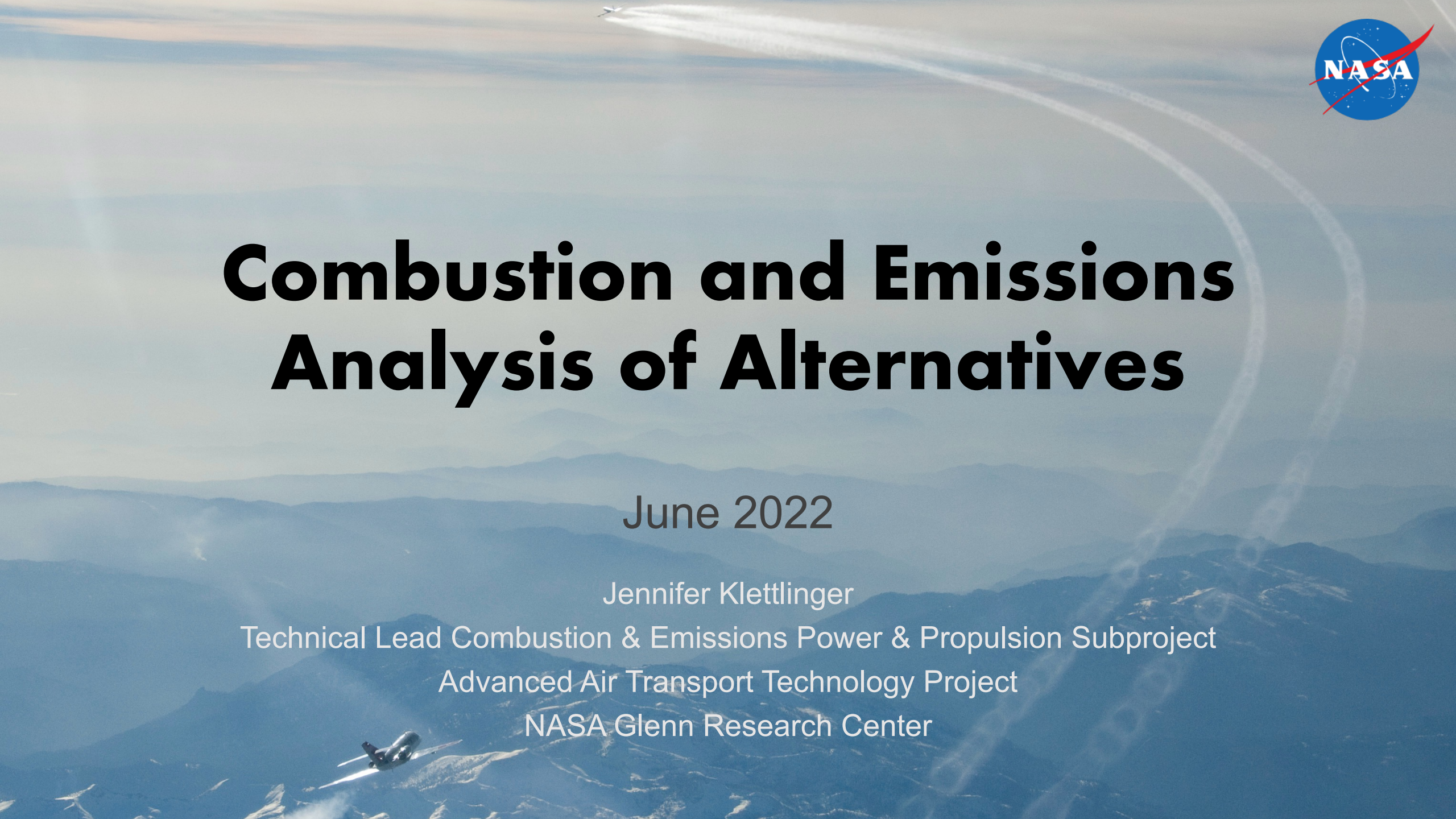

Combustion and Emissions Analysis of Alternatives

June 2022

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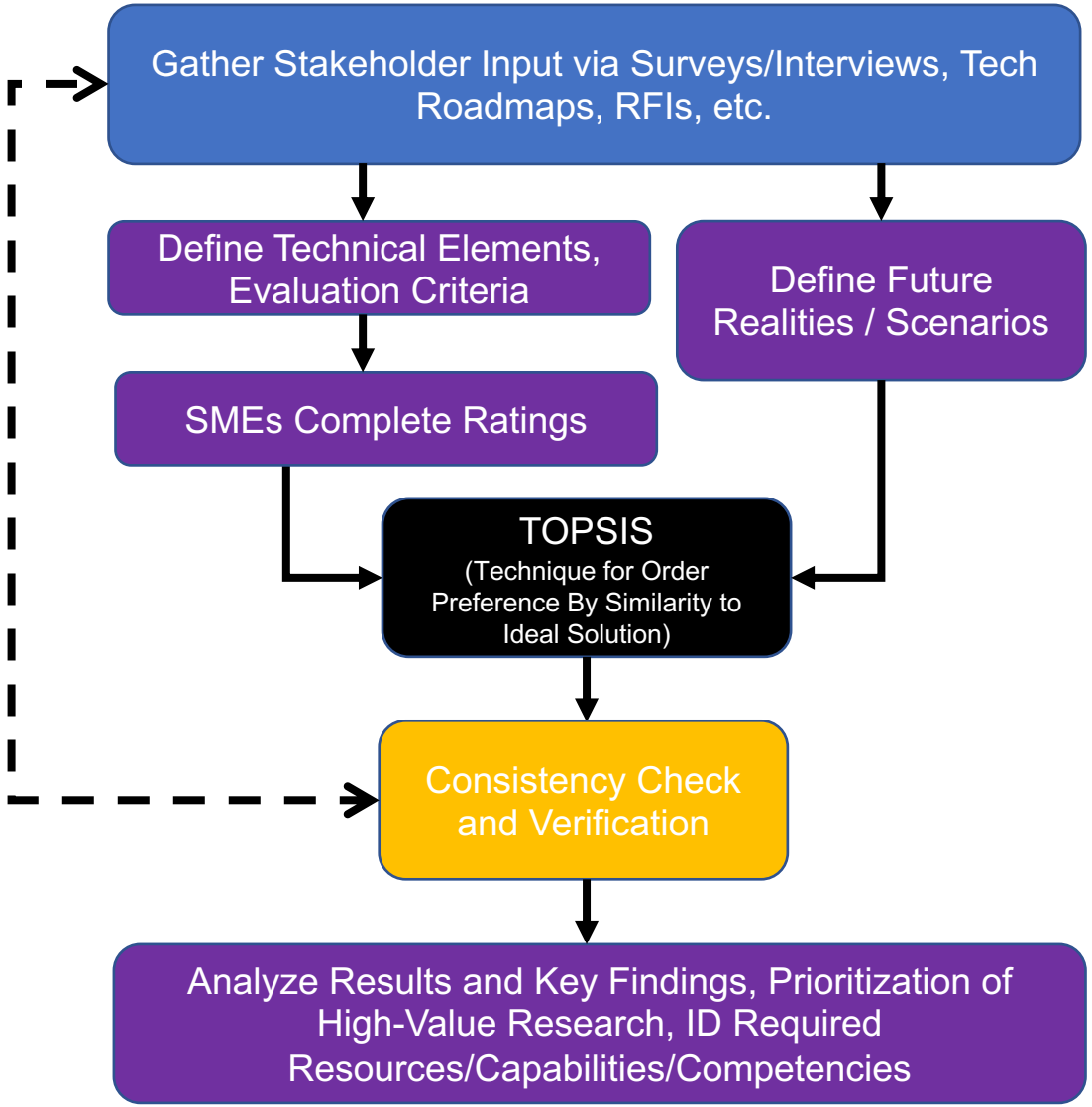
Advanced Air Transport Technology Project
NASA Glenn Research Center

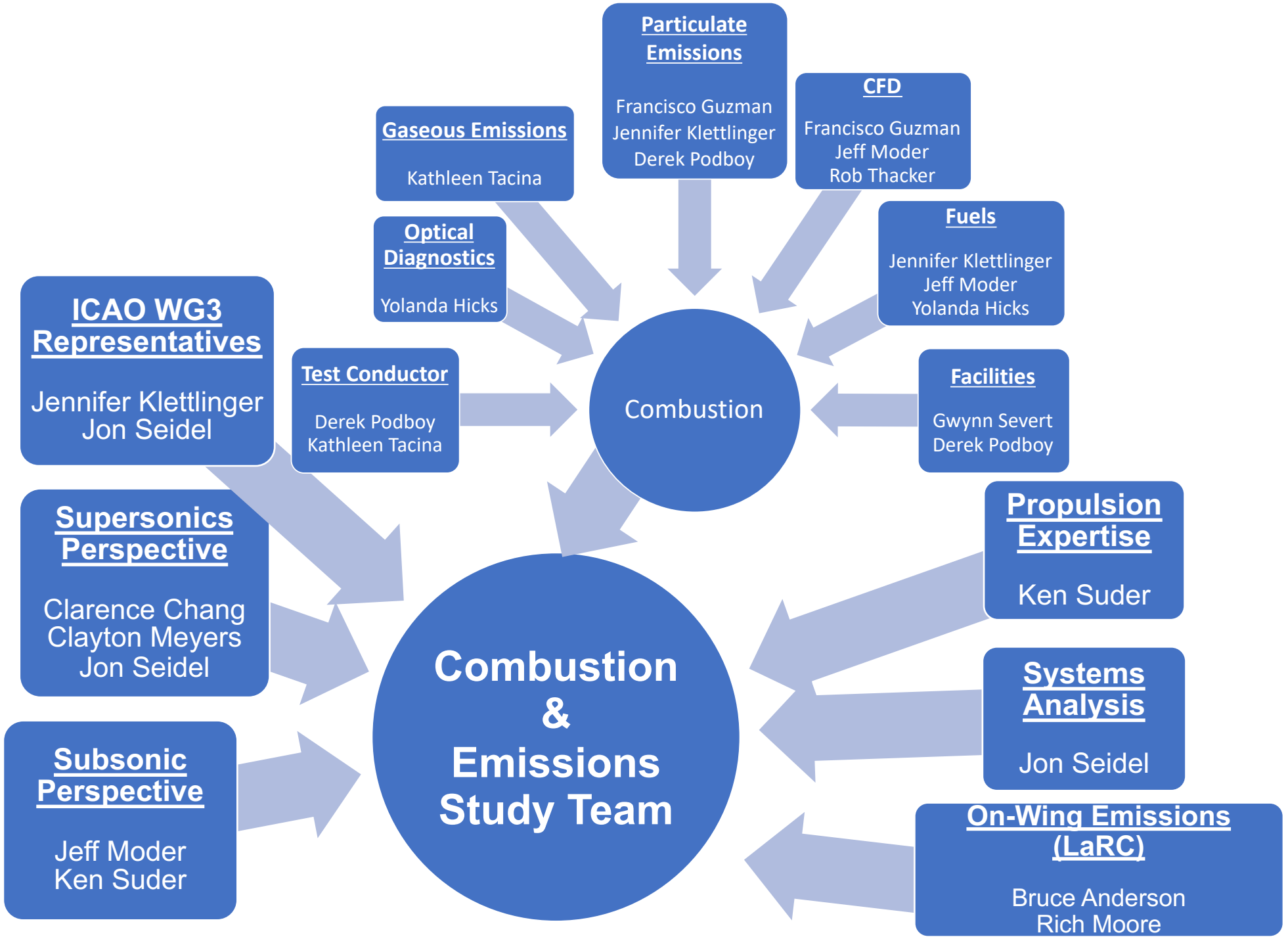
Analysis of Alternatives Common Threads/Terminology

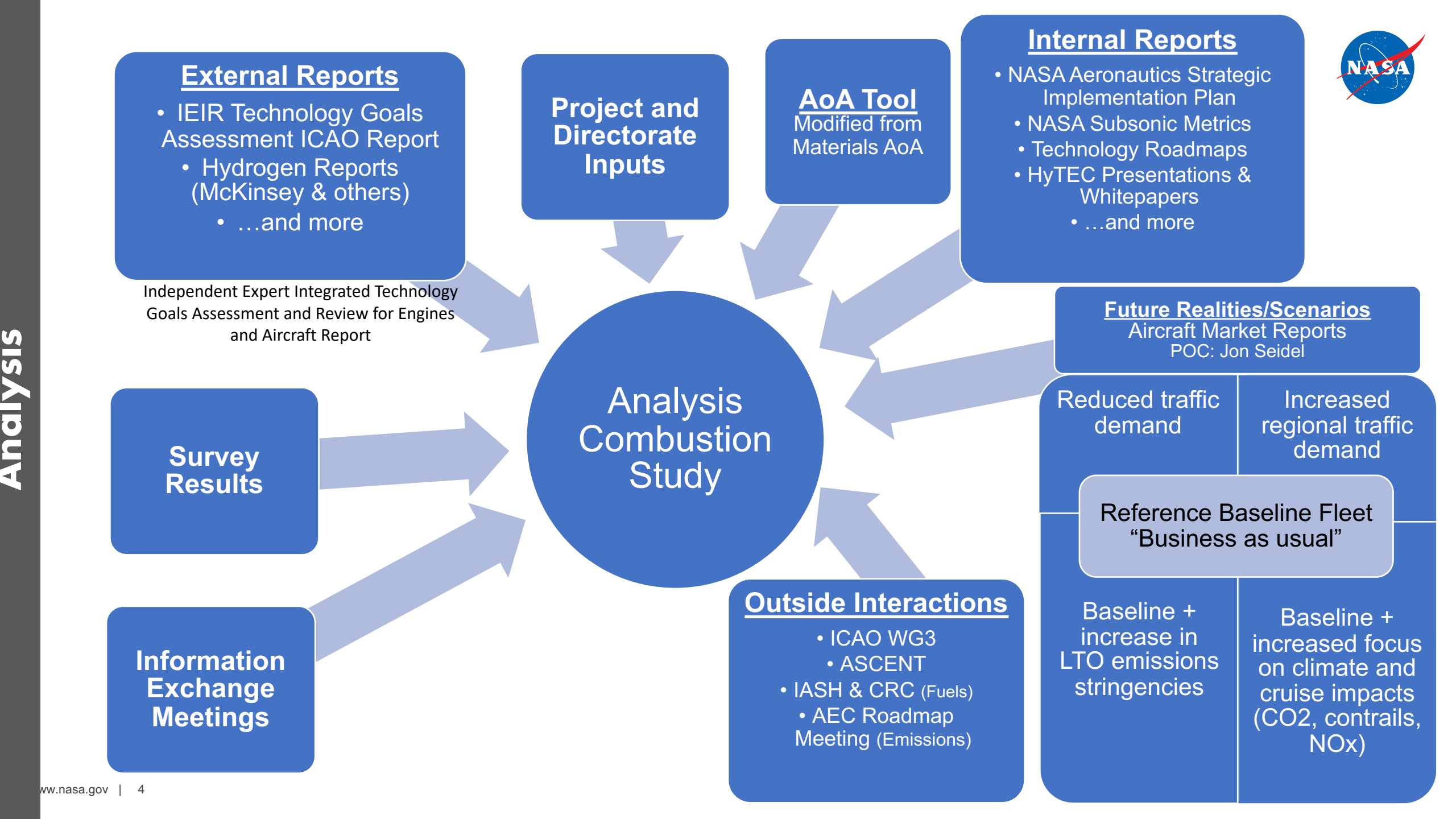
- AoA is snapshot in time
  - Projection from what we know today
  - Can not analyze unknown alternatives
- Criteria examples:
  - Industry/OGA/NASA Pull
  - Applicability to Vehicle Sectors
  - Technical Performance and Risk
  - Evolutionary or Revolutionary?
  - Why NASA?
- TOPSIS results key with interpretation considering all input data
  - Do results make sense?
  - Sensitivity to SME ratings, Scenario definitions?
  - Which criteria drive rankings?



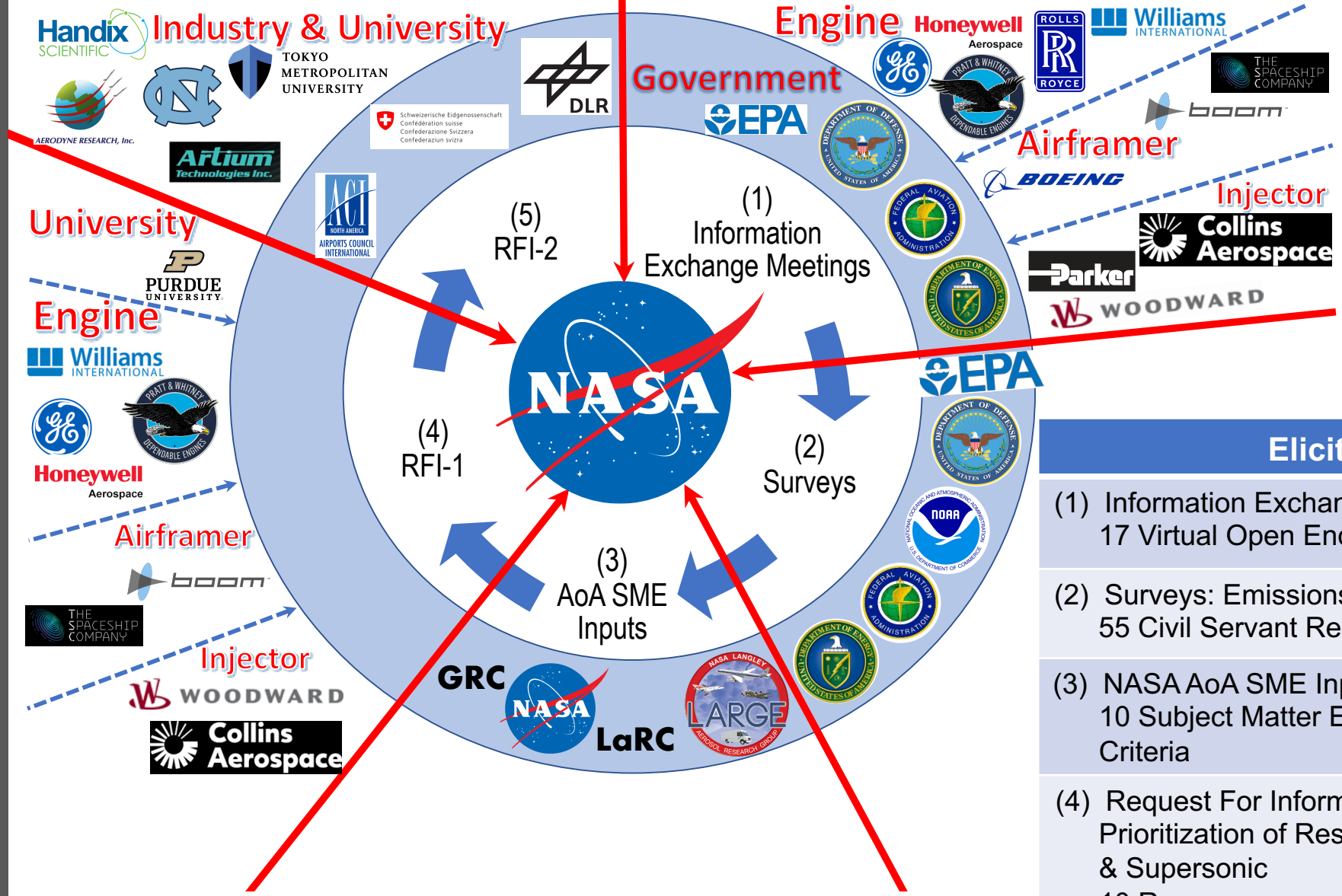
TOPSIS Facilitates: Awareness. Understanding. Acceptance. Communication.

Combustion Study Team




External Reports
• IEIR Technology Goals Assessment ICAO Report
• Hydrogen Reports (McKinsey & others)
• …and more
Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft Report
Project and Directorate Inputs
AoA Tool
Modified from Materials AoA
Internal Reports
• NASA Aeronautics Strategic Implementation Plan
• NASA Subsonic Metrics
• Technology Roadmaps
• HyTEC Presentations & Whitepapers
• …and more
Survey Results
Information Exchange Meetings
Analysis Combustion Study
Outside Interactions
• ICAO WG3
• ASCENT
• IASH & CRC (Fuels)
• AEC Roadmap Meeting (Emissions)
Future Realities/Scenarios
Aircraft Market Reports
POC: Jon Seidel
Reduced traffic demand
Increased regional traffic demand
Reference Baseline Fleet "Business as usual"
Baseline + increase in LTO emissions stringencies
Baseline + increased focus on climate and cruise impacts (CO2, contrails, NOx)

Elicitation Mechanisms



Elicitation Mechanism

(1) Information Exchange Meetings
17 Virtual Open Ended Question Discussions

(2) Surveys: Emissions, Fuel-Injector R&D, Combustor
55 Civil Servant Responses, 100+ Technical Elements

(3) NASA AoA SME Inputs
10 Subject Matter Experts rated 75 R&D Elements for 17 Criteria

(4) Request For Information (RFI-1):
Prioritization of Research Areas: mid & far term, Subsonic & Supersonic
10 Responses

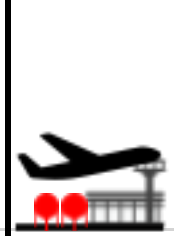
(5) Request For Information (RFI-2):
Narrative Responses to Emissions measurement/modeling needs & considering the future realities

Future Realities and Criteria

Environmental Focus

Current ARMD Focus Areas: Fab Four & Supersonics

Indirectly reduce CO2 by enabling engines with higher thermal efficiencies

Criteria \ Future Reality	 Baseline Reality	 Reduced Traffic	 Increased Regional	 LTO Stringency	 Cruise Stringency	 Hydrogen Airport
Reduces aviation's impact on climate						
Reduces aviation lifecycle CO2 emissions						
Reduces particulate emissions						
Reduces NOx emissions						
Regulatory pull/push						
Enables advanced architectures and propulsion systems						
Enables small-core architectures & propulsion systems						
Enables supersonic architectures and propulsion systems						
Improves durability						
Improves operability						
Reduces time/cost of combustor design						
NASA involvement required						
Industry pull						
Current infrastructure exists						

Analysis Summary

- 75 Technical Elements were defined based on:
  internal & external reports, stakeholder input (Information Exchange Meetings & Survey results), technical experts & their outside interactions
- 10 Subject Matter Experts scored these 75 Technical Elements on the Criteria
- 28 highly ranked elements were identified based on TOPSIS, then validated using other elicitation mechanism feedback.
- These 28 elements are aligned with direct, documented industry needs (NASA Request for Information)

Internal Reports

- NASA Aeronautics Strategic Implementation Plan
- NASA Subsonic Metrics
- Technology Roadmaps
- HyTEC Presentations & Whitepapers
- …and more

External Reports

- IEIR Technology Goals Assessment ICAO Report
- Hydrogen Reports (McKinsey & others)
- …and more

Outside Interactions

- ICAO WG3
- ASCENT
- IASH & CRC (Fuels)
- AEC Roadmap Meeting (Emissions)

Cross-Cutting Combustion Investment Areas: 26 AoA Elements

CO_2 & Fuel Burn Reduction

Combustor & Fuel Injector Research

Thermal Efficiency: High Temperature & Pressure Conditions

Fuel Injection for High OPR
- measurements
- fuel models (trans to supercritical)

- Fuel effects on combustor operability: ignition, LBO, dynamics

Durability

- Fuel coking
- Injector durability
- Prediction tools for fuel systems
- Combustor wall heat transfer tools
- Advanced materials

Heated Fuel Injection
- measurements
- fuel models
- effects on operability

- Contribute to US Hydrogen Strategy

Particulate Matter & NOx Reduction

- Engine cycle conditions & operation effect on NOx & nvPM
- Fuel staging effect on emissions: axial/radial/circumferential

- advanced liner cooling
- advanced fuel-air mixers
- advanced rich-burn combustors
- advanced lean-burn combustors
- improved combustion noise & dynamics tools

Non-CO2 Emissions Characterization

- nvPM measurement capability for high T/P
- nvPM formation and evolution models

- Fuel effects on emissions
- Cruise to ground/test cell correlation tools for NOx
- Combustor to engine exhaust correlation tools for nvPM

- Cruise: target soot-contrail & climate impacts
- Ground: target LTO cycle & air quality impacts

Key Takeaways: Combustion& Emissions

Harsh Thermal Environments

Emerging markets drive need for advanced thermal management in the fuel system and combustor. Tools & testing required to characterize & model impacts on **operability, durability and emissions**.

Non-CO_2 Climate Impacts

Characterizing and reducing **NO_x emissions and contrail formation** are important because these non-CO_2 emissions **likely have a greater** impact on climate compared to CO_2 emissions

New PM Regulations

Current (CAEP/11) and likely future PM regulations drive internal & external need for tools & testing required to understand **reducing PM while addressing tradeoffs** with NO_x emissions, noise, operability and thermal efficiency.

Fuel Effects

Increasing the use and blending ratio of Sustainable Aviation Fuels will continue to drive the need for tools & testing required to assess fuel impacts on combustor **operability and emissions**.