AQUIFER Nano-electrofuel Energy Economy and Powered Aircraft Operations

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The Aqueous, QUick-charging battery Integration For Electric flight Research project is explained and the major subsystems are described, including nano-electric fluid, rim-driven motors, and integration concepts. The nano-electric fluid concept is a new type of aqueous flow battery that could reduce or retire the fire and explosion hazards of conventional batteries and fuel cells. The nano-electric fluid itself could enable energy storage and increased available energy per fuel weight ratios. The rim-driven motor is being developed to improve propulsion system safety and stability and to reduce noise. The rim-driven motor concept could enable motors that are more efficient both electrically and aerodynamically. The Energy Economy of the project concept is presented as a potential renewable or green energy sustainment for utilizing in-place infrastructure. The nano-electric fluid energy charge-use-recharge cycle is presented using renewable energy input from solar, wind, and hydroelectricity. Powered aircraft operations are presented, and the logistics of the new nano-electric fluid technology are explored. Powered aircraft operations topics include weight and balance, fueling, recharging, safety, and derivative considerations.

I. Nomenclature

AQUIFER	=	Aqueous, QUick-charging battery Integration For Electric flight Research
CAS	=	Convergent Aeronautics Solutions
CTOL	=	conventional takeoff and landing
EMI	=	electromagnetic interference
eVTOL	=	electric vertical takeoff and landing
eSSTOL	=	electric super-short takeoff and landing
GEN	=	generation (stage of technology)
NASA	=	National Aeronautics and Space Administration
NEF	=	nano-electrofuel
RDM	=	rim-driven motor
SSTOL	=	super-short takeoff and landing
UAM	=	urban air mobility

II. Introduction

Electric propulsion has become increasingly relevant for aircraft design, testing, and operations with the introduction of numerous electric aircraft concepts as part of the growth of the concept of urban air mobility (UAM). Many UAM systems rely on lithium-ion batteries or fuel cells to produce the electric power necessary for flight or as auxiliary power. The chemical nature of these energy sources, however, present flammability and explosion hazards

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as substantial challenges for the many aircraft concepts that are expected to attempt to earn flight certification. The National Aeronautics and Space Administration (NASA) Convergent Aeronautics Solutions (CAS) project investigates new disruptive technologies for use in future aircraft concepts. The subproject Aqueous, QUick-charging battery Integration For Electric flight Research (AQUIFER) is investigating nano-electrofuel (NEF) and rim-driven motor (RDM) technologies, integrated together in a wing section in order to reduce or retire the flight fire and explosion hazards associated with the battery system, improve the acoustic signature of the electric motors, and co-locate these technologies to reduce cable lengths and electromagnetic interference (EMI) affects. The NASA researchers have contracted with Influit Energy (Chicago, Illinois) to develop, test, and integrate the nanoparticle of aqueous flow battery – the NEF battery. The NEF concept could reduce or retire the flight fire and explosion hazards of traditional battery and fuel cell systems. The NEF technology has been designed to be co-located to electric motors to substantially reduce EMI by reducing line length. Flow batteries (including NEF) retain a distinct design advantage over conventional batteries because the power requirements (stack) and energy requirements (tank) can be sized independently, whereas current state-of-the-art battery technologies, including lithium-ion, must couple the designed capacity and power. The ducted fan shape of rim-driven motors provides integration benefits when coupled with a co-located NEF stack; see Fig. 1. Some additional advantages of the technology include increased available energy density; reduced aircraft acoustic footprints; increased slow-speed take-off lift; and short-haul electric commercial aircraft operations.

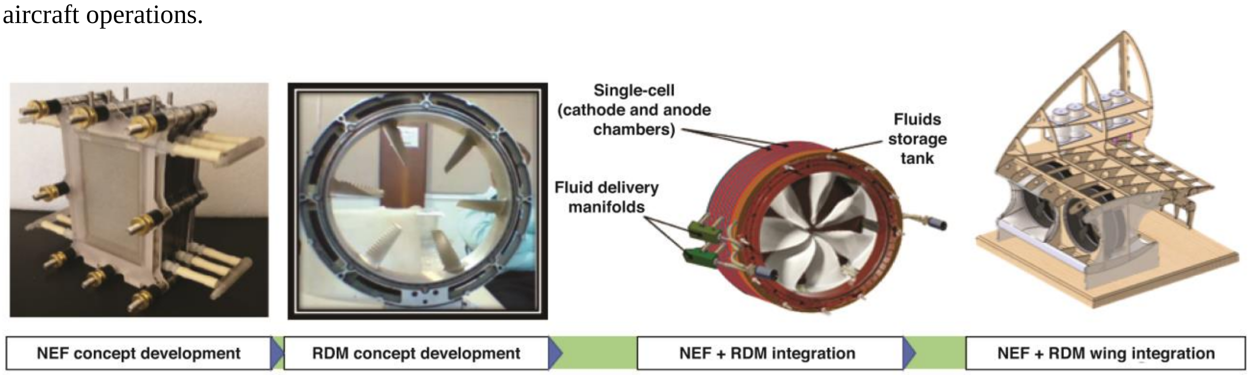

Fig. 1. Nano-electrofuel and rim-driven motor integration and wing demonstrator.

The NEF flow battery is configured with two independent fluids (cathode, and anode) which are introduced on opposite sides of a membrane, as can be seen in Fig. 2. These fluids would be discharged and recharged over many cycles - not expended as are conventional fuels. The cathode is the oxidizing agent (accepts electrons); the anode is a reducing agent (donates electrons). The electrolyte along with the membrane provides the passage through which the electrons move. This process is the oxidizing-reducing, or oxidation-reduction (redox) reaction. Nano-electrofuel flow cells contain an electrolyte solution, which is a water-based electric conducting solution. The anode and cathode are based in an alkaline electrolyte solution and passed by a membrane separating the two nanofluids to extract energy to power the rim-driven motors. The size and number of membranes determines the voltage of the system; the fluid flow rate drives the range of current. Benefits of this configuration include decoupling of power and energy, and recharging through replacement of the liquid, similar to pumping fuel. The fluid recharge would happen on the ground at a charging facility, presumably at or near the airport of need. This flow cell design would enable fast recharging of the fluid off the vehicle.

Energy density is the sustained energy that the battery or flow cell can provide per volume. Energy density provides a metric to use to estimate how long the battery will last before it needs to be recharged or replaced; energy density is dependent on application and defined at a specific discharge rate. Usually batteries are rated in capacity hours, such as a discharge rate of five hours (C5) or of twenty hours (C20). Power density is the sustained power that the battery or flow cell can provide per volume. Power density provides a metric to use to estimate the amount of the highest sustained power the battery or flow cell can provide. This metric provides an estimate of the power available during maximum acceleration conditions such as takeoff.

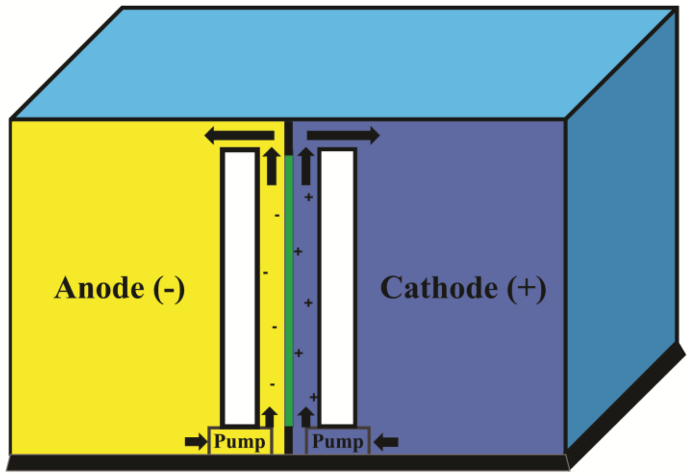

Fig. 2. The general design of the nano-electrofuel battery.

The RDM and wing integration are the other two major aspects of this project. Previous RDM work has primarily been accomplished for water-based vehicles; some challenges will be high-revolutions-per-minute (RPM) verification and noise reduction. Some of the expected benefits of the RDM are reduced blade-tip interference noise, reduced torque to run the motor, and elimination of the drag contributions from removal of the center hub. Many RDMs likely would be implemented on a particular airframe; this redundant design would be expected to improve propulsion system safety and stability. Distributed propulsion (DP) is also expected to provide additional options for control and to enable unconventional or potentially groundbreaking or revolutionary design opportunities. The wing integration is a key aspect in development and is expected to show the initial capability of this system in a flight-relevant configuration.

In order to reduce cable lengths and EMI effects, the NEF concept is being integrated with RDMs. The RDMs generate torque at the outer circumference rather than at the hub. By removing the hub and driving the fan blades from the outer circumference, the NASA researchers are seeking to improve efficiency, reduce fan tip noise, and eliminate hub noise.

III. Background

New enabling technologies in support of UAM will require an understanding of the energy economy and significant improvements in the general organization of powered aircraft operations. Nano-electrofuel could enable energy storage and increased energy per fuel weight ratios. The ideal target that is presented herein focuses on renewable or green energy as the sole power source to recharge the NEF, however, other sources of energy undoubtedly could supplement the sustainment of the concepts described in this paper.

In order to provide a defined relationship, the latest target UAM / electric vertical takeoff and landing (eVTOL) concept vehicle specifications were defined during an Uber Elevate Summit.[1] The UAM specifications were identified as “four passengers and a pilot, 150-mph cruise, 25-mile sprint range, and 60-mile maximum range as well as a 15-dB reduction in noise relative to a light turbine helicopter”.[1] Also specified was “a 2C battery-recharge rate between flights”.[1] A major characteristic of the UAM/eVTOL concept is battery energy density. Currently the energy density target for lithium-ion batteries is in the range of 160 Wh/kg to 195 Wh/kg. The near-term objective is to reduce the cost of similar capabilities by 50 percent to 40 percent.

It is well known that eVTOL will require more power during the vertical lift segments of a mission. The eVTOL might require 2 to 3 times the power of super-short takeoff and landing (SSTOL) and up to 7 times the power of conventional takeoff and landing (CTOL). The eVTOL power requirement directly relates to reduced efficiency and range compared to SSTOL- and CTOL-designed aircraft configurations. The SSTOL and CTOL designed aircraft are the target configurations of the AQUIFER project.

The NEF fluid energy density capability targets for 2019 are 29 Wh/kg with a near-term goal of 125 Wh/kg. The eventual technology goal is 575 Wh/kg by 2025 using improved chemistry, as presented in Table 1. These estimates are for the fluid components only. The individual NEF anolyte and catholyte fluids are composed of solid nanoparticles that are suspended in separate aqueous solutions to create composite fluids that are denser than water. The estimated 1000 recharge cycles are based on solid battery chemistry; at the end of 1000 cycles it is expected the fluid can be reconditioned. The settling of the nanoparticle is estimated to take 3 months to 6 months; the fluid can be mixed to redistribute the solid and fluid-based particles. The current and future NEF is expected to be non-flammable, not harmful to the Earth or its environment, and non-toxic.

Table 1. Lithium-ion and NEF energy density.

	UAM/eVTOL	**Prototype 2019**	**AQUIFER Goal 2020**	**SSTOL/CTOL 2025**
Battery / flow cell	Lithium-ion	NEF GEN 1 (Anode and cathode)		NEF GEN 2 (Air and cathode)
Energy density	125-195 Wh/kg	29 Wh/kg	125 Wh/kg	575 Wh/kg

Recharging the NEF flow-cell batteries poses significant differences from normal aircraft operations. Flow cells or flow batteries are a type of rechargeable battery which combine traits of an electrochemical battery cell with those of a fuel cell. The electrolytic fluids in flow cells (usually metallic salts in aqueous solution) are pumped from tanks through the appropriate battery cell where an electrode (anode or cathode) is located. An ion-porous membrane separates the two electrolyte chambers and their different chemistries. This kind of battery cell forms a crossflow of electrolyte liquid. This crossflow is the substrate for ion exchange, causing the flow of electrical current. One advantage of this system in general is that the concentration of an electrolytic solution contributes to the quantity of energy that it transports. The NEF technology is envisioned to be developed incrementally: Generation 1 is planned to use two separate fluids for the anode and the cathode; Generation 2 is planned to use one fluid as the anode and to use air as the cathode. There are many other benefits of flow cell technology in the nanoscale, for example, improved energy density, longevity, deep-discharge protection, high system stability, and non-flammable properties.

Two main focus topics that are investigated are the energy economy and the powered aircraft operations for the AQUIFER concept. The energy economy for the AQUIFER concept could largely utilize in-place reusable energy foundations. Specifically, the NEF technology provides the opportunity to leverage existing energy production and distribution infrastructure. Energy production independent of usage could be accomplished across the United States to include wind, solar or hydrodynamic power.

In general, powered aircraft operations identify instructions, procedures, and references to clarify the manner in which an aircraft will be maintained, modified, and inspected. Items specific to the NEF flow-cell battery and rim-driven integrated motors in the expected aircraft configuration include personnel policies and procedures, crewmember qualifications and duties, weight and balance, emergency procedures, accident-incident procedures, maintenance, aircraft servicing procedures, hazardous materials, and flight safety programs. Pertinent topics that have been identified but are not addressed in this paper include management, flight operations procedures, international and extended overwater flight, flight locating, flight-time limitations, and scheduling. Many of these topics are being addressed in other venues, such as "Urban Air Mobility Airspace Integration Concepts and considerations."[2] This reference outlines high-level narratives for topics in visions for Urban Air Mobility[3, 4] and air taxi service[5, 6, 7, 8], increased National Airspace System (NAS) demand[9, 10], and other important topics[9, 10, 11, 12, 13] such as certification and vehicle production. As well, NASA is independently working on resilient autonomy[14] for pilotless operation. Resilient autonomy based on the automatic ground collision avoidance system (Auto GCAS) will have requirements that are much stricter than current UAM systems. A primary challenge is sense-and-avoid in low-altitude operations which will include other vehicles and ground obstacles such as trees, buildings and uneven terrain.

The AQUIFER project was not established to address the NASA Aeronautics Research Mission Directorate (ARMD) Grand Challenge[15] or Revolutionary Vertical Lift Technology (RVLT)[16] projects, but it addresses some of the related objectives as well as ARMD Strategic Thrust 4 – Safe Quiet and Affordable Vertical Lift Air Vehicles. The Grand Challenge is intended to be a full-field demonstration of vehicles for UAM. Some of the objectives of the current work are to accelerate certification, develop flight procedures, establish airspace architecture, and assess community and passenger perspectives regarding noise and ride quality. The objective of the RVLT project is to realize extensive use of vertical lift vehicles for transportation and services including new missions and markets. Primary research areas for UAM eVTOL vehicles are propulsion efficiency, performance, rotor-rotor interactions, noise and annoyance, safety and airworthiness, operational effectiveness, rotor-wing interactions, aircraft design, and structure and aeroelasticity.

IV. Energy Economy

Energy economy in the context of this application is defined as human utilization of energy resources and energy commodities and the consequences of that utilization. The energy economy for the AQUIFER supply and demand could be based on energy converted from classical energy sources, renewable or green sources, or a combination of both. The energy supply likely would be provided by a combination of classical energy sources and renewable or green sources. To introduce the clean energy concepts associated with this work and provide a consistent point of reference, only renewable or green sources are discussed. The energy economy for the AQUIFER supply and demand of electrical power could largely utilize in-place infrastructure. Nano-electrofuel technology provides the opportunity to leverage existing infrastructure integration, including fuel transport, gasoline stations, and storage facilities. Energy production which would be independent from usage could be accomplished across the nation, leveraging regions with a high supply of green production resources. The utilization of green energy production could be located anywhere in the nation, but also synergistically where electric aviation is in demand. Additionally, NEF technology provides a storage solution utilizing excess energy produced during high-energy capture times (for example, midday for solar power, or on high-wind days for wind power), making this energy accessible at any time. Collectively, the green resources could have a high impact on the aviation energy economy and could also be beneficial to non-aerospace industries.

The general NEF energy charge-use-recharge cycle is shown in Fig. 3. Conceptually, the NEF production center receives renewable energy input from solar, wind, hydroelectricity, or a combination of any of these. The energy is used to create new, or recharge discharged, NEF. In addition to the renewable energy, the NEF production center receives a small portion of non-green energy needed for efficient manufacture. The charged fluid is transported to a NEF fueling station to be accessible to everyday consumers. Consumers could use the charged NEF to power trucks, cars, busses, and electric super-short takeoff and landing (eSSTOL) aircraft for safe, emission-free transportation. Once the NEF is discharged, it is brought back to the NEF processing center to repeat the cycle.

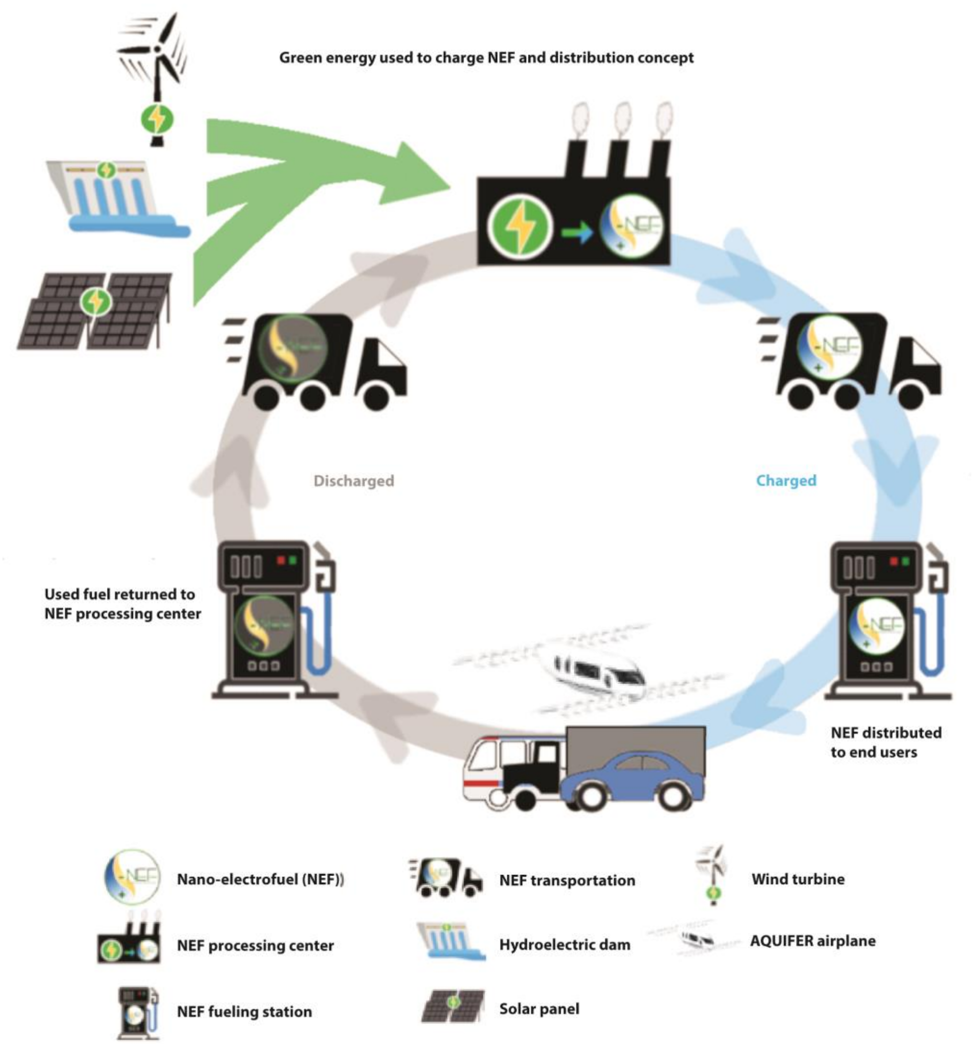

Fig. 3. Energy charge-use-recharge concept.

Data provided by the National Renewable Energy Laboratory[17] on solar and wind intensity were used to create the "Energy Potential" map shown in Fig. 4. The Energy Potential map shows the amount of energy that is expected to be produced each day in the 48 contiguous United States. This plot uses the projected average amount of wind and sun each area is expected to see each day of the year for the year 2022. The energy production for both wind and solar is based on wind turbines that are 30 m tall, solar panel energy generation during daylight hours, and rates of efficiency for each source. The results indicate that a sufficient amount electricity could be produced using wind energy and solar to provide the power used in the contiguous United States.

Data provided by the Energy Information Administration[18] on energy distribution were used to create the "Energy Used" map also shown in Fig. 4. The data show that a majority of the electricity is being used in heavily populated areas or in industry-heavy areas. Also indicated is that the majority of the electricity is not necessarily being used in areas where it could be most efficiently produced using clean energy.

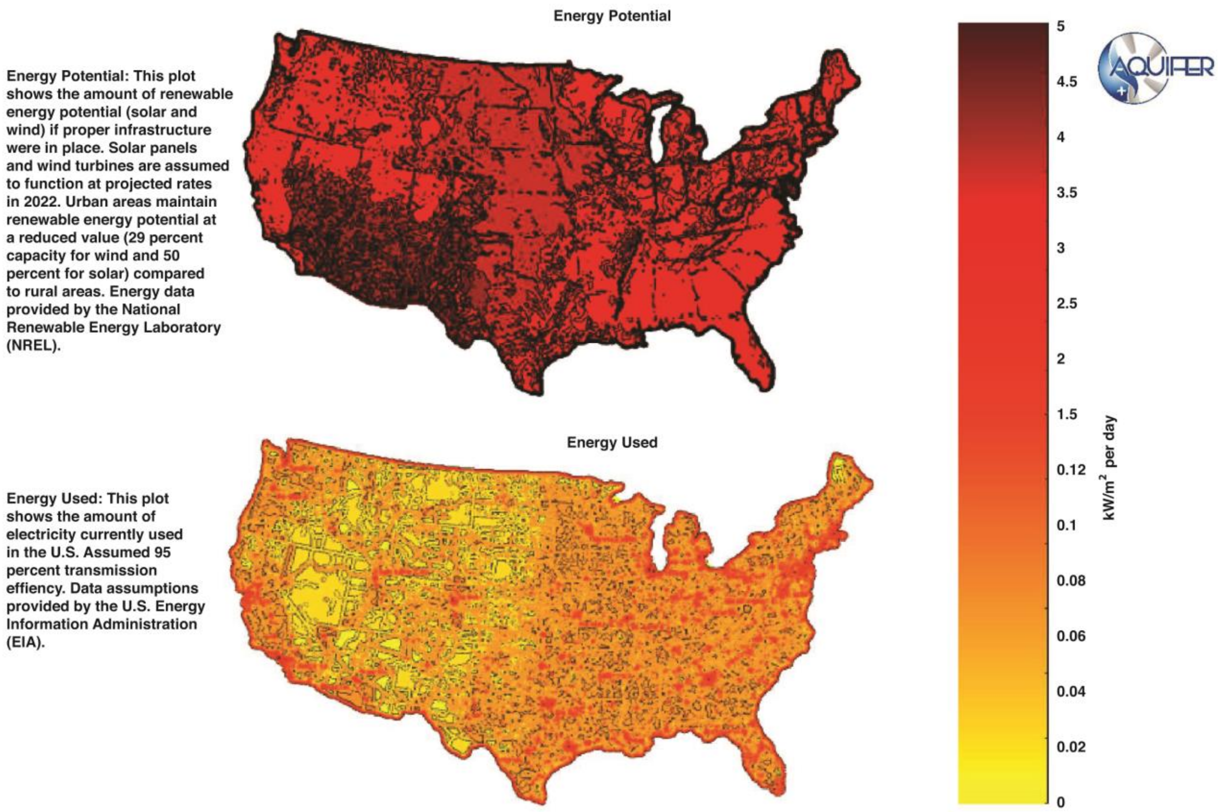

Fig. 4. Energy economy: USA Energy potential and energy used.

The "USA Perspective" map in Fig. 5 shows the energy production methods that could best be utilized in different parts of the country (for example, wind turbines in the Plains States; solar farms in Arizona, New Mexico, and California; and hydroelectric plants near major dams). The energy produced in high-potential areas can be transferred to NEF processing plants where it can be converted to fuel and then be transported to high-usage areas. Storing the electricity in the NEF allows energy to be transported more easily while minimizing the loss that is experienced with typical electrical transmission lines.

Distribution of NEF across densely populated areas could enable new, efficient, emission-free transportation. A fully functional NEF capability could be used to power various forms of transportation. Nano-electrofuel-based renewable energy was assessed in regions of the State of Texas; the cities of Dallas and Fort Worth were targeted for the efficiency of full-cycle, charge-use-recharge, NEF operations (Fig. 5). Energy potential distribution maps were evaluated to identify locations having the greatest energy potential. Wind and solar plots were evaluated as providing a gateway toward optimizing the collection of green energy. Green energy is collected through solar panels and wind turbines to recharge discharged NEF. Access to green energy enables the basic recharging processes for the NEF charge-use-recharge cycle.

Once NEF technology is fully operational, distribution could take place using tankers to various high-population cities across the state (in this case, Texas). Further analysis could identify a vehicle distribution radius versus high-voltage power distribution. Access to NEF at regional airports could provide an easy way to fuel eSSTOL aircraft. After use, the discharged NEF could be returned to the storage location, replaced with fully-charged NEF, and then transported back to the NEF processing center to be recharged from harvested green energy. The charge-use-recharge concept is projected to be a continuous, emission-free cycle. More projections include regional airports housing eSSTOL aircraft in hangars equipped with solar panels that could enable recharging discharged NEF onsite. A 200-nmi eSSTOL flight would require approximately 220kWh. Early estimations suggest that renewable energy sources could support these kinds of flight operations using NEF. A projected long-term-large-scale plan includes the use of pipelines to transport NEF. As the NEF arrived at each city, it could be stored at localized energy stations and regional airports, where it would be accessible to the everyday consumer.

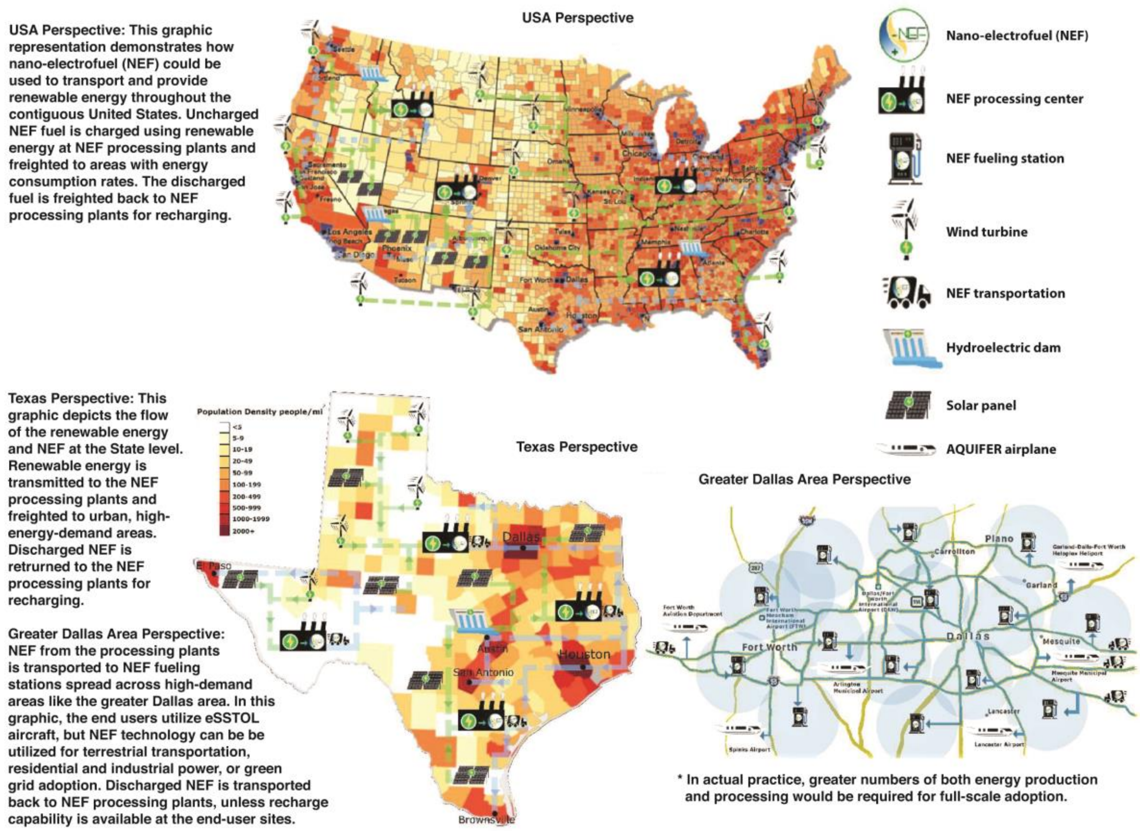

Fig. 5. Energy economy: USA, State of Texas, and greater Dallas area perspectives.

V. Powered Aircraft Operations

The target configurations of the AQUIFER project are SSTOL and CTOL. These configurations support near-term support of UAM in providing an urban range service at lower cost without addressing the many hurdles of the full UAM concept. The NASA CAS project investigates new disruptive technologies for use in future aircraft concepts. These technologies are currently being developed and the topics in this section are presented as related to general aircraft technology in the AQUIFER project.

In general, powered aircraft operations identify instructions, procedures, guidance, and references to clarify the manner in which an aircraft is to be maintained, modified, and inspected.[19] Some topics that have been identified require iterative evaluation and will be mission- or configuration-dependent. Powered aircraft operations that require specific consideration due to NEF technology include weight and balance, emergency procedures, accident-incident procedures, maintenance, aircraft servicing procedures, hazardous materials, and the flight-safety program. Early subsystem design and system integration with respect to maintenance are also identified as part or component failure rates that could affect reliability.

A. Weight and Balance

Weight and balance - a basic aircraft operation constraint - was addressed in an NEF aircraft and evaluated because of the expected movement of NEF from one tank to another (from "used" to "depleted" NEF tanks) (see Fig. 2). Nano-electrofuel fluids are not consumable, thus it was assumed that each of the anode and cathode fluids would need to be moved from an energy-rich tank to a depleted-energy tank, using at least two, and potentially four, separate fuel tanks. The design is expected to have two separate tanks (one for the anode and one for the cathode) that will recirculate each nano-electrofuel fluid separately. The current design eliminates the NEF-driven weight and balance considerations and, if implemented in the final design, is expected to improve weight and balance considerations over the entire flight envelope.

B. Emergency Procedures: Egress

Egress procedures would likely be complex given a vehicle configuration with many motors in various quadrants or zones of the passenger compartment. Similarly, emergency response considerations for first responders in the event of emergency could be problematic given the large number of small motors. If the objective of significant noise reduction is realized, the motors could be difficult to identify as hazards in an emergency situation. Other considerations would be canopy or door removal, ground procedures, and inflight procedures for the crew and passengers.

C. Accident, Incident Procedure: Mishap Response

A mishap response plan describes procedures to utilize to minimize risk to emergency responders, presents crew and passenger rescue procedures, and sets forth relevant material or chemical handling considerations to be applied in the event of a mishap. The expected AQUIFER configuration will have 12 or more low-powered ducted fans that surround the entire vehicle, where they are expected to have their own integrated power sources. Once the final aircraft configuration is identified, processes will need to be defined toward crew and passenger rescue in the event of a mishap. These processes should include instructions regarding safing all of the power sources, restrictions regarding contact with the fuel sources, and procedures for extracting anyone onboard the aircraft who is unable to move or is otherwise incapacitated. If the fuel is considered to be hazardous to the environment, liquid spill clean-up procedures will need to be developed.

D. Maintenance: Early Subsystem Design and Integration

Early subsystem design and integration often reveals many components that increase the possibility of subsystem failures. These subsystem failure rates complicate the support of future operations. Some of the NEF stack components that are likely to fail are the pumps and the membrane between the anode and cathode. Initially there are many O-rings between chambers of the NEF stack. Any of these components could be sources for NEF fluid leaks. Bearings are of critical concern for the RDM, and are a focus of critical development and as a potential noise source. It is anticipated that several iterations will simplify design and greatly reduce the number of components or eliminate areas where these potential failures have been identified during early development.

E. Aircraft Servicing Procedures

Aircraft servicing procedures in this section include fueling, defueling, recharging and recharging methods. The processes for these topics would need to be modified or altered as compared to current processes.

1. Fueling and defueling

Current processes for fueling address, among other concerns, efficiency, safety, and reduction of contamination or static electricity. The fueling process for NEF will need to be evaluated carefully. Consistent use of NEF would normalize the NEF defueling process, as compared to that of today's conventional aircraft configurations. Jet fuels and petroleum-based fuels are consumable and generally defueled for specific reasons such as maintenance or storage, whereas NEF would be removed as a matter of course for recharging.

Two types of fueling are typical for aircraft: large aircraft generally use a single-point method; most small aircraft use an over-the-wing method. The single-point fueling method is straightforward, but infrastructure alterations would need to be made. Precautions would need to be put in place to ensure neither jet nor aviation fuel could be put into an NEF-configured aircraft. Additionally, if two (Generation 1) separated fuels were used, precautions would need to be in place to ensure these fuels were neither mixed nor added to the wrong tank. The effects of mixing NEFs are currently unknown; such mixing could result in any number of adverse consequences. Defueling is generally accomplished using either gravity- or pump-feed systems; this process for NEF would of course need to be performed safely. Generation 2 is planned to use one fluid, and would be much simpler to implement logistically.

2. Recharging

The NEFs are expected to have significantly different characteristics than those of jet or aviation fuels. Special considerations will need to be understood for the NEFs regarding ratios, pressurization, vaporization, and contamination, freezing, and evaporation.

An entirely new concern for powered aircraft operations will be recharging the NEF, because it is fundamentally different from most batteries and other fuel cell technologies. It is envisioned that most of the recharging would be accomplished through green energy resources such as wind turbines, solar panels, or hydroelectric generation. The recharging infrastructure could be onsite, or the NEF could be trucked to and from offsite recharging facilities. Early in development it is expected that there will be one recharging facility to service the demonstration aircraft; this specialized recharging equipment will need to be incrementally developed into a production-type process and facility. Overall, recharging is expected to be a simple process that is software-controlled to avoid electrolysis (hydrogen production).

Movement of the anode and cathode for recharging could be logistically challenging, depending on the requirements of the system at hand. It is expected that the transportation vehicle traveling to and from the aircraft and the recharging stations could be a fuel truck similar to aviation fuel trucks in use today. Generation-1 NEF fuel trucks would need two tanks: one to be used for defueling the aircraft and one for refueling. One truck with two separate tanks, or one truck for each anode or cathode, could be utilized. The same expectations apply to the Generation-2 NEF fuel. The second generation NEF trucks would need to have either one truck with two tanks or a truck for each process of fueling and defueling.

3. Recharging methods

The project has not yet addressed some of the topics that must be investigated further, such as electrical connection requirements for electric aircraft (standards or certification), and charging keep-out zones. Both of these topics would be critical to the design and operation of the aircraft.

An important concern regarding NEF will be reducing the degradation of the battery anode and cathode fluid and chemistry components. There are several influential factors that accelerate degradation of lithium-ion batteries, including high current rate, over-voltage (overcharge), and under-voltage; thus it is important to consider the charging methods that will be utilized for NEF. Internal resistance is one of the most important indicators of degradation of a battery, but the particulars of this aspect will remain unknown until flight-ready batteries have been developed. Additionally, specialized storage tanks and procedures would be required and would likely influence the degradation of these fluid compounds.

Another potential obstacle is the amount of available green-source energy and NEF recharging time versus use time. The available energy from green sources is not expected to be a factor early in demonstration, but if the technology becomes viable the energy production and charge-use-recharge support infrastructure could be the primary limitations. Recharging power would also be limited by the minimum acceptable power among the charging cable, charging station, and vehicle. The total capacity of all of the utilized batteries is another important parameter to be investigated. Similar to the fuel capacity, it is important to choose the battery capacity relative to the mission. More likely, however, is that the technology limitations will be the threshold of the battery capacity that will limit mission capability.

F. Hazardous Materials: HAZMAT Handling and Training

It is possible that the NEF solid particles would be regarded as hazardous chemicals and would be required to be handled and stored in compliance with specific hazardous materials rules and procedures.

Nano-electrofuel flow cells contain nanoparticles made of specific materials for each of the cathode and anode fluids. Nanoparticles are very small materials that range in size from 1 nanometer (nm) to 100 nm, (1 nm is 1-billionth of one meter). Although not discussed further herein, it is important to note that materials at the nanoparticle scale can have different properties than the same material at larger scales. Generally, nanomaterials are known to potentially pose health risks,[20] thus during development and testing great care should be taken to reduce or eliminate human exposure to experimental nanomaterials. Once the pertinent parameters have been established, studies should be conducted to evaluate and fully understand any potential health hazards.

G. Flight-Safety Program

The topic of flight safety is a very broad one, covering a wide range of material and operations. The topics discussed in this section are safety and hazard elimination and are restricted to NEF rim-driven motor technologies.

Additionally, these transportation systems might be piloted, autonomous, or remotely-piloted - further complicating an already labyrinthine topic.

1. Safety

Safety is a predominant concern for electric vehicles that are intended to revolutionize the transportation and the movement of products. The safety considerations discussed in this section are the consequences of the implementation of the NEF technologies. The design and integrated systems should avoid aircraft operation procedures and requirements for which regulations already exist. Nano-electrofuel is expected to have a relatively high energy density. Some regulations restrict electrical power and battery charging near general aircraft and hangars to either be attended at all times or not be performed without waivers or strict oversight. In addition, some regulations specify that electrical connections must be a distance of at least 18 in above the floor when other flammable fueled aircraft are in the vicinity. Special consideration must be implemented with subsystem integration of the motor and the NEF so that each unit is de-energized prior to (location of motors) maintenance.

An Airbus Zephyr (Airbus SE, Leiden, Netherlands) battery[21] with silicon nanowire anode with an energy density of 435 Wh/kg was identified as a similar technology. Although NEF is not considered at this time to be a fire danger, the Zephyr program found that the energy density at the cell level creates the challenge of how to prevent a fire if a short-circuit releases that energy. The NEF team will need to understand whether the higher energy density of the NEF has the same, or similar, characteristics.

The thermal dissipation behavior of the NEF batteries must be understood in order to ensure a safe operational environment. Knowledge of the effective dissipation of the generated heat during operation of batteries, as well as storage temperatures, is critical to help ensure the life and performance of the batteries and to avoid catastrophic failures. Thermal management of battery packs for high-power applications has received significant attention over the past decade in both academia and the industry. Studies[22] have investigated different battery heat acquisition system (BHAS) approaches at different levels, from individual cells to packaged battery power systems. Studies reported in the literature indicate that the BHASs can be divided into internal and external systems.

The mixing of the cathode and the anode in discharged and charged form is a possibility. In discharged form it is expected that if the cathode and anode nanofluids were mixed there would be very little or no reaction between the nanoparticles. In charged form, if cathode and anode nanofluids were in contact but not mixed, a redox reaction (a transfer of electrons) between nanoparticles is possible. For an electron and ion exchange to occur, the redox reaction requires physical contact of the separate nanoparticles with the electrolyte. This fluid-contact redox reaction would be expected to release stored electrochemical energy in the form of heat. In a case in which mixing occurs in a spill, it would be expected that the release of stored electrochemical energy in the form of heat would be amplified. Nevertheless, once all of the water from the electrolyte had evaporated, the redox reaction would be expected to end. In nanofluids having a higher concentration of nanoparticles the electrolyte will evaporate faster, limiting the redox reaction between the nanoparticles and therefore limiting thermal effects in case of a spill. Hazards inherent to the presence of nanoparticles and alkaline electrolyte of course exist.

2. Hazard elimination

Safety is a primary concern in all aspects of a program. This section specifies some of the hazards that have been identified. Each hazard is built from a scenario-based hazard description. This description is then used to identify causes, effects, and mitigations. Although not included in the examples below, the nominal process would be to construct a hazard action matrix for the risk to human, asset, or mission that is then evaluated, after which final hazard category justification is composed to complete the analysis. These items together are used to make decisions about the risk and mitigation of the risk. Early identifications of these hazards are intended to inform project members. The project members then can use these informationally identified hazards to proactively implement actions or changes to reduce or eliminate causes, effects, or the overall hazard.

Preliminary hazard analysis of AQUIFER identified the annular NEF battery stacks and the RDMs as possible hazards. Some of the hazards that have been identified are defined below; a summary of the hazards is provided. These hazards are identified as: hazardous release of NEF; and gaseous H2 or O2 release due to exceeding the nominal operating conditions of the NEF battery. Each hazard is outlined below.

Hazard 1: Hazardous release of nano-electrofuel

The AQUIFER system contains two annular NEF battery stacks. The NEF fluids (anode and cathode) are to be delivered to the NEF stack by a network of tanks, tubing, manifolds, and pumps. During operation, a failure of NEF system components or seals, system interface components, or NEF refueling or transportation operation anomalies could result in leakage of NEF onto surrounding components, resulting in material degradation or corrosion, or injury to personnel. The causes and effects are listed in Table 2.

Table 2. Hazardous release of nano-electrofuel.

Causes	Effects
System leaks (NEF)	Contamination of test area
Refueling operation anomaly (NEF spill) Note: Includes transportation of NEF.	Thermal reaction due to mixing of the NEF fluids
Component failure (NEF spray)	Hazardous gas evolution
System design deficiency	Material degradation or corrosion
Improper assembly (mechanical or electrical)	Damage to Center assets; injury to personnel

Some mitigations include a drip tray, refueling procedures, briefing personnel on all associated hazards, utilizing required personal protective equipment, protective shielding, emergency stop, and subsystem leak tests. Furthermore, complications with the NEF stack such as leakage could compromise the performance of the RDM, thus possibly causing a structural failure to any of its components or to the interface mounting structure.

Hazard 2: Gaseous H2 or O2 release due to exceeding the nominal operating conditions of the NEF battery

The AQUIFER Wing will contain annular NEF battery stacks. During operation, the NEF fluid will be pumped through the stacks during use. During normal operation, the NEF system will be operated within a nominal voltage window. Exceeding the window voltages can result in the evolution of hydrogen (during charge) or oxygen gas. Over time, sufficient hydrogen could be evolved that could lead to fire or explosion, resulting in damage to or loss of project assets, damage to assets, or injury to or the death of personnel. The causes and effects are listed in Table 3.

Table 3. Gaseous H2 or O2 release due to exceeding the nominal operating conditions of the NEF battery.

Causes	Effects
Overcharging	Fire or explosion
Overdischarging	Damage or loss of project assets
External short circuit	Damage to Center assets; injury to or death of personnel

Some mitigations include using non-conductive battery terminal caps, physically separating the battery controller system, insulating the positive and negative terminals, utilizing a charging checklist, requiring that charging activities be monitored and performed by qualified personnel only, and using a hydrogen sensor with inputs to the battery control system (BCS) and observable warning beacons, and operating the system in a well-ventilated area.

These hazards can be routinely mitigated as the project advances. Early identification of these elements can inform the project team of potential system hazards. The project members then could proactively implement actions or changes to reduce or eliminate causes, effects, or the overall hazard.

VI. Summary

The objectives of the AQUIFER project include technology advancement of the nano-electrofuel (NEF) and rim-driven motor (RDM) technologies. The NEF technology is focused on the development, testing, and integration of a new type of aqueous flow battery concept that could greatly reduce or retire the flight fire and explosion hazards of conventional battery and fuel cell systems. The RDM and wing integration are two other two major aspects of this project. The RDM work is being developed to reduce blade-tip interference noise, reduce the required torque to run the motor, and eliminate conventional motor drag contributions.

The energy economy of the AQUIFER concept outlines a potential renewable or green energy sustainment for future sustainment. The energy economy for the AQUIFER supply demand and of electrical power is specified to largely utilize in-place infrastructure. Energy production which would be independent from usage could be accomplished across the nation. The NEF energy charge-use-recharge cycle could be accomplished using renewable energy input from solar power, wind power, or hydroelectricity. The concept of charge-use-recharge is projected to be a continuous and emission-free cycle. Notably, the NEF technology provides a storage solution utilizing excess energy produced during high-energy capture times, making this energy accessible at any time.

Powered aircraft operations considerations of the NEF technology identified important topics that alter or change well-established instructions, procedures, and guidance. These topics include weight and balance, fueling, recharging, safety, and derivative considerations. Fueling and defueling safeguards would need to be put in place to ensure neither jet nor aviation fuel could be inadvertently put into an NEF-configured aircraft. Additionally, safeguards would need to be in place to ensure that NEFs were not mixed or added to the wrong tank. The NEF fluid recharging topic was introduced, where movement of the anode and cathode was identified as logistically challenging. Refueling trucks would need to carry either one dedicated tank (anode or cathode), or two separate tanks (a tank for each, anode or cathode) both for fueling and defueling. This topic identified charging connection requirements for electric aircraft (standards or certification) and charging keep-out zones. Both of the recharging topics could be critical to the design and operation of the aircraft. Potential barriers are the available energy from green sources, and NEF recharging time versus use time. Safety considerations were limited to NEF or RDM or consequences of the implementation of these technologies. Special consideration must be taken so that each NEF unit is de-energized prior to (location of motors) maintenance. It is possible that the NEF solid particles will be regarded as hazardous chemicals and thus will be subject to specific rules and storage procedures. The NEF flow cells contain nanoparticles made of specific materials for each of the cathode and anode fluids; generally, nanomaterial solid particles are known to potentially pose health risks. Were the cathode and anode to mix in discharged form, very little or no reaction would be expected between the fluids. Other topics regarding hazards, mishap response, egress, and early subsystem design and integration were discussed. Early identification of hazard causes and effects could identify procedural or integration concerns for which investigators could take actions or implement changes to reduce or eliminate one or more of these safety challenges.

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