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Low Energy Nuclear Reaction Aircraft—2013 ARMD Seedling Fund Phase I Project

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Abstract

This report serves as the final written documentation for the Aeronautic Research Mission Directorate (ARMD) Seedling Fund's Low Energy Nuclear Reaction (LENR) Aircraft Phase I project. The findings presented include propulsion system concepts, synergistic missions, and aircraft concepts. LENR is a form of nuclear energy that potentially has over 4,000 times the energy density of chemical energy sources. It is not expected to have any harmful emissions or radiation which makes it extremely appealing. There is a lot of interest in LENR, but there are no proven theories. This report does not explore the feasibility of LENR. Instead, it assumes that a working system is available. A design space exploration shows that LENR can enable long range and high speed missions. Six propulsion concepts, six missions, and four aircraft concepts are presented. This report also includes discussion of several issues and concerns that were uncovered during the study and potential research areas to infuse LENR aircraft into NASA's aeronautics research.

1.0 Introduction

NASA's mission includes driving advances in aeronautics to "enhance knowledge, education, innovation, economic vitality, and stewardship of Earth." NASA's aeronautics research is focused on solving technical challenges for mobility and reducing environmental impacts. This innovative research strives to enable revolutionary transformations in aviation. A critical piece is to research and develop revolutionary technologies that enable that vision.[1]

New sources of energy could be one way to achieve NASA's aeronautics goals. LENR could be that new source of energy. The technology became known in 1989 with what Pons and Fleishmann called, "cold fusion."[2] It was called cold fusion to distinguish it from familiar fusion approaches which relied on extremely high temperatures to initiate nuclear reactions. The nuclear reactions that have been observed in the sun are an example of high temperature fusion. "Cold fusion" as it was known, was found to be impossible. However, experiments continued including at NASA.[3] Many theories surfaced to explain the energy output from a lower energy input, but there is one theory that seems to explain it using existing physics models: the Widom-Larsen Theory.[4] The Widom-Larsen Weak Interaction Low Energy Nuclear Reaction (LENR) Theory is believed to be the best explanation of the LENR process because it does not require new physics models.[5] The phenomenon now called LENR requires relatively low temperatures or energy stimulus to initiate reactions. It is a form of nuclear energy which has conservatively been estimated to have over 4,000 times the energy density of chemical energy sources and potentially much more.[6]

The objective of this project was to explore the use of LENR as an energy source for aircraft. This report includes descriptions of different LENR propulsion or energy conversion systems, synergistic missions, and some aircraft concepts. Brief discussions of constraints that are removed by LENR and new constraints that arise are also included. This report concludes with potential research areas to infuse

LENR aircraft into NASA research.

2.0 Nomenclature

Chemical Elements

D – Deuterium

H – Hydrogen

Ni – Nickel

Pd – Palladium

Abbreviations

AIAA – American Institute of Aeronautics and Astronautics

ANP – Aircraft Nuclear Propulsion Program

ANS – American Nuclear Society

APU – Auxiliary Power Unit

ARMD – Aeronautics Research Mission Directorate

ARPA-E – Advanced Research Projects Agency-Energy

ASRG – Advanced Stirling Radioisotope Generator

Cal Poly – California Polytechnic State University

CERN – European Centre for Nuclear Research

DARPA – Defense Advanced Research Projects Agency

FLOPS – Flight Optimization System

GE – General Electric Corporation

GRC – Glenn Research Center

HALE – High Altitude Long Endurance

ISR – Intelligence, Surveillance, and Reconnaissance

LaRC – Langley Research Center

LENR – Low Energy Nuclear Reaction

MAV – Micro Unmanned Aerial Vehicle

MEMS – Microelectromechanical System

NAM – Non-Dimensional Aircraft Mass ratio

NARI – NASA Aeronautics Research Institute

NASA – National Aeronautics and Space Administration

NEPA – Nuclear Energy for Propulsion of Aircraft

NRA – NASA Research Announcement

RI – Runway Independent

TRL – Technology Readiness Level

UAS – Unmanned Aerial System

UAV – Unmanned Aerial Vehicle

VTOL – Vertical Takeoff and Landing

3.0 Purpose

The purpose of this research is to investigate the potential vehicle performance impacts of applying the emergent Low Energy Nuclear Reaction (LENR) technology to aircraft propulsion systems. This technology could enable the use of an abundance of inexpensive energy to remove active design constraints such as range and endurance, leading to new aircraft designs with very low fuel consumption, low noise, and no emissions. The objectives of this project were to: (1) gather as many perspectives as possible on how and where to use LENR for aircraft including the benefits arising from its application, (2) explore the performance, safety, and operational impacts to individual aircraft and the fleet, (3) evaluate potential propulsion system concepts, and (4) foster multi-disciplinary interaction within NASA.

4.0 Background

LENR is a type of nuclear energy based on the weak force.[6] It has similar characteristics to fission and fusion, except there is no harmful radiation or hazardous waste. As an energy source, LENR works by generating heat in a catalyst process. The fuels or materials that are usually used in the LENR process are nickel metal (Ni) with hydrogen gas (H) or palladium (Pd) with deuterium (D). The initial testing and theory show that radiation and radioisotopes are extremely short lived and can be easily shielded.[6]

LENR would be an ideal energetics solution. It could meet the world's energy requirements while being cleaner and safer than current methods.[7] NASA's interest in LENR increased after the Widom-Larsen Theory was published. NASA began conducting experiments to determine how the LENR surface reactions occur and their characteristics.[6]

One appealing application for LENR previously identified by NASA is single-stage-to-orbit vehicles. LENR's high energy density would be a huge advantage for these types of vehicles.[8] NASA conducted a study in 2009 to design a LENR powered launch vehicle. LENR enabled very high performance engines that could revolutionize access to space.[6]

LENR could also revolutionize the aviation industry. The energy density is considered scalable, which means it can be used in small to very large applications. It does not have dangerous effects like fission power, which makes it very portable. LENR could result in what would essentially be "fuel-less" aircraft. In addition, the very high energy-density characteristics of LENR could alter current design constraints and create new missions and markets.[9] It was a promising source of alternative energy examined as part of a NASA subsonic aircraft research study.[10] The study determined that LENR would have a "game changing" impact. Feasibility, safety, weight, and customer acceptance were listed as major concerns.

Reference 11 describes some motivation for exploring LENR as an energy source for use in aircraft. It is also important to note that the Nuclear Energy for Propulsion of Aircraft (NEPA) Project started looking at nuclear powered aircraft in 1946. Nuclear powered flight was found to be feasible. The program ended in 1951, but was followed by the Aircraft Nuclear Propulsion Program (ANP), which continued until 1961. During that time, engine prototypes were tested, aircraft and propulsion design studies were conducted, and the effect of radiation was studied for pilots, crew, and aircraft.[12] Most of this work is relevant to LENR powered aircraft.

Despite the previous work in this area, questions remained. How would LENR affect aviation? What new aircraft and missions could LENR enable? NASA was interested in the answers and there was a good foundation from which to launch this study.

5.0 Approach

Assembling a diverse team was important to gather a variety of perspectives. The team included LENR experts, propulsion system experts, aircraft performance and design experts, and student researchers – all at varying levels of experience. The team members were located at NASA Langley Research Center (LaRC), NASA Glenn Research Center (GRC), and California Polytechnic State University (Cal Poly). The team held technical collaboration meetings about once a month to foster inter-disciplinary and inter-center collaboration.

Early in the project, Cal Poly offered an aircraft design course that focused on LENR powered aircraft. Then they transitioned to a sponsored research project team. The Cal Poly team focused on exploring many ideas and concepts from a fundamental physical principles perspective. The first round of propulsion, mission, and aircraft concepts generation started with the student team. The initial team collaboration determined the aircraft and propulsion concepts. Further research refined these new and innovative concepts to show how LENR can solve the current challenges in aeronautics. Cal Poly's valuable efforts and research supported their LENR aircraft concept development as well as the NASA team concept developments.

LENR is a controversial technology; there are varying claims of its performance and overall success. Thus, for the purpose of this project the team decided on several assumptions to enable assessments and analyses. First, LENR was assumed to exist in the form of a "black box". This meant that thermal energy was produced from an assumed volume of material that made up the reactor. The initial LENR reactors were assumed to have limited power which would improve through years of development.

The LENR experts defined the reactor characteristics early in the project. Building on the initial research, a first order design space exploration was performed. Results showed where LENR aircraft fit in the trade space and what mission capabilities could be enabled. The first order design space exploration also showed the initial impact of LENR on design constraints. Next, missions were selected and propulsion system concepts were developed. The propulsion concepts and missions guided the aircraft concept development. Qualitative safety and operational impacts were also explored.

6.0 Research Status

The research started with a literature search of nuclear aircraft, propulsion systems, and missions. It allowed the team to recognize the accomplishments and problems from decades of nuclear aircraft projects. A long list of long endurance missions for military and civilian applications was also found through research. Once the starting point was established, the team then focused on the specific concept areas that led to the design of the LENR powered aircraft concepts.

The study efforts included following the advancements in LENR technology, creating aircraft and propulsion system concepts, finding technologies that remove constraints, investigating integration of propulsion concepts into aircraft and analyzing the performance, safety, and operational impacts.

6.1 LENR Characteristics

One of the first efforts of this project was to compile the LENR reactor parameters that were required for a conceptual level propulsion system and aircraft design. Current estimates of the required parameters were determined through a literature search. Table 1 shows the parameters of LENR reactors that have been claimed to be in development by private entities. Where possible, the values given are for the reactor only and do not included ancillary systems. The devices found use Nickel-Hydrogen or Palladium-Deuterium as the reactants. Their reported output power is low compared to the input power. The maximum temperatures are also relatively low, with the highest at 600 degrees Celsius. Reactor volumes range from 126 to 2,600 cubic centimeters and don't seem to be related to the output power. Relatively low amounts of reactant mass and one to two hour start times were required for the experiments. The sources used for this literature search did not have any devices for sale, thus no hardware is known to exist. Therefore, the data reported in the table could not be validated. The leading LENR researchers and innovators were not consulted directly during this project because of the uncertainty and skepticism that surrounds this revolutionary technology.

Table 1. LENR parameters for devices in development.

Organization	Leonardo Corp (Ref. 13, 14, 15)		Defkalion (Ref. 16, 17)	LENUCO (Ref. 18)	Celani (Ref. 19)	Brillouin Energy (Ref. 20, 21)	
Device	Low-Temp E-Cat	High-Temp E-Cat (test data)	Hyperion Prototype			Brillouin Boiler	New Hydrogen Boiler
Reactants	Ni-H_2	Ni-H_2	Ni-H_2	Pd-D_2 / Ni-H_2	Ni-H_2	Ni-distilled H_2O	Ni-H_2
Power Output (net, thermal) (kW)	8	7	5	3	0.016	~0.1	
Power Input (electric) (kW)	1.67	4	1.0 (start phase)		0.048	~0.45	
Max. Temperature (°C)	120	308	600	140	150	150	500
Reactor Volume (cm^3)	400	2,600	125.6		250	1000	
Fuel Charge (g)	H_2: 10	Ni: 1					
Start/Stop Transient (min)	60	120	120				

The LENR reactor parameters were projected for the years 2025 and 2035. Estimates were made of the expected power, volume, weight, temperature, and fuel flows for each time period. Some of the critical parameters were difficult to project because there is no proven theory to establish them. Table 2 shows the values chosen for 2025 and 2035. Maximum temperature was measured as the thermal output temperature of the LENR reactor. The power increases significantly over the ten-year period, because it is assumed that once LENR is available there will be a tremendous investment in the technology and advancement of its performance. The 2025 projections are similar to the parameters found in Table 1, reflecting the idea that LENR will not see significant investment until around 2025.

Table 2. LENR projected parameters for 2025 and 2035.

	2025	2035
Power Output (thermal) (kW)	10	1000
Max. Temperature (°C)	2000	7000
Power/Volume (kW/m^3)	30	1000
Fuel Burn (H_2 gas) (GJ/g)	0.37	1.0
Fuel Burn (Ni powder) (MJ/g)	5	20

LENR aircraft propulsion systems are currently at a Technology Readiness Level (TRL) of two. LENR propulsion system concepts have been explored and working LENR reactors have demonstrated the energy production process. There are several groups trying to push LENR to TRL 3, which is the proof-of-concept stage. After that point, it will be a race to have production-ready LENR systems. It is critical to have the knowledge of how LENR can be used in aircraft now so that if it is proven to be a viable energy source, it can be put into use in aircraft immediately.

Major automobile corporations are already exploring the use of LENR in transportation. Honda, Toyota, and Mitsubishi are financing research with the goal of LENR powered cars that rarely need refueling.[22] LENR is also gaining research momentum. The Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) announced a funding opportunity for low-energy nuclear reaction research in 2013.[23] In 2012, the American Nuclear Society (ANS) held a panel discussion on LENR and the European Centre for Nuclear Research (CERN) hosted a colloquium on LENR research.[24, 25]

6.2 Energy Conversion and Propulsion Concepts

LENRs produce energy in the form of thermal energy. Several systems were initially explored that were capable of converting thermal energy from LENR to usable energy for aircraft propulsion. Some of the systems were found to be very useful with a wide range of applications, but many have large barriers to overcome. Some interesting characteristics of thermal energy conversion systems were found during this project. For example, heat transfer capability drops as altitude increases when using forced convection. Therefore, low altitude is better for a forced convection heat transfer system utilizing free-stream air.[26] A description of six LENR propulsion concepts follows.

6.2.1 Micro LENR Power Plant

One of the energy conversion systems investigated uses LENR in a power plant in the size and shape of a battery.[26] Batteries have convenient modularity, form factor, and a wide range of existing applications. The micro power plant would use Microelectromechanical systems (MEMS) gas turbomachinery, which is currently under development. A LENR reactor would supply heat to the turbomachinery which would convert it to mechanical energy. A generator would be required to convert the mechanical energy to electricity. This system would be suited for a micro unmanned aerial vehicle (MAV) powered by motors with propellers because of its small size. MEMS gas turbomachinery is an inefficient energy conversion system.[27] Another potential issue is that the exhaust heat of the system is near that of the LENR reactor. This system would also require an air supply, ducting, and heat dissipation. A micro LENR power plant is a very appealing system, but there are also a lot of barriers that must be overcome for it to be practical.

6.2.2 Thermoelectrics

The thermoelectric effect (also known as the Seebeck effect) is a conversion of temperature differential into electric voltage. Thermoelectric systems use semiconductors to achieve energy conversion. Thermoelectrics could be used to convert the thermal energy from a LENR reactor to electricity in a thermoelectric generator. It could power one or more electric motors for the propulsion system. Aircraft with large wetted areas could use the aircraft skin for the thermoelectric system's cold side. The cold side temperature could decrease as aircraft altitude increases, however density will also decrease at a rate that results in poor thermal conversion. Thermoelectrics are simple and reliable systems, but have very low conversion efficiency. Increased power can be achieved through higher operating temperature at the expense of life span. Due to the material limits and the poor thermal conversion as altitude increases, thermoelectric generators may be an impractical system for aircraft.[26]

6.2.3 Stirling Cycle Engine

A Stirling cycle engine is a closed-cycle system that uses compression and expansion of the working fluid at a temperature differential. The system operates so there is a net conversion of thermal energy to mechanical work. A Stirling engine could be used to mechanically drive propellers. Stirling engines are highly reliable and very efficient. However, they have a very low power-to-weight ratio. A Stirling engine NASA worked on for automobile applications had a power-to-weight ratio of 0.18 HP/lb, almost four times less than the engine used in the Cirrus SR22 aircraft.[28,29] Stirling cycle efficiency is also highly dependent on the temperature of operation, which creates a challenge similar to that encountered for the thermoelectric generator. For these reasons, Stirling engines may also be impractical systems for aircraft propulsion.[26]

6.2.4 Brayton Cycle with LENR Nanoparticles

The open-loop Brayton thermodynamic cycle incorporates isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-pressure heat rejection to produce work output. This propulsion concept would replace the combustor section of a turbojet or turbofan engine with an open LENR reactor. Nickel nanoparticles are injected like fuel into the LENR reactor. The reacting nanoparticles would directly transfer heat to the surrounding air in the reactor section. One of the advantages of this architecture is that only the combustor section of the engine would change. This system operates like a traditional turbojet or turbofan. However, it is more of a far-term solution since it requires precise injection and control systems.[26] The Brayton cycle with LENR nanoparticles would still generate emissions from the high “combustion” temperatures and from the nickel powder.

6.2.5 Brayton Cycle with Heat Exchanger

The Brayton cycle engine with heat exchanger is another concept for LENR propulsion. This type of engine was used for the nuclear aircraft studies of the 1940s - 1970s. One study selected the open Brayton cycle as the best option for a nuclear fission reactor powered cargo aircraft.[30] This propulsion system concept would replace the fuel burning combustor section of a conventional gas turbine engine with a heat exchanger. The LENR reactor would heat a heat transfer fluid in a closed-loop heat exchanger. The heated fluid would add heat to the engine in place of the combustor. One concern with this system was how the heat exchanger performance would change with altitude. Two engine models were created to explore this concern: a model based on the General Electric (GE) J85 turbojet and a model based on the GE 90 turbofan. Reference 26 describes the GE J85 analysis and results. The results show that the thrust lapse and thrust specific energy consumption are similar for an equivalent fuel burning engine. The GE90 model showed similar results. The trends for thrust, internal flow conditions, temperature, and efficiency were similar for both the fueled and LENR heated propulsion systems. Thus, the conclusion was made that the turbomachinery has essentially the same performance no matter how the heat is added. A high temperature reactor is required to match takeoff performance of jet-fueled engines and high LENR reactor temperatures are better for engine efficiency, size, and weight. The history and experience with this propulsion system make it very appealing. Since it was commonly chosen for the nuclear powered aircraft in the past, it is a good candidate for early use in LENR aircraft.

Another closely related propulsion concept is a turbine alternator, but this concept was not explored as part of this study. It would essentially be a LENR Auxiliary Power Unit (APU). This system could supply electric power to a distributed or centralized propulsion system.

6.2.6 Brayton Cycle Ramjet

A ramjet was the final Brayton cycle propulsion system considered. Again, the combustion section would be replaced, but this time with a LENR reactor supplying heat to the flow. It is a direct heat to thrust conversion and is reliable because there are few moving parts. It could operate at subsonic speeds, but would require more area than a supersonic ramjet. Ramjets are not self-starting, so this system would require a means to reach the operating speed of the ramjet. Two World War II era designs were found: the Lippisch P13, coal powered ramjet and the Leduc 0.10, liquid fueled ramjet.[31, 32, 33] In 1957, Project PLUTO developed and ground tested a nuclear powered ramjet for a supersonic missile.[34] The ramjet is another appealing propulsion system architecture. Experience with this system and especially its use in the nuclear aircraft program make it another good candidate for early use in LENR aircraft.

6.3 Exploration of the Design Space

A design space exploration was performed based on a Non-dimensional Aircraft Mass (NAM) ratio diagram.[35] Reference 11 contains more details and conclusions from this process. The NAM ratio diagram is designed to find the most suitable propulsion system for a given mission. For this project, it was used to compare a LENR system to currently available systems that perform High Altitude Long Endurance (HALE) or similar missions. The NAM ratio diagram is composed of four quadrants: Power that describes aerodynamics and propulsion system weight, Mass that describes advanced materials and integration, Energy that describes aerodynamics and energy efficiency, and Mission that describes vehicle performance. Figure 1 is the NAM ratio diagram from reference 11 that plots eleven existing aircraft that were designed for high altitude and/or long endurance missions, twelve HALE aircraft from a NASA study,[36] and two sets of LENR powered aircraft.

Both sets of LENR powered aircraft used LENR power and energy densities that were assumed for this project and outlined in the previous LENR section of this report. The LENR HALE aircraft data set was based on various cruise velocities. The LENR HALE aircraft (reference empty weight) data set was based on empty weight fractions from the NASA HALE study solar regenerative aircraft and the NAM equations were used to solve for the cruise velocity. The NAM ratio diagram was an effective tool for the design space exploration. Three conclusions were made: (1) LENR powered aircraft could enable long range missions, (2) the high power density could be used to obtain high velocity at cruise, and (3) a LENR power source would decouple the propulsion system size from the power capability. Therefore, LENR could remove the traditional aircraft design constraints for long range/endurance and high speed missions.

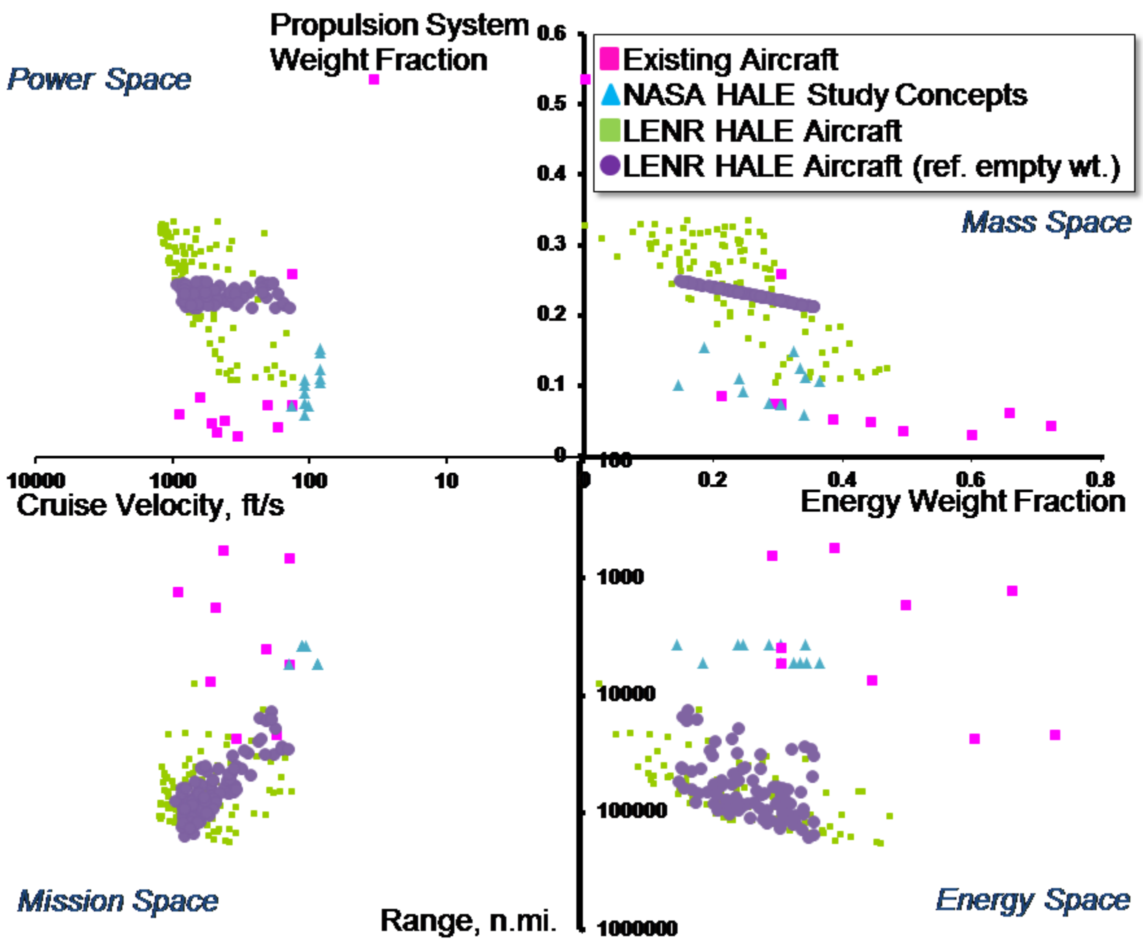


Figure 1. NAM ratio diagram of existing high altitude and long endurance vehicles, solar regenerative aircraft from a NASA study, and notional LENR powered aircraft

6.4 Missions and Aircraft

Missions that exploit the unique capabilities of a LENR propulsion system or are enabled by LENR were identified through literature searches and brainstorming. One such mission is HALE or any mission that requires a long endurance aircraft. High speed missions that require supersonic speeds could also exploit LENR capability. Small aircraft that operate independent of runways could exploit LENR to keep their weight low in order to achieve vertical takeoff and landing (VTOL) operation. Another type of mission that exploits LENR is large and/or heavy cargo or passenger transport aircraft, especially if they require long range. The design space exploration identified long range/endurance and high speed missions as missions for which LENR powered aircraft would have an advantage over fuel burning aircraft. The remainder of this section will describe these missions and some aircraft concepts and ideas for each mission.

An early attempt was made to devise weight regression and mission sizing equations for LENR aircraft. Traditional methods use fuel burn and weight ratios to close on a sized aircraft. This presented a challenge for LENR sizing because the weight of the aircraft was assumed constant throughout the mission due to negligible fuel burn. NASA's Flight Optimization System (FLOPS) was tested as a possible aircraft sizing tool for LENR.[37] FLOPS was unable to perform mission analysis and sizing for aircraft that burn zero fuel, therefore it could not be used for this project. The aircraft were therefore sized by comparing to aircraft with similar requirements and capabilities.

6.4.1 Long Endurance

The long endurance and range missions will most likely be unmanned because of the limits of a human pilot/operator demonstrated in previous around the world flights. Geo-stationary satellite, communications relay, hurricane tracking, border patrol, port surveillance, disaster relief support, animal tracking, and high altitude atmospheric research are examples of civilian HALE missions. Military missions include intelligence, surveillance, and reconnaissance (ISR), persistent surveillance, and airspace denial. The HALE mission requires low power and unlimited energy. Exploration of the HALE mission led to the discovery that reliability will become a constraint once the endurance constraint is removed by use of LENR propulsion. Satellite, engine, and some Unmanned Aerial System (UAS) reliability data were examined for ways to quantify reliability as a new constraint for HALE aircraft.[26]

The Defense Advanced Research Projects Agency (DARPA) Vulture project defined a challenging HALE mission. The Vulture mission requirements were an operating altitude of 60,000 to 90,000 ft, a payload capacity of 1,000 lb with 5 kW power for the payload, 5 year endurance, and 99% probability of station keeping.[38] A more near term HALE mission would be a science mission that matches the Boeing Phantom Eye performance. The operating ceiling for Phantom Eye is 65,000 ft, with a 1,000 to 5,000 lb payload, 150 kt cruise speed, and a 3 to 5 day endurance.[39]

The Cluster Wing is an aircraft concept that could be suitable for several HALE missions including distributed sensor network, ordinance delivery, and environmental missions. It is composed of several smaller aircraft joined at the wing tip that could fly out to a mission zone, distribute, perform their individual missions, and rejoin once the mission is complete. When together, induced drag reduction allows additional climb capability, which reduces the installed thrust required. Figure 2 shows the Cluster Wing concept.

The Cluster Wing shown uses a LENR powered ramjet as the propulsion system. It is capable of high speed and high wing loading. The individual aircraft can join together at the wing tips with a latch system similar to what was used in Project Tip-Tow.[40] Table 3 shows the performance design goals for each Cluster wing vehicle.

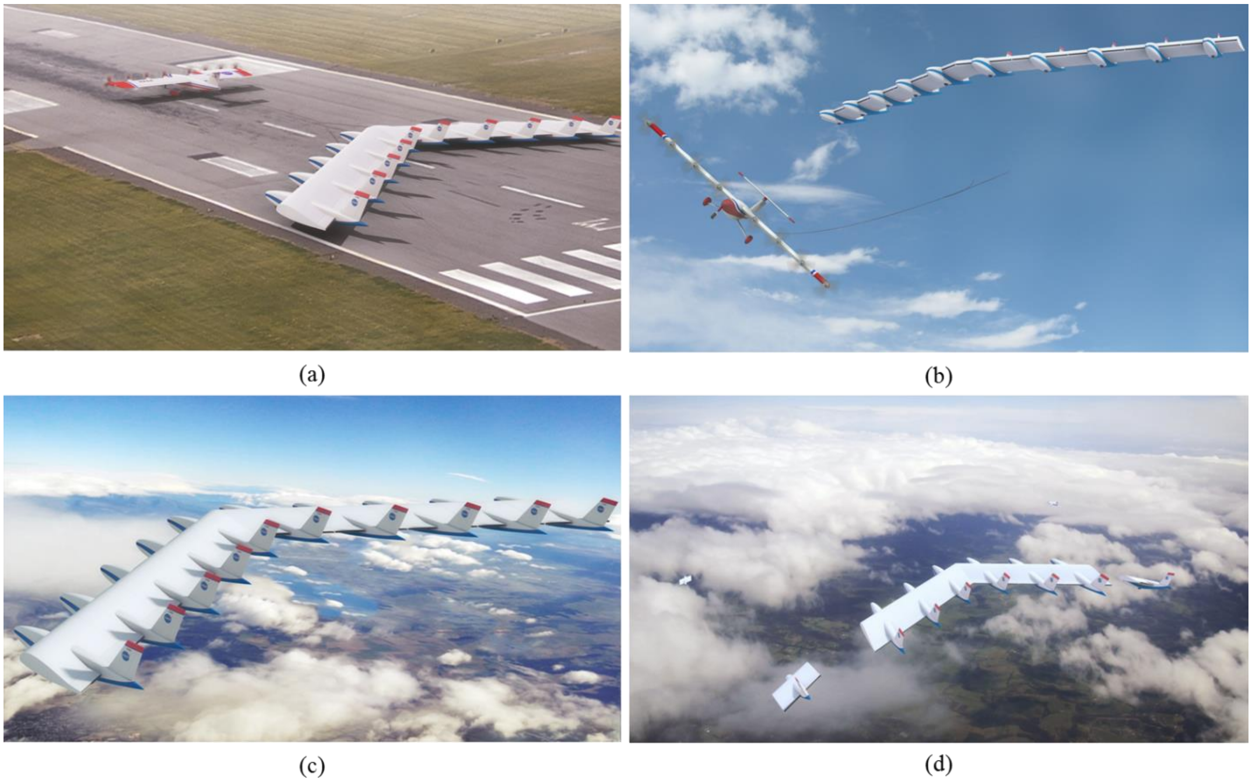


Figure 2. Conceptual image of the Cluster Wing vehicles (a) Takeoff with tow aircraft (b) Tow aircraft releases the Cluster Wing at top of climb (c) Vehicles together during cruise (d) Vehicles seperating to complete mission

Table 3. Cluster Wing conceptual design performance goals for each vehicle

	Units	Design Goals
Takeoff Gross Weight	lb	2,000
Maximum Payload	lb	1,000
Cruise Thrust	lb	125
Wing Area	ft^2	90
Wing Span	ft	10
Wing Loading	lb/ft^2	22

6.4.2 Supersonic Transport

A supersonic business jet or small transport is another mission which can exploit the benefits of LENR propulsion. It could combine Elon Musk’s vision for an electric VTOL supersonic transport and NASA’s “N+3 Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period” NASA Research Announcement (NRA) for an aircraft carrying 10 passengers, 1,000 nautical miles or more, at Mach 1.6-1.8 cruise with low boom, and VTOL.[41, 42] Figure 3 is a supersonic business jet concept. The main propulsion would utilize LENR turbojets or turbofans, which are not expected to be much larger than the current concepts. LENR removes the massive amounts of jet fuel required for this mission, leaving lots of volume in the aircraft for stowable rotors to accomplish the VTOL. Table 4 shows the performance design goals for the supersonic VTOL transport concept.

(a) (b) (c)

Figure 3. Supersonic VTOL concept aircraft (a) With rotors deployed for vertical takeoff (b) In transition flight from vertical takeoff to horizontal flight (c) With rotors retracted during cruise flight

Table 4. Supersonic VTOL transport conceptual design performance goals

	Units	Design Goals
Takeoff Gross Weight	lb	100,000
Maximum Payload	lb	2,200
Takeoff Thrust	lb	130,000
Wing Area	ft^2	1,430
Wing Span	ft	50
Wing Loading	lb/ft^2	70

6.4.3 Micro Unmanned Aerial Vehicles

MAVs are unique vehicles that could take advantage of the massive amount of energy available from LENR for the small reaction mass.[26] LENR propulsion systems for MAVs will be small and still allow for long range/endurance. MAVs share some of the same missions as HALE aircraft. Communications relay, border patrol, port surveillance, air sampling, police surveillance, and crowd control are examples of civilian MAV missions.[43] Military missions could include ISR.

6.4.4 Runway-Independent Aircraft

The runway-independent (RI) aircraft requires high power and high energy. This type of vehicle could transport people from home to work and completely change local transportation operations. Other missions could include autonomous package deliveries to remote locations.[26]

6.4.5 Global Transport

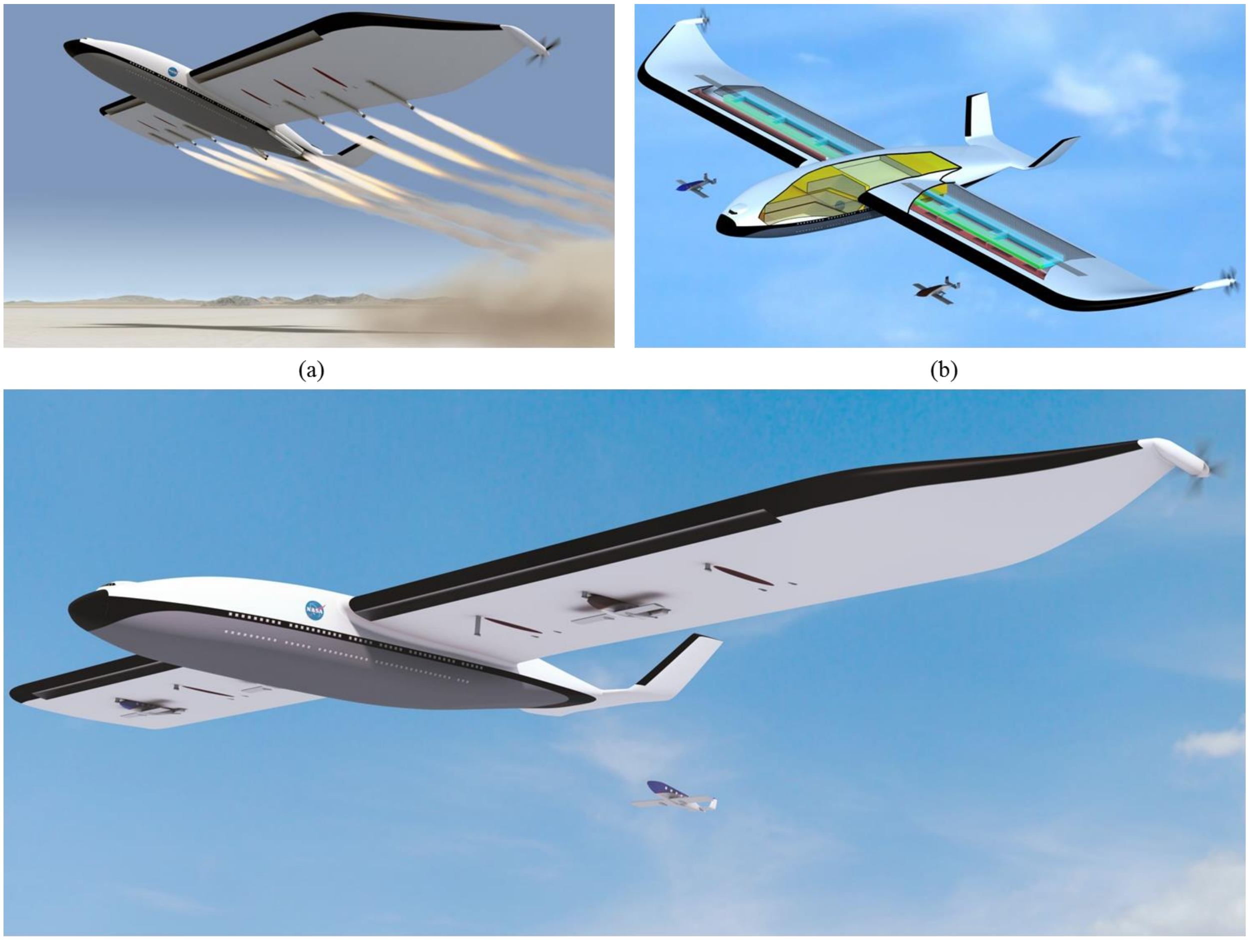
The comfortable global passenger transport powered by LENR could change how airlines operate and compete. There may be more non-stop flights, cabin area per passenger, and customer comforts.[26] It could operate at subsonic or transonic speeds and have long range capability.

A large cargo transport is another applicable mission. This mission was a common one used in the past nuclear aircraft design studies. One report specified 0.75 cruise Mach, 400,000 – 600,000 pound payload, 60,000 operation hours, and crew of four.[30] The performance goals for one of the conceptual designs is shown in Table 5. The nuclear aircraft of the past had very heavy weights due to the radiation shielding weight required. LENR does not require shielding, which could reduce total weight while matching the performance of the fission nuclear aircraft.

Table 5. Nuclear cargo transport conceptual design performance goals[30]

	Units	Design Goals
Takeoff Gross Weight	lb	2,154,390
Maximum Payload	lb	600,000
Takeoff Thrust	lb	509,400
Wing Area	ft^2	17,350
Wing Span	ft	340
Wing Loading	lb/ft^2	120

The Sky Train is a concept that would perform a cargo and luxury passenger mission. It would process and sort cargo using an on-board, automated cargo processing center and operate as a “cruise” vacation. It was designed to operate around 10,000 feet altitude and use feeder aircraft to load and unload passengers and cargo. A docking system similar to the Apollo system could be used.[44] The Sky Train would be a massive dual-role aircraft. Figure 4 is an image of the Sky Train in cruise with feeder aircraft approaching. The Sky Train can dock with up to 6 feeder aircraft, each carrying 8 passengers or cargo. It can accommodate up to 150 passengers with each passenger cabin volume measuring 1,000 ft^3. The passenger section of the Sky Train could also include cruise ship amenities like restaurants, movie theatres, night clubs, mini golf, and more. The cargo sorting facility would be separated from the passengers. The conceptual design performance goals for the Sky Train are shown in Table 6. This Sky Train concept was estimated to have a takeoff gross weight of about 9,685,000 lbs. The wing span is about 800 ft with an area of about 74,500 ft^2. Sky Train would use large rocket boosters for takeoff assistance. Once in the air, the rockets would be jettisoned with any undercarriage used during takeoff. Maintenance could be performed while Sky Train is in cruise.



(c)

Figure 4. Conceptual images of the Sky Train aircraft (a) During takeoff with booster rockets providing additional thrust (b) In cruise with cutaway to show interior sections (c) In cruise with feeder aircraft approaching and docking

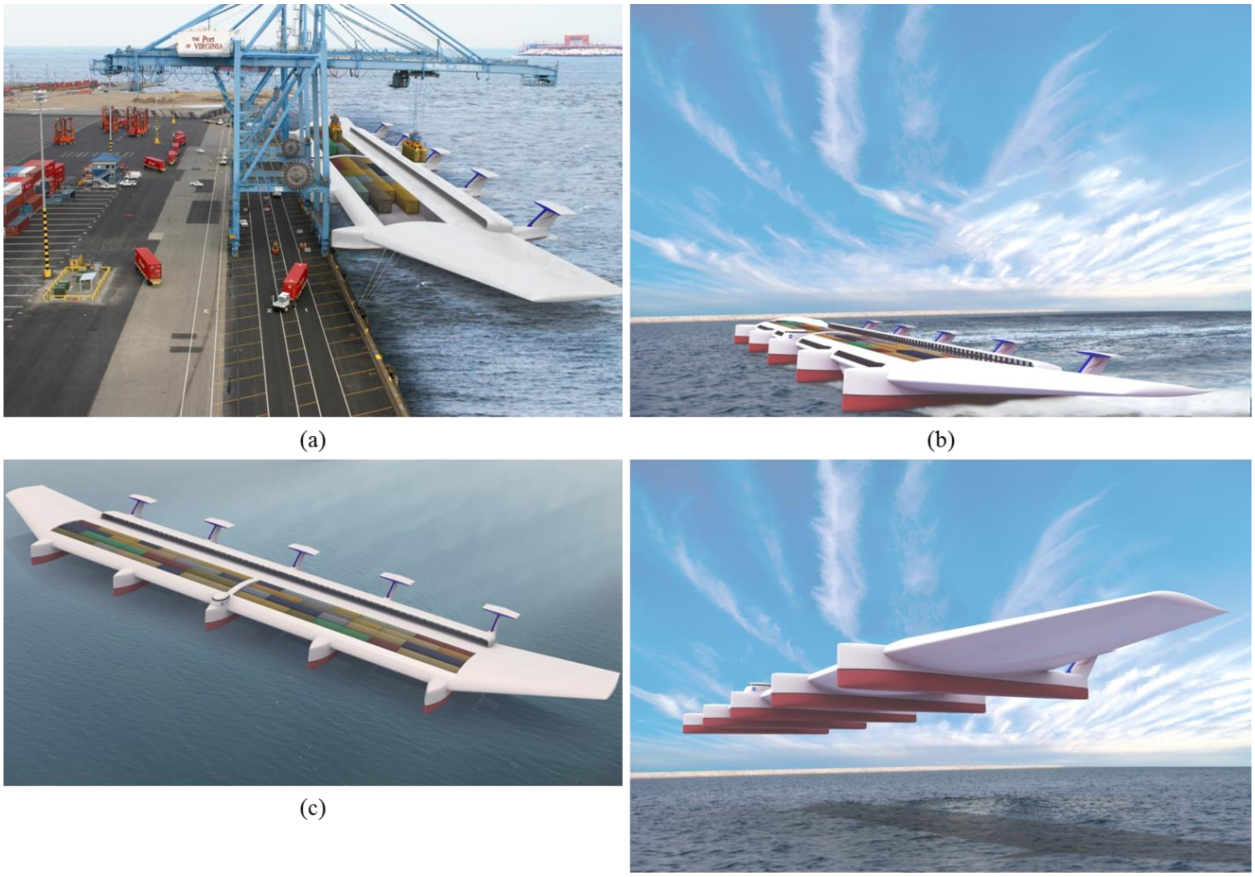
Table 6. Sky Train global transport conceptual design performance goals

	Units	Design Goals
Takeoff Gross Weight	lb	9,685,000
Maximum Payload	lb	33,000
Takeoff Thrust	lb	2,550,000
Wing Area	ft^2	74,500
Wing Span	ft	800
Wing Loading	lb/ft^2	130

6.4.6 Ocean Cargo Transport

The ocean cargo transport mission would fill the gap between large cargo aircraft that deliver packages in two days and large ocean ships that deliver cargo in two to four weeks. A similar concept was proposed by Boeing called the Pelican.[45] However, the aircraft concept described here would carry standard shipping containers and use the existing pier-side infrastructure to enable easy integration. Missions would have a range of about 10,000 nautical miles and at least a 150 knot cruise velocity. This would allow for delivery in 4 to 5 days. LENR would enable new configurations that could be easily integrated with the current ocean cargo infrastructure and it would enable more cargo to be carried for longer range/endurance.

Figure 5 shows a LENR powered ocean cargo concept aircraft. The shipping containers are carried in the wings. This concept was designed to carry thirty-two 40 foot long containers. It has a wing span of about 500 ft, well within the Panamax cargo ship dimensions.[46] The Panamax dimensions specify the dimensional limit of any cargo ship that can pass through the Panama Canal. They were used to reference the size of the existing pier-side cargo infrastructure. The conceptual design performance goals for the Sky Train are shown in Table 7. The takeoff gross weight would be around 4.65 million pounds and use additional thrust at takeoff from fans in the leading edge. The design wing loading would be 130 lb/ft^2. It would fly at about 20 feet above the water during cruise to take advantage of wing-in-ground-effect benefits and reduce engine thrust requirements.



(a) (b) (c) (d)

Figure 5. Ocean cargo transport concept aircraft (a) In port being loaded with cargo containers (b) On takeoff with forward lift fans operating for additional thrust (c) In cruise flight (d) In cruise flight

Table 7. Ocean cargo transport conceptual design performance goals

	Units	Design Goals
Takeoff Gross Weight	lb	4,650,000
Maximum Payload	lb	1,856,000
Takeoff Thrust	lb	2,325,000
Wing Area	ft^2	35,680
Wing Span	ft	490
Wing Loading	lb/ft^2	130

6.5 Publications

Several publications were created during the period of performance for this project. Cal Poly wrote and presented "Impact of Advanced Energy Technologies on Aircraft Design" at the American Institute of Aeronautics and Astronautics (AIAA) SciTech 2014 conference in January 2014.[26] "The Application of LENR to Synergistic Mission Capabilities" was written as a final report for a graduate course.[11] The paper was published and presented at the AIAA AVIATION 2014 conference in June 2014. A final presentation was made as part of the NASA Aeronautics Research Institute (NARI) 6-day virtual technical 2014 Seedling Seminar. The presentation slides are available on the NARI 2014 Seedling Seminar website along with a recorded video of the presentation.[47]

7.0 Conclusions and Recommendations

Six propulsion concepts were identified that utilize LENR. After an exploration of the design space, six missions were identified that are enabled by LENR or exploit its unique capabilities and four aircraft concepts were developed. Several advanced technologies were used in the aircraft concepts to remove current constraints like using the stowable rotors on the supersonic VTOL concept. The LENR propulsion systems were integrated into the aircraft concepts and performance was estimated. No additional safety impacts specific to LENR aircraft were identified beyond what is considered in high energy density batteries. LENR could have major impacts on aircraft operations, which vary based on the specific vehicle solution. The design space exploration showed that range/endurance and high speed mission constraints could be eliminated by using LENR. A new constraint identified for long endurance missions is aircraft systems reliability.

This project identified four critical research areas for realization of LENR aircraft. The most critical area is the establishment of an underlying LENR theory. Complete understanding for applications will not come without a theory to explain all of the phenomena. Next, high efficiency thermal energy conversion will be critical to convert the LENR reactor heat to usable energy. Heat exchangers, lightweight Stirling engines, and thermo-electric systems require increased efficiency for use in aircraft. Development of high temperature materials and cooling systems for gas turbine engines is another area needing future research. Increased reliability of aircraft systems is another key research area to enable long endurance aircraft.

The application of LENR to aircraft would open new research opportunities in aeronautics. It would open aircraft performance and push back the current constraints that tightly bind the design space. The fuel mass and volume would no longer drive aircraft design. Energy is essentially decoupled from the reaction mass, yielding the potential for extreme range and endurance and infrequent refueling operations. These characteristics are critical for long endurance missions. The application of energy/propulsion to achieve inter-disciplinary coupling and benefits is only conservatively applied to current designs. For example, in hybrid laminar flow control on jet transports, power from the turbofan engines is used to power hybrid laminar flow systems. In current practice, this energy use burdens the propulsion sizing and fuel capacity resulting in aircraft sizing penalties. If LENR were used to power a boundary layer control system, there would be virtually no penalty and significant amounts of energy could be applied without worrying about propulsion sizing sensitivities. LENR could provide the energy necessary to exceed Aeronautics Research Mission Directorate's (ARMD)'s environmental goals for future vehicles.

LENR is an energy source technology that can benefit all of the aviation research at NASA, potentially creating a radical transformation in aeronautics. LENR could create a new set of constraints and capabilities that will increase throughput and efficiency for the airspace system. For example, transport aircraft could be large docking aircraft fed by smaller commuters. New propulsion, heat exchanger, heat transfer, and energy storage systems need further research and development. Systems that were developed to reduce noise but were heavy or required additional energy should be reevaluated for use on LENR powered aircraft. LENR will most likely start as a ground based power system, creating a new opportunity to converge into aeronautics technology.

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14. ABSTRACT
This report serves as the final written documentation for the Aeronautic Research Mission Directorate (ARMD) Seedling Fund's Low Energy Nuclear Reaction (LENR) Aircraft Phase I project. The findings presented include propulsion system concepts, synergistic missions, and aircraft concepts. LENR is a form of nuclear energy that potentially has over 4,000 times the energy density of chemical energy sources. It is not expected to have any harmful emissions or radiation which makes it extremely appealing. There is a lot of interest in LENR, but there are no proven theories. This report does not explore the feasibility of LENR. Instead, it assumes that a working system is available. A design space exploration shows that LENR can enable long range and high speed missions. Six propulsion concepts, six missions, and four aircraft concepts are presented. This report also includes discussion of several issues and concerns that were uncovered during the study and potential research areas to infuse LENR aircraft into NASA's aeronautics research.

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