Overview of the relationship between fuel properties and engine performance

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Outline of Presentation

- OEMs' joint test program
- Evaluation of fully synthetic aviation kerosene
  - Full annular combustor test
  - Material compatibility
  - Full system evaluation
- Summary
- Concluding remarks

Alternative fuels requirements

Suitability

energy density
fuel specification

+

Sustainability

CO_2 benefit
Food / water

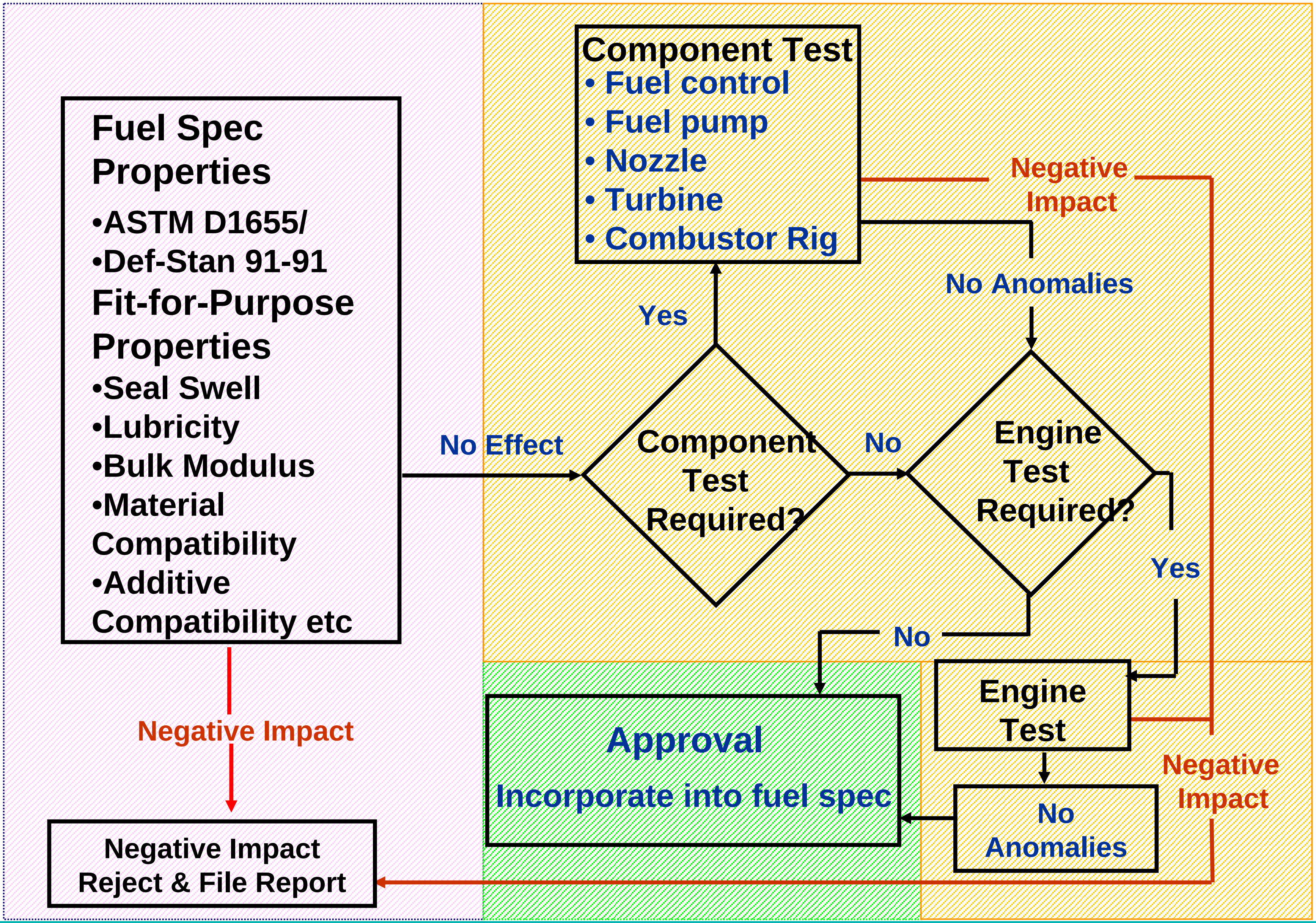
+

Industrialisation

mass production
global distribution

Offering longer term potential for ‘drop-in’ fuels

Fuel approval process - Now in ASTM ballot



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OEMs engine and combustor test program

To assess effects of SASOL fully synthetic jet fuel (FSJF) on engine performance and operation, engine manufacturers (RR, P&W, GE and Honeywell), in coordination with SwRI, conducted engine and combustor tests:

- Engine performance and endurance (P&W)
- Emissions (United Technologies - P&W)
- Low temperature atomization (Honeywell)
- Cold ignition, altitude relight and lean blowout (Rolls-Royce and Honeywell)

Pratt & Whitney – United Technologies tests

- JT9D engine endurance test for 500 test cycles
- Pre and post-test inspection involved:
  - Fuel delivery system including control scheduling, O-rings, filters, etc.
  - Fuel nozzles (position, flow, internal passages, etc.)
  - Combustor liners (visual and video borescope)
- Emissions tests for an 80º, four-nozzle arc sector of commercial combustor involved:
  - ICAO LTO cycle and cruise:
    - NOx, CO, and UHC
    - CO2 and combustion efficiency
    - Smoke number

Honeywell cold atomization tests

- Cold fuel atomization bench test for spray measurements
- Fuel atomizers tested included:
  - Two representative pressure atomizers used in APUs of commercial and military transport in addition to regional aircraft
  - Airblast atomizer used in several propulsion engines and some APUs
- Malvern particle analyzer determined spray droplet size distribution and Sauter mean diameter (SMD)
- Spray visualization and angle
- Fuel temperature down to level consistent with high altitude temperatures

Rolls-Royce cold-day ignition and altitude relight test

- Test conducted at high altitude test facility with an annular combustion system fully representative of a modern gas turbine
- Testing involved:
  - Ignition under high altitude condition across full altitude relight envelope
  - A ground ambient cold day condition – ignition and extinction
  - Extinction boundaries and blowout

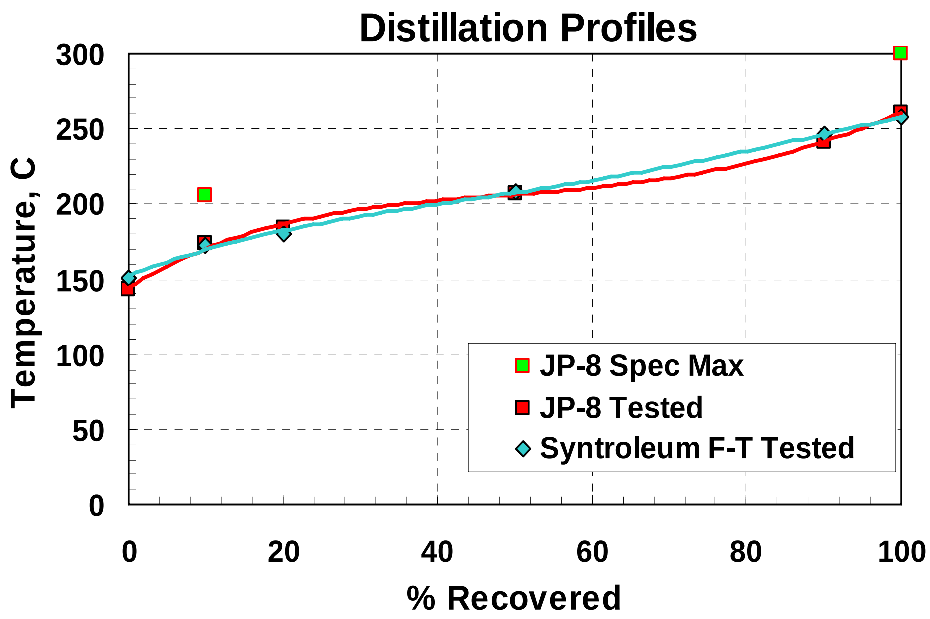
Honeywell combustor lean stability test

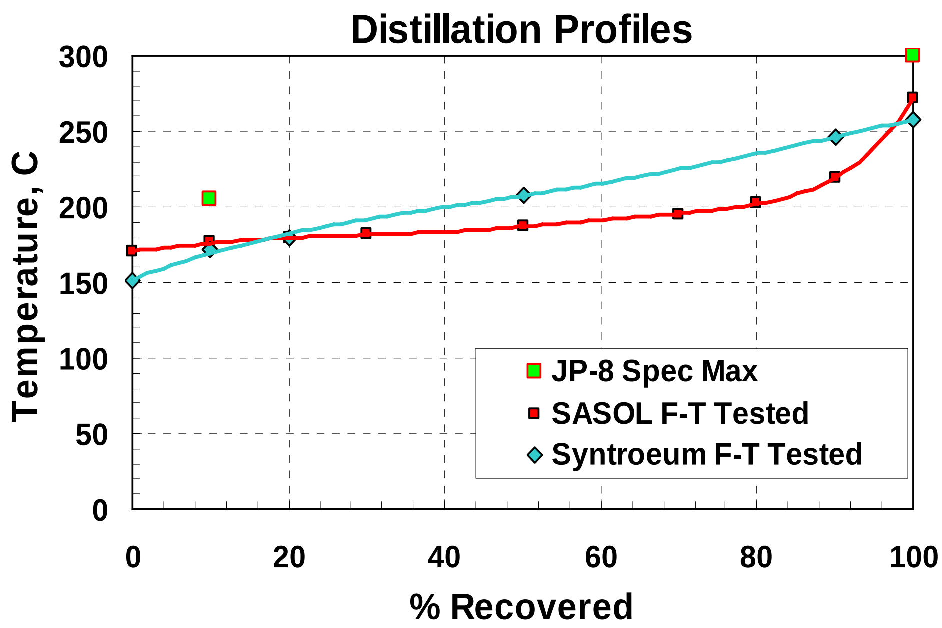
- An annular combustor rig for a small turboshaft (helicopter) engine was used
- Lean blowout testing completed at representative flight and ground deceleration conditions
- Testing used FSJF, Jet A fuel, and weathered JP-5 fuel for comparisons
- FSJF and weathered JP-5 had flat distillation curves
- Lean blowout was detected by a rapid drop in combustor exit temperature

Rolls-Royce experimental evaluation of FSJF

- Objective: Assess impact of Syntroleum Fischer-Tropsch fully synthetic aviation kerosene on performance and material compatibility of aircraft gas turbine engines by evaluating:
  - Combustion characteristics in a production annular combustor and fuel nozzle assembly
  - Effect on oxidation of turbine blade and vane alloys in a cyclic oxidation rig
- Project sponsored by Wright Patterson AFRL
- University of Dayton participated in material analysis

Distillation profiles of F-T and JP-8 fuels





- Syntroleum F-T fully synthetic fuel exhibits fairly similar distillation profile to that of JP-8 tested under present study and both meet the JP-8 specifications
- SASOL F-T fuel has been approved for use in commercial aircraft but has distillation limitations to ensure typical profile

Annular combustor rig

F-T fuel trailer

- Full annular combustor rig is used for testing AE 3007, AE 2100, and AE 1107 combustors, which have common parts with minor variations
- F-T and JP-8 tests used same combustor build
- The 100% SPK was held in a specially cleaned trailer and passed directly to the annular combustor

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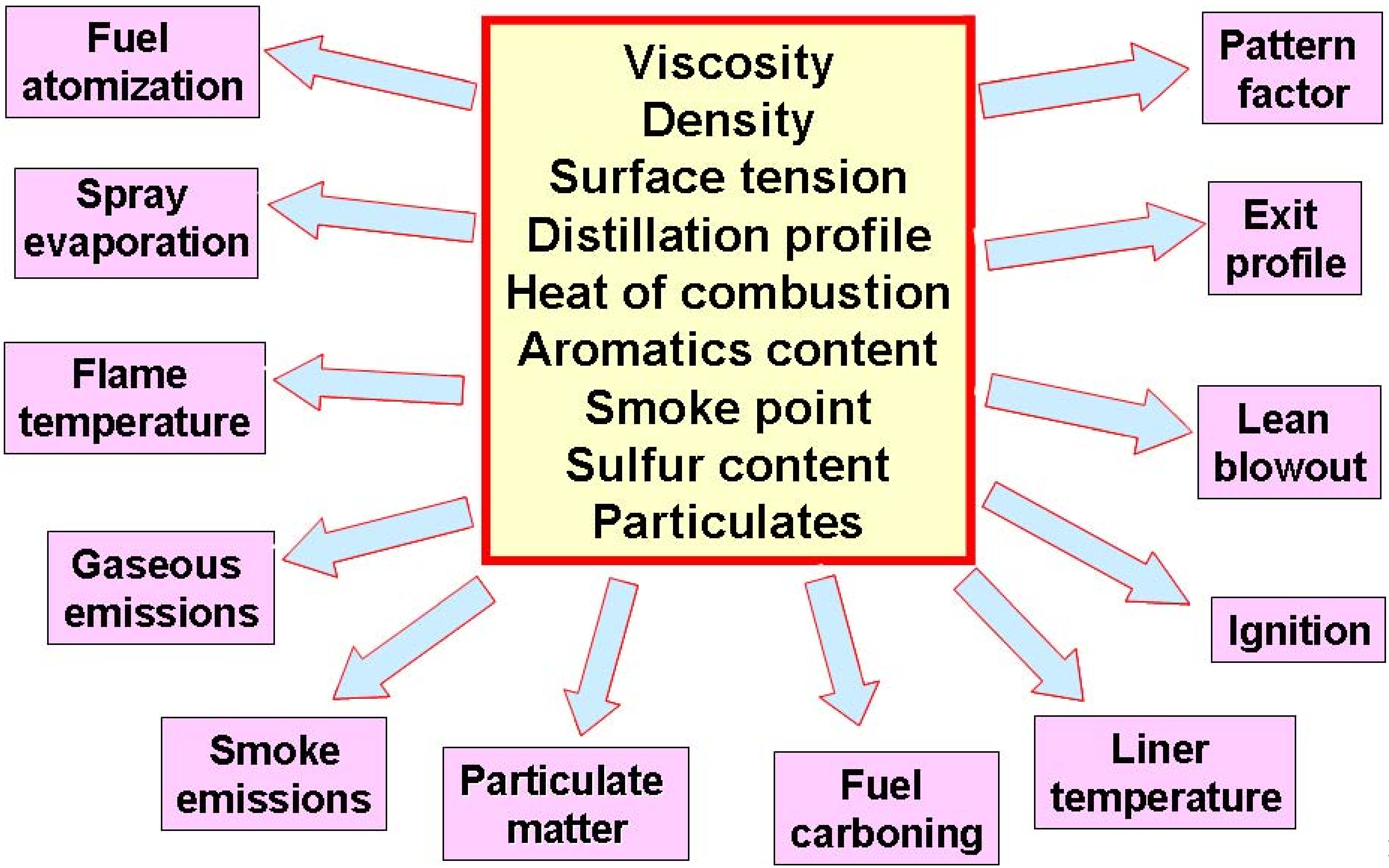
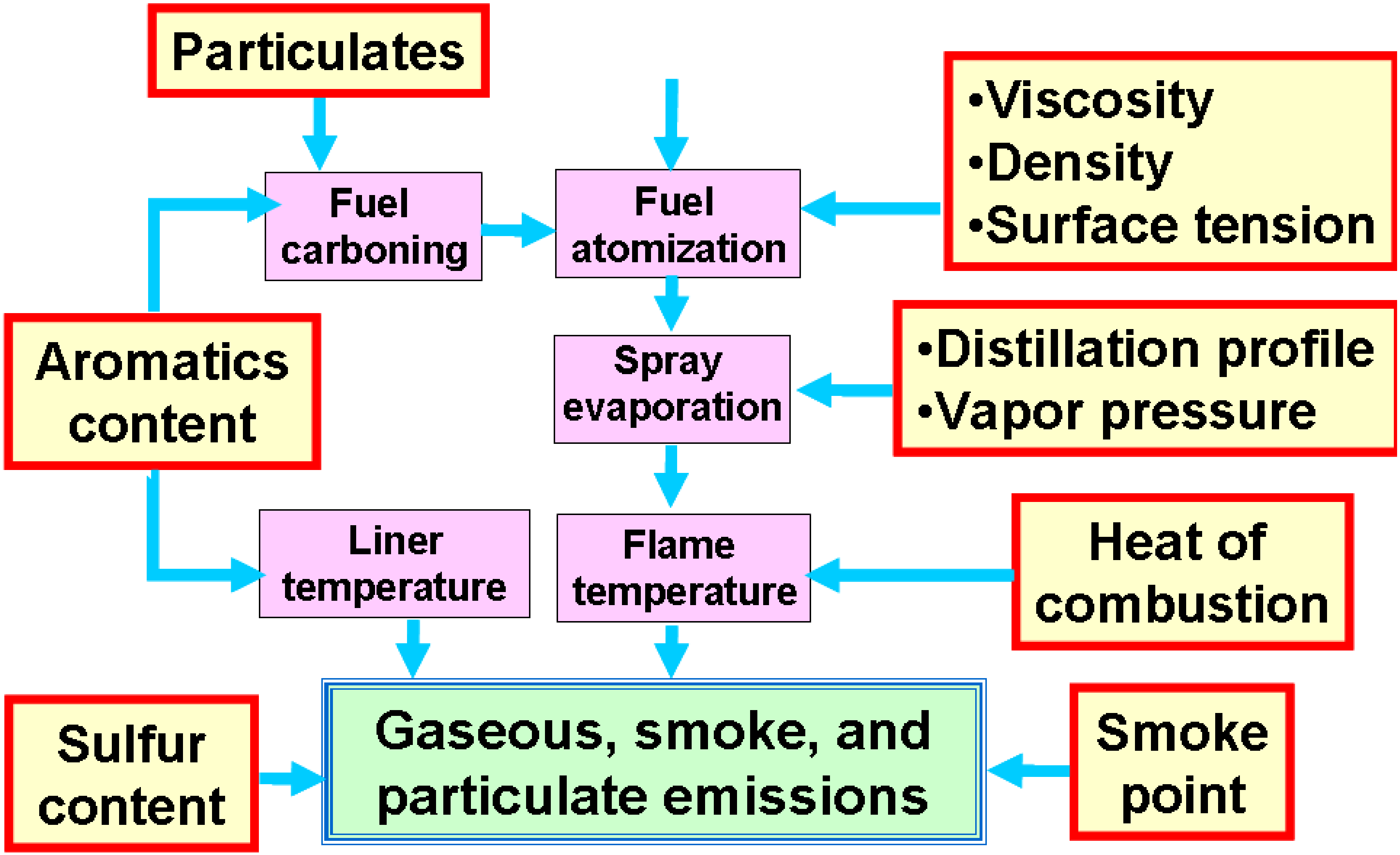
Full annular combustor test

- Stability boundaries
  - Ignition and LBO characteristics
- Emissions at selected performance points
  - Combustion efficiency map
  - Gaseous emissions (NOx, CO, and UHC)
  - Smoke
- Exhaust gas temperature profiles
  - Radial temperature profiles
  - Exit pattern factor
- Combustor liner temperatures
  - Thermocouples measurement
  - Thermal paint

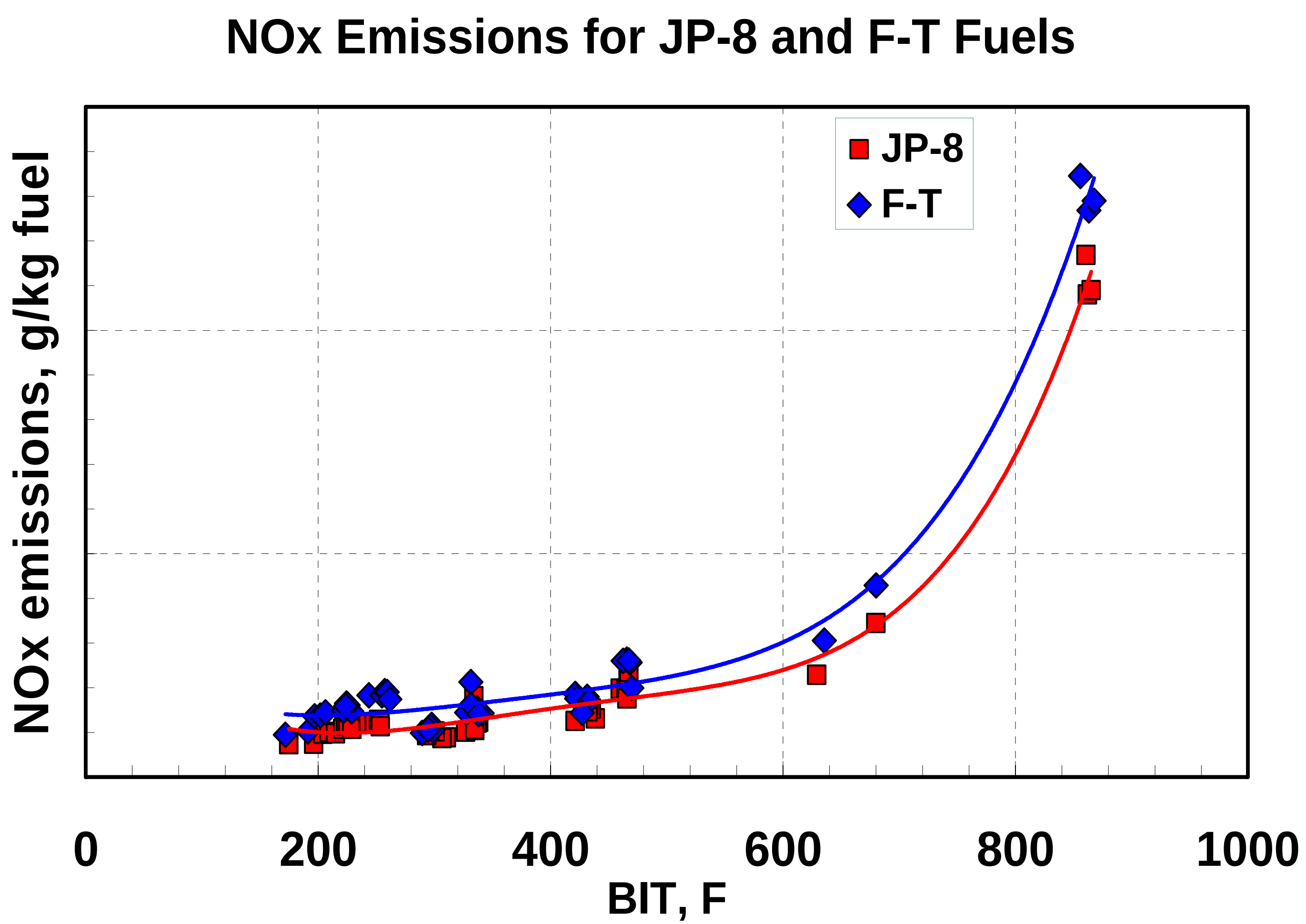
Impact of key properties on performance



Impact of fuel on gaseous emissions

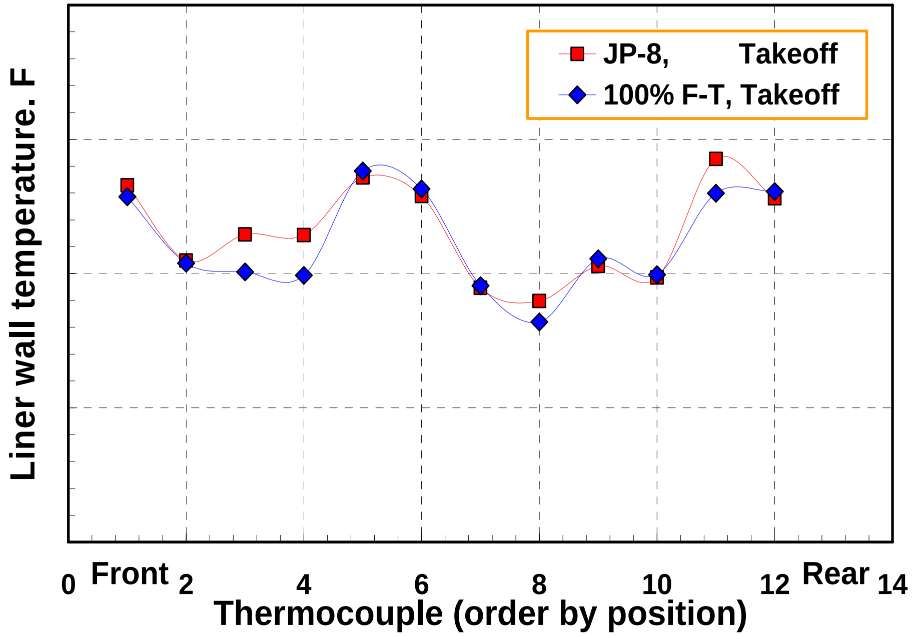


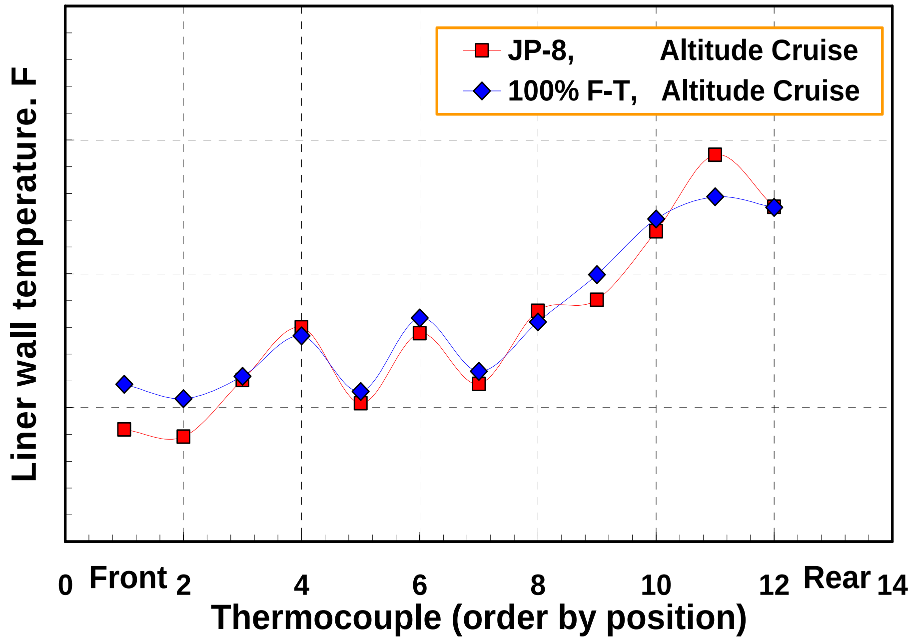
NOx emissions



- NOx emissions for FSJF are in general higher than for JP-8
- Higher combustion heating value of FSJF results in favorable conditions for NOx formation

Liner thermocouple temperature



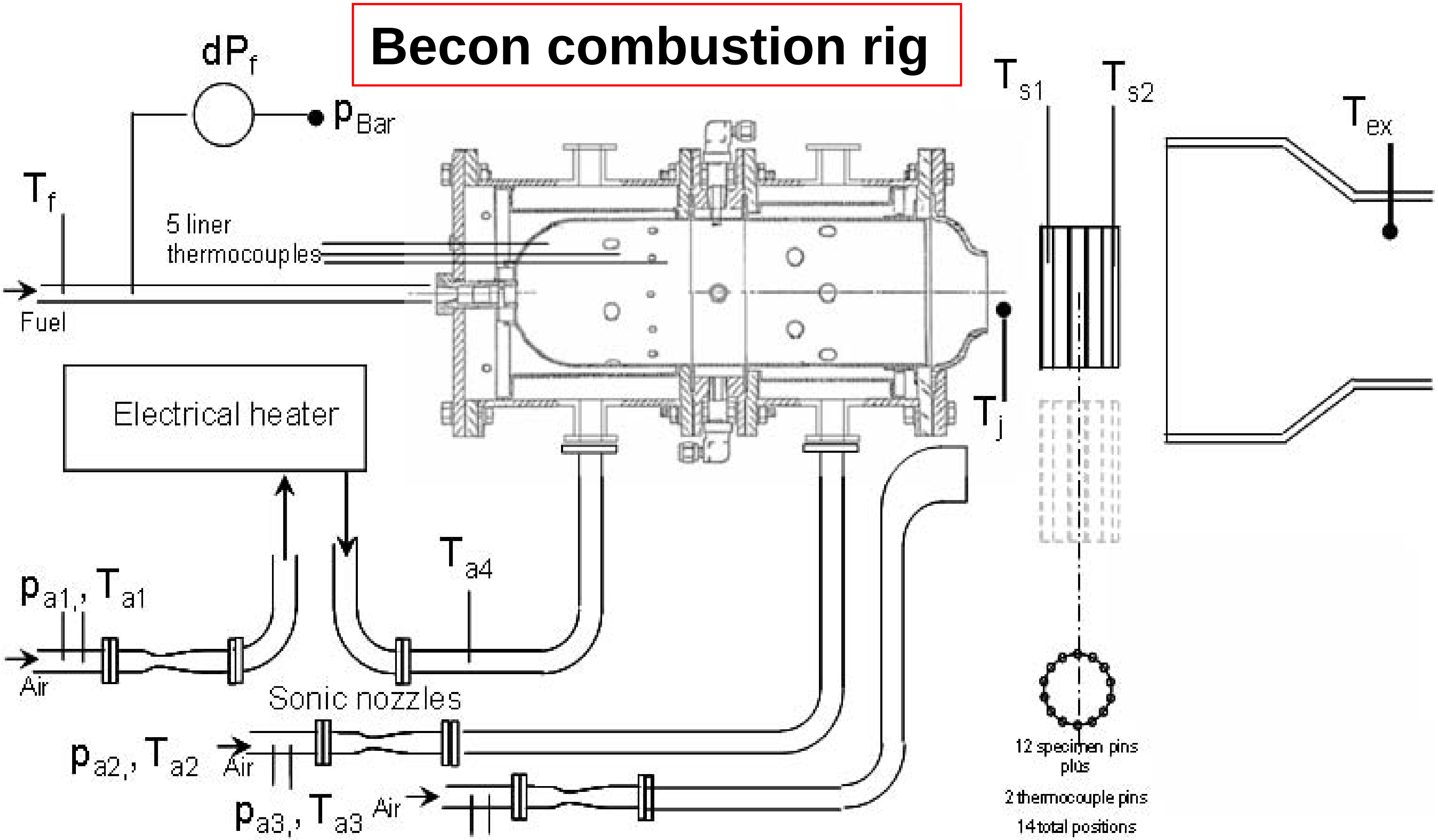


- Thermocouple data were compared at two conditions having similar BOT:
  - Moderate FAR and high pressure representative of T/O
  - High FAR, low pressure such as during cruise-climb
- FSJF had a higher heating value resulting in an increase in BOT relative to JP-8 under same operating conditions
- Liner temperatures are fairly similar at most locations with some advantage for FSJF under T/O conditions
- Thermal paint results did not reveal differences in localized hot or cold spots

Impact on other key performance parameters

- FSJF fuel exhibits similar stability and ignition characteristics at low and higher operating conditions to those for JP-8 fuel within experimental error
- CO and UHC emissions are similar for both fuels
- Full annular AE3007 combustor behaves like engine in producing extremely low smoke and remains nearly smoke free for both FSJF and JP-8 fuels
- No measurable differences are observed in pattern factor and radial profiles between JP-8 and FSJF fuels suggesting no adverse impact on turbine vane lives

Impact of F-T fuel on material



- A set of 12 alloy specimen rods and 2 thermocouple rods were mounted in a 600 RPM rotating carousel and cycled between hot and cold jets

Analysis of test specimens

- In order to determine whether FSJF fuel had same or different effect on several alloys used in engines as normal JP-8 fuel, test pins from Becon combustion rig test were analyzed by University of Dayton
- Samples were examined by two main methods:
  - Visual analysis and optical metallography
  - X-ray-fluorescence (XRF) and scanning electron microscopy (SEM)
- Photomicrographs of sections of 12 samples at both 100x and 400x magnifications showed that no significant difference was evident for any material in the two fuel environments
- Also, based on elemental intensity values, it would appear that the use of FSJF does not result in any significant compositional differences in material relative to compositions found for materials that were tested using JP-8 fuel

Airbus / Shell / Rolls-Royce A380 demo

- Flight evaluation of a 40% GTL kerosene fuel blended with conventional fuel
- Part of research program to understand renewable fuels and potential future applications:
  - Aircraft - Airbus A380 MSN4
  - Engine - Trent 900 – only one engine used the derived fuel
  - Timing – 1 Feb 2008
- Data gathered throughout the test process reported and contributing to the capabilities and limitations of FT and also more recently renewable synthetic fuels

Rolls-Royce joins Air New Zealand, UOP and Boeing in renewable fuels study program

- Flight evaluation of a renewable bio fuel blended with kerosene fuel source
  - Aircraft ANZ 747-400, Engine RB211-524GT, only one engine uses the fuel
  - Timing –30th Dec 2008
- Fuel analysis shows fuel meets/exceeds current specification requirements
  - 50:50 Blend - Jatropha derived SPK (Hydrogenated Vegetable Oil) and standard Jet A-1, therefore is drop-in
- Data gathered throughout the test process has contributed to understanding of the capabilities and limitations of renewable fuels
- Pre and Post engine hardware inspection is taking place

Summary

- OEMs joint test program, in coordination with SASOL and SwRI, provided significant engine and component performance data in support of FSJF assessment and approval
- Rolls-Royce assessed impact of Syntroleum fully synthetic aviation kerosene on performance and material compatibility of aircraft gas turbine though combustion testing in production annular combustor and Becon combustion rig
- Fuel properties impact almost all engine performance parameters and hot section material durability through their effects on fuel injection/spray evaporation processes and combustion characteristics
- Engine operability has been demonstrated for 2 different alternative fuels
- ICAO can play a significant role in promoting development of alternative fuels and incorporation in future regulation activities

Concluding remarks - The future

- **Existing Rolls-Royce programs goals**
- **Meeting the challenge**
  - Supporting development of truly sustainable and viable alternative fuels for aviation:
    - Whole life cycle evaluation
    - Performance measurement and prediction
    - Integration with engine development programs
- **Creating the opportunities**
  - Creating new collaborative partners to evaluate and demonstrate alternative fuels e.g Qatar Consortium
  - Contribution to European Union funded sustainable fuel programs- e.g, ALFA-BIRD, SWAFEA
  - Engagement with key industry bodies – e.g. CAAFI, Specification Owners (ASTM, Defence Standards), US Coordinating Research Council
  - Improving test and evaluation capability, e.g, university collaborations
  - Supporting the approval and rapid adoption of suitable alternative fuels

Thank you.