Effect of Jet Fuel Properties on Solid Particle Number and Mass Emission from Aircraft Gas Turbine Engine: Development of a Jet Fuel Particle Index

JET FUEL PARTICLE INDEX
A Consortium of SwRI

SOUTHWEST RESEARCH INSTITUTE®

Imad A. Khalek, Ph.D., Sr. Program Manager

Ikhalek@swri.org , San Antonio, Texas, USA

20th ETH Conference on Combustion Generated Particles, Zurich, Switzerland, June 14-16, 2016

Project Team

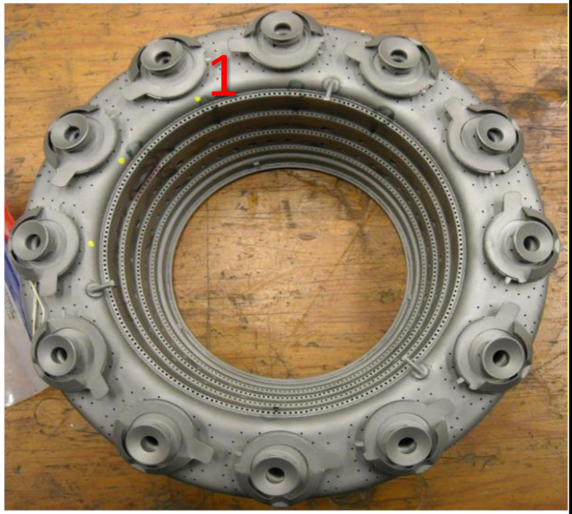
- This research was funded by SwRI Internal Research & Development Program:

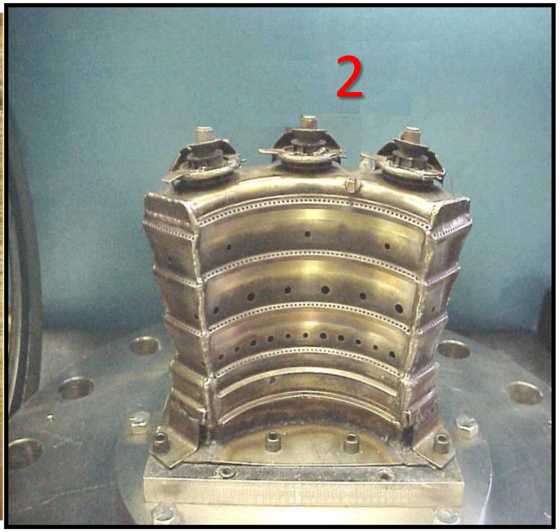
- Principal Investigator: Imad Khalek, Ph.D.
- Co-Investigator: Nigil Jeyashekar, Ph.D.
- Experimental Efforts: Vinay Premnath, Daniel Preece & Richard Mechler, and Michael Gass
- Fuel Technical Advisor: George Wilson

Our Work

- SwRI has done some very recent experimental work on the effects of fuel properties on particle emissions from a gas turbine combustor:
  - We also developed a Jet Fuel Particle Index (JFPI) for the five fuels tested in the program:
    - The JFPI is a single parameter that combines the chemistry and physics of fuel properties to rank fuels in terms of their soot forming tendency leading to particle emissions
      - **Over 800 fuel properties are used to calculate the JFPI**
    - The JFPI is an extension of the Gasoline Fuel Particle Index (GFPI) that has gained a lot of momentum in the area of gasoline fuels

T700 Combustor Liner





AH-64 Apache

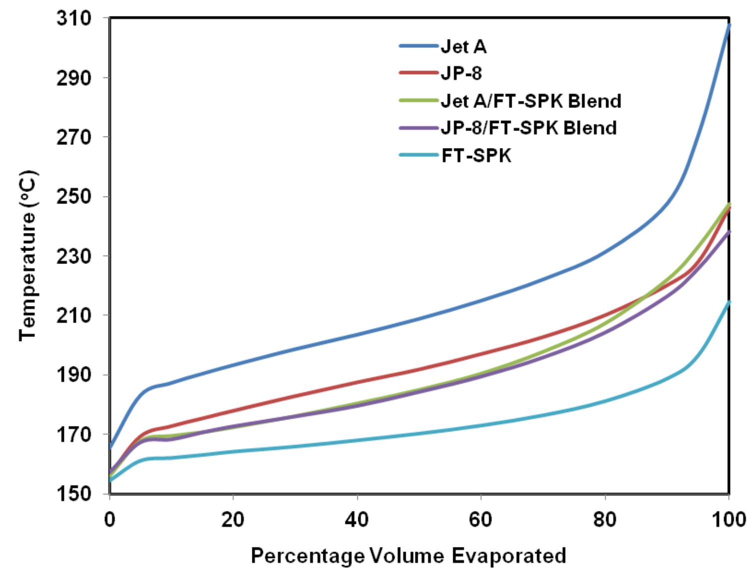
UH-60 Black Hawk

- Figure 1 is a complete T700 combustor liner manufactured by GE
- Figure 2 is a 3 sector cup
  - Three fuel nozzles
    - Emissions measured at the center cup
- A scaled down version of other combustor designs can be added

Jet Fuel Properties Tested (5 Fuels)

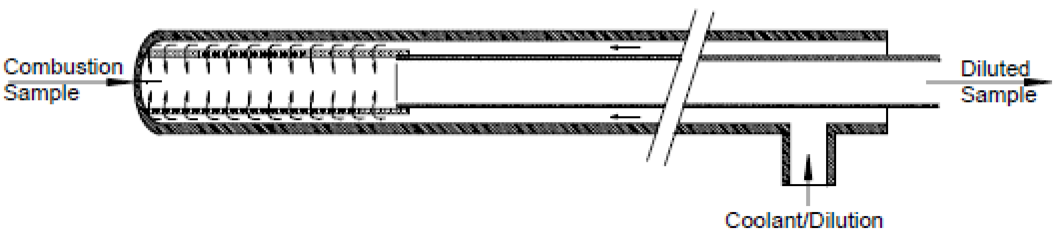
JET FUEL PARTICLE INDEX
A Consortium of SwRI

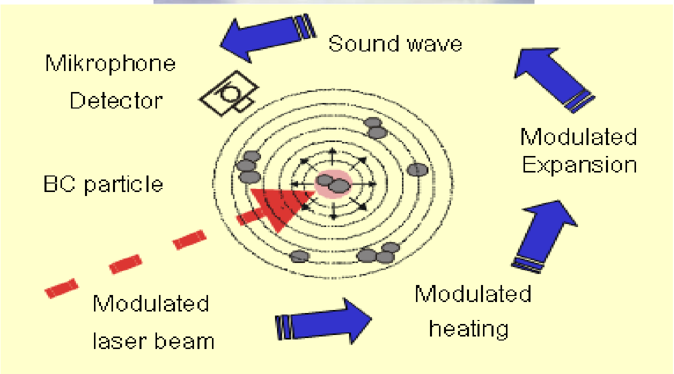
ASTM Fuel Property	Jet A	JP-8	Jet A/ FT-SPK Blend	JP-8/ FT-SPK Blend	FT-SPK
Density – D4052 (kg/m^3) at 20°C	799.2	772.3	764.0	770.4	739.2
Smoke Point (D1322) (mm)	23.5	32.2	38.5	32.3	54.4
Chemical Composition (D1319)					
Aromatics (vol. %)	18.4	11.4	6.7	9.9	1.3
Olefins (vol. %)	1.8	0.8	0.7	1.5	1.1
Saturates (vol. %)	79.8	87.8	92.6	88.6	97.6
Napthalene Content (D1840) (vol. %)	1.26	0.46	0.30	0.33	0.06
Carbon/Hydrogen (D5291) CH					
Carbon (mass %)	86.13	85.32	85.18	85.09	84.63
Hydrogen (mass %)	14.02	14.51	14.85	14.57	15.46
D5453 (ppm)	1006.5	51.2	72	5.7	1.8
Vapor Pressure (D6378)					
T=0°C (P_{abs})	0.03	0.02	0.03	0.04	0.00
T=20°C (P_{abs})	0.06	0.07	0.09	0.14	0.08
T=40°C (P_{abs})	0.11	0.14	0.18	0.18	0.21
T=60°C (P_{abs})	0.21	0.34	0.34	0.41	0.47
T=80°C (P_{abs})	0.52	0.78	0.77	0.87	1.01
T=100°C (P_{abs})	1.08	1.61	1.63	1.78	2.11
T=120°C (P_{abs})	2.06	3.06	3.20	3.46	3.95



Jet A: Commercial Jet Fuel
JP-8: US Air Force Jet Fuel

Particle Measurement (Soot Mass, Solid & Total Particle Number)





Soot Mass Measured by AVL Micro-Soot Sensor

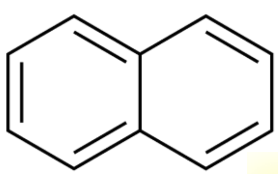
Particle Size and Number using Cambustion DMS500 with and without SwRI Catalytic Stripper

Fuel Particle Index (DBE, VP, Wt)

- Why are the DBE and vapor pressure important factors in the PM Index equation?
  - Fuel components of low vapor pressure evaporate slowly, and promotes local rich burning regions (This could be important at idle, very low temperature)
  - DBE (Double Bond Equivalent) is essentially an indication of the degree of unsaturation of a molecule. Fuel components with high DBE values are typically polyaromatic hydrocarbons (PAHs). PAHs in the fuel are known to be precursors for exhaust particulates.

- Note that PAHs have high DBE values and very low vapor pressures. Even a small amount of PAHs in the fuel will cause it to have a high PM Index.

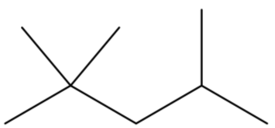
PAH Example
(major effect on PM Index)



Naphthalene
DBE = 7
VP(443K) = 34 kPa

Paraffin Example
(minor effect on PM Index)

2,2,4-Trimethylpentane
(iso-octane)
DBE = 0
VP(443K) = 624 kPa



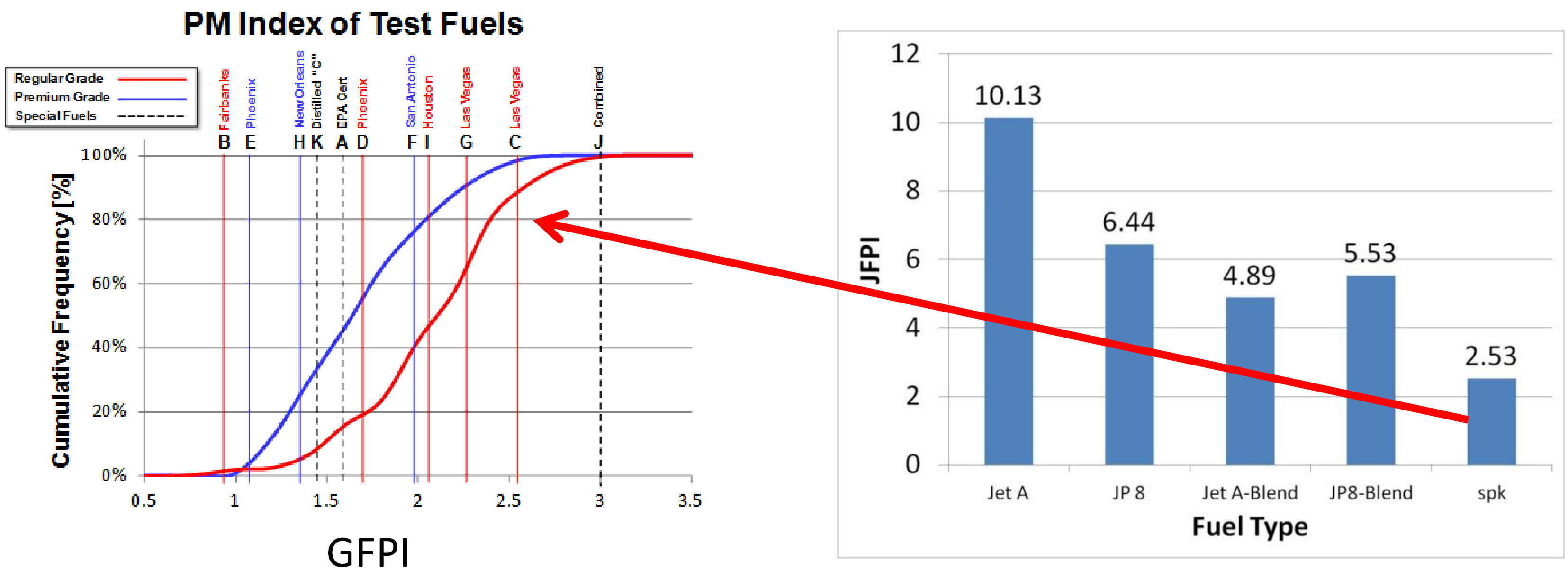
$$GFPI = \sum_{i=1}^{n} I_{[443K]} = \sum_{i=1}^{n} \left(\frac{DBE_i + 1}{V.P(443K)_i} \times Wt_i \right)$$

Gasoline & Jet Fuel Particle Index (GFPI & JFPI)

JET FUEL PARTICLE INDEX
A Consortium of SwRI

Gasoline Fuel: GFPI Distribution in the USA

Jet Fuel: JFPI for Five Different Fuels, we recently tested



Khalek & Jetter, 2012 CRC Workshop. Work Funded by Honda R&D America

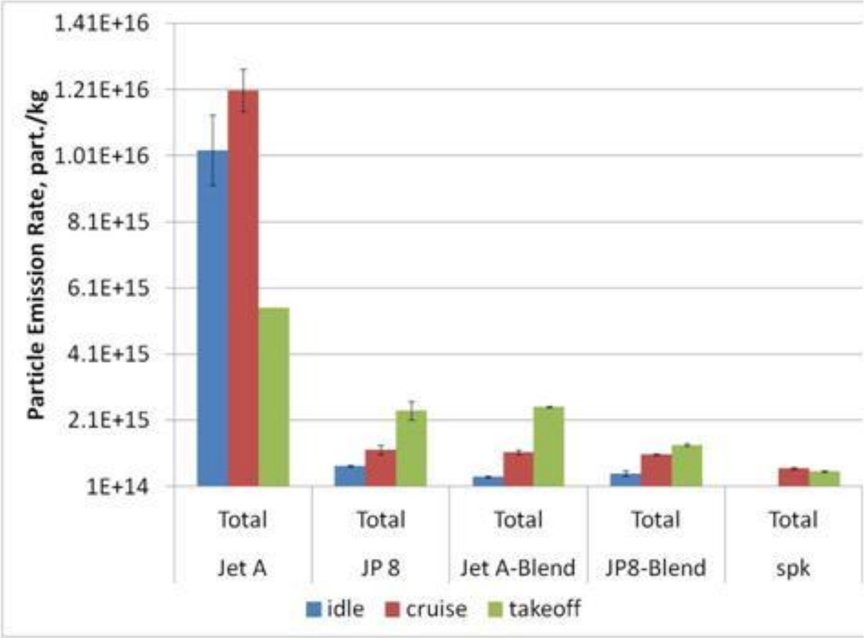
Khalek & Jeyashekar, *October 2015, Funded by SwRI Internal Research & Development*

Experimental Results

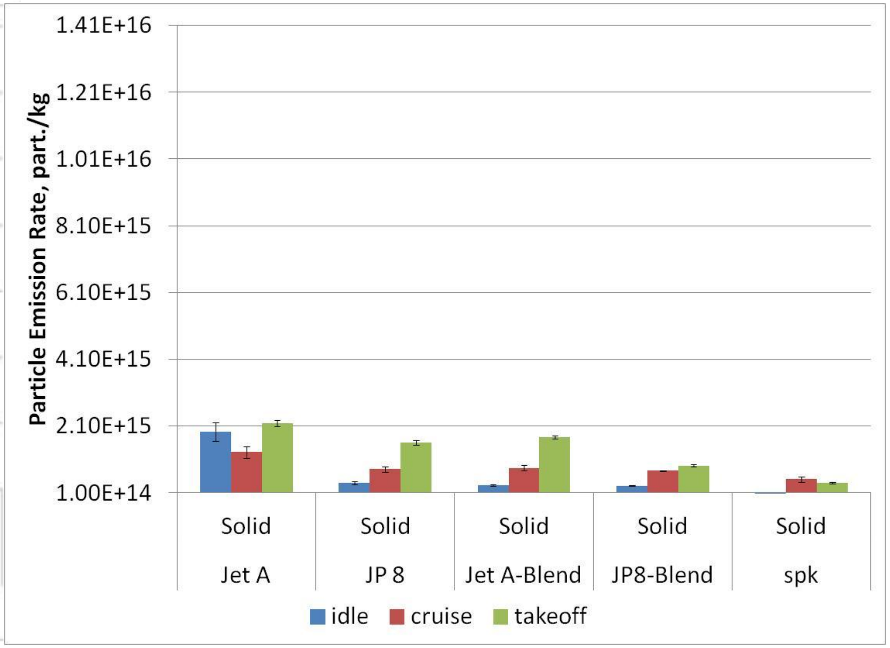
Particle Emissions at Idle, Take-Off & Cruise

- Solid + Volatile Particle Emissions
- Solid Particle Emissions

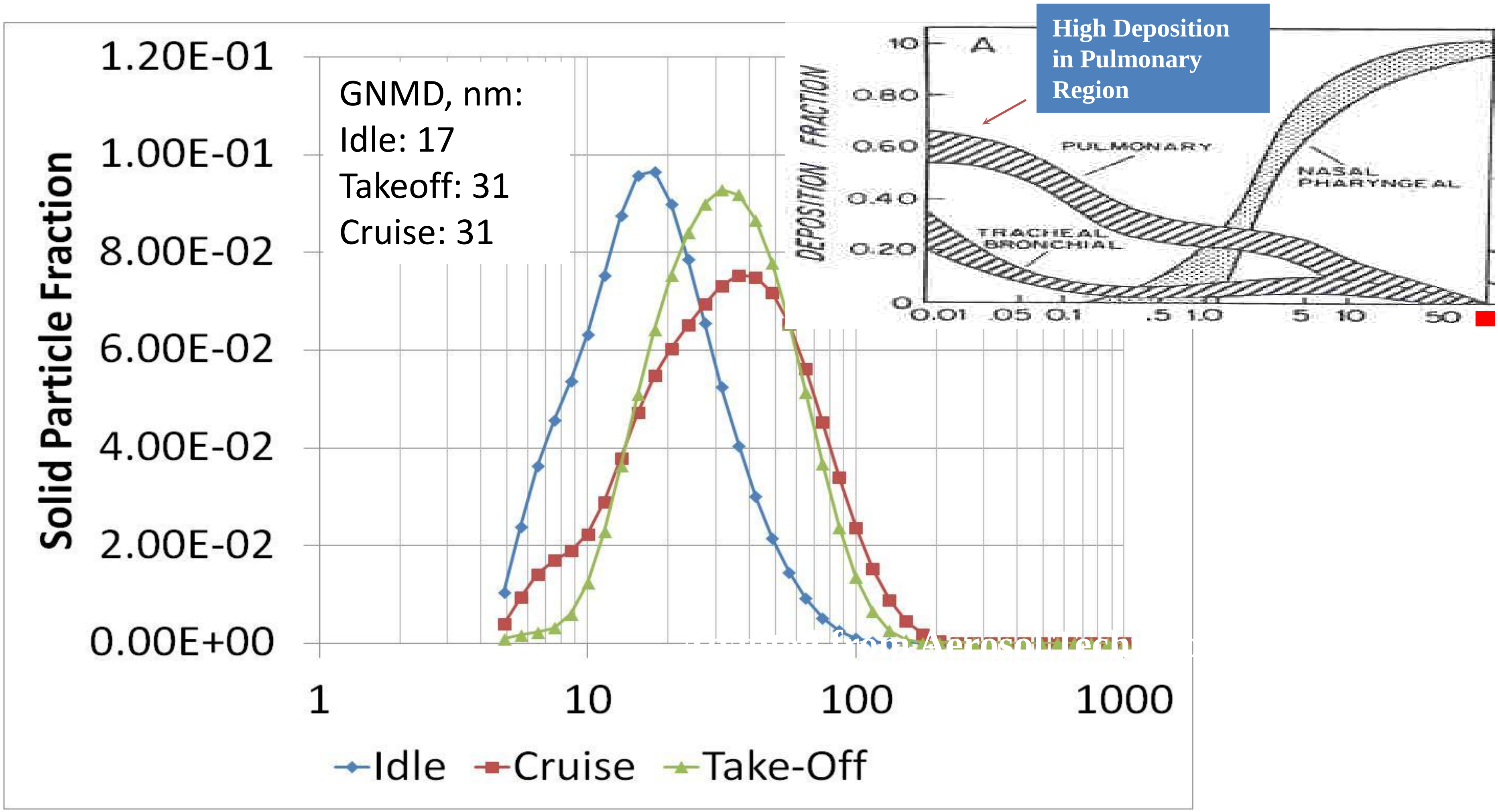
Not Part of the Regulation



Part of the Regulation

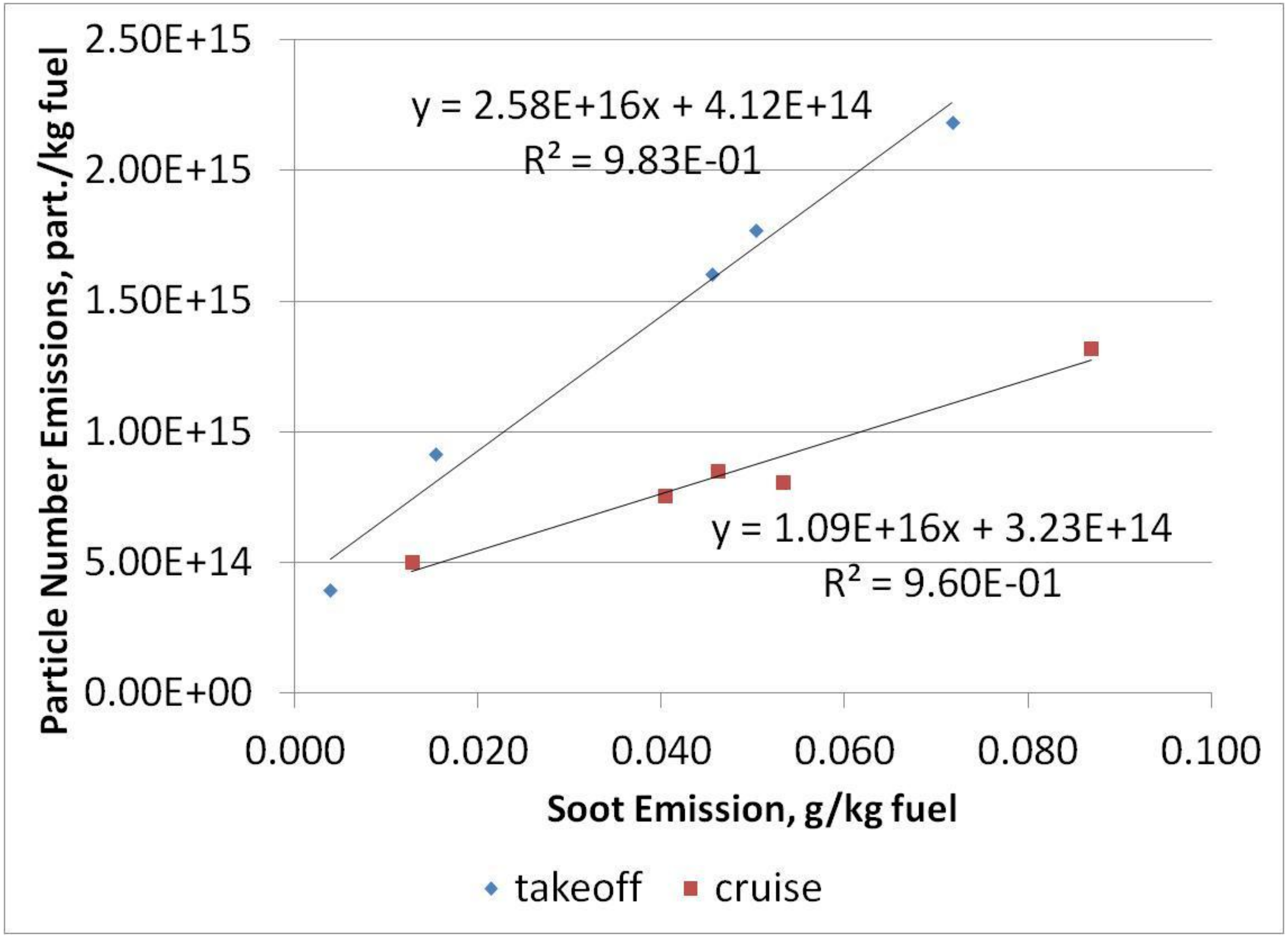


Measured Size Distribution (Jet A)



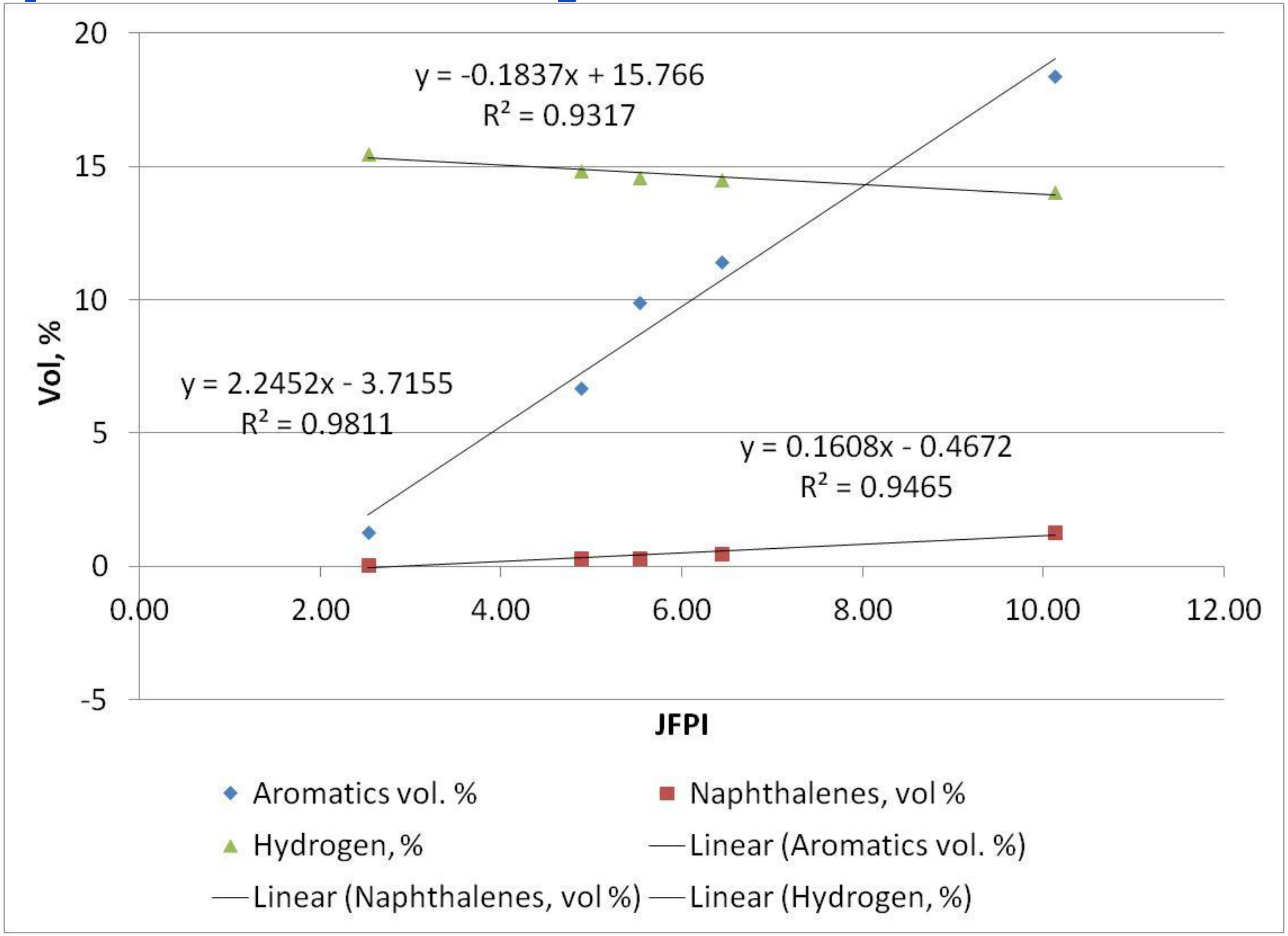
GNMD is 10 to 40 nm smaller than those typically observed in Gasoline and Diesel Engine Exhaust

Relationship Between Solid Particle Number and Soot Mass

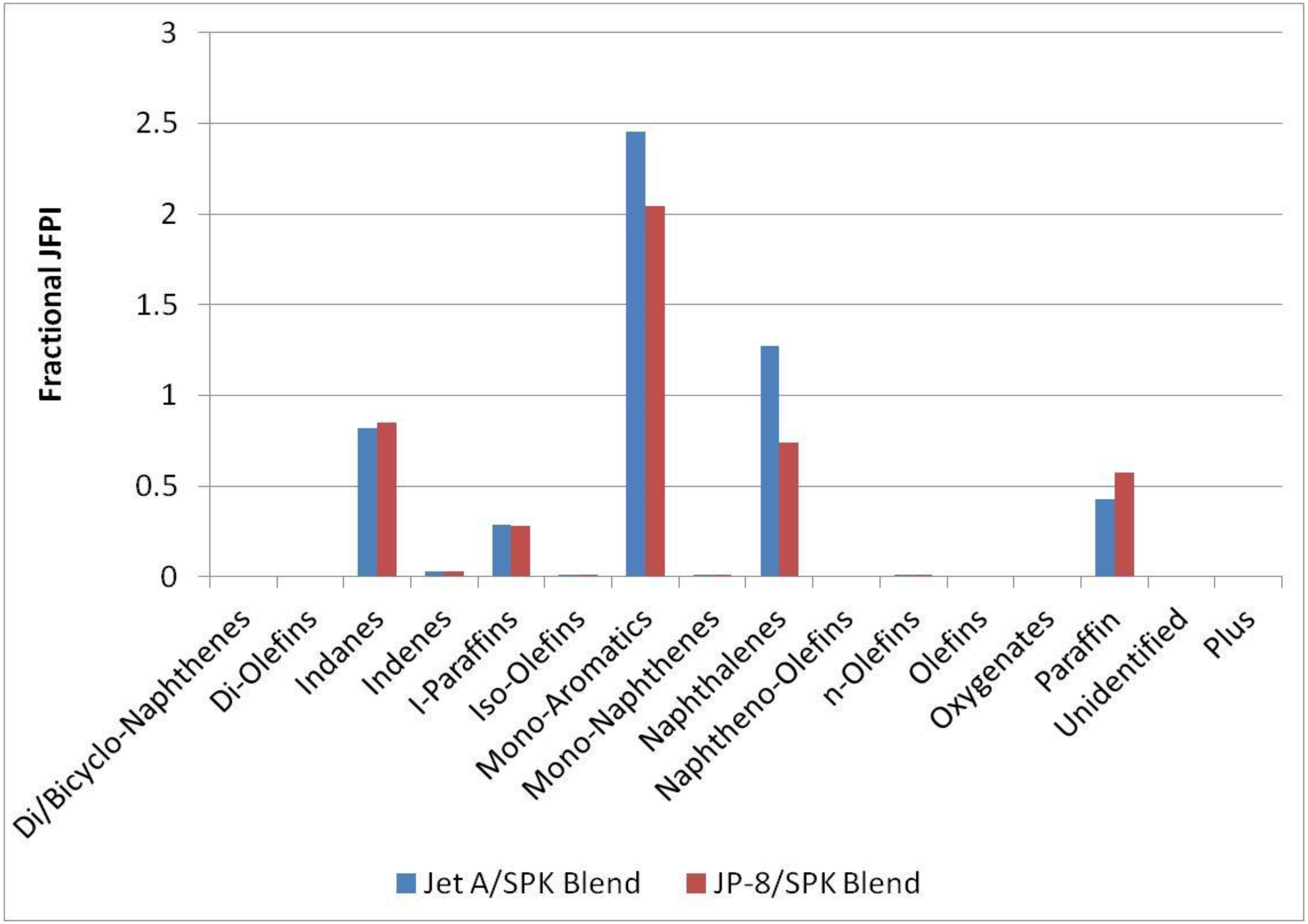


Slope is <u>one order of magnitude higher</u> than Gasoline Direct Injection (GDI) Engines

Relationship Between Select Fuel Properties and the JFPI

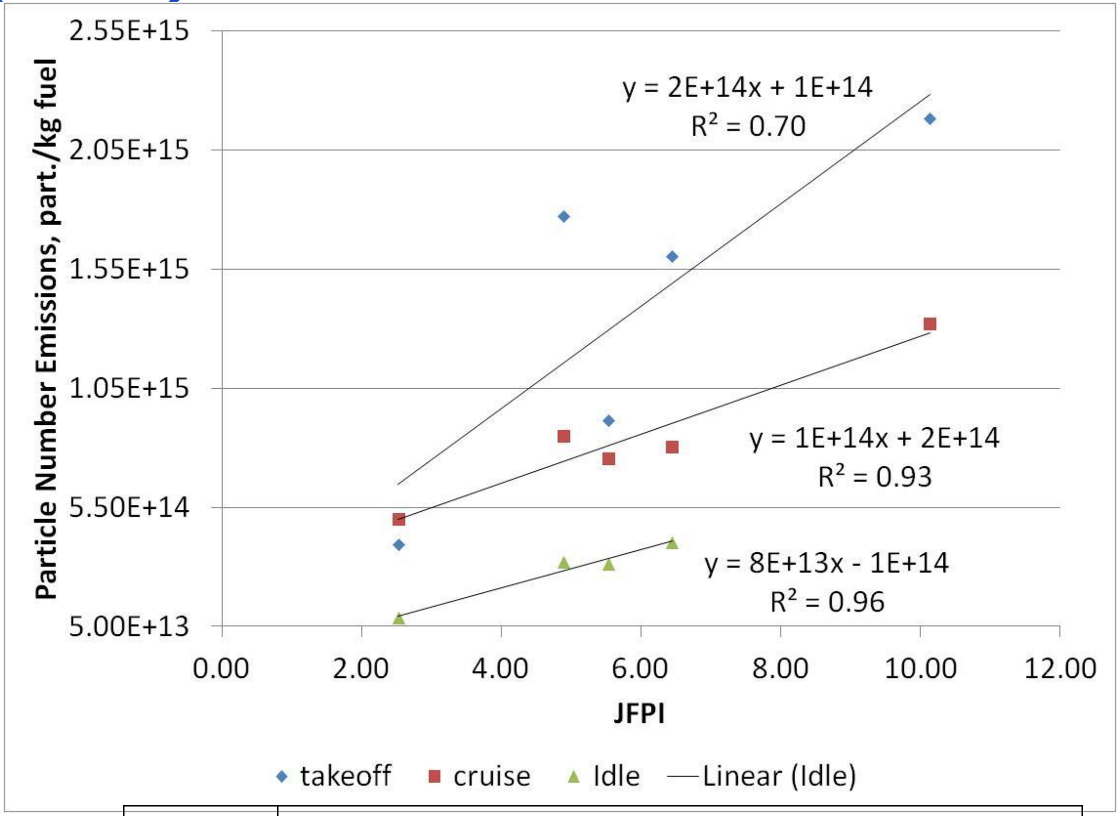


Example of Major Fuel Components Contributor to the JFPI



Correlation between Jet Fuel Particle Index (JFPI) and Particle Emissions

JET FUEL PARTICLE INDEX
A Consortium of SwRI



	Correlation Coefficient			
	Naphthalenes	Mono-Aromatics	Hydrogen	JFPI
Idle*	0.98	0.90	0.91	0.96
Take-Off	0.62	0.64	0.70	0.70
Cruise	0.93	0.86	0.81	0.93

* Jet A was omitted because it resulted in high emissions at idle

Summary

JET FUEL
PARTICLE INDEX
A Consortium of SwRI

- Based on this limited work, we have identified a:
  - Jet Fuel Particle Index (JFPI) that is a continuation of the Gasoline Fuel Particle Index (GFPI)
  - Similar to the GFPI, the JFPI can be used as a predictor of soot forming tendency of Jet fuel in combustion worldwide
  - The JFPI can be used as a singular parameter to represent the sooting tendency of jet fuels worldwide
    - This can be very valuable prior to the upcoming regulations on particle emissions from jet engines
    - This can be also used for fine tuning fuel properties for particle emissions reduction
- SwRI plans to continue this development in collaboration of industry/government
  - This can provide valuable information to engine developers and fuel developers, including alternative fuels