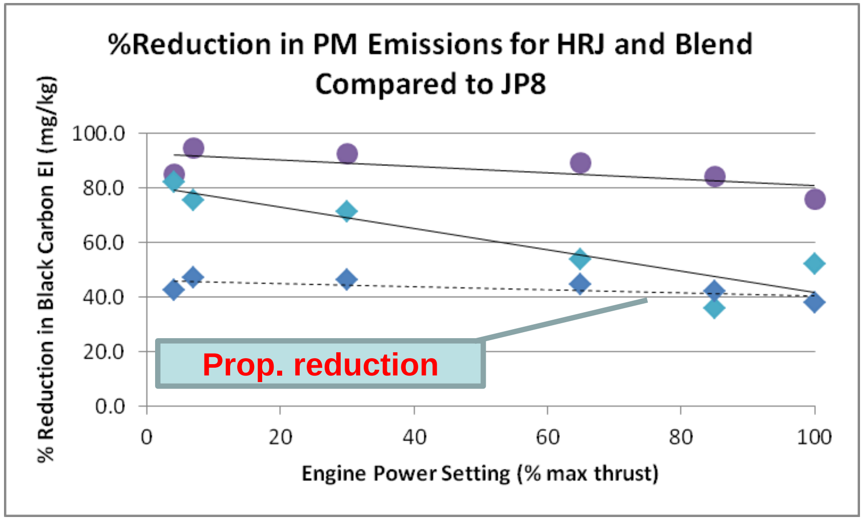
PRELIMINARY DATA – DO NOT CITE






%Reduction in PM Emissions for HRJ and Blend Compared to JP8

Prop. reduction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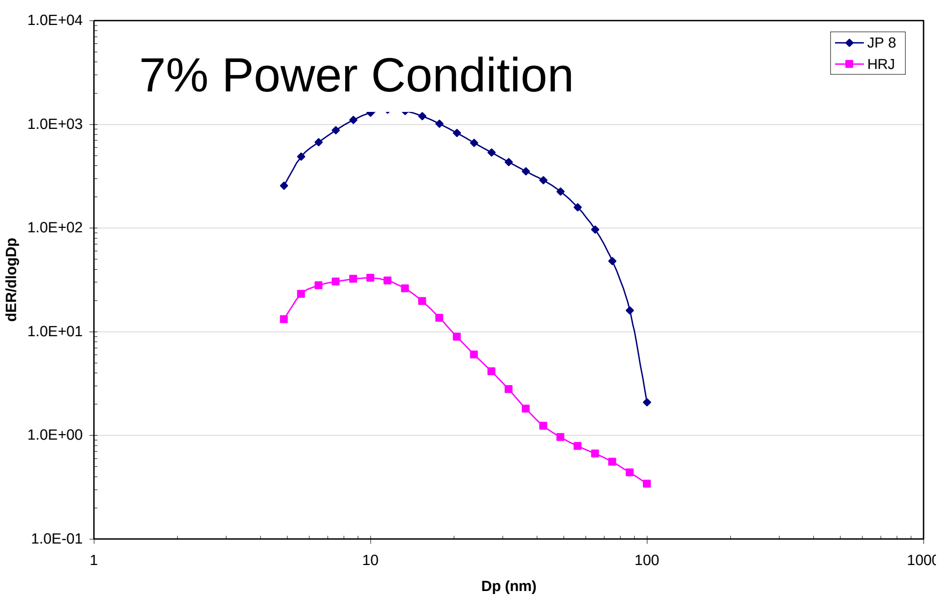
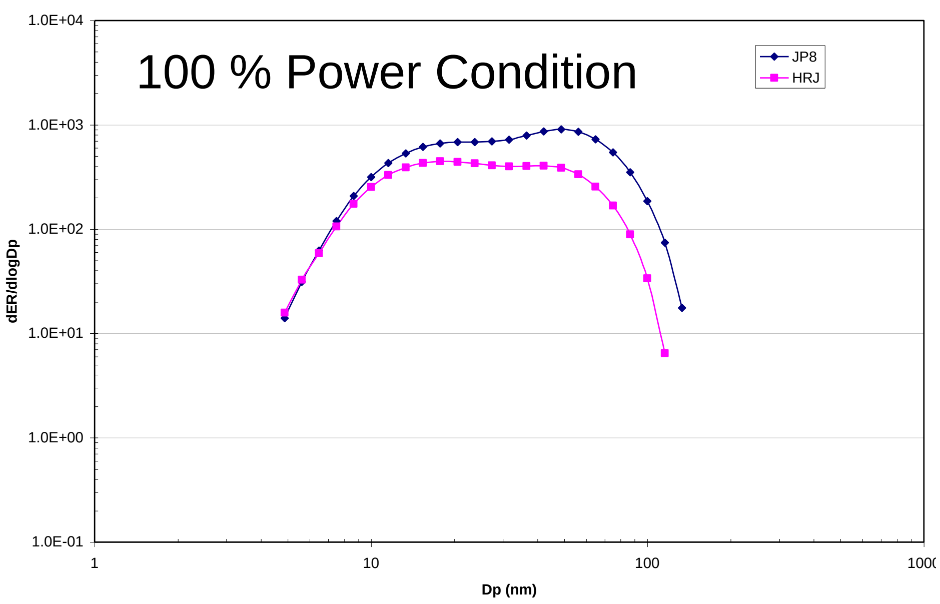
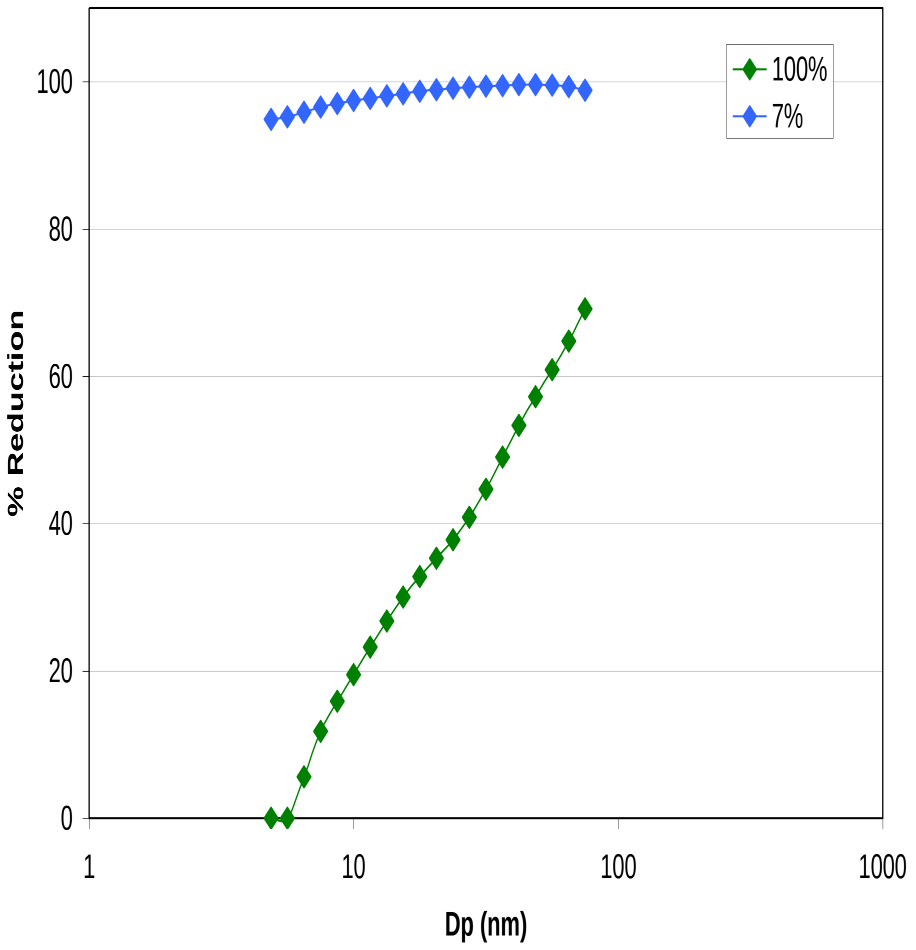

7% Power Condition


100% Power Condition

PRELIMINARY DATA – DO NOT CITE

% Reduction as a function of PM Size



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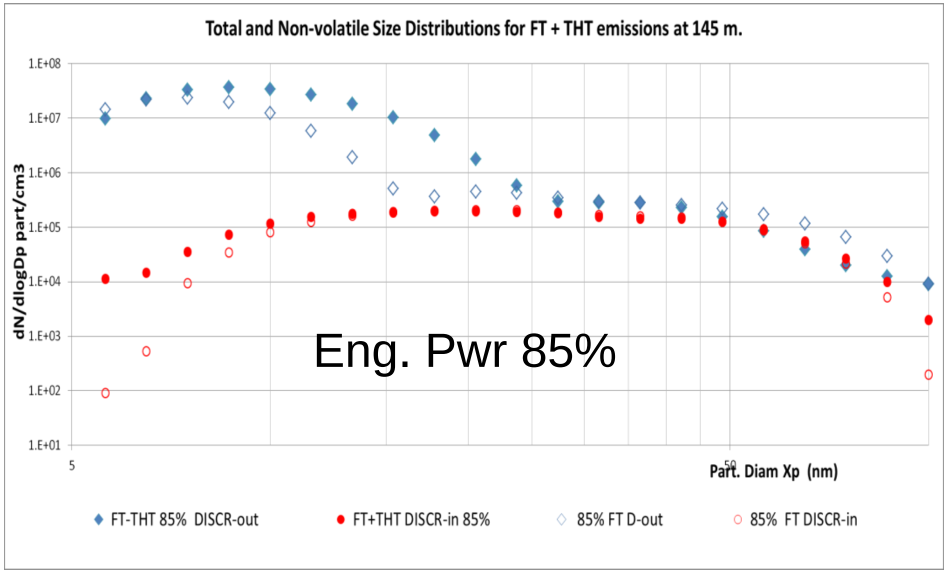
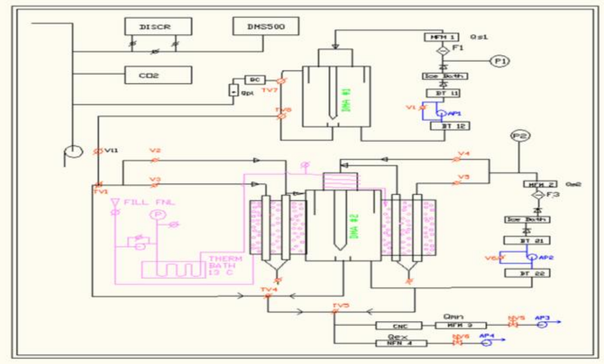
Hydration Properties – soluble mass fraction

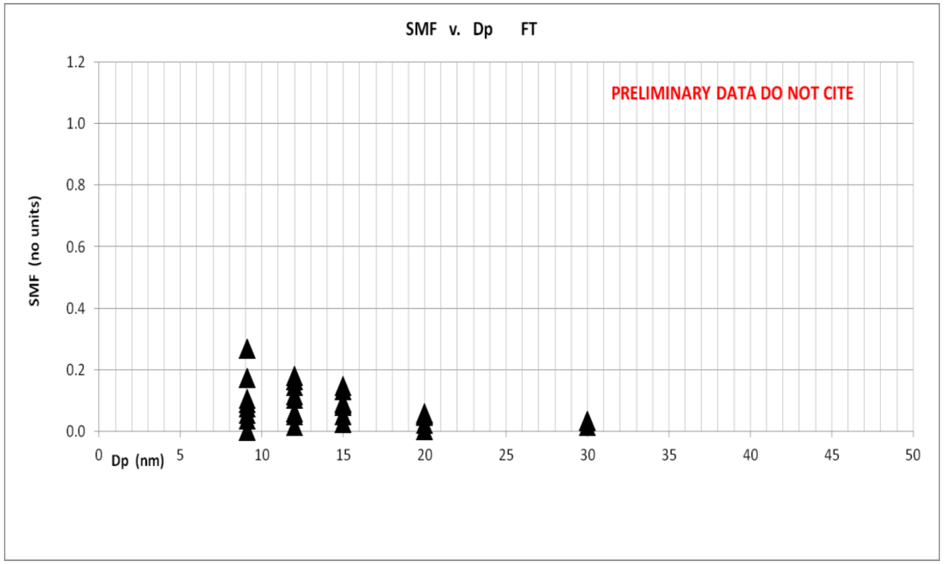


Total and Non-volatile Size Distributions for FT + THT emissions at 145 m.

Eng. Pwr 85%

Fuel Type	Tot. PM (cm-3)	NV PM (cm-3)	Tot. GMD (nm)
FT + THT	(1.2±0.3) E 7	(1.4±0.5) E 5	9.8±0.2
FT	(6.7±0.9) E 6	(1.3±0.3) E 5	5.0±0.1





SMF v. Dp FT

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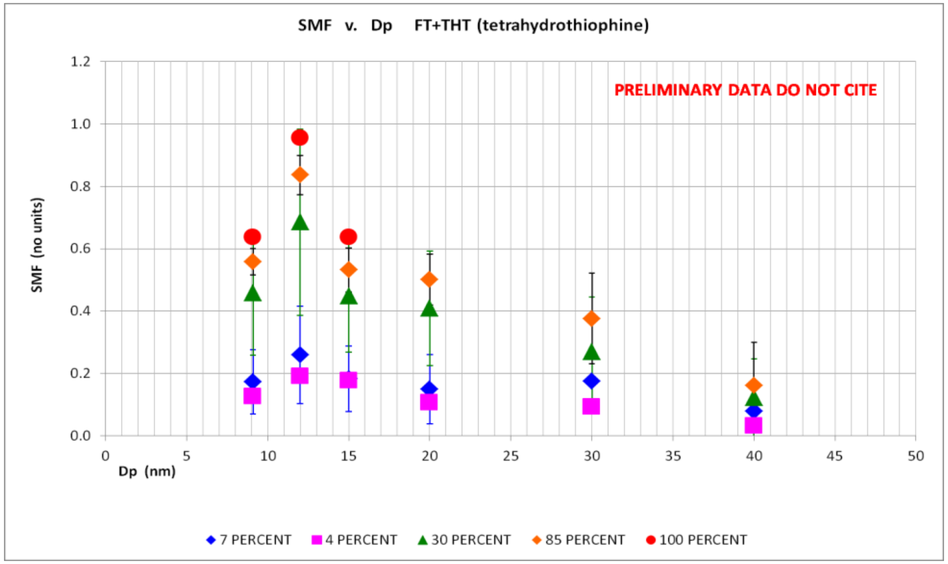

SMF v. Dp FT+THT (tetrahydrothiophine)

PRELIMINARY DATA DO NOT CITE

Hydration Properties – SMF Power Dependence

Observation –

- For a given fuel at any given particle diameter, SMF increases with engine power:
  - Higher power corresponds to increase CO2 concentration per unit volume of exhaust gas and hence a higher concentration of combustion products per unit volume of exhaust gas to drive gas-to-particle conversion.
  - Higher power corresponds to higher temperature at the exhaust plane, and thus a larger ΔT (exhaust plane to ambient) to drive gas-to-particle conversion.
- For a given fuel at any given power, SMF decreases with increasing particle diameter:
  - Mass of soluble material taken up by a particle is proportional to the particle surface area which in turn is proportional to D^2
  - Particle mass is proportional to d^3 hence the SMF must decrease with increasing diameter