Federal Aviation Administration

Emissions Update

Presented to: REDAC Subcommittee Meeting

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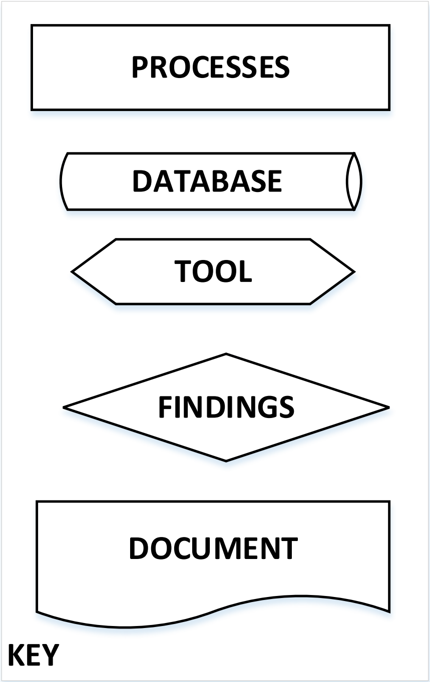
Update on Emissions Activities

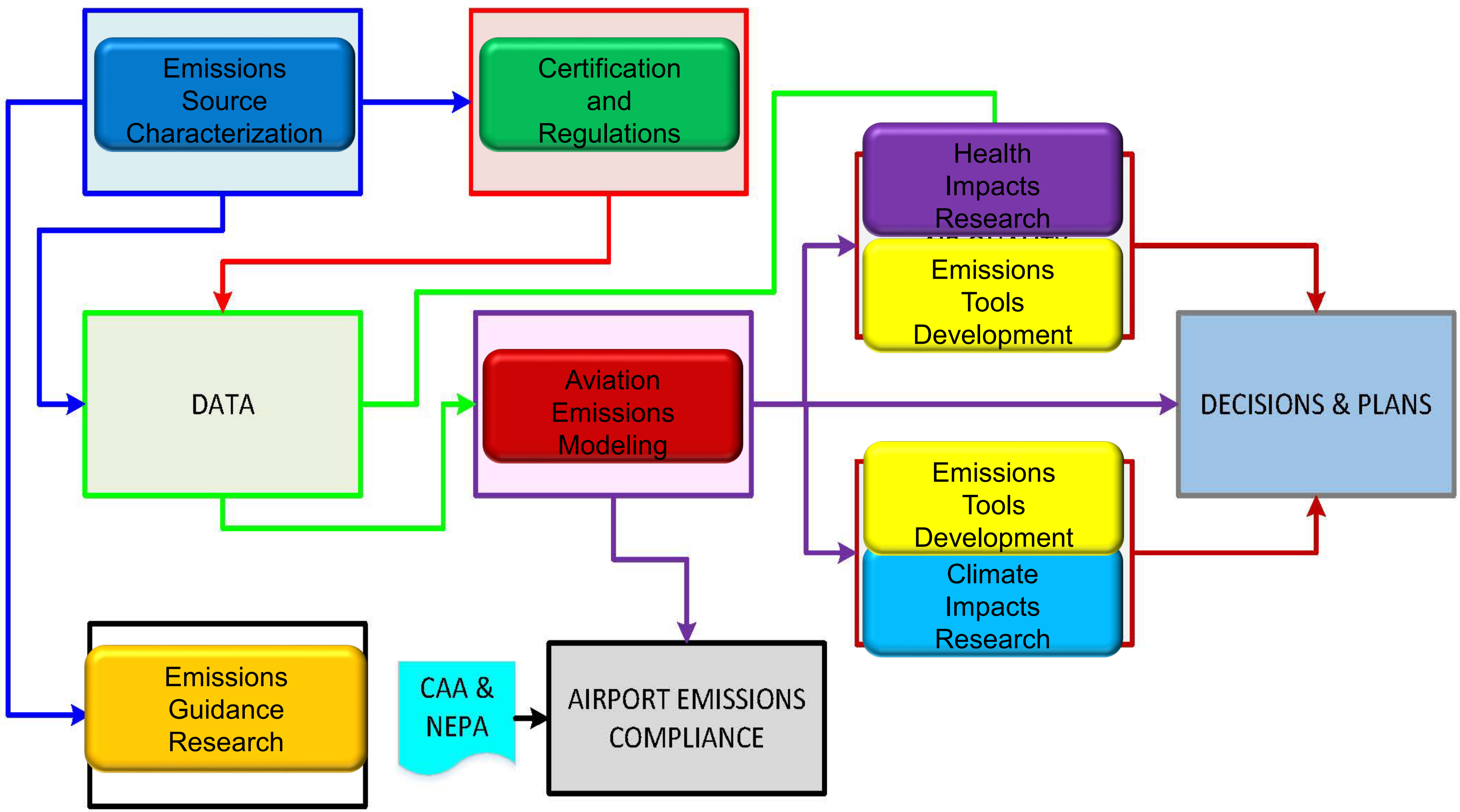
- Emissions Research Roadmap
- NonVolatile Particulate Matter (nvPM) Status Update
- Commercial Space Emissions
- Research needs out to 2025

Emissions Research Roadmap

1. Primary Elements
2. Current Capabilities
   - Processes
   - Findings
   - Documentation
   - Tools
   - Databases
3. Connections



Emissions Research Roadmap



Emissions Research Overview

ASCENT Project	Description	Emissions Roadmap
2	nvPM Emissions Engine Measurements	
10	Forecast Technology and Influence of Commercial SST	
18	Health Effects of Aviation Emissions	
19	CMAQ-based Airport AQ Model Development	
20	Fast-time **APMT-I AQ** Model Development (Adjoint)	
21	Updates to **APMT-I Climate** Model	
22	Independent Evaluation of **APMT-I Climate** Model	
39	Removing Naphthalene from Jet-A	
48	Engine nvPM Emissions Standard Setting Support	

Health Impacts Research

Emissions Tools Development

Emissions Source Characterization

Climate Impacts Research

Certification and Regulations

Aviation Emissions Modeling

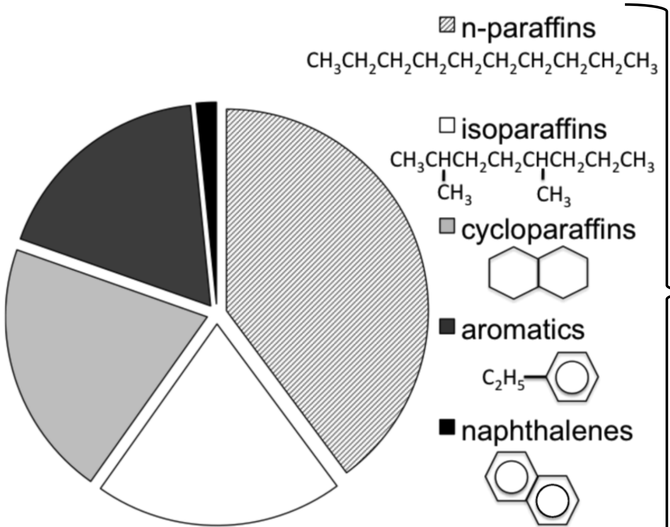
Emissions Guidance Research

Non-volatile Particulate Matter Status

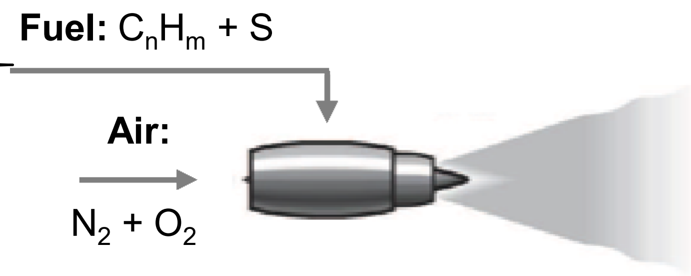
- **Non-volatile Particulate Matter (nvPM):** Emitted particles that exist at gas turbine engine exhaust nozzle exit plane that do not volatilize when heated to a temperature of 350°C.
- Characterization of nvPM mass and number emissions
- Size distribution

Impact of Emissions on Surface Air Quality – nvPM Context

Fuel composition and engine design determine emissions

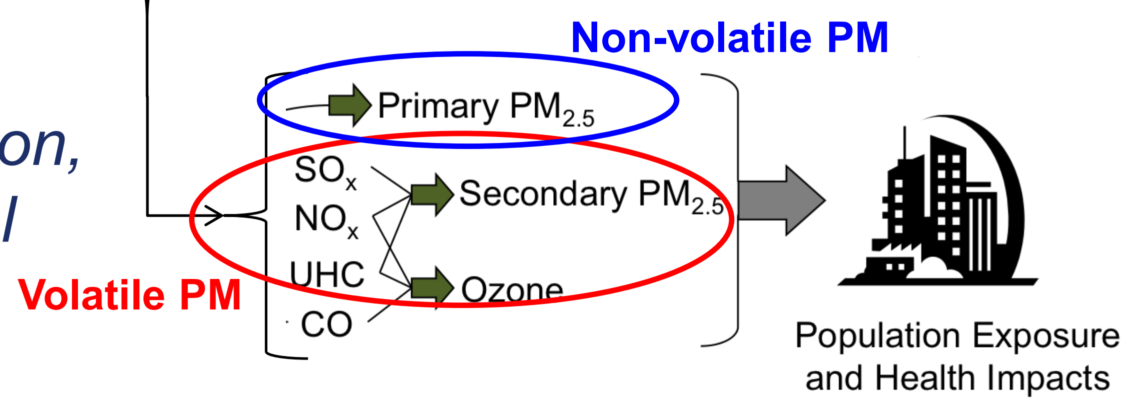


Weighted Mean Fuel Sulfur Content (PPM)		
	2006	2007
US East	446	321
US Gulf	858	800
US West	240	395
Nationwide	709	677



Tank-to-Wake Actual Combustion Emissions

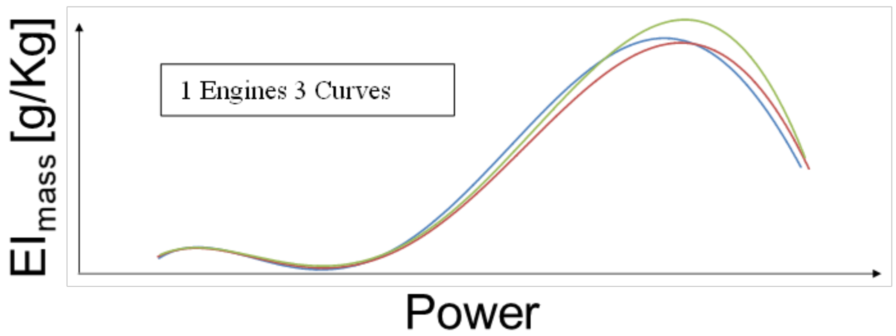
$CO_2 + H_2O + NO_X + SO_X + soot + CO + HC + N_2 + O_2$

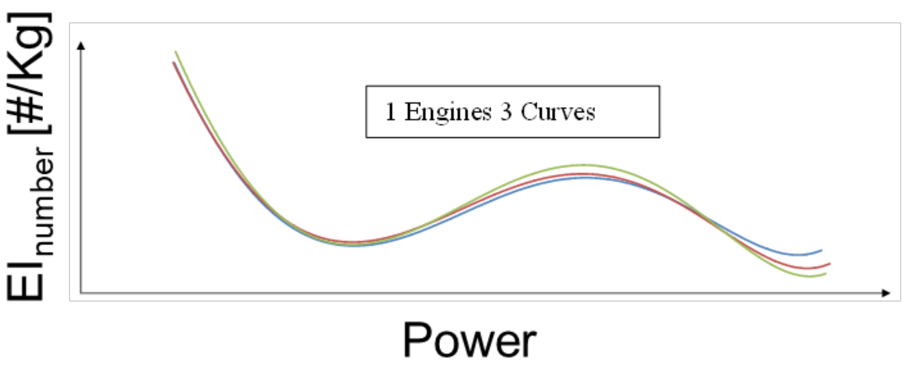


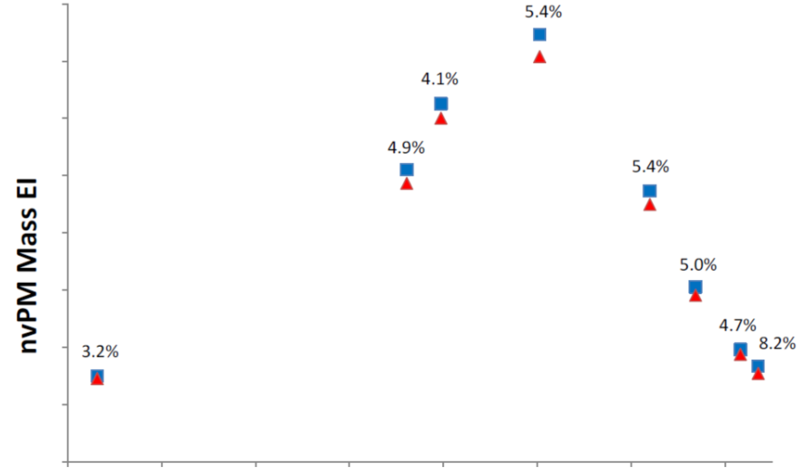
Atmospheric transformation, dispersion and removal determine pollutant concentration

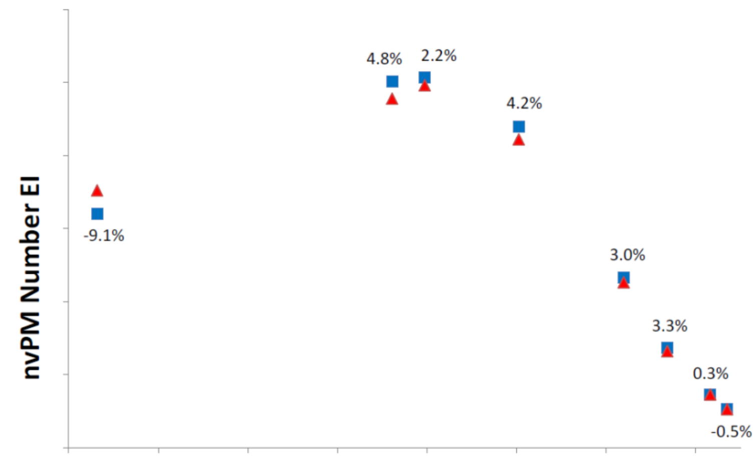
Technology Effects on nvPM Mass and Number

- No Landing Takeoff (LTO) nvPM Standard





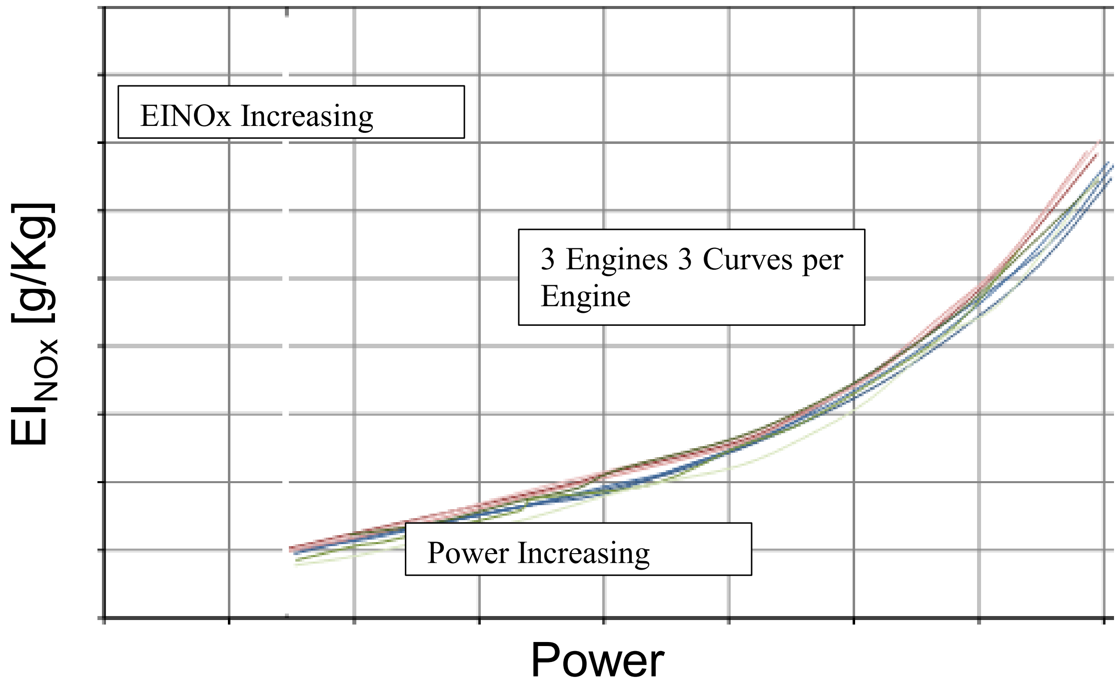




EI_{Mass} and EI_{Number} vs. Thrust for two modern combustors

By Contrast, NO_X is Well Behaved

- Impact of engine NO_X standards



EI$_{NOx}$ vs. Thrust for a Modern Rich Burn Combustor Led to the development of Lean Burn Combustor

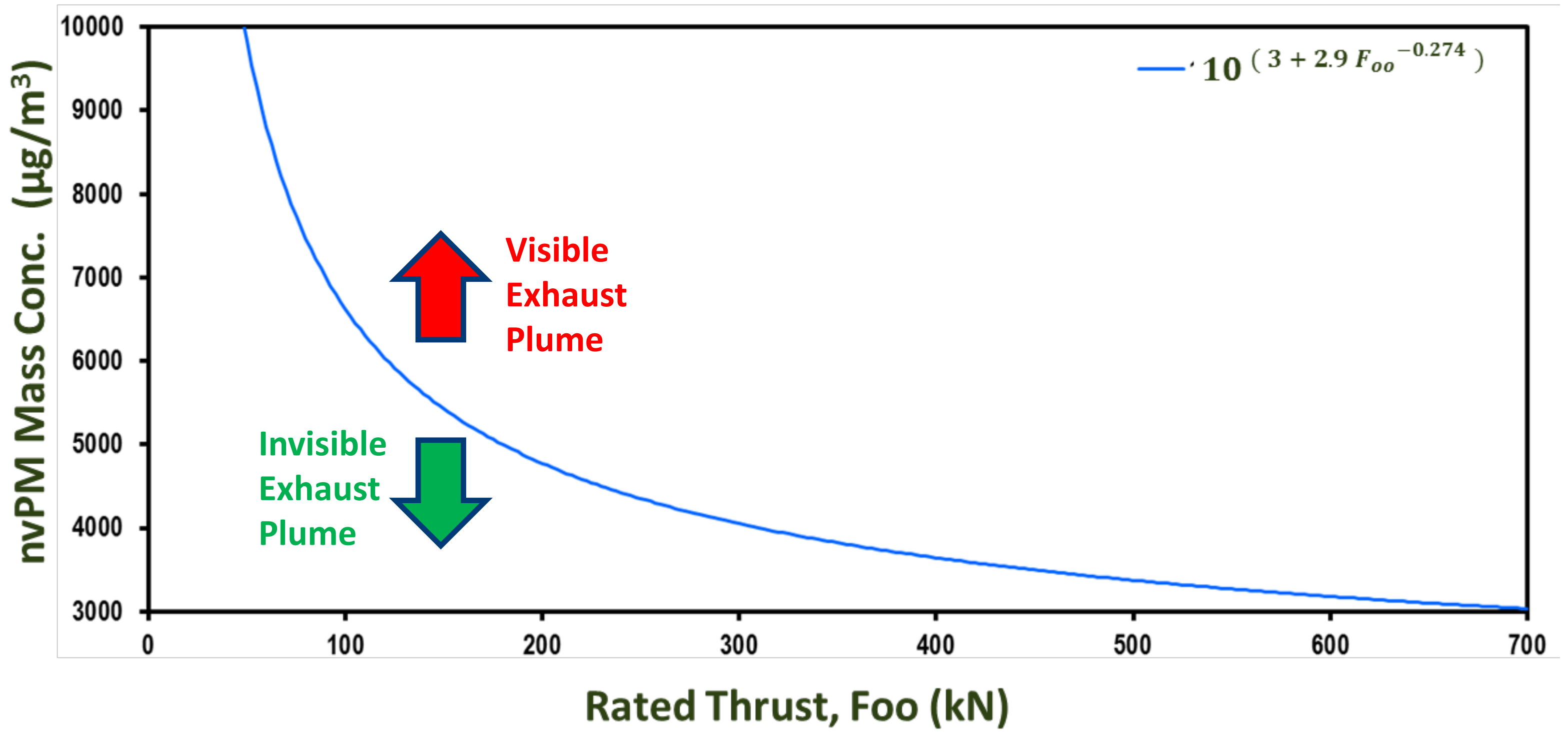
nvPM Standard: Source Limits

- **CAEP/10 (February 2016) agreed to the inaugural engine nvPM Certification Requirement and nvPM Emissions Standard**

- **CAEP/10 Certification Requirement**
  - Standardized nvPM Measurement System
  - New Appendix 7 to Annex 16 Vol. II

- **Engine nvPM Emissions Standard**
  - CAEP/10 Standard based on smoke visibility limit
  - New Chapter 4 to Annex 16 Vol. II

The CAEP/10 nvPM Standard Regulatory Level



$$Regulatory\ limit\ concentration\ of\ nvPM_{mass} = 10^{(3 + 2.9\, F_{oo}^{-0.274})}$$

CAEP/11 nvPM Remits

- Provide representative engine data for assessing the nvPM emissions standard for mass and number regarding turbofan/turbojet engines ≥26.7kN by February 2017.
- Provide recommendations on metrics systems, stringency options, technology responses and applicability to CAEP Steering Group 2017.
- Develop an aircraft engine based LTO nvPM mass and number standard for turbofan/turbojet engines ≥26.7kN.
- Investigation of the possible replacement of the smoke number standard for engine categories ≥26.7kN and other engine categories <26.7kN.
- Develop improved nvPM model inputs to both local air quality models

CAEP/11 LTO Based nvPM Mass and Number Standard Tasks

- **Full Standard Setting Process in CAEP/11:**
  - Develop metric system ✓
  - Develop stringency options ✓
  - Develop technology response ✓
  - Conduct cost effectiveness analyses ✓
  - Determine LTO-based nvPM mass and number regulatory levels – February 2019
- **Refine and finalize corrections for ambient conditions, fuel composition and engine-to-engine variability**
- **Refine steps to replace SN standard with nvPM mass and number standard based on CAEP/10 nvPM standard**

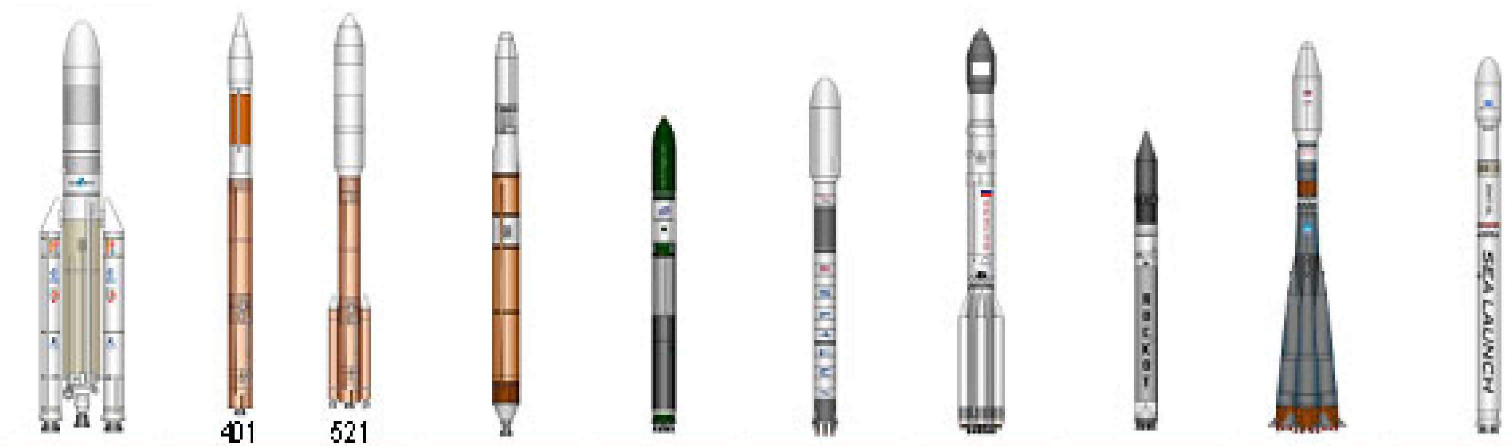
nvPM Standard Status Summary

- Fuel Composition Corrections ✓
- Engine to Engine Variability and Characteristic Factors ✓
- Ambient Conditions Corrections needs further refinement
- Smoke Number Replacement Studies Underway

Commercial Space Emissions

- Launch Vehicles are 90% Propellants & 2% Payload
- Limited Propellant Combinations to Satisfy Payload to Orbit
- Limited Engine Types but Driven by Performance
- Thrust Level Driven by Size of Vehicle Engines from 100k to 6M pounds of thrust
- Operated Fuel Rich Due to Temperature Extremes
- Combustion Products Driven by Propellant Selection and Quantity Propellants

Rocket Types

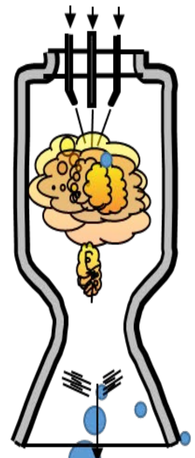


Vehicle	Ariane 5	Atlas V	Delta IV Medium	Dnepr M	Falcon 9	Proton M	Rockot	Soyuz 2	Zenit 3SL
Country	Europe	USA	USA	Russia	USA	Russia	Russia	Russia	Multinational
LEO kg (lbs)	17,250 (37,950)	9,800-29,400 (21,600-64,820)	8,120 (17,885)	4,100 (9,030)	10,450 (22,990)	21,000 (46,305)	1,850 (4,075)	7,800 (17,100)	15,246 (33.611)
GTO kg (lbs)	10,500 (23,127)	4,750-13,000 (10,470-28,660)	4,210 (9,273)	--	4,680 (10,296)	5,500 (12,125)	--	1,700 (3,800)	6,100 (13,448)

LEO = low Earth orbit
GTO = geostationary transfer orbit

Rocket Types and Fuels

RP = rocket propellant
HTPB = Hydroxyl-Terminated PolyButadiene
PBAN = PolyButadiene AcryloNitrile
CH4 = Methane
H2O2= Hydrogen Peroxide
H2= Hydrogen
NTO = Nitrogen Tetroxide
MMH = MonoMethyl Hydrazine
UDMH = Unsymmetrical DiMethyl Hydrazine



Ancillary

Solids

Typically a Natural Salt with Aluminum and Binder

PBAN

HTPB

Liquids

Typically cryogenic Oxygen with another cryogenic for fuel

H2(L)

CH4 (L)

RP-1

Storables

Typically liquids with Pressure Fed Systems

H202/RP-1

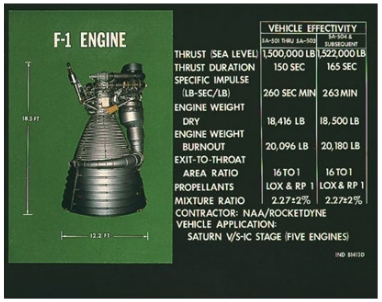
Hypergolic NTO with MMH/UDMH

Hybrids

Typically a Solid Grain with a liquid oxidizer

Exhaust Products

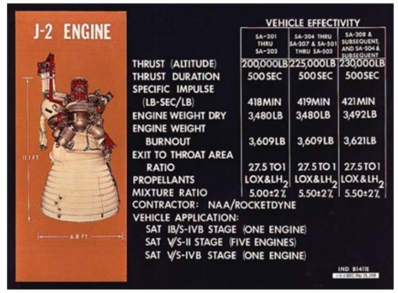
Kerosene



F-1, Merlin, RD-170 Family,NK-33

LOX/RP-1	
CO	32%
CO2	44%
H2O	23%

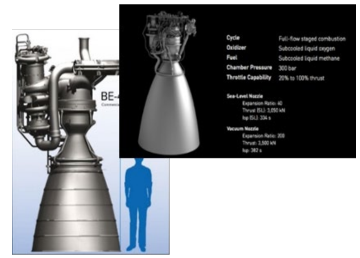
Hydrogen



J-2, J-2S,J-2X,RL-10,SSME,RS-68,BE-3

LOX/LH2	
H2	3%
H2O	97%

Methane



BE-4,Raptor

LOX/CH4	
CO	15%
CO2	41%
H2	12%
H2O	42%

Solids

Castor/GEM/RSRM

HTPB	
CO	22%
CO2	2%
CL	2%
HCL	21%
H2	2%
H2O	8%
N2	8%
AL2O3(L)	36%

PBAN	
CO	24%
CO2	3%
HCL	21%
H2	2%
H2O	9%
N2	9%
AL2O3(L)	30%

LOX = liquid oxygen
LH = liquid hydrogen
RP = rocket propellant
HTPB = hydroxyl-terminated polybutadiene
PBAN = polybutadiene Acrylonitrile

GEM - Graphite Epoxy Motor
RSRM – Reusable Solid Rocket Motor
SSME – Space Shuttle Main Engine

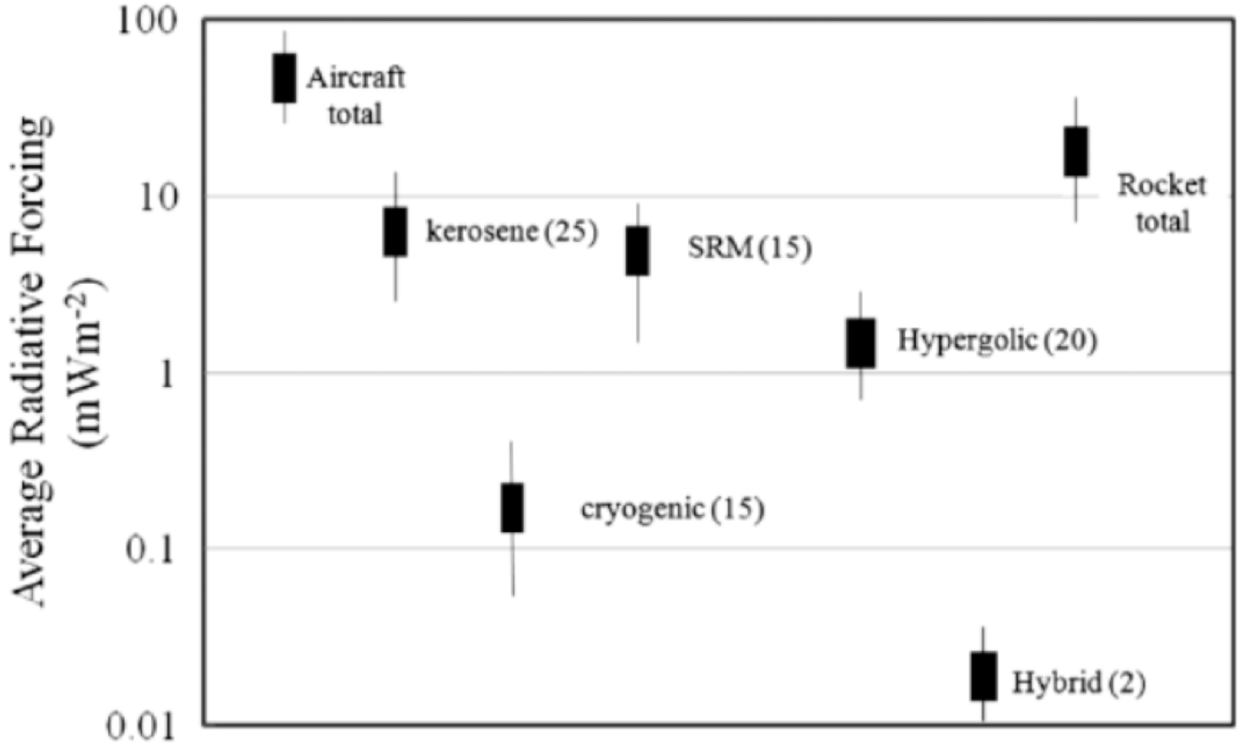
Emissions Indices

Aircraft Engine	3159	1231	0.008,0.03,0.4	
Rocket Type	**EI (CO_2)**	**EI (H_2O)**	**EI (BC)**	**EI (SMF)**
Kerosene	600	350	10–20–40	0
Cryogenic	0	1000	0	0
SRM	200	350	2–4–8	10–60–120
Hypergolic	150	550	2–4–8	0
Hybrid	200	200	20–40–80	0

In g/Kg of fuel burned
Based on very limited plume measurements

SMF – Submicron Fraction of Alumina

Climate Impacts



From one study - needs to be further refined

Gaps

- Emission Profiles and Emission Rates
- Launch Profiles and Fuel Burn
- Launch Frequency and Fuel Specifications
- Modeling Inputs and Inventory Generation
- Integration with Tools
- Quantification of Impacts

FY2020 and FY2021 Research Needs (1/2)

Certification/ Regulations

- Domestic Implementation of International Engine LTO nvPM standards
- Guidance for Aircraft CO_2 standards
- Research Support for Supersonic Certification
- Potential research on UAS, UAM, UAT

Aviation and Emissions Concentrations

- Source Characterization
- Source Apportionment

FY2020 and FY2021 Research Needs (2/2)

Modeling

- Climb / Cruise NOx
- Cruise nvPM
- Plume dispersion
- Measurements versus modeled concentrations

Atmospheric Impacts

- Contrail Formation and Microphysics
- Impacts of changes to fuel composition
- Operation in the upper atmosphere and impacts on ozone layer and climate change

Commercial Space

- Data Gaps to develop an emissions inventory
- Research on Impacts

2025 Emissions Research Needs

Emerging Technologies / Markets

- Supersonic Transport
- Commercial Space
- Potential research need: UAS/ UAM/ UAT
- Potential research need: Electric propulsion and emissions

Impacts

- Ultra Fine Particulate Matter mass and number
- Volatile Particulate Matter Modeling
- Source Apportionment and Human Exposure in Airport Vicinity
- Contrail avoidance
- Climate and ozone impacts to account for improved knowledge of vehicle operations in upper atmosphere

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