I was asked to discuss the future of Aero Engines for the next 20-30 years. In brief the future is BRIGHT. I will focus on commercial aircraft which represent the largest part of the market. I will discuss the drivers and the elements of the market, including the technologies which are essential for its success. I will conclude by laying out the structures of electrical propulsion which would disrupt the regional and single aisle commercial aircraft in years to come.

THE MARKET AND THE DRIVERS

As mentioned earlier the commercial aircraft market exceeds the military market today [figure 1] and is growing at a much faster paces of almost 2 to 1 in value. We will therefore concentrate on commercial aircraft, its needs and drivers.

The Global Aerospace Industry is worth over 800 billion dollars with the Americas leading the world, followed by European countries and Asia being a distant 3rd but growing fast [figure 2].
What are the market needs? One way to address this question is to look at NASA’s Aeronautics Strategic Plan [figure 3]. There are 6 Strategic Thrusts for the future:

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial Supersonic Aircraft
- Ultra-Efficient Commercial Aircraft
- Transition to Alternative Propulsion and Energy
- In-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

The GDP growth driver for aviation is shown in [figure 4]. A look at the GDP growth for different markets between 2013-2033 shows that the emerging countries like China and South East Asia are driving the growth.
What is the need for airplanes? [Figure 5] shows that over 36,000 new airplanes will be needed in the next 20 years. Almost 42% will be needed for replacement and 58% will be needed for growth. The best question is what kind of airplanes will be needed?

**New Airplanes, for Expansion and Efficiency**

Projected number of airplanes in worldwide fleet, 2013 to 2033

A look at [figure 6] shows that the single aisle airplanes will drive the demands followed by twin aisle and regional jets.
The environment needs and regulations will be a major factor for the demand for new airplanes. While commercial aviation accounts for the 2% of the production of CO2 emissions in the world in the year 2000, it will exceed 3% in the year 2030. As regulations are reducing other industrial pollutants in the world [figure 7] there is a push to drive CO2 emissions down and this will be a big goal for the aircraft propulsion industry as we move forward.

Aviation’s Carbon Emissions: Currently Small – But Actions Needed to Prevent Increase

![fig. 7](image)

Safety is an overwhelming goal for industry, as shown in [figure 8]. Programs have been put in place around the world, specifically by U.S. and Canadian operators. Any introduction of new products will have to pass these safety tests.

A Safe Mode of Transportation

![fig. 8](image)
The improvements in commercial airplanes come from different sources but a main driver is coming from the engines [figure 9]. If one looked at a main driver like CO2, which is equivalent to fuel burn, the majority of the efficiency improvements is coming from the propulsion system.

**Sources of Improved Capabilities**

![Diagram showing sources of improved capabilities: Engines, Materials, Aerodynamics, Systems.]

*Fig. 9*

Let us look at history [figure 10]. About 100 years ago the Wright Brothers designed an airplane with 5:1 compression engine producing 12 HP. Their first flight on the North Carolina seashore lasted 12 seconds and went 120 feet. Today with a Boeing 777x propelled by 2 GE9x engines with 105,000 lb. thrust at 60:1 pressure ratio, the airplane carries 400 passengers, has 9000+ mileage range over an 18+ hour flight. Most important it does this every day with minimum fuel burn and pollution. So considerable progress has been made. Where do we go from here?

**Aviation ... driven by technical innovation ...**

*Highlights from the first Century+ of flight*

<table>
<thead>
<tr>
<th>The beginning ...</th>
<th>Now ...</th>
</tr>
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<tbody>
<tr>
<td><strong>Wright Flyer</strong></td>
<td><strong>B777x</strong></td>
</tr>
<tr>
<td>1 occupant</td>
<td>400+ passengers</td>
</tr>
<tr>
<td>120 ft flight</td>
<td>9000+ mile range</td>
</tr>
<tr>
<td>12 sec flight</td>
<td>18+ hour flight</td>
</tr>
<tr>
<td>Wright engine: 12 HP</td>
<td>GE9x engines: 105,000 lb thrust</td>
</tr>
<tr>
<td></td>
<td>105,000 HP</td>
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<td>60:1 pressure ratio</td>
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*Fig. 10*
The Aero Engine Industry faces a broad task. The task is getting tougher on programs as progress is more difficult to achieve. In [figure 11] it shows what the industry is looking for:

- Improved fuel consumption
- Improved emission and noise
- Lower ownership cost
- Lower maintenance
- Fewer disruptions

### Our Industry's broad task

*Deliver customer value with technology: clean, efficient, quiet, affordable & reliable*

### Technology investments …

- Cycles / Architectures
- Materials
- Aero-thermal
- Combustion
- Additive / Adv. Mfg
- Controls & Digital

![Fig. 11](image)

Technology investments have to be made in a host of areas that will have short and longtime payoffs. New cycles and architectures need to be investigated. Improved materials are needed throughout the engines with new aerodynamics and improved combustion is paramount. We want lower NOx emissions while we are driving to higher pressure ratio making our job harder. The customer (airlines) will want to have the new fuel efficiencies at lower costs. We need new advanced manufacturing with 3D printing to drive the costs down. As there propulsion systems are getting more sophisticated, they need to be driven by smarter controls. So how can we get better efficiencies as we move forward? [Figure 12].

![The Basics of Efficiency ...](image)

![Fig. 12](image)
Will be looking for adaptive and modified Brayton Cycles primarily on military engines. Distributed power transmission needs to be looked at as higher bypass rotors are being considered. Electric generation is becoming the major power source on new airplanes, like Boeing 786 series airplanes. Unducted fans are being considered. Distributed propulsion and Boundary Layer Ingestion is being considered with Electric Propulsion. New engine architectures have to be considered as we move forward.

Carbon-fiber composites with advanced fan technology are changing the power plants. Composite fans first introduced and configured on the GE 90-94B engine in 1995 have evolved going down from 22 blades on the 94B to 16 blades on the GE9X [figure 13]. Big improvements in weight and efficiency. By the time the GE9X goes into service, the Boeing 777x composites fan blades will have over 100 million flight hours with a model of reliability.

**Carbon-fiber composites & fan aero technology ...**

Ceramic matrix composites are being introduced in the hot section. First on military and now a commercial engine, with a considerable benefit in performance and in operation [figure 14]. They can operate at 500°F hotter temperatures with a 1/3 the weight of metal with a significant improvement in fuel efficiency.
A revolution in jet engines is coming with additive manufacturing [figure 15]. It started at General Electric with the manufacturing of fuel nozzles, a complicated part. AM reduced the number of parts by a factor of 20 for a 25% reduction in weight and 4 times increase in reliability. On a total power plant, the progress made on the Advanced Turboprop engine (ATP) designed and built in Europe under GE leadership is impressive. Reduction from 855 to 12 parts, 20% improvement in fuel burn and 5% reduction in weight. A preview of things to come.

Advanced Manufacturing - Accelerating the Additive Revolution

Digital technologies will accelerate everything we do, from design to manufacturing to operations and maintenance. [Figure 16] shows a LEAP Engine that gets a cycle signature with a “Personalized” NPSS/Cycle model that identifies any issues and helps remedial actions. In itself it represents a revolution in engine maintenance with a significant reduction in operational costs. A breakthrough facilitated by modeling and digitization.
Aircraft Electrification is happening [figure 17]. It’s moving from more electric aircraft in commercial and military aircrafts to hybrid electric systems with potential to being a disruption to industry.

Is electric propulsion in the future? The opportunities are enormous, so are the challenges. [Figure 18 & 19]

Electric propulsion…the future?

- Hybrid electric could provide 20-25% improvement in fuel burn and CO2.

- Component Development
  - Power Electronics
  - Electric Motors
  - Batteries – Energy Storage
  - Thermal Management
- Ground Demonstrator
- Flight Demonstrator
To make it happen we need solid technology development. Let us define the potential Electric Architectures as well as the necessary components for development. There are a number of electric propulsion architectures under consideration [figure 20].

![Fig. 20]

They span from an all-electric configuration which is battery powered to a turbo electric configuration which is entirely fuel driven with a turboshift. The original National Academy study in 2016 recommended a turbo electric configuration. More recent studies introduce the benefit in hybrid electric systems where battery powered gets engaged in part of the envelope. So what does it take to make all this happen? First we need a strong set of power electronics with a power density equivalent on or above 25kW/kg [figure 21]. These drives need to operate in 2000 dc voltage in low pressure environment (high altitude). A system control strategy needs to be developed for the aircraft to assure system stability under electric fluctuations.

### Power Electronics

**Objectives:**
- Develop MW motor drives working with 2000 dc voltage in low pressure and high temperature environment while achieving a power density > 25 kW/kg
- Develop a system level control strategy for aircraft on board power system to improve system stability.

![Fig. 21]
Second is electric motors. Develop, build and test MW motors with a specific power density > 14 kW/kg [figure 22].

Develop, build and test MW motors with a specific power density > 14 kW/kg.

Third, batteries with power densities of 300 Wh/kg will need to be developed [Figure 23].

Identify and Qualify Commercially Available Batteries

- **Pouch cells**: 170-260 Wh/kg
  - Kukam (Lithium-polymer, 130 - 255 Wh/kg up to 50C, automotive / industrial application)
  - Eagle Picher/Yardney (NMC, 125 – 135 Wh/kg, aerospace application)
  - XALT Energy (NMC, 220 Wh/kg)

- **Cylindrical cells**: 240-270 Wh/kg
  - Panasonic/Sanyo/Samsung (NCR, 260 Wh/kg, automotive application)
  - LG (IMR, 240-260 Wh/kg, automotive application)
  - Efest (IMR, 270 Wh/kg)

- **Pouch cells**: 300-400 Wh/kg
  - American Lithium Energy (up to 400 Wh/kg)
  - Solid Power (Li-metal, ~325 Wh/kg)
  - Solid Energy Systems (Li-metal, 400 - 500 Wh/kg)
  - Sion Power (Li-S, 500 Wh/kg)
  - Oasis Energy (Li-S, 345 Wh/kg)
  - Envia Systems (Li-S, 350 Wh/kg)
  - Enovate Energy (Li-S, 300 Wh/kg)
Most of all we need a high power thermal management system and fuel system integration [figure 24] to bring all these pieces together and control the fleet operation and megawatt components.

These components are being developed across the globe. The Ohio State University is leading a team of universities (University of Wisconsin-Madison, Georgia Institute of Technology, University of Maryland, and North Carolina A&T State University) under NASA sponsorship to develop such a megawatt system. Most important is the test bed needed to evaluate such a system with an altitude chamber capability. This facility is available at NASA [figure 25] as a part of the NASA Glenn Center and can simulate altitude up to 50,000 feet.
SUMMARY

In summary the future of Aero Engines is bright. The demand is growing, so is the competition. Technology is the driver for success. Electric propulsion will come in slowly first for small vehicles like UAV’s and PAV’s (personal vehicles). Regional and single aisle airplanes will follow in the early 2030’s. So great opportunities are in front of us in the short and long range. They will require good collaboration between industry, academics and government. The future is BRIGHT!
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