NRC·CNRC

Hybrid-Electric Aviation: A New Research Direction for NRC Aerospace

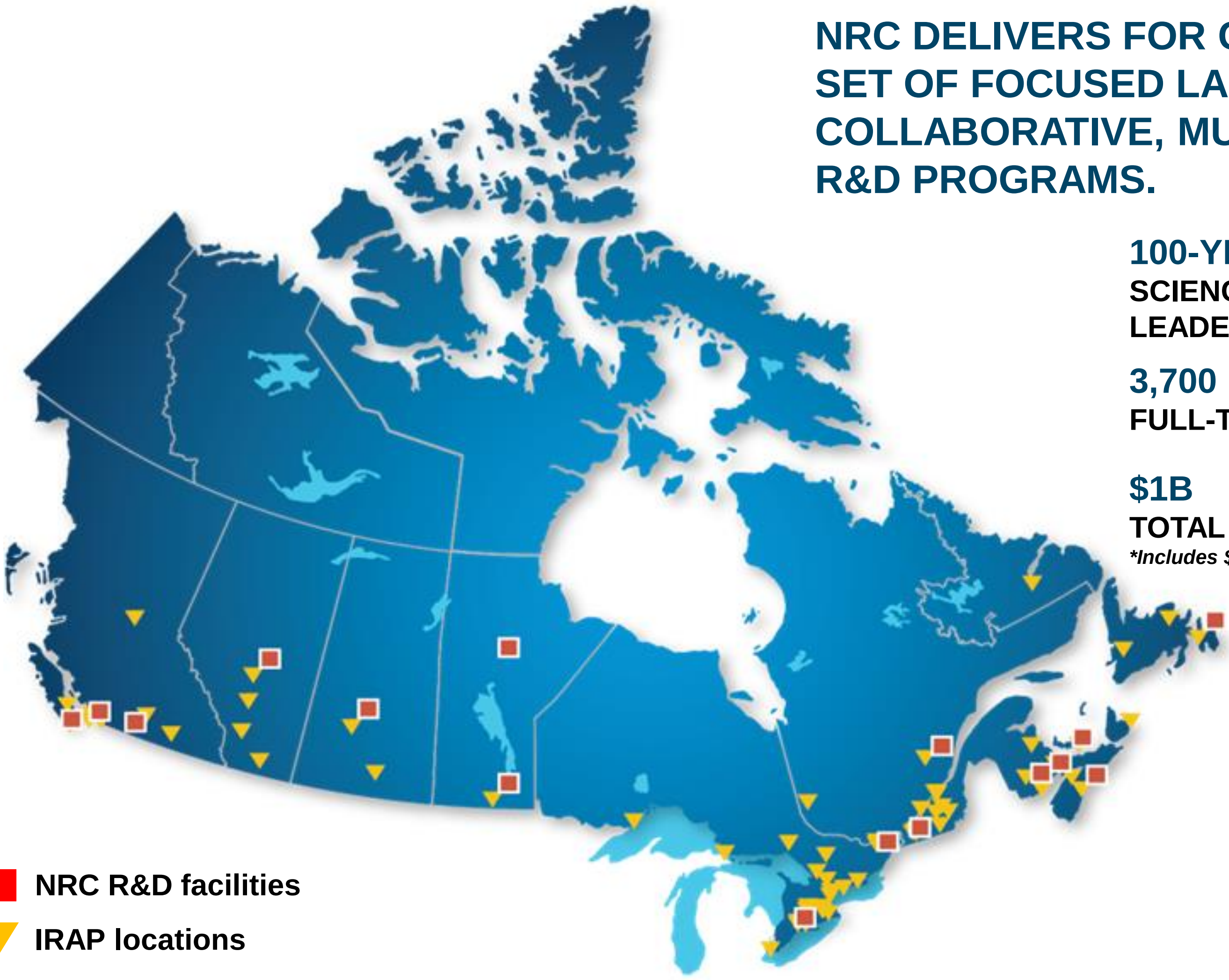
Dr. Michael Benner, Director R&D, Aerodynamics

National Colloquium on Sustainable Aviation 2017

June 22, 2017

NRC at a glance

A national organization with regional presence and global reach



NRC R&D facilities

IRAP locations

NRC DELIVERS FOR CANADA THROUGH A SET OF FOCUSED LARGE-SCALE, COLLABORATIVE, MULTI-DISCIPLINARY R&D PROGRAMS.

100-YEAR TRACK RECORD
SCIENCE AND INNOVATION LEADERSHIP FOR CANADA

3,700
FULL-TIME EQUIVALENTS

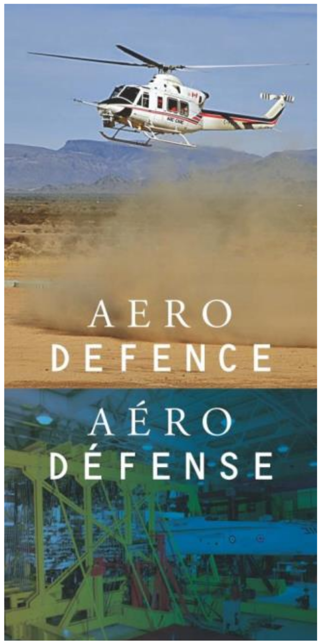
$1B
TOTAL EXPENDITURES IN 2016/17
**Includes $300M in IRAP support for SMEs, etc.*

NRC Aerospace – Key Differentiating Capabilities

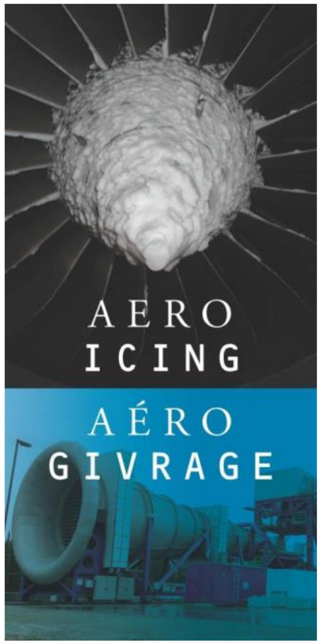
Supporting Environmentally Responsible, Safe, Secure and Efficient Air Transportation:

More than 300 Technical Experts and $500M in Research Infrastructure

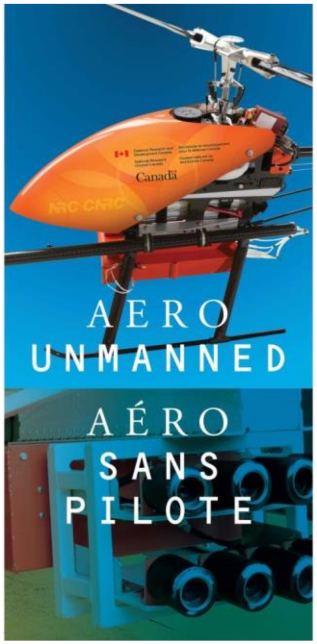
Five NRC Programs Focused on Aerospace



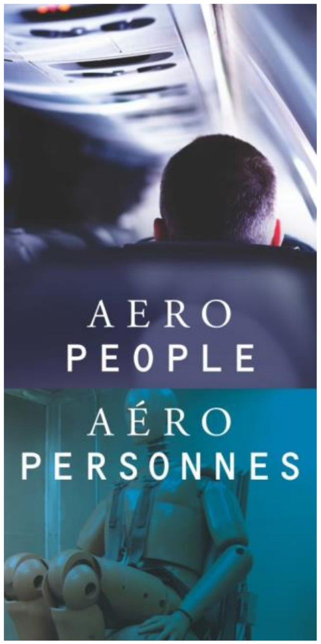
Air Defence Systems (ADS)



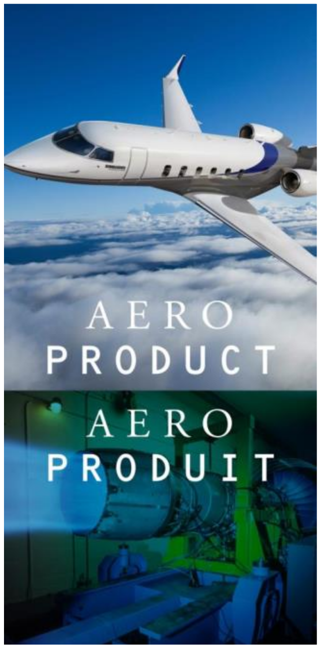
Reducing Aviation Icing Risks (RAIR)



Civ. Unmanned Aircraft Systems (CivUAS)



Working & Traveling on Aircraft (WTA)



Aeronautical Product Development (APD)

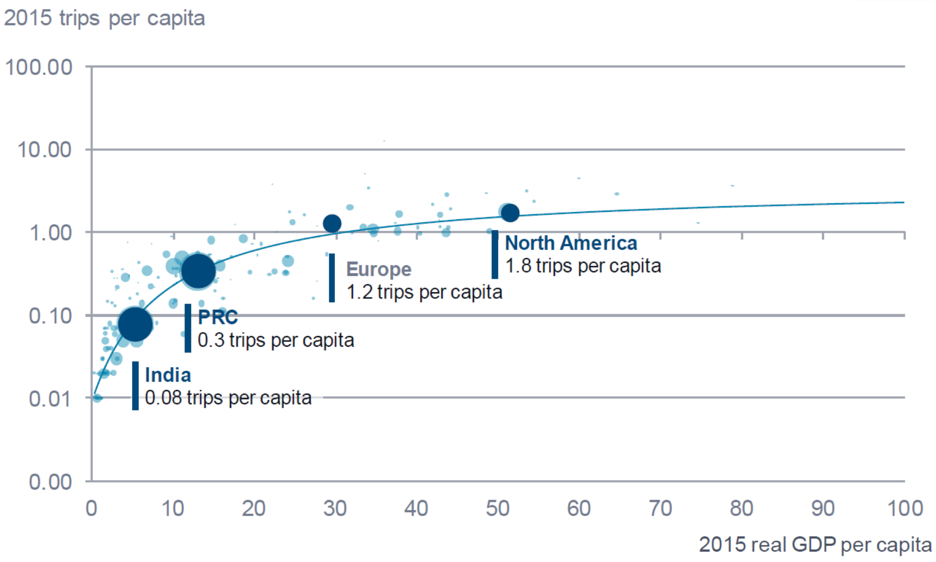
NRC·CNRC

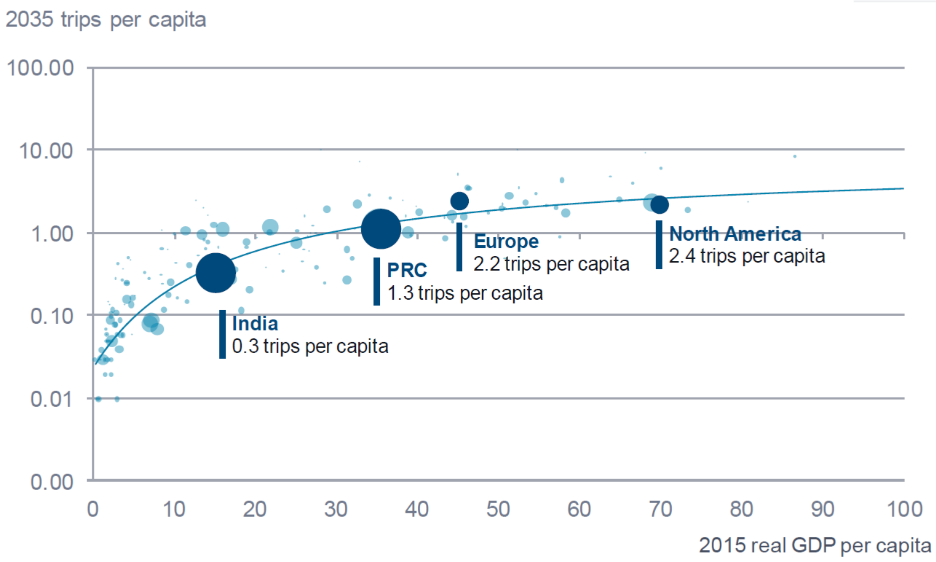
A Case for Hybrid-Electric Aviation

http://yournewsticker.com/2014/04/airbus-developing-hybrid-electric-jet-aircraft.html

Civil Aviation: Significant Growth Ahead

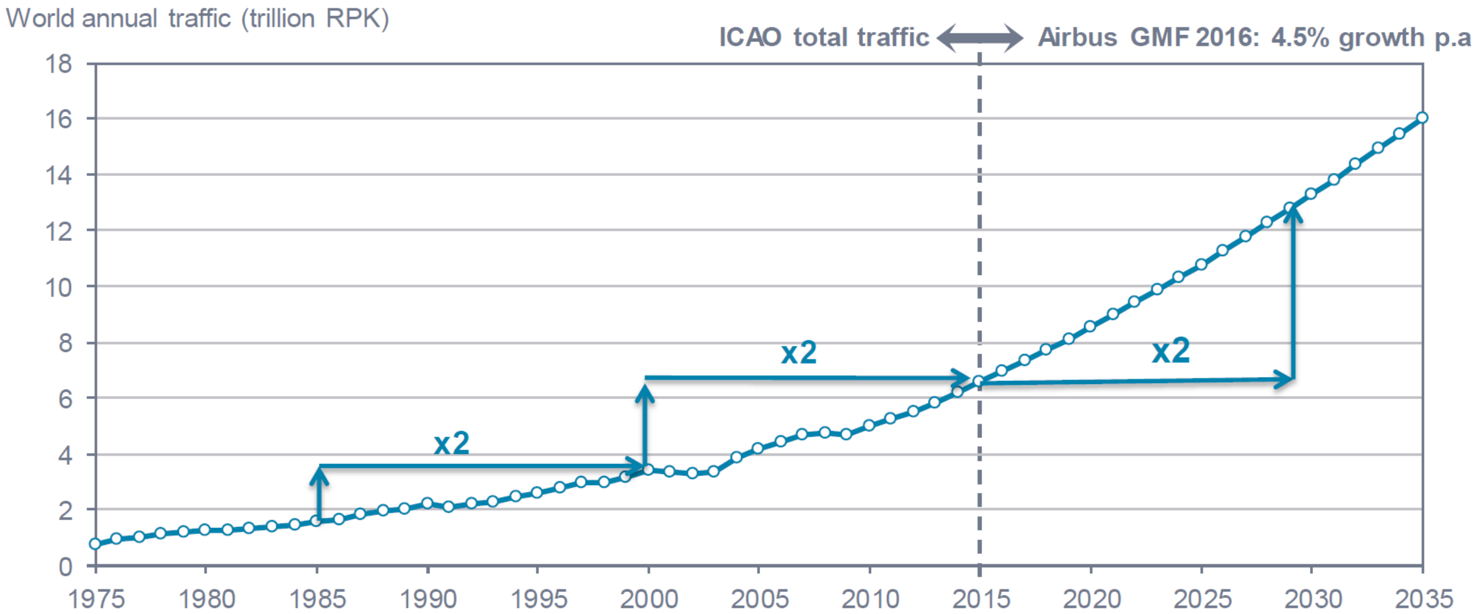
- Economic growth and propensity to fly in emerging markets are significant
  - GDP will increase 2.9% per year for next 20 years
  - 75% of people in emerging countries will take at trip in 2035 cf. 25% in 2015





http://www.airbus.com/company/market/global-market-forecast-2016-2035/

Civil Aviation: Significant Growth Ahead



Source: ICAO, Airbus GMF 2016

- Boeing, Airbus, Bombardier, Embraer, ICAO all forecast over 4.5% growth in RPK (largely a function of GDP forecast)

Global Civil Aircraft Fleet Forecast

› What is impact on global civil aircraft fleet?

- Over the next 15 years: 27,000 new passenger aircraft; 24,000 new business jets (KPMG Report)
- Bombardier predicts 12,700 new aircraft deliveries in the 60- to 150-seat segment over next 20 years
- IATA projects an approximate doubling of air passengers by 2035 (from 3.8 to 7.2 billion)

› Aircraft manufacturers are seeing significant opportunity for growth

NRC·CNRC

What's Driving Innovation in Civil Aviation?

- Demand by aircraft operators for more fuel efficient aircraft
  - Profitability is increasingly driven by fuel costs
    - Fuel costs are approximately 20% of total operating cost and are highly variable
    - Profit margins are slim: varied over past 5 years from ~2% to 5%
  - International commitments/regulations for significant reductions in greenhouse gas production
  - Comply with EU legislation concerning aviation emissions
- Need for quieter aircraft to meet current and future noise regulations
- Market growth and the need for greener aircraft are driving R&D investments into technologies that **enable reduced fuel burn**, noise and emissions (Market pull)

NRC·CNRC

Aviation Emissions

- Aviation emissions: carbon dioxide (CO_2) and oxides of nitrogen (NOx)
- Climate change
  - CO_2 emissions at altitude (NOx also important)
  - 2% of global greenhouse gas (GHG) emissions
  - 3.5% human-generated radiative forcing
- Local air quality health concerns
  - NOx, PM, VOC, etc.
  - Known to be detrimental to human health (e.g., cardiovascular and respiratory systems)

Regulations and Targets

› NOx emissions

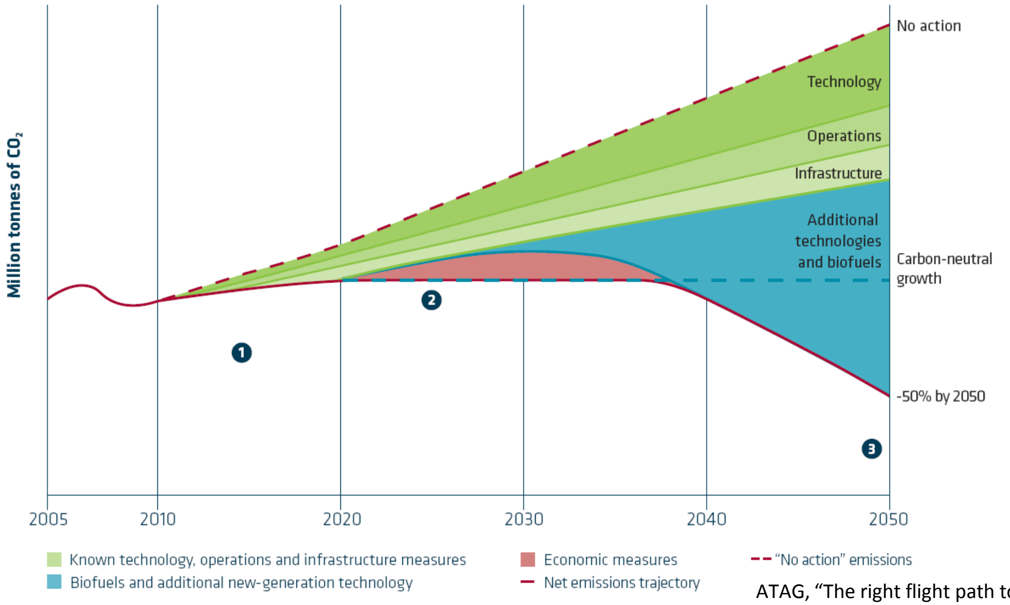
- Certification standards put in place by ICAO
  - Updated periodically to increase levels of stringency
- ACARE reduction targets (non-binding):
  - 80% relative to 2000 level by 2020
  - Current aircraft cannot meet targets

› CO_2 emissions

- Global aviation industry reduction targets (non-binding)
- IATA - carbon-neutral growth by 2020 and 50% CO_2 reduction by 2050
- ICAO has adopted a new carbon dioxide emissions design certification standard
  - Any aircraft that begins type certification after 2020 will need to comply.
  - By 2028, all aircraft will be required to meet the standard, whether new or currently produced.

Response Needed from Aviation Stakeholders

- Multi-faceted approach needed
  - Technology advancements ← Focus
  - Improvements to operational practices
  - Improvements to air transport infrastructure
  - Positive economic measures



ATAG, "The right flight path to reduce aviation emissions," November 2010

Technology Advancements for Reduced GHG Reductions

Reduce Fuel Burn

Reduce Noxious Emissions

Airframe weight reduction

Composites development

Drag reduction

Technology advancements for conventional configurations

Green Aeropropulsion

New propulsion systems
- Hybrid-electric
- Electric

Incremental reductions - gas turbines
- Improved component efficiencies
- Improved propulsive efficiency

Blended-wing bodies with distributed propulsion systems

Importance to Canadians

- Aerospace industry is important to national economic prosperity
  - Aerospace contribution to GDP: $29.8B
  - 5th behind US, UK, Germany and France compared to 10th overall
  - Employed over 87,000 Canadians
  - Generated close to 30% of Canadian manufacturing R&D investment (yet Aerospace GDP is only 16% of total manufacturing GDP)
- Government has identified innovation in ***Clean Technology*** as a high priority
- Budget 2017:
  - The Innovation and Skills Plan is an effort to make Canada a world leader in innovation, with a focus on expanding growth and creating good, well paying jobs:
    - $950M over five years to develop superclusters
    - $0.8B to support clean technology research, development and adoption
    - $1.4B to accelerate growth of clean tech companies

Future Direction of Research at NRC Aerospace

- **Beyond studies on:**
  - Technology trends
  - Market trends and outlooks
  - Mergers and acquisitions
  - Competitive context

- **Have sought valuable advice**
  - Industry and academia
  - National and regional associations
  - Other government departments
  - Implementation risks

Environment Canada

Transport Canada
www.tc.gc.ca

Strategic Roundtable Consultations: Industry and Academia

› **Seeking valuable advice on priorities for NRC Aerospace:**

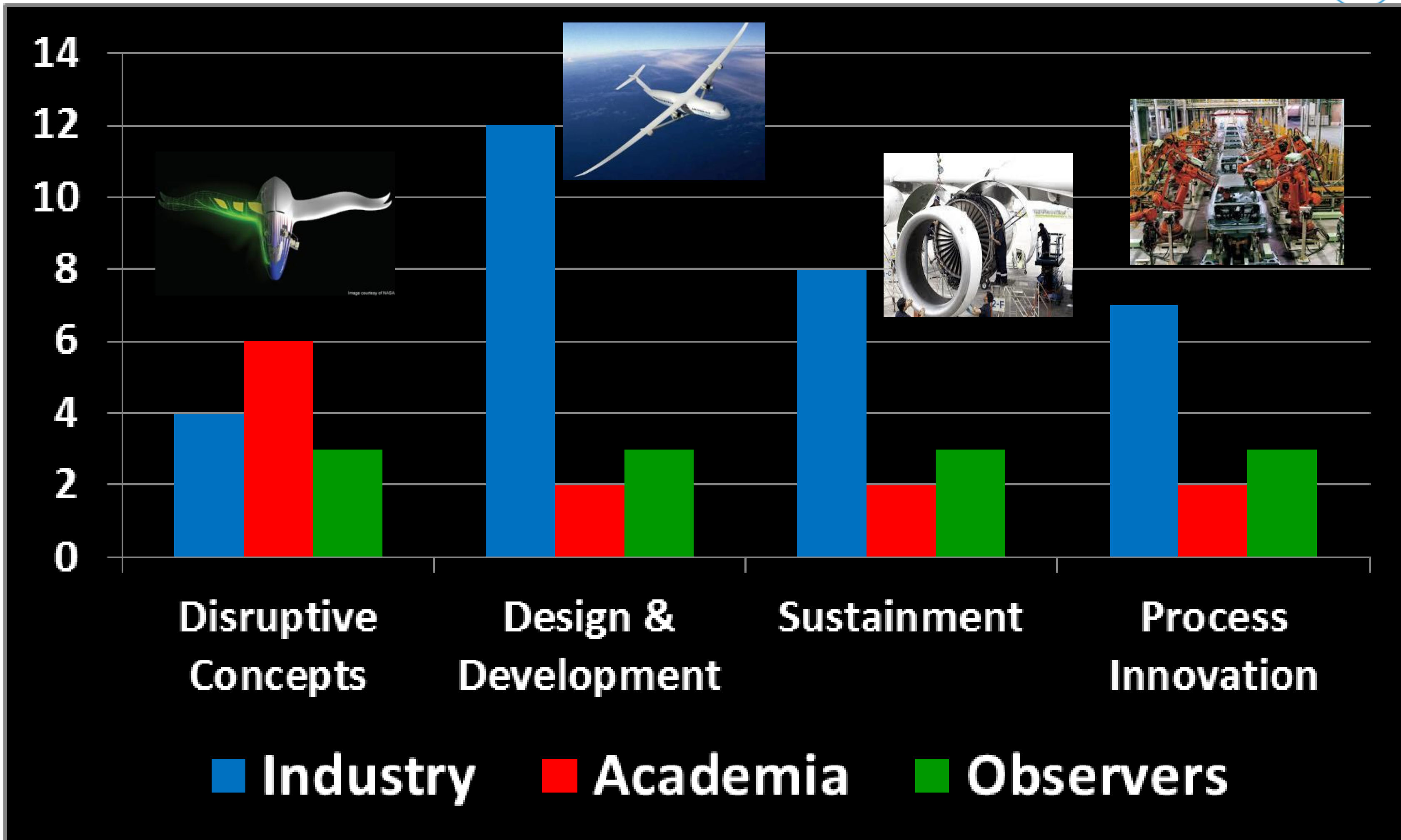
- **What's ahead in aerospace**
  - Future market opportunities, key S&T drivers
- **Value added by NRC in the innovation ecosystem**
  - Capability gaps (with respect to academia and industry)
  - Expectations from NRC in terms of access to facilities and expertise
- **Working with NRC**
  - Technology transfer and management of intellectual property
  - Co-funding opportunities
  - Challenges or hurdles

› **Four half-day roundtable discussion sessions in Ottawa (November, 2016):**

- Disruptive Concepts; Design & Development; Sustainment; and Process Innovation

› **Sessions facilitated by the renowned aerospace analyst, Dr. Kevin Michaels**

Roundtable Attendees



Research & Technology Recommendations

- **28 R&TD recommendations put forward**
- **Synthesized and evaluated by consultant, based on three criteria:**

Long-term impact on aerospace industry

Perceived ability of Canadian Aerospace Industry to leverage technology

Fit with broader government objectives

- **Findings – six promising areas:**
  - Accelerate additive manufacturing development – both standards and technology
  - Develop a prognostics & health management demonstrator aircraft
  - Accelerate innovation in landing systems
  - Accelerate innovation in energy harvesting and more electric aircraft systems
  - Manufacturing process innovation and enhanced productivity including adaptive programing, data analytics and automation
  - Unmanned aerial vehicles and unmanned systems

Looking Forward – NRC's Views

Role:

- Leadership in technology development and talent growth

Support:

- Air defence operation and sustainment goals
- Air transportation regulations and product certification objectives
- Space program aspirations

Technology Opportunities:

- More electric aircraft (including hybrid-electric aviation) and supersonic travel
- Process innovation
- Digitalization in aerospace
- Autonomous and optionally-piloted vehicles
- Cabin, interior and systems
- Integrated technology demonstrators: landing gear and flight

NRC Aerospace – Plans for Hybrid-Electric Aviation Research

› New NRC Program call coming in summer months

- New programs will need to support priorities highlighted in Budget 2017
- Priority of significance to Aerospace: Clean Technology and Clean Resources

› Program proposal is planned to include

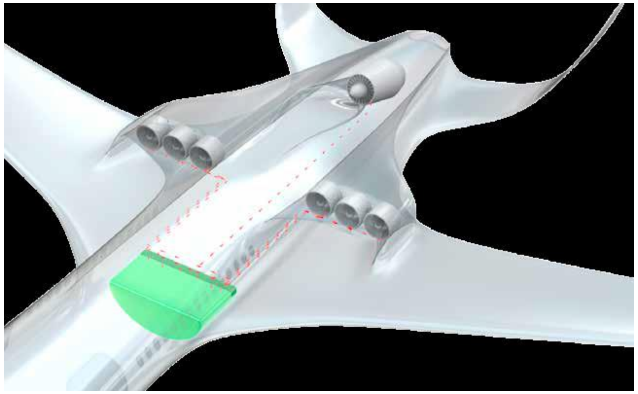
- Technology development for new aircraft configurations, engine architectures and autonomous aviation
- Significant component to include hybrid-electric aviation

› In the interim – two projects have been initiated through

- Aerospace Futures Initiative
  - $2M competition-based fund
  - Intended to spawn and grow new ideas, build competencies and develop partnerships
  - For utilization in new programs
- Aeronautical Product Development Technologies (APDT) Program ($60M over 5 years)
  - **Value Proposition:** *Help industrial partners de-risk aeronautical product development by providing priority access to highly-capable national facilities, and technologies to accelerate product qualification testing*

AFI Project – Boundary Layer Ingestion (BLI)

- Hybrid-electric engines will enable distributed propulsion systems
- Fully integrating engines into airframe will give rise to step change in fuel burn
  - 15% reduction by some estimates cf. 1-1.5% reduction in fuel burn per year over the past decades
- AFI funding ($600K) awarded to two-year project focused on boundary layer ingestion for distributed propulsion



Rolls Royce/Airbus E-Thrust Collaboration

NRC·CNRC

AFI Project – Boundary Layer Ingestion

- Mechanisms affecting vehicle performance are well understood
  - ↓ jet mixing losses ∴ propulsion efficiency ↑
  - ↓ wake mixing losses due to BL ingestion
  - ↓ in nacelle and pylon wetted area losses
  - ↓ in engine fan efficiency due to inlet distortion

- Focus here is BLI effects on engine performance and operability


Image Source: NASA/Northrop Grumman

NRC·CNRC

AFI Project – Why isn't BLI currently used?

- BLI creates non-uniform engine inlet flow which may:
  - Reduce engine performance
  - Create unsteady blade forces and vibration
  - Reduce engine stall margin

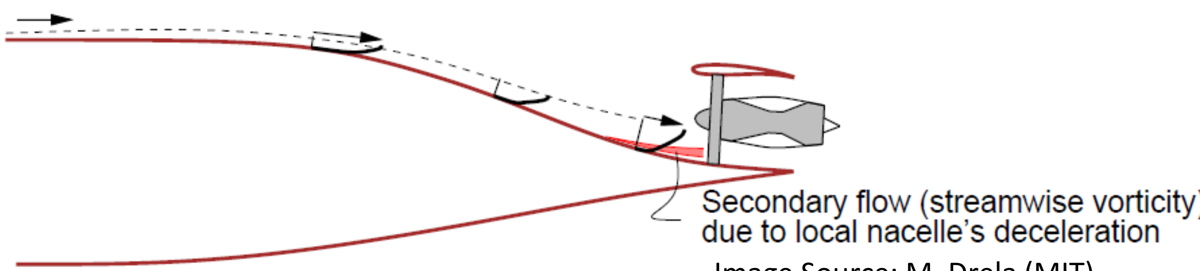


Image Source: M. Drela (MIT)

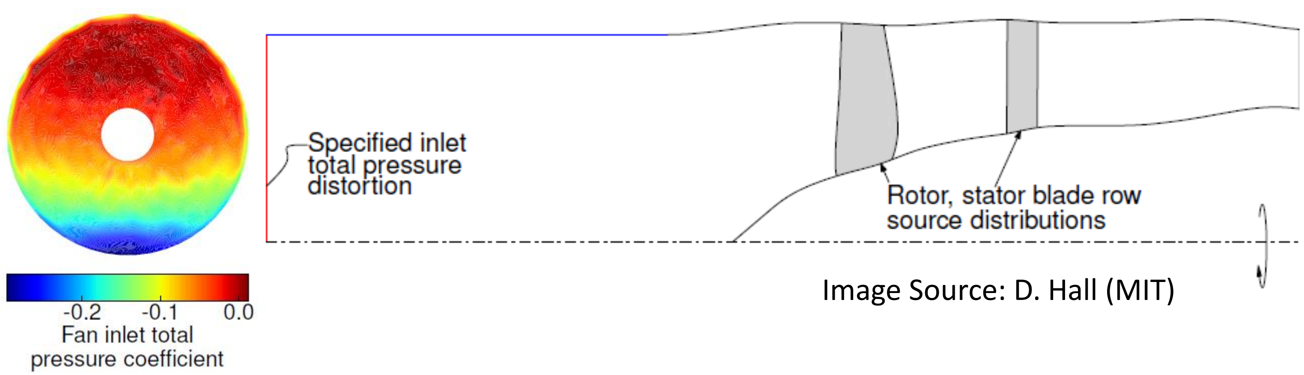
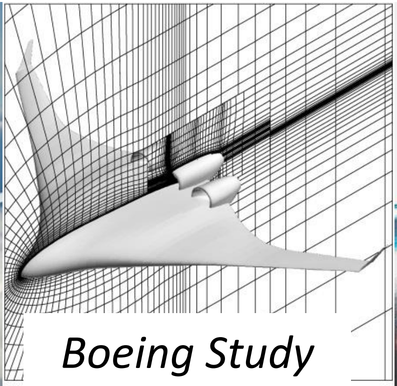


Image Source: D. Hall (MIT)

Contributions of the Work

- No full-scale experiments with operational engines have been completed
  - Steady-state performance, and
  - Engine operability and forced response
  - Supplement recent work by NASA
    - CFD + scaled wind tunnel work on NASA D8 Concept (NASA, 2015)
    - Engine fan test at NASA Glenn (NASA, Dec. 2016)


NASA D8 Concept


Boeing Study


NASA Fan Test

BLI Project Objectives

- Create **Integrated Technology Demonstrator** of full-scale BLI with an operating engine
- Determine effects on engine fan, core, *and* combustion efficiency when engine and/or aircraft are operating at off-design conditions due to BLI
- Further increase BLI benefits by using passive or active flow control to reduce non-uniformity of inlet flow

Test Facilities and Capabilities

- Historically, engine and external aerodynamic R&D done in isolation
- No longer possible to do so with BLI, as with many new technologies
- Expertise exists to assess both simultaneously
- Facilities in place
  - Two turbofan engine test cells (baseline testing)
  - Propulsion Icing Wind Tunnel (PIWT)

NRC·CNRC

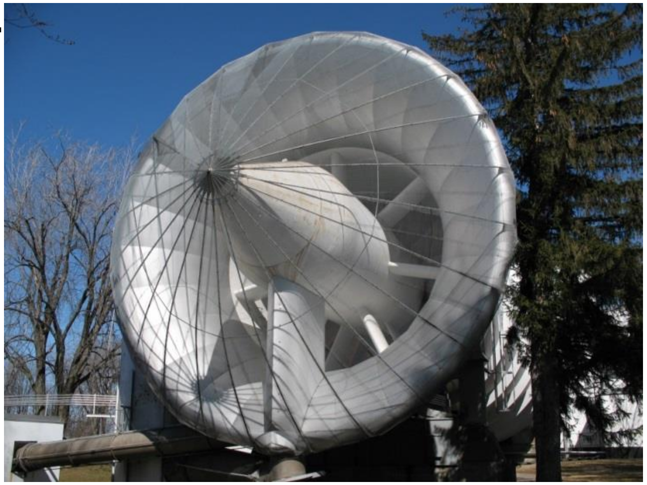
Turbofan Engine Test Cells

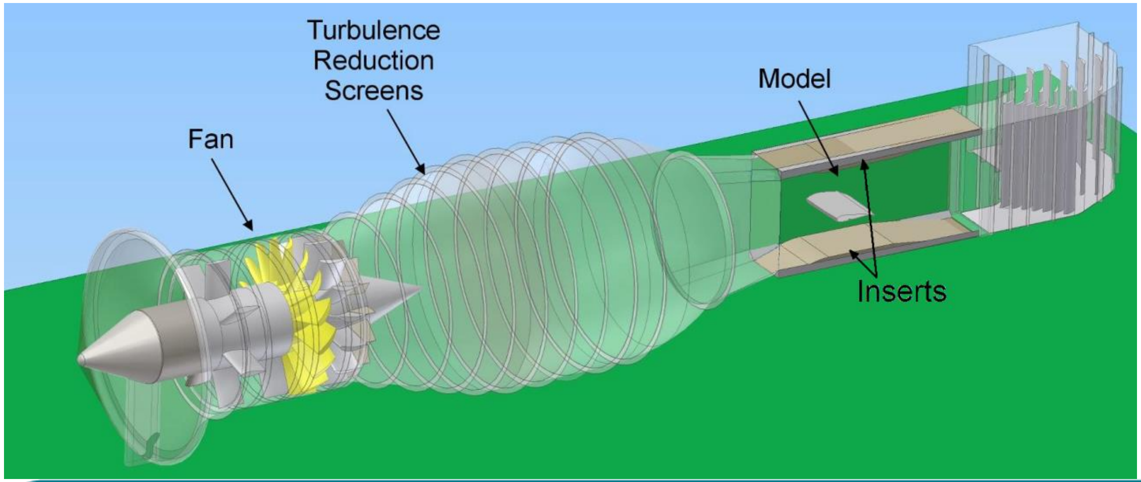
- Needed for baseline engine and operability testing
- Significant experience in engine testing (dating back to 1947)
- Can easily accommodate engines of the size needed for the project
  - Max. air flow:1,000 lb/s
  - Max thrust: 50,000lbf of thrust
- Engine instrumentation with specialized sensors for measuring steady-state and transient performance

NRC·CNRC

Propulsion Icing Wind Tunnel (PIWT)

- Commissioned in the early 1960’s for V/STOL gas turbine development
- Large-scale open-circuit tunnel
- Tunnel specifications:
  - 3 m x 6 m (~45 m/s); electric drive
  - 3 m x 5 m (~65 m/s); gas-turbine drive





NRC·CNRC

Partners Required for BLI Project

- Partner(s) from Academia needed
- Airframe design including inlet geometry
- CFD design and analysis support
- Engine to test
- Have obtained expressions of interest from various companies

Potential Industry Partners

BOMBARDIER AEROSPACE

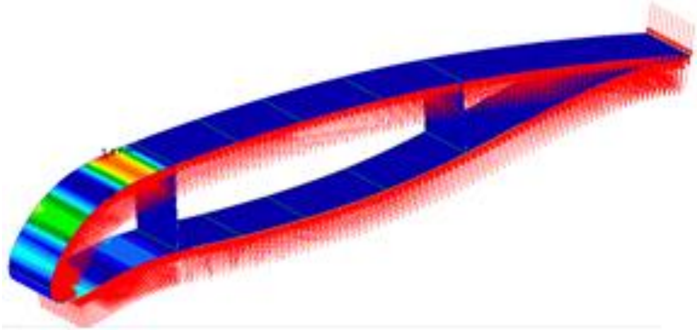
ROLLS ROYCE

Pratt & Whitney Canada
A United Technologies Company

Williams International
The Power of Vision

Further Areas of BLI R&D: Adaptive Intake Technologies - 1

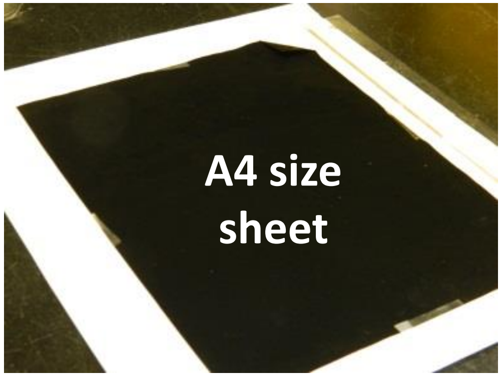
- Reduction of inlet flow distortion
- Building on experience from Smart Wing with Integrated Multi-functional Surfaces (SWIMS) Project
  - Development of stretchable and deformable multi-functional materials and smart support structures
  - Focus of SWIMS was on developing airfoil with drooping leading edge, full-functionality demonstration and 2-D subsonic wind-tunnel test

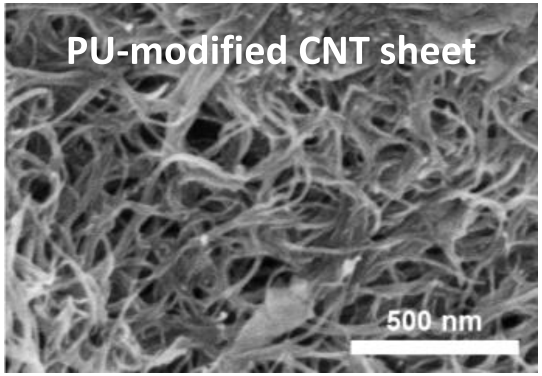


NRC·CNRC

Adaptive Intake Technologies - 2

- Significant progress to date particularly on new skin materials and sub-structures
- Have examined a number of possible skin candidates (literature): elastomers (silicones, rubber), polyurethanes, shape-memory polymers, nonwovens
- Selection: Skin based on a non-woven carbon nanotube – polyurethane composite sheet*

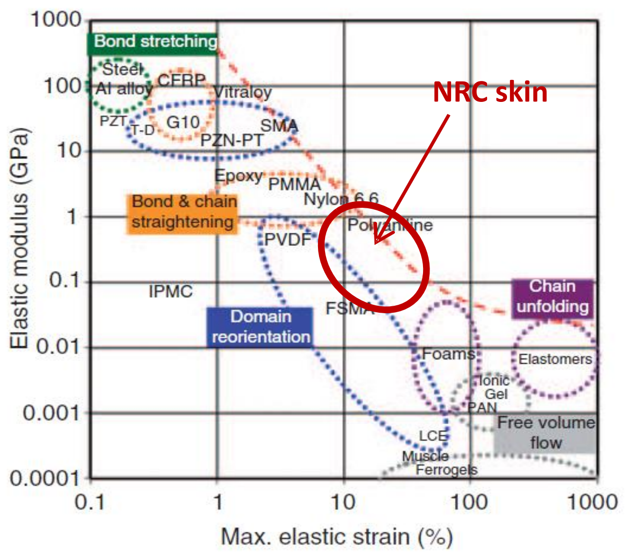




*US patent application: STRETCHABLE NANOCOMPOSITE SKIN MATERIAL AND RELATED STRUCTURES (NRC Filed May 2017)

Adaptive Intake Technologies - 3

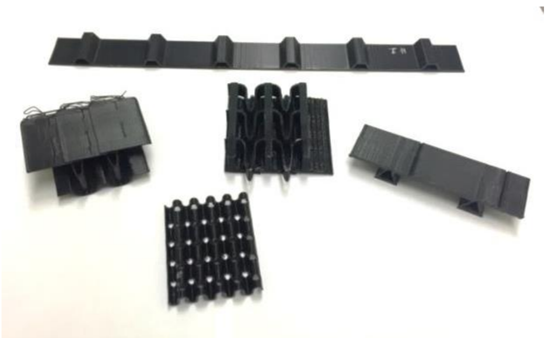
- Material properties and performance
  - Nanocomposite stiffness much higher than neat polymer candidates
  - Tailorable strength–stiffness (20% stretch target)

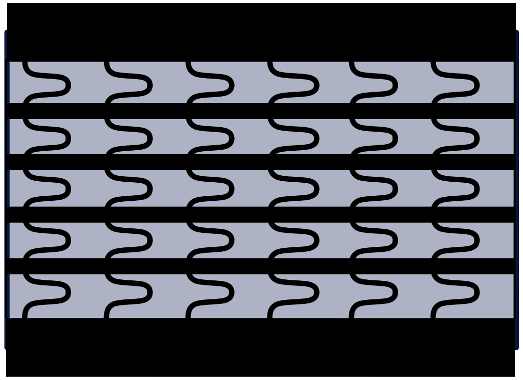


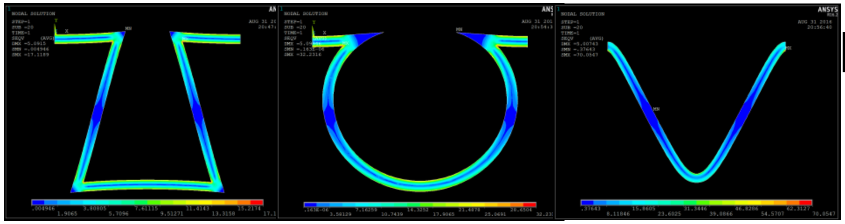
Adapted from: McKnight et al., J Intellig Mater Sys Struct, 21, 1783, 2010)

Adaptive Intake Technologies - 4

- Sub-structure development has also advanced
- Composite "accordion" (discontinous support)
- FRP stiffeners; extendable nylon sections

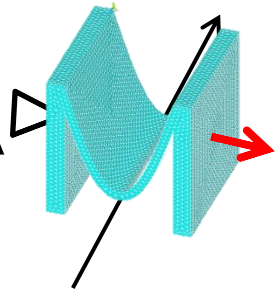




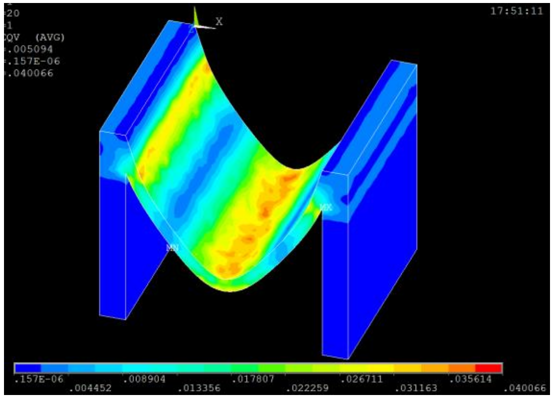


Initial shape selection

FEA



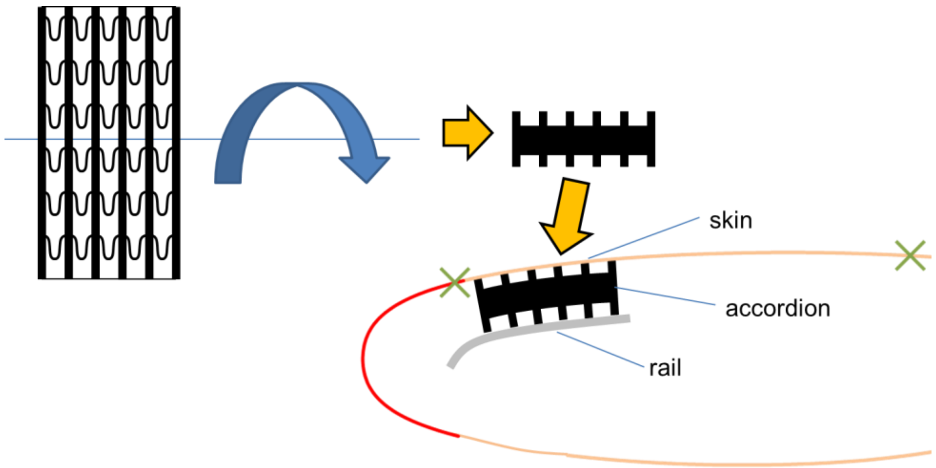
Span direction



NRC·CNRC

Adaptive Intake Technologies - 5

- Structural integration
  - Skin bonded to accordion support structure; support structure slides on rigid rails
    - Avoids skin lift-off under aerodynamic suction loads
    - Airfoil shape not affected by varying pressure loads caused by changing AOA



Adaptive Intake Technologies - 6

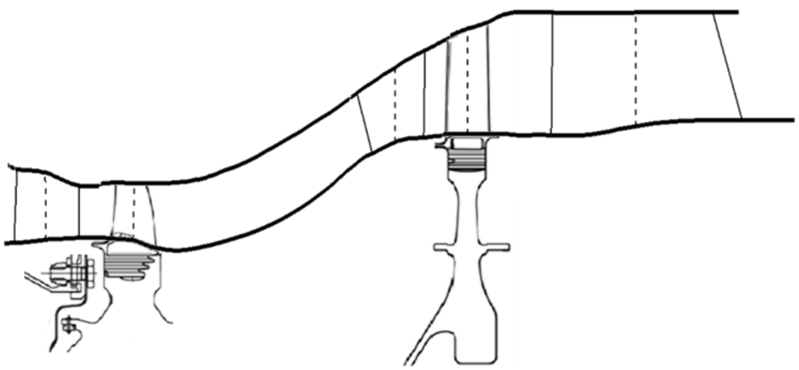
- SWIMS project has provided an excellent materials and structural basis for adaptive intake technology development
- Project funding will be proposed under new program
- Low-TRL project – well suited for collaborative R&D

Image source: https://phys.org/news/2014-03-morphing-aircraft-efficient.html

Further Areas of BLI R&D: Low-Distortion S-Ducts - 1

- Building on experience with the design and experimental testing of inter-turbine transition ducts (ITD)

- Multi-year project aimed at achieving aggressive low-loss low-distortion ducts with
  - Minimum length and/or
  - Maximum radial offset and/or
  - Maximum area ratio

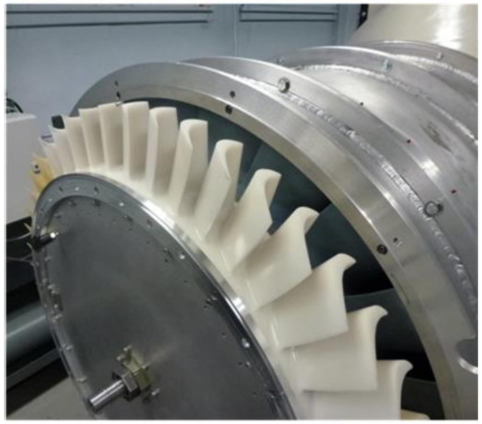


- Approach: Experimental testing, CFD analysis and numerical optimization (at least initially)

NRC·CNRC

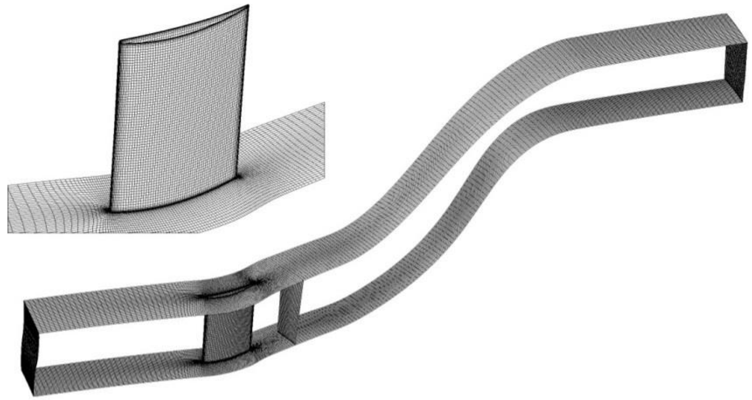
Low-Distortion S-Ducts - 2

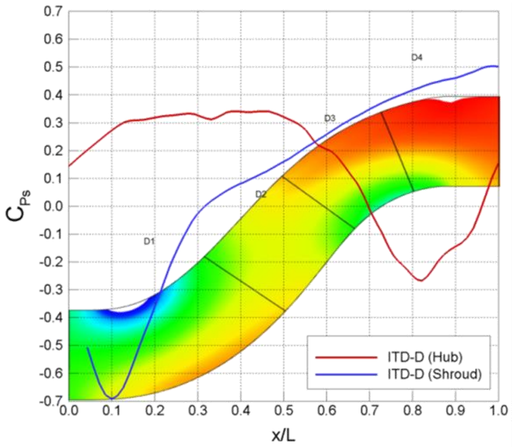
- Turbine test rig developed
  - Low-operating cost
  - Considerable experience gained with SLA manufacturing for both rotating and non-rotating parts (low cost)
  - Extensive suite of instrumentation for detailed interrogation of flow field (e.g., PIV, unsteady multi-hole pressure probes, etc.)
- Facility components could be used into an inlet test facility



Low-Distortion S-Ducts - 3

- Numerical optimization of duct carried out early on in the project during steady phase
  - Numeca used with built-in optimizer
  - Several optimized shapes developed, manufactured and tested
  - Missed important physics
  - Unsteady design ultimately carried out based on intuition and physical insights





Low-Distortion S-Ducts - 4

- Low-distortion S-duct development project
  - Ideally suited for collaboration with universities
  - Numerical tools and shape optimization
  - Low-TRL experimental set-up

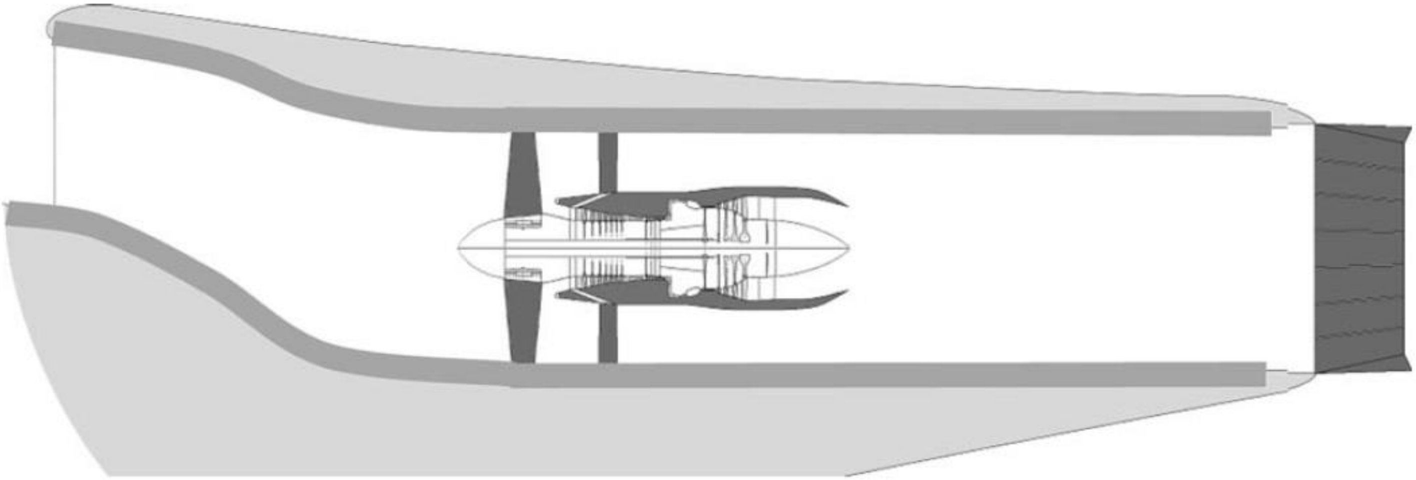


Image Source: Greitzer, E.M., 2009, ASME Journal of Turbomachinery, Vol. 131

Further Areas of BLI R&D: Certification Challenges

- How will hazardous atmospheric conditions affect embedded engines?
  - Rain, hail, supercooled clouds, glaciated clouds, ice sheets
  - Cross-wind effects

NRC·CNRC

APDT Project - Hybrid Electric Aircraft Testbed (HEAT)

- Second "Lead-in" project into new to-be proposed NRC Program on disruptive aviation technologies
- For General Aviation and Regional Aircraft, Electric or hybrid-electric propulsion *is* coming to market soon
- NRC's engagement in this area is recognized to be very limited to date – needs to take on a leadership role

Image source: http://zunum.aero/#were-changing

HEAT – Objectives

- Develop *and* demonstrate a flying hybrid-electric test-bed aircraft at NRC
- Build operational experience
- Demonstrate solutions related to installation, integration and thermal management
- To support Industry and Transport Canada in the development, evaluation and certification of hybrid-electric and electric aircraft and their components
- For example, certification strategies for:
  - Electric motors
  - Various battery chemistries and configurations (fuel cells)
  - Generators, motor controllers
  - Wiring standards

Capabilities and Test Facilities - 1

- NRC Aero has decades of experience and world-class expertise in supporting industry in bringing new technologies to market
  - Flight Research Laboratory
    - Transport Canada (TC) Accreditation for Experimental Flight Permits
    - Airworthiness assessment expertise with in-house design, fabrication, installation and flight operation leading to Supplemental Type Certification
  - Gas Turbine Laboratory
    - Component-level technology development
    - Engine performance and operability testing at simulated altitude conditions
    - Engine certification testing (e.g., icing, hail, snow, birds, ice slabs, etc.)

Capabilities and Test Facilities - 2

- General Aviation Cessna 337 Super Skymaster
  - Convert rear engine to pure electric with COTS components (e.g., batteries, controllers, motors) to begin
  - Powerplant redundancy
  - Maximum continuous power (2 x 210HP)
  - Availability of high power-density electrical motor

YASA-750 R (http://www.yasamotors.com)

Power (Max. Cont.)	93HP at 3000RPM
Speed	0 – 3250RPM
Mass	37kg
Diameter	370mm

NRC·CNRC

Capabilities and Test Facilities - 3

- Thermal management significant issue
- Assessment of component, and system safety and performance under various flight conditions
- Testing in Research Altitude Test Facility will be integral to achieving experimental type permit

Description	Value
Maximum flow rate (unrefrigerated/undried air)	11.2 kg/s (24.6 lb/s)
Min. altitude (refrigerated dried air)	100 m (328 ft)
Min. altitude (unrefrigerated/undried air)	91 m (300 ft)
Max. altitude	15,760 m (51,700 ft)
Min. temperature at min. flow rate 0.23 kg/s (0.5 lbm/s)	-45 °C (-49 °F)
Min. temperature* at max. flow rate of 4.5 kg/s (10 lbm/s)	-50 °C (-58 °F)
Heated inlet air at a flow rate of up to 1.8 kg/s (4 lbm/s)	+48 °C (+118 °F)

NRC·CNRC

Other Initiatives and Expertise Supporting Hybrid Electric Project

- Development of virtual electric propulsion demonstrator for:
  - Evaluating and optimizing individual and integrated system performance of component-level technologies for various powertrain configurations and load profiles
  - Reducing risk for aeronautical product development and integration and streamline the development process from concept to test flight
  - Supporting failure mode analysis (safety, reliability)
  - Supporting development of certification (regulatory) roadmap
- Electrochemical storage system – testing, integration, safety and compliance
- Li-Ion batteries and fuel cells
- Investigating effects of extreme atmospheric conditions

Development of Partnerships

- Multi-disciplinary project that will require significant collaboration with academia and industry and also within NRC

- NRC - Automotive and Surface Transportation
  - Electric motors and battery performance: packaging, safety fast charging, diagnostics
  - Industry contacts: TM4, several Montreal companies that package bus batteries

- NRC - Energy, Mining and the Environment
  - Power engineers and technologists with hybrid-electric experience

- NRC - Design and Fabrication Services with specialization in implementing aircraft modifications

NRC·CNRC

Long-term Canadian Relevance and Impact

- Establishes a competency that has a number of possible Canadian receptors that compete in the global market
  - A physical asset and operational experience enabling test and development of various electric aircraft technologies

Possible Canadian Receptors:

- Major engine OEM recently approached Canada/NRC for electric aircraft program
- P&WC: Electric likely to impact small turbines first
- RR and GE both working on electric-cored turbines
- Canadian Solar Ship Inc., and its humanitarian mission, depend on electric propulsion
- Boeing is supporting a Canada-centric (NRC, Look North, C-CORE) IRB-funded high-altitude, long-endurance Arctic surveillance UAS

Questions?