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A Comprehensive Overview of Electric Aircraft Propulsion

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Abstract: Electric aircraft propulsion is a potential and relatively choice for a reduction of emissions in flight operations. This paper showcases four architectures of aircraft propulsion systems being now considered to utilise the advantages of electric propulsion with commercially profitable operating range and payload capabilities. One of the largest technological obstacles to the widespread use of electric propulsion in aviation is the low energy density of modern electric batteries. The aircraft of the future will be simpler to operate and more capable than today's singlepiston-engine aircraft due to a rare convergence of technologies, mainly Electric Propulsion and Information Technology. The transformation is already shaping the automotive industry with most of the legacy car manufacturers and some outsiders as well jumping into the electric car mass production bandwagon, all of them hoping to carve out bigger slices of the market. This paper describes some of the challenges and opportunities that arise when the upcoming technology convergence wave finds applications in a four/five seat general aviation aircraft to enter in service by 2025.

I. INTRODUCTION

Electric Propulsion (EP) is a class of space propulsion which makes use of electrical power to accelerate a propellant by different possible electrical and/or magnetic means. The use of electrical power enhances the propulsive performances of the EP thrusters compared with conventional chemical thrusters. Unlike chemical systems, electric propulsion requires very little mass to accelerate a spacecraft. The propellant is ejected up to twenty times faster than from a classical chemical thruster and therefore the overall system is many times more mass efficient. This method offers several advantages over conventional chemical propulsion, including higher efficiency, greater specific impulse, and the potential for longer mission durations. Electric Propulsion, when compared with chemical propulsion, is not limited in energy, but is only limited by the available electrical power on-board the spacecraft.

Therefore, EP is suitable for low-thrust (micro and milli-newton levels) long-duration applications on board spacecrafts. The propellant used in EP systems varies with the type of thruster and can be a rare gas (i.e. xenon or argon), a liquid metal or, in some cases, a conventional propellant. EP systems can eventually accelerate to really high speeds and hence work better than chemical systems for deep space missions. The typical EP system consists of a power processing unit (PPU), a fluid management system or propellant components, an optional pointing mechanism and the crucial thruster component.

II. BASIC COMPONENTS

Electric propulsion systems consist of several key components that work together to generate thrust. The specific components can vary depending on the type of electric propulsion system, but the following are common elements found in many designs;

1. **Power Source:** Electric propulsion systems require a power source to supply the energy needed to accelerate particles and generate thrust. This power can come from solar panels, nuclear reactors, batteries, or other electrical generators. Solar panels are commonly used for missions in Earth orbit or near the Sun, while nuclear reactors may be used for deep space missions requiring high power levels.

2. **Propellant Feed System:** Electric propulsion systems use a propellant to generate thrust. The propellant is typically stored in tanks on the spacecraft and fed into the propulsion system as needed. The feed system may include valves, regulators, and other components to control the flow of propellant to the thruster.

3. **Thruster:** The thruster is the heart of the electric propulsion system, where electrical energy is converted into thrust. There are various types of thrusters used in electric propulsion, including ion thrusters, Hall-effect thrusters, and

magneto plasma dynamic thrusters. Each type operates on different principles but generally involves ionizing or accelerating particles to produce thrust.

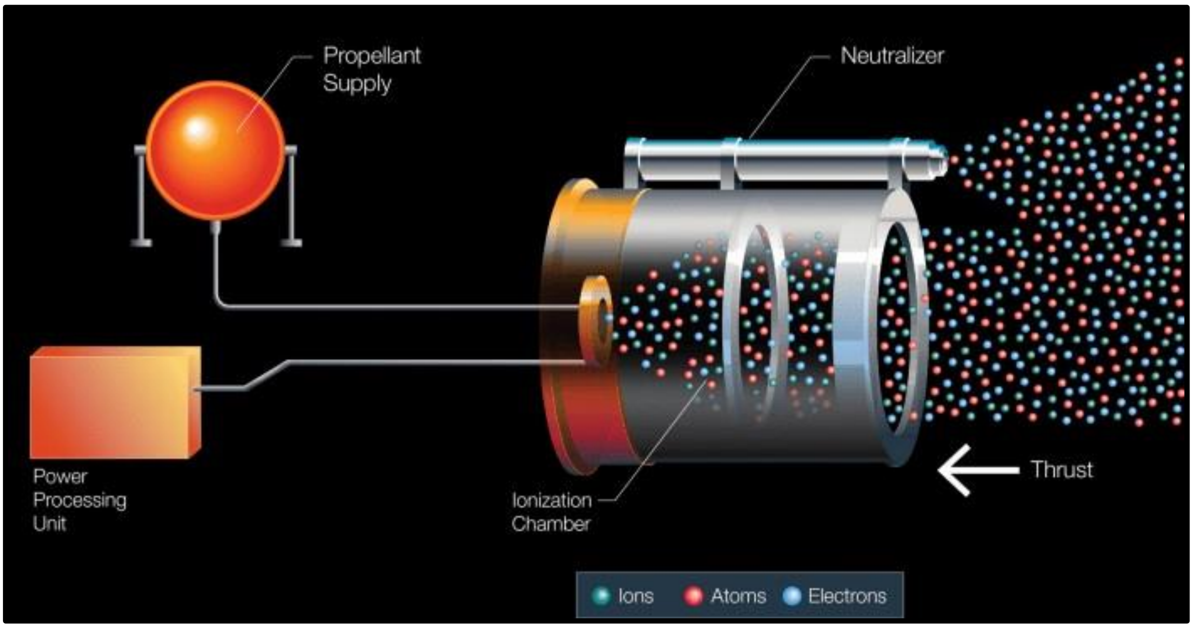

Fig 1: Electric Propulsion (Basic Concept)

4. **Ionization Chamber:** In ion thrusters and other similar systems, the ionization chamber is where neutral propellant gas is ionized to create ions. This process typically involves electron bombardment or other methods to strip electrons from the propellant atoms or molecules, creating positively charged ions.

5. **Acceleration System:** Once the propellant is ionized, it needs to be accelerated to generate thrust. This is typically achieved using electromagnetic fields in ion thrusters or a combination of electric and magnetic fields in other types of thrusters. The acceleration system applies forces to the ions, accelerating them to high velocities before they are expelled from the thruster.

6. **Nozzle:** The nozzle is where the accelerated ions exit the thruster and generate thrust. It is designed to direct the flow of ions in a specific direction to produce thrust in the desired direction. The design of the nozzle is crucial for optimizing thrust efficiency and minimizing losses.

7. **Control System:** The control system regulates the operation of the electric propulsion system, including managing power levels, controlling the flow of propellant, and adjusting thrust direction and magnitude. It may include sensors, actuators, and computer systems to monitor and adjust the performance of the propulsion system in real-time.

III. TYPES OF ELECTRIC AIRCRAFT PROPULSION

1. Electrothermal thrusters

Electrothermal thrusters differ from both electromagnetic and electrostatic propulsion systems due to their operational design; electromagnetic and electrostatic systems propel charged ions through the use of electric and magnetic fields, while electrothermal systems heat the propellant, and rely upon thermal dynamics to propel the system. In typical operation, a propellant is electrically heated, which increases the pressure and expands the gas, forcing the energized mass out of the nozzle and providing thrust to the spacecraft. In this category, the electric energy is used to heat the propellant, which is then thermodynamically expanded through a nozzle. There are two basic types in use today:

- Resistojets

A resistojet propulsion system relies upon the outlined concept for electrothermal thrusters; as shown in the below figure, a propellant is injected into the resistojet assembly, heated by a power supply and radiative heat transfer, and then expelled through a compressive exhaust nozzle.

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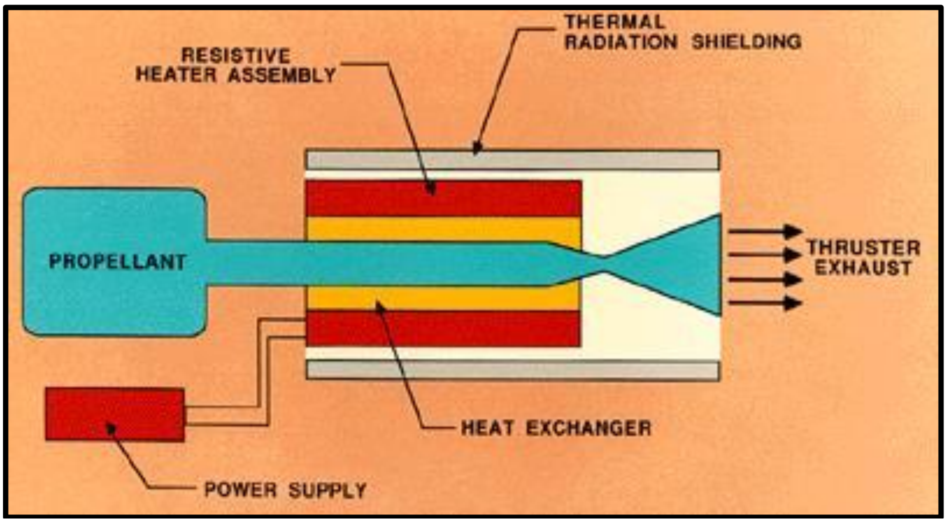

Fig 2: A Schematic Diagram Of A Resistojet Thruster

- Arcjets

This propulsion system relies upon a centrally located cathode surrounded by an anode; a high voltage electric field is generated between the cathode and anode, while the propellant is injected between the two electrodes. As shown in the below figure, the anode additionally functions as the nozzle for expelling the superheated gas.

2. Electrostatic Thrusters:

Electrostatic thrusters rely on Coulomb forces to accelerate a propellant composed of non-neutral charged particles. They can operate only in a near vacuum. The electric force depends only on the charge, and all charged particles must be of the same "sign" if they are to move in the same direction. Electrons are easy to produce and are readily accelerated, but they are so extremely light in mass as to be impractical for electric propulsion. Electrostatic thrusters can be categorized by their source of charged particles as follows:

- Electron bombardment thrusters

Positive ions from a monatomic gas are produced by bombarding the gas or vapour, such as xenon or mercury, with electrons emitted from a heated cathode. Ionization can be either DC or RF.

- Ion contact thrusters

Positive ions are produced by passing the propellant vapour, usually caesium, through a hot (about 11000C or 20000F) porous tungsten contact ionizer. Caesium vapour was used extensively in the original ion engines.

- Field emission or colloid thrusters

Tiny droplets of propellant are charged either positively or negatively as these droplets pass through an intense electric field discharge. The stability of large, charged particles remains a challenge.

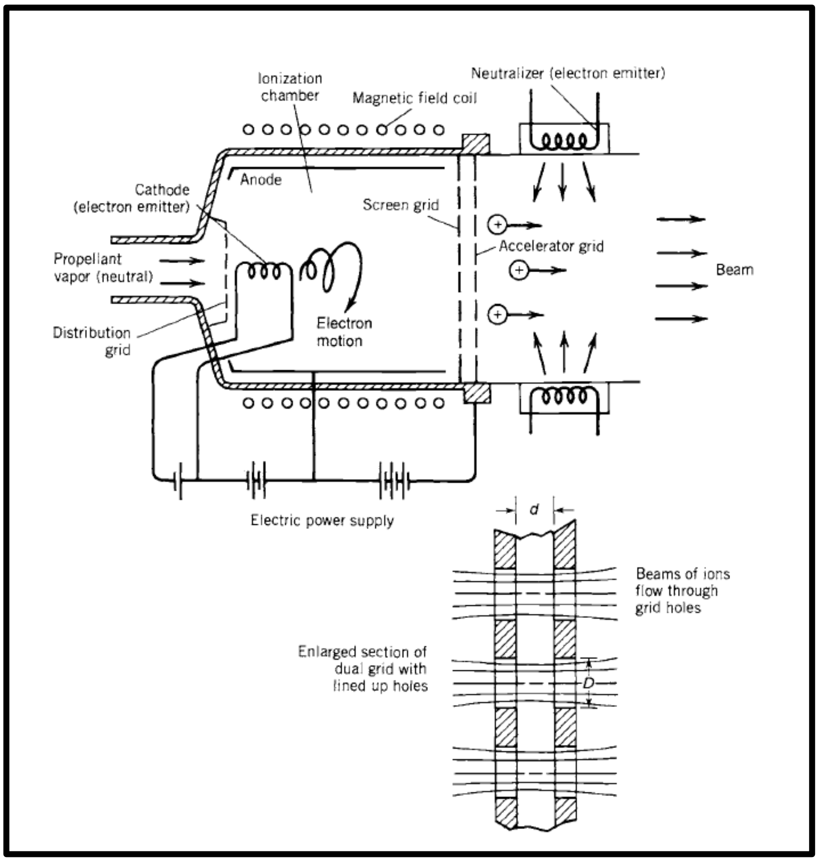

Fig 3: Schematic Diagram of An Electron Bombardment Ion Thruster

3. Electromagnetic Thrusters:

This third major type of electric propulsion device accelerates propellant gas that has been heated to a plasma state. Plasmas are mixtures of electrons, positive ions, and neutrals that readily conduct electricity at temperatures usually above 5000 K or 9000 R. According to electromagnetic theory, whenever a conductor carries a current perpendicular to a magnetic field, a body force is exerted on the conductor in a direction at right angles to both the current and the magnetic field. Unlike the ion engine, this acceleration process yields a neutral exhaust beam. Some of the electromagnetic thrusters are as follows,

- **Magneto Plasma Dynamic Thruster (MPDT)**

A magneto plasma dynamic (MPD) thruster (MPDT) is a form of electrically powered spacecraft propulsion which uses the Lorentz force (the force on a charged particle by an electromagnetic field) to generate thrust. It is sometimes referred to as Lorentz Force Accelerator (LFA) or (mostly in Japan) MPD arcjet.

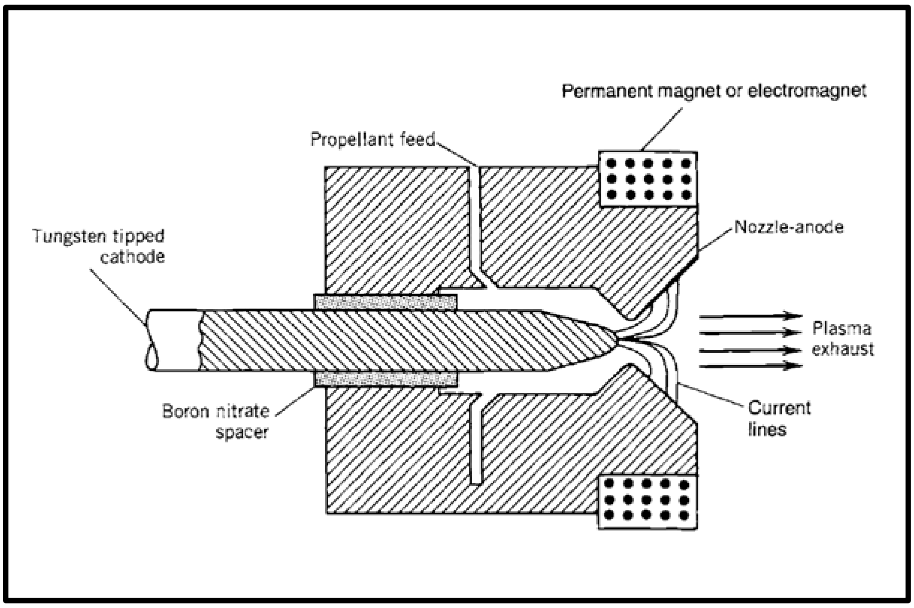

Fig 4: Simplified Diagram of a Magneto Plasma Dynamic (MPD) Arcjet Thruster

- **Pulsed Plasma Electromagnetic Thrusters (PPT)**

A pulsed plasma thruster (PPT), also known as a plasma jet engine, is a form of electric spacecraft propulsion. PPTs are generally flown on spacecraft with a surplus of electricity from abundantly available solar energy. Most PPTs use a solid material (normally PTFE, more commonly known as Teflon) for propellant, although very few use liquid or gaseous propellants.

- **Hall Effect Thrusters**

In spacecraft propulsion, a Hall-effect thruster (HET) is a type of ion thruster in which the propellant is accelerated by an electric field. Hall-effect thrusters (based on the discovery by Edwin Hall) are sometimes referred to as Hall thrusters or Hall-current thrusters. Hall-effect thrusters use a magnetic field to limit the electrons' axial motion and then use them to ionize propellant, efficiently accelerate the ions to produce thrust, and neutralize the ions in the plume.

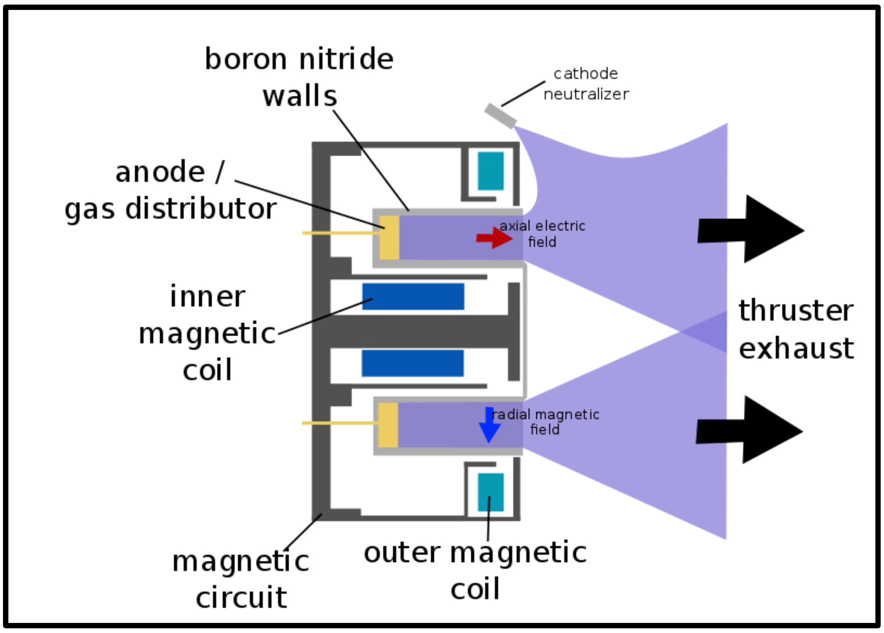

Fig 5: Simplified Diagram of a Hall Effect Thruster.

IV. WORKING

1. **Power Source:** Electric aircraft are typically powered by batteries or fuel cells, which provide electrical energy to drive the propulsion system. Batteries store electrical energy chemically and release it as needed, while fuel cells generate electricity through electrochemical reactions using hydrogen or other fuels.
2. **Electric Motor:** The electric motor is the primary component responsible for converting electrical energy into mechanical energy to drive the aircraft's propulsion system. Electric motors used in aircraft propulsion systems are typically brushless DC motors or synchronous motors, which offer high efficiency and power density.
3. **Propeller or Fan:** In electric aircraft propulsion systems, the electric motor drives a propeller or fan to generate thrust. The propeller or fan accelerates air to create a forward force, propelling the aircraft forward. The design of the propeller or fan can vary depending on the specific requirements of the aircraft, including desired thrust level and efficiency.
4. **Power Electronics:** Power electronics components, such as inverters and controllers, are used to regulate and control the flow of electrical energy between the power source, electric motor, and other subsystems. They ensure efficient operation of the propulsion system by managing power flow, voltage, and frequency.
5. **Thrust Control**: Electric aircraft propulsion systems typically incorporate mechanisms for controlling thrust to adjust speed, altitude, and direction during flight. This may involve varying the speed of the electric motor, adjusting the pitch of the propeller blades, or modulating power output from the power source.
6. **Cooling System:** Electric propulsion systems generate heat during operation, particularly in the electric motor and power electronics components. A cooling system is typically employed to dissipate heat and maintain optimal operating temperatures, ensuring efficient and reliable performance of the propulsion system.
7. **Energy Management System:** An energy management system monitors and manages the flow of electrical energy within the aircraft, optimizing energy usage for propulsion and other onboard systems. It may include battery management systems, power distribution systems, and energy storage devices to ensure safe and efficient operation of the aircraft.

V. ADVANTAGES

1. There are several advantages claimed for electric motors over gas turbines, but motors are only one part of an electric propulsion system. Just as turbine engines need fuel tanks, pumps, pipes and other systems, electric propulsion needs energy storage, power electronics, distribution buses and cooling systems. It is at the system level that electrified propulsion faces challenges.

2. One advantage is noise. An electric motor is quieter than an engine that combusts fuel. It still has to drive a propulsor-rotor, propeller or fan-and that produces noise on take-off and climb out. But electric propulsion will be quieter when taxiing and cruising. Electric motors also enable distributed propulsion systems with multiple smaller, quieter rotors or fans.

3. Efficiency is another advantage. Electric drivetrains can be more than 90% efficient, compared with 55% for today’s large turbofans and 35% for small turboprops. That disparity in efficiency between large and small turbines is one reason why the electrification of propulsion is beginning with the modification of regional aircraft powered by turboprops such as the Pratt & Whitney PT6.

4. Another advantage is scalability. Whether you use one or two large motors or many small motors in a distributed electric propulsion architecture, performance is about the same. That is not the case with turbines. Development of electric motors for aircraft is still in its early days with many different topologies to pursue-both conventional and superconducting—so time will tell.

VI. DISADVANTAGES

1. **Low Thrust-to-Weight Ratio:** Electric propulsion systems typically have lower thrust-to-weight ratios compared to chemical propulsion systems. This limitation can impact the acceleration and manoeuvrability of spacecraft, particularly during mission phases that require high thrust levels.

2. **Limited Thrust Levels:** Electric propulsion systems generally provide lower thrust levels compared to chemical rockets, which may restrict their applicability for certain mission profiles, such as rapid orbit insertion or trajectory changes.

3. **Power Requirements:** Electric propulsion systems require a significant amount of electrical power to operate efficiently. This power may be generated using solar arrays or nuclear reactors, which can add complexity, mass, and cost to the spacecraft design.

4. **Complexity and Cost:** Electric propulsion systems are often more complex and expensive to develop, manufacture, and operate compared to chemical propulsion systems. They require specialized components, such as ion thrusters or Hall-effect thrusters, which can increase system complexity and cost.

5. **Ionizing Radiation Hazard:** Some electric propulsion systems, particularly those powered by nuclear reactors, may produce ionizing radiation that poses a hazard to spacecraft components and crew members. Shielding and safety measures may be required to mitigate this risk.

6. **Limited Propellant Options**: Electric propulsion systems typically rely on specific propellants, such as xenon gas for ion thrusters. Limited availability and higher cost of propellants compared to traditional rocket fuels can be a disadvantage, particularly for long-duration missions.

7. **Thermal Management:** Electric propulsion systems generate heat during operation, which must be effectively managed to prevent overheating of spacecraft components and maintain system efficiency. Thermal management can add complexity to spacecraft design and increase mass.

VII. FUTURE SCOPE

1. **Reduced Emissions:** Electric propulsion systems offer the potential to significantly reduce emissions compared to traditional fossil fuel-powered aircraft. Future advancements in electric propulsion technology could lead to even greater reductions in greenhouse gas emissions, contributing to efforts to mitigate climate change and improve air quality.

2. **Lower Operating Costs:** Electric aircraft propulsion systems have the potential to lower operating costs by reducing fuel consumption and maintenance requirements. As battery technology improves and becomes more cost-effective, electric aircraft could offer lower operating costs per flight hour compared to conventional aircraft.

3. **Noise Reduction:** Electric propulsion systems produce less noise than traditional jet engines, leading to quieter aircraft operations. Future developments in electric aircraft propulsion could further reduce noise levels, making air travel more environmentally friendly and reducing noise pollution in communities near airports.

4. **Increased Range and Performance:** Future advancements in battery technology, power electronics, and electric motor design could lead to electric aircraft with increased range, payload capacity, and performance. Longer flight ranges and improved performance characteristics would enable electric aircraft to serve a wider range of missions and markets, including regional and intercontinental air travel.

5. **Hybrid Electric Propulsion:** Hybrid electric propulsion systems, which combine electric and traditional propulsion technologies, offer the potential for increased efficiency and range compared to pure electric propulsion systems. Future developments in hybrid electric aircraft could lead to aircraft with improved fuel efficiency, reduced emissions, and greater operational flexibility.

VIII. CONCLUSION

Electric aircraft propulsion offers a promising pathway towards a more sustainable, efficient, and environmentally friendly aviation sector. By harnessing the power of electricity, electric propulsion systems have the potential to significantly reduce emissions, noise, and operating costs while enhancing performance and operational flexibility. It seems then that the greatest interest in electric aircraft at its first stage of evolution will come from general aviation, with applications in flight training and pleasure flights, urban air taxis, and potentially, regional and business aircraft. In conclusion, the technical seminar on electric aircraft propulsion has shed light on the transformative potential of electric propulsion technology in the aviation industry. Throughout the seminar, we have explored the various aspects of electric aircraft propulsion, including its advantages, challenges, and future prospects.

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