Low Energy Nuclear Reaction Aircraft

NASA Aeronautics Research Mission Directorate (ARMD)
2014 Seedling Technical Seminar
February 19–27, 2014
Outline

The Team
Overview
The Innovation
Technical Approach
Impact of Implementation
Results
Information Distribution
Next Steps
The Team

California Polytechnic State University
• Dr. Rob McDonald
• Advanced Topics in Aircraft Design course (10wks)
• Sponsored Research Project Team

NASA Glenn Research Center
• Jim Felder, Chris Snyder

NASA Langley Research Center
• Bill Fredericks, Roger Lepsch, John Martin, Mark Moore, Doug Wells, Joe Zawodny
Background

Low Energy Nuclear Reactions is a form of nuclear energy that potentially has over 4,000 times the density of chemical energy with zero greenhouse gas or hydrocarbon emissions\(^1\)

Enables use of an abundance of inexpensive energy to remove active design constraints in aircraft design

Current testing and work on theory


Current LENR Technology

Reaction materials: hydrogen loaded nickel powder

Reactor:
- Silicon nitride ceramic outer shell
- AISI 310 steel inner cylinder
- 2 AISI 316 steel end caps
- 33 cm long
- 9 cm diameter

Table 1: LENR reactor Dec. 2012 and Mar. 2013 test results

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Energy Produced (Wh)</td>
<td>62,000</td>
<td>160,000</td>
</tr>
<tr>
<td>Power Density (W/kg)</td>
<td>5.3x10^6</td>
<td>7.0x10^3</td>
</tr>
<tr>
<td>Thermal Energy Density (Wh/kg)</td>
<td>6.1x10^7</td>
<td>6.8x10^6</td>
</tr>
<tr>
<td>Initial Input Power (W)</td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>Reaction Mass (g)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Start-up Time (h)</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Total Test Duration (h)</td>
<td>96</td>
<td>116</td>
</tr>
<tr>
<td>Max. Temperature (deg. C)</td>
<td>496</td>
<td>308</td>
</tr>
</tbody>
</table>

Objective

Identify and Define Aircraft and Propulsion Concepts

- Exploit unique capabilities of LENR
- Investigate new systems enabled by LENR

Explore the application of LENR technology not the technical aspects and feasibility

- No peer reviewed, published sources
- Assumed device existed with these parameters
LENR is expected to be a clean, safe, portable scalable, and abundant energy source

Open ended question how to apply and benefits

- Range constraint disappears
- Drag reduction only necessary to reduce noise
- Propulsion sizing no longer burdened by other system energy requirements
- Current airport fueling systems could be removed
Technical Approach

Gather as many perspectives on how and where to use

- Two NASA centers and Cal Poly

Explore propulsion / energy conversion concepts
Explore performance, safety, and operation impacts
Foster multi-disciplinary interaction
Impact of Implementation

• Green aircraft with no harmful emissions

• New operations mentality
  • No concern for fuel cost

• New way to approach aircraft design
  • Fuel mass/volume is no longer a driving factor
  • Point performance may drive the design
  • Mission and point performance may come “for free”

• Certain missions/aircraft become more feasible
Results

Propulsion Systems
Exploration of Design Space
Missions & Aircraft
Issues / Concerns
Potential Research Areas
1. LENR Battery
   • Size and power of AA battery
     – 0.8 oz, 1.5 V, 700 mA
   • Employs MEMS gas turbine
   • Convenient modularity, form factor, and applications
   • Virtually unlimited life
   • Enables micro UAVs

Findings:
• Inefficient
• High waste heat
• Need air supply, ducting, and heat dissipation

Figure 2: Complete micro-turbopump chip

Figure 3: Micro-turbopump rotor

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2. Thermo-Electric$^2$

- Requires heat source and cold sink
- Efficiency depends on the semiconductor material used and the operating temperature


Propulsion Systems

Thermo-Electric

Findings:

• Low efficiency
  – Commercial systems have achieved 4% (in 2002)\(^4\)
  – Lab tests have achieved 6-7%\(^4\)

• Low temperature hot side\(^5\)

• Higher operating temperatures diminish life


Propulsion Systems

3. Stirling Engine\(^2\)

- Produces power in the presence of a constant temperature differential
- Highly reliable
  - Manufactured with maintenance free operation period of up to 11 years
- Typically used for converting low-grade waste heat into useable energy
- Efficiency can approach “ideal” Carnot Cycle

Findings:
- Low power-to-weight

Propulsion Systems

Stirling Engine

- Infinia 30 kW Stirling engine design\(^6\)
  - 6 interconnected 5 kW engine cylinders
  - Total estimated prototype weight: 1985 lbs
  - Total estimated production weight: 1190 lbs
  - Power-to-weight: 0.00563 HP/lb

- NASA Advanced Stirling Radioisotope Generator (ASRG)\(^7\)
  - Power produced: 140 W
  - Total ASRG weight: 55 lbs
  - Power-to-weight: 0.00341 HP/lb
  (25x less than 1903 Wright Flyer\(^8\))

\(^7\)“Advanced Stirling Radioisotope Generator (ASRG)”, NASA Facts, 2013.
\(^8\)“Fact Sheet: 1903 Wright Brothers Engine Tests”, Experimental Aircraft Association, 2013.
4. Brayton Cycle with LENR Nanoparticles

- New LENR combustor
  - Inject nickel nanoparticles like fuel
  - Forced convection with area change
  - Thrust is a function of $m_{\text{LENR}}$ and $T_{\text{LENR}}$

- Compressor and turbine stay the same

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10Drawn using XaraXtreme by Emoscopes, 2005.
Propulsion Systems

Brayton Cycle with LENR Nanoparticles

Findings:
- Simple integration
- Maintain traditional turbojet/turbofan behavior
- Precise injection control needed
- Far-term solution
5. Brayton Cycle with Heat Exchanger

- Constant output LENR
  - Isothermal wall
  - Can’t manipulate thrust through temperature
- No fuel
  - Can’t manipulate flow with mass flow
- Constant area
  - Can’t manipulate flow with area

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Propulsion Systems

Brayton Cycle with Heat Exchanger

- Selected as basic cycle for greater background and design experience
- Used JP-fuel for takeoff, climb, and emergency cruise

Reference System Parameters\textsuperscript{12}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power Level (MW)</td>
<td>230</td>
</tr>
<tr>
<td>Rated Thrust (lb)</td>
<td>84,800</td>
</tr>
<tr>
<td>Bypass Ratio</td>
<td>8.4</td>
</tr>
<tr>
<td>Turbine Inlet Temperature, Cruise (deg. F)</td>
<td>1600</td>
</tr>
<tr>
<td>Total Nuclear System (lb)</td>
<td>391,400</td>
</tr>
<tr>
<td>Core Lifetime (hr)</td>
<td>10,000</td>
</tr>
<tr>
<td>Coolant</td>
<td>Lithium</td>
</tr>
</tbody>
</table>


Figure 10: Open Brayton Cycle nuclear aircraft propulsion system schematic from 1977 Lockheed-Georgia report\textsuperscript{12}
Propulsion Systems

Brayton Cycle Engine Model:

• Built a turbojet model - based off GE J85
• On design
  – Scaled compressor and turbine maps to desired performance
• Off design
  – Built operating lines for each Mach number
  – Mach and altitude engine performance for mission analysis
• Heat exchanger design
  – On design solves for engine and heat exchanger dimensions
  – Off design gives us the new engine performance
    » Alter wall temperature as “Throttle”
    » Monitor maximum wall temperature
    » Measure heat available
Propulsion Systems

Engine Model with Heat Exchanger Design Point:

<table>
<thead>
<tr>
<th></th>
<th>Gas Turbine</th>
<th>Heat Exchanger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Altitude (ft)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mass Air Flow (lbm/sec)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>T₀₄ (R)</td>
<td>1,970</td>
<td>1,970</td>
</tr>
<tr>
<td>Engine Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust (lb)</td>
<td>3,462</td>
<td>3,325</td>
</tr>
<tr>
<td>A₂ (ft²)</td>
<td>1.36</td>
<td>1.36</td>
</tr>
</tbody>
</table>
• Turbomachinery is constant regardless of how heat is added
Propulsion Systems

Brayton Cycle with Heat Exchanger

Findings:

• Behavior is similar to JP-fueled engine
  – Trends for thrust, internal conditions, temperature, and efficiency

• Higher temperature reactor required to match takeoff performance of JP-fueled engine

• Higher LENR temperatures better for engine efficiency and would reduce size and weight
6. Brayton Cycle - Ramjet

- Heat added to air in nozzle produces thrust
- Reliable
  - No moving parts
- Direct heat to thrust conversion
  - Requires more inlet area
- New LENR combustor
- Not self starting

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Figure 11: Schematic diagram of a ramjet engine

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13 Vector image made by Cryonic07. Source png-drawing was made by Emoscopes and later slightly modified by Wolfkeeper, 2008.
Propulsion Systems

Brayton Cycle - Ramjet

- Lippisch P13\textsuperscript{14}
  - 1944 ramjet powered interceptor
  - Liquid fuel rocket to altitude
  - Powder coal fed ramjet

- Leduc 0.10\textsuperscript{16}
  - 1946 liquid fueled ramjet
  - Carried to altitude by Sud-Est SE-161 Languedoc transport


\textsuperscript{15} “A Lippisch P13a szuperszonikus vadászgép”, http://www.jetfly.hu/rovatok/jetfly/cikkopalyazat/palyazat_04.10.25./, [internet database], 2014

\textsuperscript{16} Damen, A., “Leduc 0.10 to 0.22”, http://1000aircraftphotos.com/HistoryBriefs/Leduc.htm, [internet database], 2014.
Propulsion Systems

Brayton Cycle - Ramjet

• Project PLUTO\textsuperscript{17}
  • 1957-1964 Air Force Project
  • Powered by 500 MW nuclear reactor
  • Low complexity, high durability
  • Designed for use in Supersonic Low Altitude Missile (SLAM)
  • Launched by cluster of rocket boosters

\textsuperscript{17}Herken, G., “The Flying Crowbar”, Air and Space, Vol. 5, May 1990, pp.28-34.
Design Space Exploration

Non-Dimensional Aircraft Mass (NAM) Ratio Diagram\(^\text{16}\)
- High level aircraft system exploration
- Aid in propulsion system selection for a given mission

Figure 16: Illustration of a notional NAM ratio diagram\(^\text{18}\)

Design Space Exploration

NAM Ratio Diagram Assumptions:

• Propulsion system efficiency: 0.2 - 0.25
• L/D: 5 - 30
• Thrust Lapse: 0.21
• 1) Cruise Velocity: 100 - 1960 ft/s
  2) Empty weight fraction: 0.7 - 0.8
  • Based on solar regenerative\(^{19}\)
• Ranges cover various aircraft types

Figure 17: NAM ratio diagram of existing high altitude and long endurance vehicles, solar regenerative aircraft from a NASA study, and notional LENR powered aircraft. 

Design Space Exploration

Figure 18: NAM ratio diagram of existing high altitude and long endurance vehicles, solar regenerative aircraft from a NASA study, and notional LENR powered aircraft.

Missions

High Altitude Long Endurance (HALE)

• Low power, unlimited energy
• Unmanned systems
• Civilian
  • Communications, hurricane tracking, border patrol, port surveillance, disaster relief support, high-altitude scientific research, animal population tracking, earth observation
• Military
  • Intelligence, surveillance, and reconnaissance (ISR), persistence surveillance, mothership airspace denial vehicle
Missions

HALE

- 1,000 – 5,000 lb payload
- 4 Day + endurance
- 150 kt cruise
- 65,000 ft ceiling

Reliability

Long Endurance Mission aircraft need satellite-like reliability

- Mean time between failure
- Case to remove some permanent systems
- Mass penalty increases with design life

Figure 19: Spacecraft percent mass penalty as a function of the design lifetime\(^{21}\)

Aircraft

Cluster Wing

• Reduced induced drag when together
• Distributed sensor network, ordinance delivery, environmental missions
• ~ 0.5 Mach
Aircraft

Cluster Wing
Aircraft

Cluster Wing
Aircraft

Cluster Wing
Missions

Low Supersonic\textsuperscript{22,23}

- 10 Passengers
- $> 1,000$ nm range
- 1.6 – 1.8 Mach cruise
- Low boom
- VTOL


Aircraft

Supersonic, Low Boom, VTOL Transport
Aircraft

Supersonic, Low Boom, VTOL Transport
Missions

International Cargo Wing-in-Ground Effect$^{24}$

- Standard cargo shipping containers payload
- Use existing pier side infrastructure
- $\sim 10,000$ nm mission (4-5 days)
- $> 150$ kt cruise

Aircraft

Wing-in-Ground Effect
• ~ Panamax dimensions (965 ft x 106 ft)$^{25}$

<table>
<thead>
<tr>
<th>Design Goals</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Capacity</td>
<td>32 Containers</td>
</tr>
<tr>
<td>TOGW (lb)</td>
<td>4.65 M</td>
</tr>
<tr>
<td>Wing Loading (lb/ft$^2$)</td>
<td>130</td>
</tr>
<tr>
<td>Wing Area (ft$^2$)</td>
<td>35,700</td>
</tr>
<tr>
<td>Wing Span (ft)</td>
<td>490</td>
</tr>
</tbody>
</table>

Aircraft

Wing-in-Ground Effect
Aircraft

Wing-in-Ground Effect
Aircraft

Wing-in-Ground Effect
Missions

Small Runway Independent (RI) Transport

- High power, high energy
- 300 lb payload
- Personal aircraft or autonomous package delivery
- Conform to residential noise pollution requirements

Comfortable Global Transport

- Disruptive change to transportation business model
- Global range: 12,500 miles
- Subsonic/transonic
- Level of comfort based on ft²/passenger metric

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Aircraft

Cargo

- 0.75 Mach cruise
- 400,000 – 600,000 lb payload
- 60,000 operational hours
- 4 crew

<table>
<thead>
<tr>
<th>Design Goals</th>
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<tbody>
<tr>
<td>Payload (lb)</td>
<td>600,000</td>
</tr>
<tr>
<td>Nuclear Subsystem (lb)</td>
<td>446,290</td>
</tr>
<tr>
<td>TOGW (lb)</td>
<td>2,154,392</td>
</tr>
<tr>
<td>Wing Loading (lb/ft^2)</td>
<td>120</td>
</tr>
<tr>
<td>Wing Area (ft^2)</td>
<td>17,351</td>
</tr>
</tbody>
</table>

Figure 20: Refined Canard Configuration from 1977 Lockheed-Georgia report

Sky Train

- Cargo delivery / sorting and “cruise” vacation
- 10,000 ft cruise altitude
- Automated cargo handling
- Rocket booster takeoff
- 6 “feeder” aircraft
  - Apollo docking system

<table>
<thead>
<tr>
<th>Design Goals</th>
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</thead>
<tbody>
<tr>
<td>Payload</td>
<td>150 passengers</td>
</tr>
<tr>
<td>Cargo System Weight (lb)</td>
<td>100,000</td>
</tr>
<tr>
<td>TOGW (lb)</td>
<td>637,000</td>
</tr>
</tbody>
</table>

Feeder Aircraft

<table>
<thead>
<tr>
<th>Payload</th>
<th>8 passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGW (lb)</td>
<td>8,000</td>
</tr>
</tbody>
</table>

Figure 21: Docking system of the Apollo spacecraft

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Aircraft

Sky Train
Aircraft

Sky Train
Aircraft

Sky Train
Issues / Concerns

• No clear model of how LENR systems will scale
  • Drives vehicle mass and volume requirements

• Throttle-ability of LENR system
  • Current assumption is that LENR is not throttle-able
  • Aircraft design and concept of operations driven by LENR throttle-ability
  • Start/stop transient times

• Energy management and dissipation
  • Will need robust methods to move, store, and dissipate energy
  • Aircraft mission profile should seek minimum power variance to reduce requirements on thermal system
Issues / Concerns

• Energy management and dissipation
  • Thermal system should be robust to dissipate excess energy that could result from subsystem failure

• What are the underlying physics?
  • Heat to thrust
  • Characteristics of that thrust
  • What constraints are relaxed/eliminated
Potential Research Areas

LENR Reactors and Theory

High Efficiency Energy Conversion
- Heat exchangers, light-weight Stirling engines, thermoelectrics

High temperature materials and cooling systems for gas turbine engines

Reliability in aircraft systems
Information Distribution

• This presentation will be posted to the NARI website


• Wells, D., “The Application of LENR to Synergistic Mission Capabilities”, Submitted for publication and presentation at AIAA Aviation 2014 Conference.
Next Steps

Continue to integrate the latest LENR research and testing results

Proposal for Phase II

• Refine existing propulsion and aircraft concepts
• Create easy to share ideas and data
  • Promotional videos and pictures