Federal Aviation Administration

Framework for Speciated Hydrocarbon Emissions Inventories from Commercial Aircraft

Presented to: Western Pacific Airports Conference

By: Ralph Iovinelli
Office of Environment & Energy

Date: 6 May 2008

Acknowledgements

- **EPA**
  - Bryan Manning
  - Rich Cook
  - John Kinsey
- **California ARB**
  - Steve Francis
  - Steve Church
- **Aerodyne Research, Inc.**
  - Data Source Comparisons & APEX data processing
    - Rick Miake-Lye
    - Scott Herndon
    - Berk Knighton (Montana State University)
- **KB Environmental Sciences, Inc.**
  - Assembling guidance and QAPP
    - Carrol Bryant & Mike Kenney & Mike Ratte

Outline

- **Where we were…**
  - Limited data
  - Analytical inconsistency

- **Where we are…**
  - More data
  - Analytical consistency

Where we were… limited data

- **Spicer, et al.** **(Spicer et al. Ann. Geophysicae 12:944-955, 1994)**
  - US Air Force – Engineering & Services Center
  - Performed: 1984-1990
  - Various Test Methods
    - Sampling rake, test cell
  - Tested 10 military gas turbine engines w/ 6 civilian variants
    - TF-39-1C : CF6-6
    - CFM-56-3 : CFM-56-3
    - TF-41-A2 : Rolls Royce Spey
    - TF33-P3 : JT3-D
    - TF33-37 : JT3-D
    - J79 : CJ805
  - Majority of tests performed with JP-4 (some with JP-5, JP-8)

<1.7% of national fleet

Where we were… limited data

- **Gerstle, et al.** **(Gerstle et al. ADA361474/XABI Technical Report, 1999)**
  - US Air Force – Institute for Environment, Safety & Occupational Risk Analysis
  - Performed: 1997-2002
  - US EPA test methods in test cells
  - Exhaust tests 11 turbofan, 2 turbojet, 2 turboshaft, 1 turboprop
    - Of the 16 engines, 10 have civilian variants
    - TF - F108-CF-100 : CFM-56
    - TF - F117-PW-100 : PW2037
    - TF - TF33-P-102 : JT3D-7
    - TF - TF33-P-7/7A : JT3D-7
    - TF - TF34-GE-100A : CF34
    - TF - TF39-GE-1C : CF6
    - TJ - J69-T-25 : Marbore II Model 352
    - TJ - J85-GE-5A : CJ610
    - TP - T56-A-7 : T501D
    - TS - T700-GE-700 : CT7-2
  - Tests performed with JP-8 fuel

Where we were… limited data

- **Shumway, et al.**
  - US Navy – Aircraft Environmental Support Office
  - Performed: 2000
  - Fuel Tests only: Jet-A, JP-8, JP-5
  - Various laboratory test methods

Where we were… limited data

Turbofan Engines

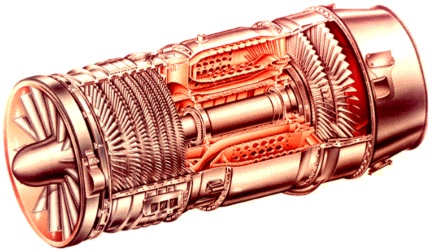
Tested Engine	Civilian Variants	In Use	% of National Fleet
TF-39-1C (S) / TF39-GE-1C (G)	CF6-6	DC-10-10	0.3%
CFM-56-3 (S) / F108-CF-100 (G)	CFM-56-3	707, DC-8, 737, A319, A320	8.0%
TF-41-A2 (S)	Rolls Royce Spey	F-28, BAC-111-200/400	1.7%
TF33-P3 (S) / TF33-P7 (S)	JT3-D	-	-
J79 (S)	CJ805	-	-
F117-PW-100 (G)	PW2037	757	1.3%
TF33-P-102 (G) / TF33-P-7/7A (G)	JT3D-7	707	0.3%
TF34-GE-100A (G)	CF34	CL-600, EMB-170	0.3%
Total			11.9%

(S) = Spicer, (G) = Gerstle

Where we were… limited data

Turbojet Engines

Tested Engine	Civilian Variants	In Use	% of National Fleet
J69-T-25 (G)	Marbore II – Model 352	-	-
J85-GE-5A (G)	CJ610	Learjet 23/24/25	1.8%
Total			1.8%



Learjet 25D

(S) = Spicer, (G) = Gerstle

Turboprop Engines

Tested Engine	Civilian Variants	In Use	% of National Fleet
T56-A-7 (G)	T501-D	Convair 580, Lockheed L-188 Electra	-

Convair 580

Lockheed L-188 Electra

(S) = Spicer, (G) = Gerstle

9

Where we were… limited data

Turboshaft Engines

Tested Engine	Civilian Variants	In Use	% of National Fleet
T700-GE-700 (G)	**CT7-2**	**Bell 214ST and Sikorsky S-70**	**< 0.2%**

Bell 214ST

Sikorsky S-70

(S) = Spicer, (G) = Gerstle

Are Historical Hydrocarbon Data Representative of Current Fleet?

Engine Type	Approximate % of US Fleet Tested	Test Performed With JP-8 or Jet-A?
Turbofan	11.9	No
Turbojet	1.8	No
Turboprop	-	-
Turboshaft	<0.2	No
Piston	-	-
Total	<13.9	No

Optimistic Prediction

[a] Source: With the exception of turboshaft data, BACK database for April 2005.

Where we were… limited data

Database of Hydrocarbon Profiles

- **EPA SPECIATE Database v4**
  - 20 aviation profiles
    - 2 “airport” profiles from ATL
    - Commercial, Military, & General Aviation specific profiles
      - All from Spicer’s 1984 test on a CFM56 engine (JP-4 fuel for 7%, 30%, and 80% power settings)
      - EPA indicates applying to full LTO cycle
    - 7 profiles for PAHs only
    - All profiles add up to 100%
    - JP-4, JP-5, JP-8 fuels
  - 147 Compounds
    - 15 PAHs
    - 22 without CAS numbers including “unknowns”
  - How do we apply this resource to represent today’s fleet?

Outline

- **Where we were…**
  - Limited data
  - Analytical inconsistency
- **Where we are…**
  - More data
  - Analytical consistency

Where we are… more data

Motivation

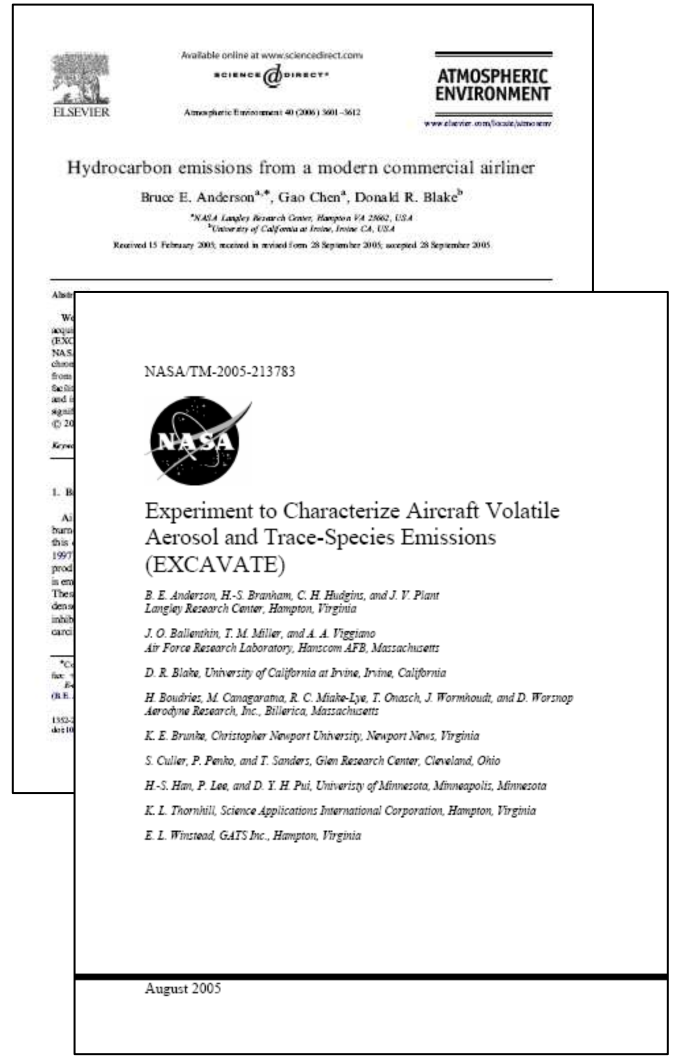
- **EPA Regions frequently request HAPs analyses as part of airport NEPA efforts**
- **Recognized that aircraft HAPs emissions inventory methodology does not exist**
  - Nationally consistent
  - Supported by scientific data
  - Representative of today's flying fleet
- **New aircraft HAPs data publicly available (e.g., EXCAVATE & APEX1,2,3) since Spicer**
- **Time is right to improve speciated HC emissions inventory guidance**

Recent Measurement Campaigns

Where we are… more data

EXCAVATE – Jan 2002

- **NASA Langley, Virginia**
- **Boeing757 with RB211-535E4**
- **10m probe, diluted tip**
- **Low & high sulfur JP-5**
- **4-7%, 26%, 47%, 61% rated thrust settings**
- **Wide range of HCs, no formaldehyde**
- **Consistent w/ Spicer**


Available online at www.sciencedirect.com

ELSEVIER

ATMOSPHERIC ENVIRONMENT

Hydrocarbon emissions from a modern commercial airliner

Bruce E. Anderson[a,*], Gao Chen[a], Donald R. Blake[b]

NASA/TM-2005-213783

Experiment to Characterize Aircraft Volatile Aerosol and Trace-Species Emissions (EXCAVATE)

B. E. Anderson, H.-S. Branham, C. H. Hudgins, and J. V. Plant
Langley Research Center, Hampton, Virginia

J. O. Ballenthin, T. M. Miller, and A. A. Viggiano
Air Force Research Laboratory, Hanscom AFB, Massachusetts

D. R. Blake, University of California at Irvine, Irvine, California

H. Boudries, M. Canagaratna, R. C. Miake-Lye, T. Onasch, J. Wormhoudt, and D. Worsnop
Aerodyne Research, Inc., Billerica, Massachusetts

K. E. Brunke, Christopher Newport University, Newport News, Virginia

S. Culler, P. Penko, and T. Sanders, Glen Research Center, Cleveland, Ohio

H.-S. Han, P. Lee, and D. Y. H. Pui, University of Minnesota, Minneapolis, Minnesota

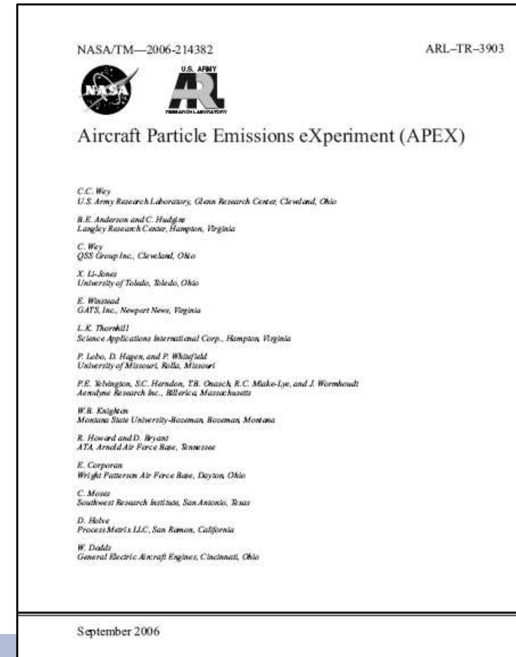
K. L. Thornhill, Science Applications International Corporation, Hampton, Virginia

E. L. Winstead, GATS Inc., Hampton, Virginia

August 2005

Where we are… more data

APEX 1 – April 2004


NASA/TM—2006-214382 ARL–TR–3903

Aircraft Particle Emissions eXperiment (APEX)

C.C. Wey
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

B.E. Anderson and C. Hudgins
Langley Research Center, Hampton, Virginia

C. Wey
QSS Group Inc., Cleveland, Ohio

X. Li-Jones
University of Toledo, Toledo, Ohio

E. Winstead
GATS, Inc., Newport News, Virginia

L.K. Thornhill
Science Applications International Corp., Hampton, Virginia

P. Lobo, D. Hagen, and P. Whitefield
University of Missouri, Rolla, Missouri

P.E. Yelvington, S.C. Herndon, T.B. Onasch, R.C. Miake-Lye, and J. Wormhoudt
Aerodyne Research Inc., Billerica, Massachusetts

W.B. Knighton
Montana State University-Bozeman, Bozeman, Montana

R. Howard and D. Bryant
ATA, Arnold Air Force Base, Tennessee

E. Corporan
Wright Patterson Air Force Base, Dayton, Ohio

C. Moses
Southwest Research Institute, San Antonio, Texas

D. Holve
Process Metrix LLC, San Ramon, California

W. Dodds
General Electric Aircraft Engines, Cincinnati, Ohio

September 2006

- **NASA Dryden Facility**
- **NASA DC-8 w/ CFM56-2C1 engines**
- **EPA & Aerodyne – measured HAPs**
- **UC Riverside – measured HAPs**
  - Not published
- **2 probes: 1m & 30m**
- **3 fuels**
  - JP-8
  - High sulfur
  - High aromatics
- ***http://particles.grc.nasa.gov***

Where we are… more data

APEX 2 – August 2005

- **Oakland International Airport**
- **Southwest Airlines engines**
  - CFM56-3B1
  - CFM56-7B24
- **Partially sponsored by CARB & California Environmental Protection Agency**
- **EPA & Aerodyne – measured HAPs**
- **UC Riverside – measured HAPs**
- ***http://particles.grc.nasa.gov***

Center of Excellence for Aerospace Particulate Emissions Reduction Research

Final Report

The Development of Exhaust Speciation Profiles for Commercial Jet Engines

Prepared by

Prem Lobo, Philip D. Whitefield and Donald E. Hagen
Center of Excellence for Aerospace Particulate Emissions Reduction Research
G-7 Norwood Hall, University of Missouri – Rolla, Rolla, MO 65409
Contact: plobo@umr.edu or pwhite@umr.edu

Scott C. Herndon, John T. Jayne, Ezra C. Wood, W. Berk Knighton, Megan J. Northway and Richard C. Miake-Lye
Aerodyne Research Inc.,
45 Manning Road, Billerica, MA 01821
Contact: herndon@aerodyne.com or rick@aerodyne.com

David Cocker, Aniket Sawant, Harshit Agrawal and J. Wayne Miller
University of California - Riverside
Room 105, Administrative Bldg., 1084 Columbia Ave., Riverside, CA 92507
Contact: wayne.miller@ucr.edu or dcocker@engr.ucr.edu

Contract number: 04-344

Principal Investigator: Philip D. Whitefield

Contractor Organization: University of Missouri - Rolla

Date: October 31, 2007

Prepared for the California Air Resources Board and the California Environmental Protection Agency

i

APEX 3 – November 2005

- **Cleveland International Airport**
- **Multiple engines**
  - Pratt & Whitney
  - GE
  - Rolls Royce
- **EPA & Aerodyne**
  - Measured HAPs
- **Probe distances**
  - 1 meter
  - 30 meter
  - 43 meter

Where we are… more data

APEX 1,2,3 Summary

	Commercial Engine	Engine Type	Aircraft Types	% Total US Fleet	% Total Non-US Fleet
APEX1	CFM56-2C1	Turbofan	DC8, B737s	0.3%	<0.05%
APEX2	CFM56-7B24	Turbofan	B737s	0.4%	1.0%
APEX2 / APEX3	CFM56-3B1	Turbofan	B737s	1.7%	1.2%
APEX3	AE3007-A1E	Turbofan	EMB145	0.4%	0.1%
APEX3	PW4158	Turbofan	A300	0.2%	0.3%
APEX3	CJ610-8A	Turbojet	LEAR25	1.0%	0.3%
APEX3	RB211-535E4B	Turbofan	B757	0.8%	0.1%
Total				5.0%	3.0%

Where we are… more data

Total Fleet Coverage

	Spicer 1 exact civilian engine & multi civilian variants	APEX1,2,3 7 exact civilian engines
1-to-1 exact engine match	1.7% US 1.2% Non-US	5.0% US 3.0% Non-US
Extrapolation to engine family	13.9% US 16.1% Non-US	16.5% US 18.5% Non-US

Where we are… more data

Measurement Approaches

- **Spicer: multiport, heated cruciform rake**
  - GC-FID with cryo-traps/resin for organics
  - GC-MS for PAHs
  - DNPH (with HPLC) for carbonyls
- **APEX: single point*, diluted probe**
  - Tunable diode laser spectroscopy (HCHO, C_2H_4, {acrolein} …)
  - Proton Transfer Reaction Mass Spectroscopy (PTR-MS) for many other HCs

Table 1. Variables measured during the emission experiments

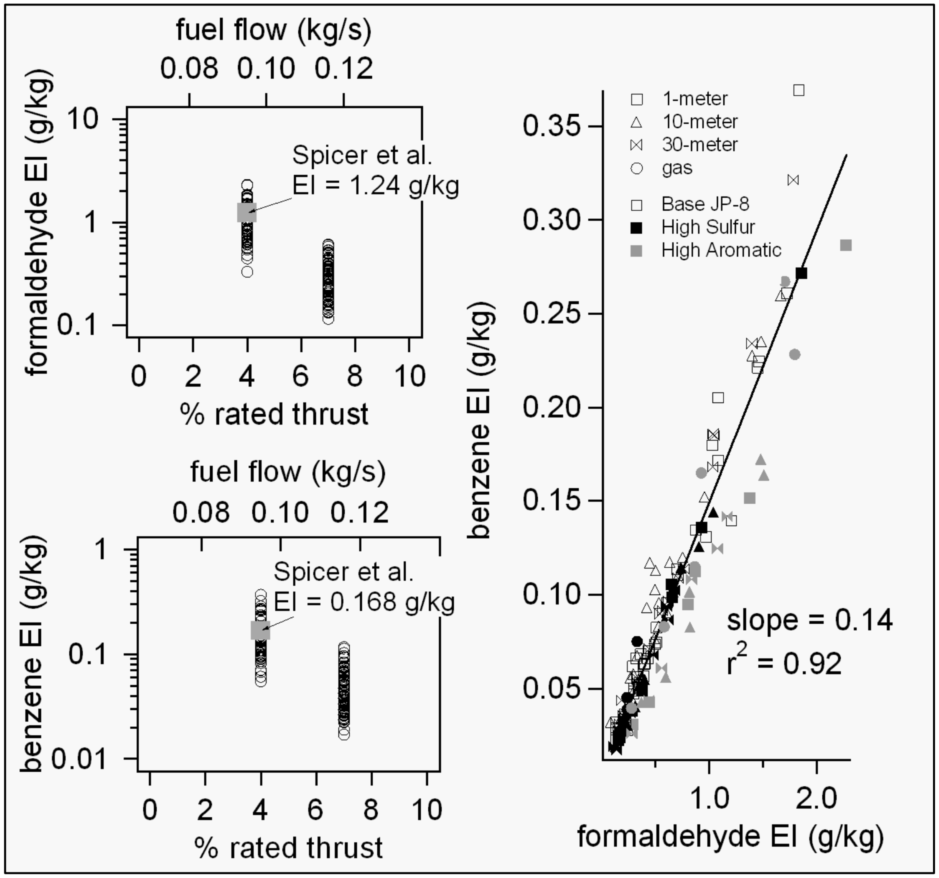
Variable	Technique	Instrument
Inorganic Species		
NO/NO_x	Chemiluminescence	Beckman 951
CO	Nondispersive Infrared	Beckman 865
CO_2	Nondispersive Infrared	Beckman 864
Organic Species		
Methane	Canister Samples/Flame Ionization GC	Beckman 6800
C_2–C_{10} Organics	On-Line Flame Ionization GC	Hewlett-Packard 5880
C_{10}–C_{17} Organics	XAD-2/Flame Ionization GC	Hewlett-Packard 5730
PAH Compounds	XAD-2/Gas Chromatography/Mass Spectrometry	Finnigan 4000
Carbonyl Compounds	DNPH Derivatization/HPLC	Altex 110A HPLC system With LDC Spectro Monitor III UV Detector
Total Hydrocarbons (THC)	Flame Ionization	Beckman 402

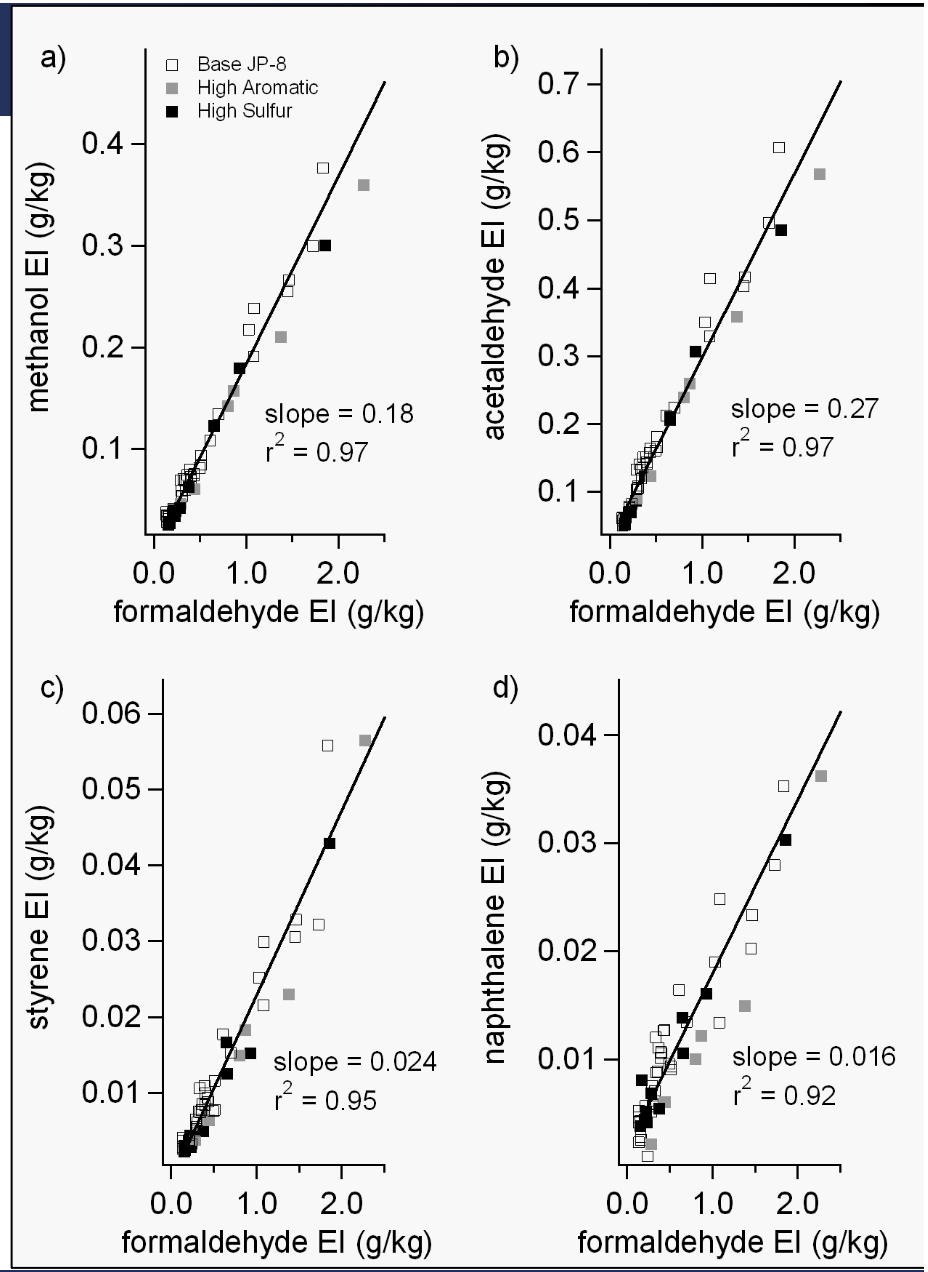
* But compared at multiple downstream locations

Spicer et al., *Chemical composition and photochemical reactivity of exhaust from aircraft turbine engines*, Ann. Geophysicae 12, 944-955, 1994.

Where we are… more data

APEX1 Results

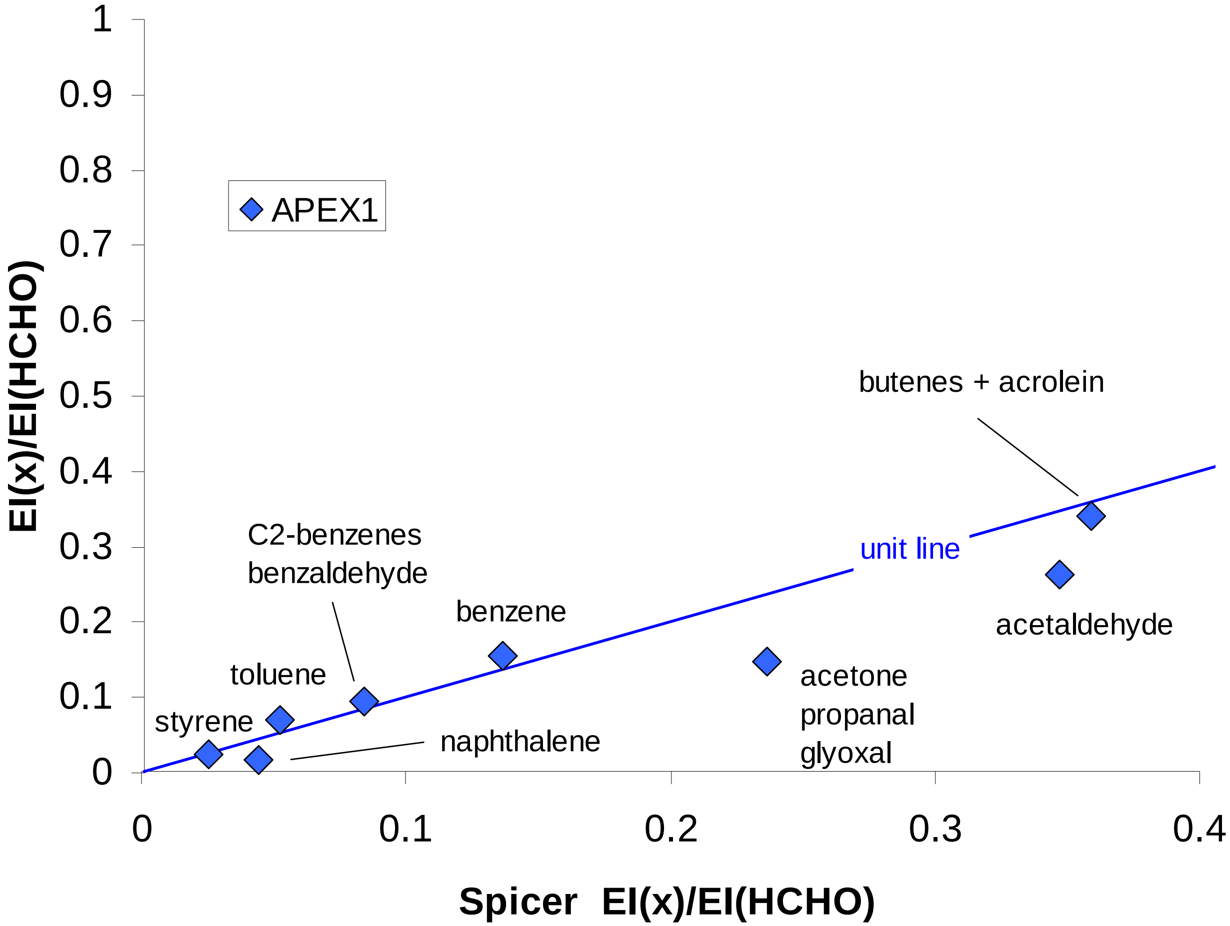




- ❖Wide variability in EI's vs. engine operating condition.
- ❖Emission scaling independent of engine operating condition, fuel, or probe location.

Where we are… more data

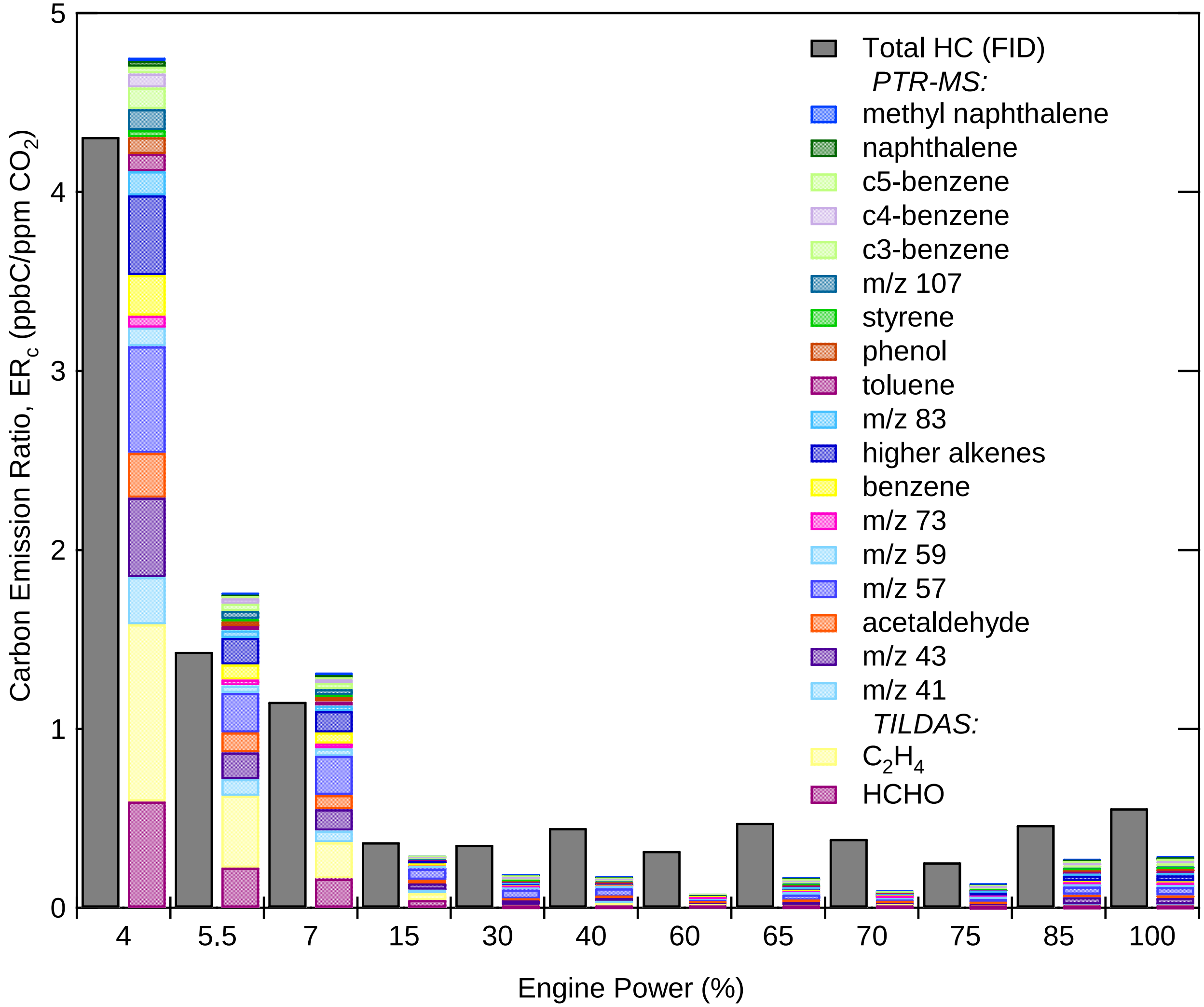
APEX1 Results



APEX1 chemical speciation results show good agreement with Spicer et al.

Where we are… more data

APEX 1 Results

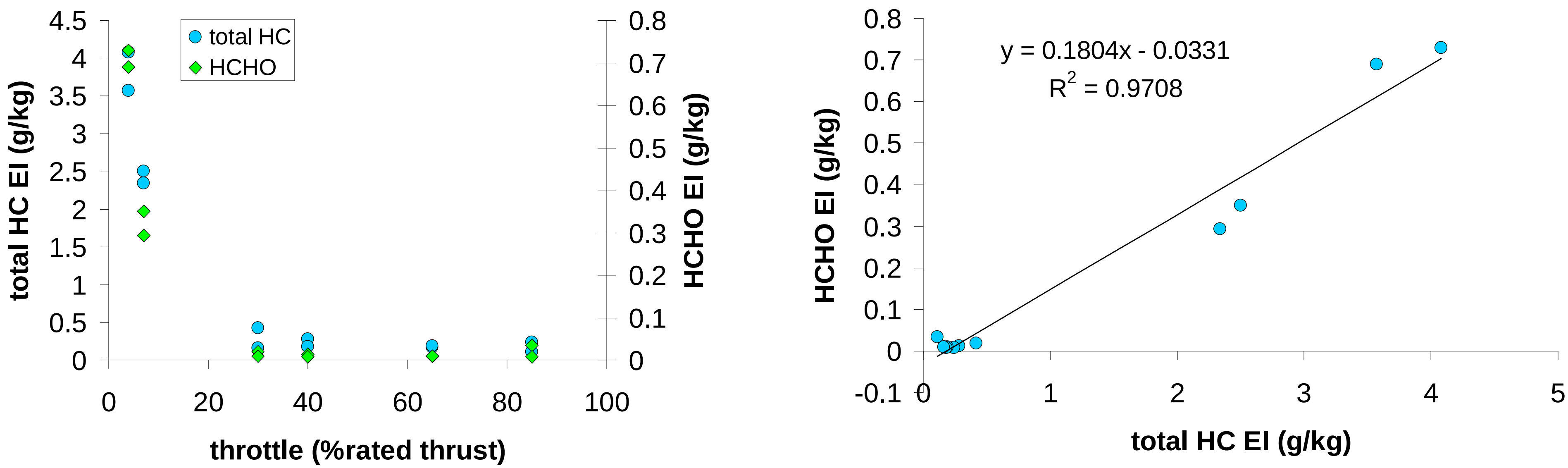


The sum of the speciated HC's shows good agreement with the total HC measurements

m/z	Compound (s)
41 & 43	propene (major) + higher fragments (minor)
57	Acrolein (55%) + 2 butene isomers (45%)
73	Methyl Glyoxal + Butanal
83	cylcohexene, C6-diene, or a fragment of hexanal
107	Xylene (major) + Ethylbenzene (minor) + Benzaldehyde (minor)

Further Confirmation from APEX2: HC EI Scales with HCHO

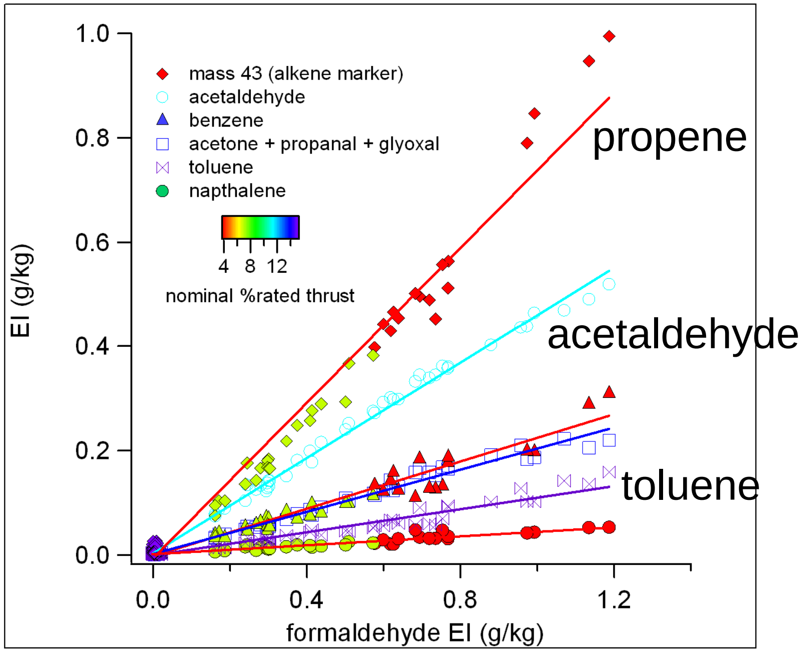
APEX 2 B-737 CFM56
August 23, 2005



Where we are… more data

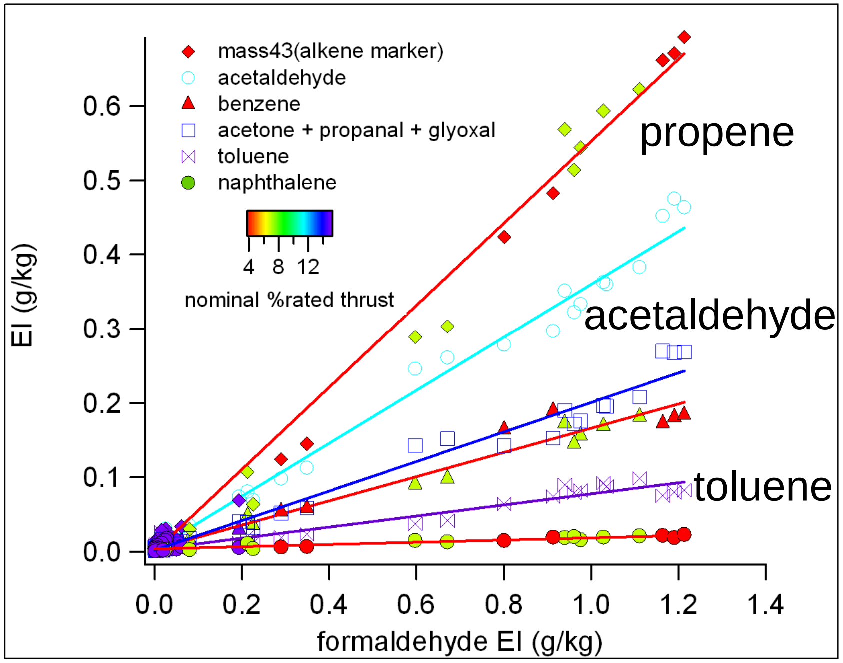
HC behavior is predictable and scalable

APEX 2



Includes 4 B737s.

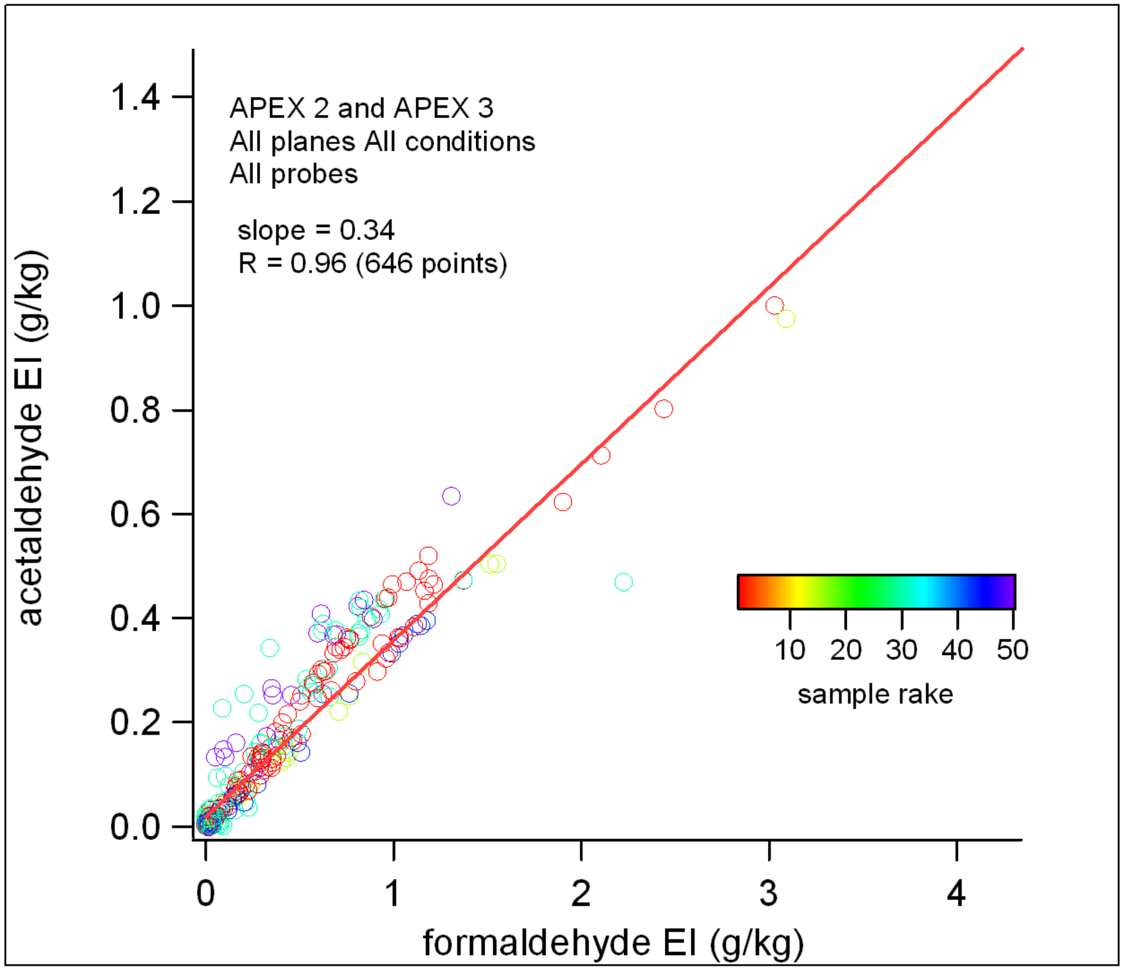
APEX 3



Includes 1-B737, 2-B757, 1-A300.

Where we are… more data

Speciated HC emissions from aircraft engines are predictable



Take Home Message!

- **High pressure & temperature trump everything…**
  - HC behavior appears to hold true irrespective of
    - Engine manufacturer
    - Engine size
    - Thrust level / fuel flow
    - Ambient test conditions
    - Rich burn vs. lean burn
    - Probe distance downstream
    - Measurement equipment
  - APEX = landmark studies

Proposed Hydrocarbon Emissions Inventory Methodology

New HAPs Profile for Commercial Aircraft

- **Review of simple HAPs methodology**

[Total HC Emissions] X [Individual Mass Fraction of 78 Species in Hydrocarbon Profile] = Emissions Inventory of individual Hydrocarbon Species for Commercial Aircraft

Where we are… New HC Profile

- **Old HC Profile for Commercial Aircraft**
  - 58 species
  - Based on 1 Spicer test
  - No unidentified mass
  - ~10% methane
  - SPECIATE Profile #1098

- **New HC Profile for Commercial Aircraft**
  - Based on Spicer + APEX 1, 2, 3 tests
  - Removed 12 from old, added 32 additional
  - 78 species
    - **15 HAPs listed in section 112 of Clean Air Act**
    - **2 additional HAPs not in section 112 of CAA, but listed in EPA's IRIS database**
    - **Unidentified mass (23.3%)**
    - No methane

ACETALDEHYDE	0.04567	METHANOL	0.01930
ACETONE	0.00395	METHYL GLYOXAL	0.01607
ACETYLENE	0.04211	2-METHYL NAPHTHALENE	0.00220
ACROLEIN	0.02619	1-METHYL NAPHTHALENE	0.00264
METHACROLEIN	0.00573	DIMETHYLNAPTHALENES	0.00096
BENZALDEHYDE	0.00502	2-METHYL-2-BUTENE	0.00197
BENZENE	0.01798	2-METHYLPENTANE	0.00437
ISOPROPYLBENZENE	0.00004	NAPTHALENE	0.00579
N-PROPYLBENZENE	0.00071	N-NONANE	0.00067
1,2,3-TRIMETHYLBENZENE	0.00142	1-NONENE	0.00263
1,2,4-TRIMETHYLBENZENE	0.00468	N-OCTANE	0.00067
1,3,5-TRIMETHYLBENZENE	0.00072	OCTENE	0.00295
C4-BENZENE + C3-AROALD	0.00702	N-PENTADECANE	0.00185
C5-BENZENE+C4-AROALD	0.00347	N-PENTANE	0.00212
1,3-BUTADIENE	0.01804	1-PENTENE	0.00830
1-BUTENE	0.01875	TRANS-2-PENTENE	0.00384
CIS-2-BUTENE	0.00225	CIS-2-PENTENE	0.00295
3-METHYL-1-BUTENE	0.00150	4-METHYL-1-PENTENE	0.00092
2-METHYL-1-BUTENE	0.00187	2-METHYL-1-PENTENE	0.00046
BUTYRALDEHYDE	0.00158	PHENOL	0.00776
C16 BRANCHED ALKANE	0.00156	PROPANE	0.00083
C14-ALKANE	0.00199	PROPIONALDEHYDE	0.00777
C15-ALKANE	0.00189	PROPYLENE	0.04847
C18-ALKANE	0.00002	STYRENE	0.00331
CROTONALDEHYDE	0.01380	N-TETRADECANE	0.00445
N-DECANE	0.00342	TOLUENE	0.00687
1-DECENE	0.00197	M-ETHYLTOLUENE	0.00206
N-DODECANE	0.00493	O-ETHYLTOLUENE	0.00087
ETHANE	0.00558	P-ETHYLTOLUENE	0.00086
ETHYLBENZENE	0.00186	M-TOLUALDEHYDE	0.00371
ETHYLENE	0.16529	O-TOLUALDEHYDE	0.00307
FORMALDEHYDE	0.13160	P-TOLUALDEHYDE	0.00064
GLYOXAL	0.01942	N-TRIDECANE	0.00572
N-HEPTADECANE	0.00009	N-UNDECANE	0.00475
N-HEPTANE	0.00068	VALERALDEHYDE	0.00328
HEPTENE	0.00469	ISOVALERALDEHYDE	0.00043
HEXADECANE	0.00052	M-XYLENE AND P-XYLENE	0.00302
1-HEXENE	0.00787	O-XYLENE	0.00177
TRANS-2-HEXENE	0.00040	UNIDENTIFIED	0.23340

Where we are… Improved Guidance

1 year ago…

- **Start a process with EPA to develop policy and guidance for commercial aircraft**
  - "EPA/FAA Commercial Aircraft Speciated HC Guidance"
  - Improved data & science-based aircraft methodology
  - Produce formal guidance and update tools (EDMS)
  - Establish "living" guidance approach
- **Produce FAA's <u>Airport</u> Speciated HC guidance doc**
  - EDMS 5.1 update

EPA/FAA Speciated HC Guidance for Commercial Aircraft

•Only commercial aircraft

•Addresses conversions HC-VOC-TOG

•New SPECIATE Profile

•EDMS5.1 update

Coming this year!

FAA <u>Airport</u> Speciated HC Guidance Document

•All airport sources

•Point to commercial aircraft guidance

•Point to other EPA guidance

•EDMS5.1 update

33

Conversions HC – VOC – TOG

- **HC - Organic compounds that comprise all of the hydrocarbons species in exhaust.**
- **NMHC - The sum of all hydrocarbon air pollutants except methane.**
- **VOC - Includes any compound of carbon that participates in atmospheric photochemical reactions, excluding: CO, CO_2, c~~arbonic acid~~, ~~metallic carbides or carbonates, and ammonium carbonate.~~**
- **TOG - All organic gas compounds, including the low reactivity compounds (e.g., ~~methane~~, ethane, ~~various chlorinated fluorocarbons~~, acetone, ~~perchloroethylene, volatile methyl siloxanes, etc~~.), excluding CO, CO_2, ~~carbonic acid, metallic carbides or carbonates, and ammonium carbonate.~~**

Since commercial aircraft engines consume methane and ethane, therefore:

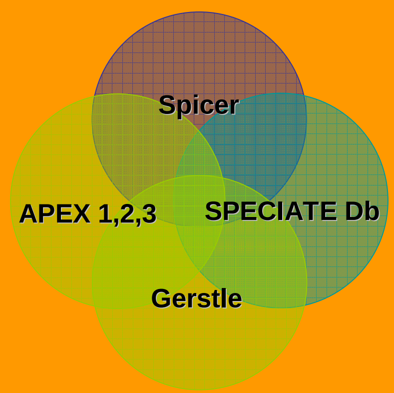
HC = NMHC = VOC = TOG

Commercial aircraft engines are unique!

Where we are… Agency Process

EPA/FAA Speciated HC Process

Data Analyses



- FAA, EPA OTAQ, EPA Regions, EPA ORD, CARB, Aerodyne, KBE
- SPECIATE Profile 1098
  - Spicer Data – CFM56
  - Commercial Aircraft only

Quality Control

- EPA Quality System Requirements
  - Project Plans
  - Peer Review
  - Suitable Documentation

Deliverables

- Technical Support Document
- EPA/FAA Guidance Document
- New SPECIATE Profile for commercial aircraft
- Quality Control Documentation
- EDMS 5.1 Update

Repeat as needed with scientific advances, new data, etc.

Where we are… Interim Guidelines

Interim FAA Guidelines (Sept 2005)

- Inconsistent approach regarding HAPs in NEPA studies
- Good EPA/FAA collaboration on the O'Hare EIS
- FAA emailed quasi-guidance to promote National consistency for NEPA reporting
- Allows for a systematic approach to scientifically establish speciated HC emissions inventory

- **1. For those EIS efforts that warrant a HAPs analysis, FAA contractors should perform a HAPs emissions inventory only.**
- **2. For aircraft emissions, FAA contractors should adhere to the HAPs speciation profiles listed on pages I-152 through I-153 of Appendix I of the Chicago O'Hare Final EIS (see URL below).**
- **3. The methodologies, assumptions, and rationale for the HAPs speciation profiles are provided in Appendix I, and should be relied upon for discussions with reviewing agencies. Note that these methodologies were reviewed and approved by EPA Region V and the EPA aircraft emission experts in Ann Arbor, MI.**
- **4. Although addressed in O'Hare's EIS, FAA contractors should ignore the steps of toxicity weighting and priority ranking of HAPs. These elements should not appear in future EISs unless specifically warranted by regulations and through review/guidance by EPA.**
- **5. No interpretation of the HAPs inventory results should be provided in an EIS. Facts and descriptions of individual HAPs may be provided similar to the language in section I.2.2 and Attachment I-1.**
- **6. HAPs inventories should be provided in a technical appendix for disclosure purposes and not discussed in the Environmental Consequences chapter.**
- **7. For disclosure purposes, the results of the EIS HAPs inventory should be put into context with regional inventories and ambient monitoring results, if they exist. Trends should also be presented and discussed if available.**
- **8. There should not be a comparison of HAPs inventory results relative to other airport inventories.**
- **9. Uncertainties & limitations of HAPs analyses must be discussed on par with the language on pages I-14 through I-19 of O'Hare's EIS Appendix I.**
- **URL to O'Hare's Final EIS, Appendix I pertaining to HAPs: http://www.agl.faa.gov/OMP/FEIS.htm**

Where we are… Emissions Inventory Guidance

Conclusion

- **New guidance underway for commercial aircraft speciated HC emissions inventory**
  – Full partnership between FAA and EPA
  – California ARB assisted
  – Science-based approach
  – Representative of modern fleet
  – Incorporate methodology into EDMS5.1
  – "Living" – will grow as we become smarter