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

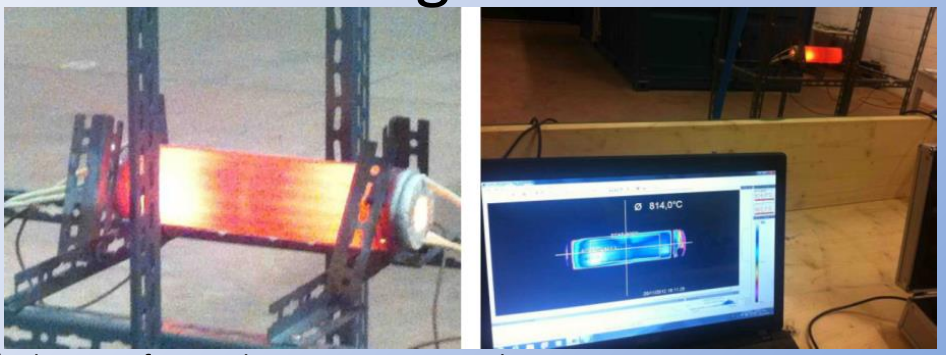


Figure 1: LENR reactor test images from November 2012[1]

[1]Levi, G., et al., "Indication of Anomalous Heat Energy Production in a Reactor Device Containing Hydrogen Loaded Nickel Powder", May 2013.
Other References: <http://technologygateway.nasa.gov/media/CC/lenr/lenr.html>, <http://skeptoid.com/blog/2013/02/26/lenr-a-bright-future-part-1/ >, <http://lenr-canr.org/>, <http://www.dieterbritz.dk/fusweb/index.php>

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[1]

	Dec. 2012	Mar. 2013
Energy Produced (Wh)	62,000	160,000
Power Density (W/kg)	5.3×10^5	7.0×10^3
Thermal Energy Density (Wh/kg)	6.1×10^7	6.8×10^5
Initial Input Power (W)		120
Reaction Mass (g)	1	1
Start-up Time (h)		2
Total Test Duration (h)	96	116
Max. Temperature (deg. C)	496	308

[1]Levi, G., Foshi, E., Hartman, T., Hoistad, B., Pettersson, R., Tegner, L., and Essen, H., "Indication of Anomalous Heat Energy Production in a Reactor Device Containing Hydrogen Loaded Nickel Powder", May 2013.

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

The Innovation

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

Propulsion Systems

1. LENR Battery[2]

- 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

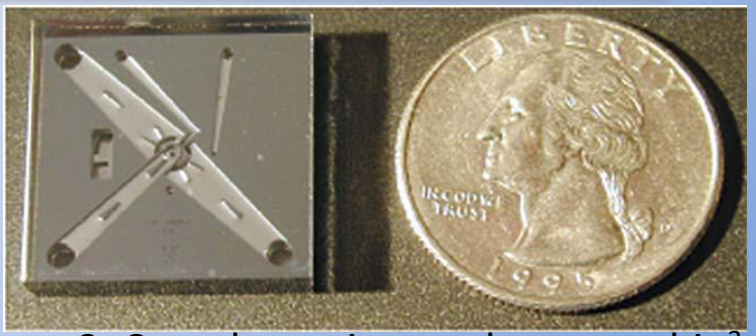


Figure 2: Complete micro-turbopump chip[3]

Findings:

- Inefficient
- High waste heat
- Need air supply, ducting, and heat dissipation

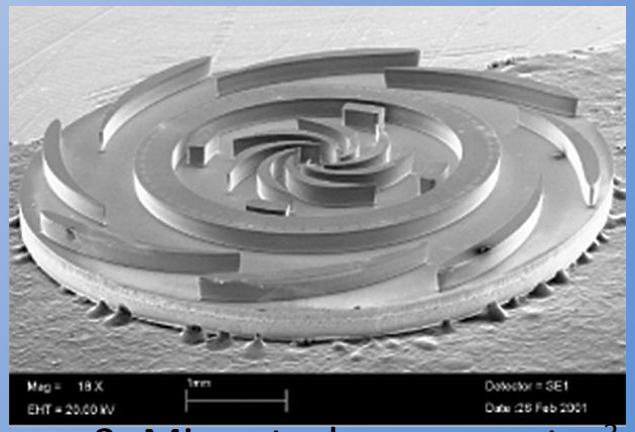


Figure 3: Micro-turbopump rotor[3]

[2]McDonald, R. A., "Impact of Advanced Energy Technologies on Aircraft Design", AIAA Conference Paper 2014-0538, Jan. 2014.

[3]Marcu, B., Prueger, G., Epstein, A., and Jacobson, S., "The Commoditization of Space Propulsion: Modular Propulsion Based on MEMS Technology", AIAA Conference Paper 2005-3650, Jul. 2005.

Propulsion Systems

2. Thermo-Electric[2]

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

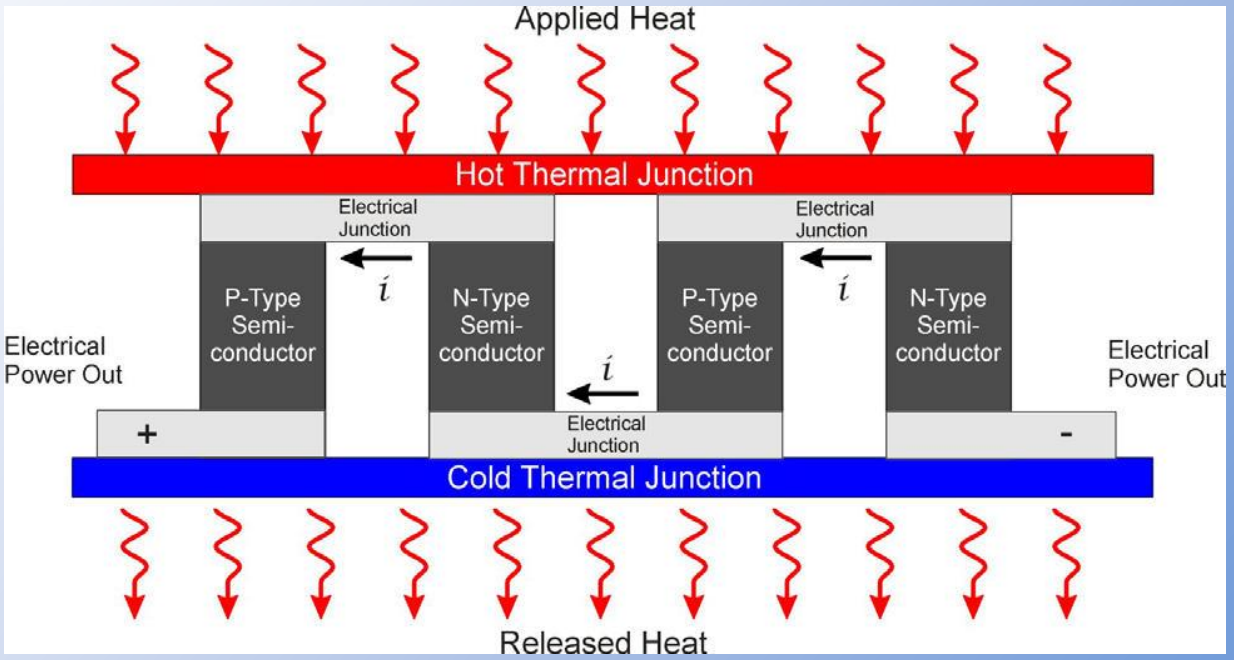


Figure 4: Schematic of basic thermoelectric operation[4]

[2]McDonald, R. A., "Impact of Advanced Energy Technologies on Aircraft Design", AIAA Conference Paper 2014-0538, Jan. 2014.
[4]Fleming, J., Ng, W., and Ghamaty, S., "Thermoelectric-Based Power System for UAV/MAV Applications", AIAA Conference Paper 2002-3412, May 2002.

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

[4]Fleming, J., Ng, W., and Ghamaty, S., "Thermoelectric-Based Power System for UAV/MAV Applications", AIAA Conference Paper 2002-3412, May 2002.

[5]Fleming, J., Ng, W., and Ghamaty, S., "Thermoelectric Power Generation for UAV Applications", AIAA Conference Paper 2003-6092, Aug. 2003.

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

[2]McDonald, R. A., "Impact of Advanced Energy Technologies on Aircraft Design", AIAA Conference Paper 2014-0538, Jan. 2014.

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])

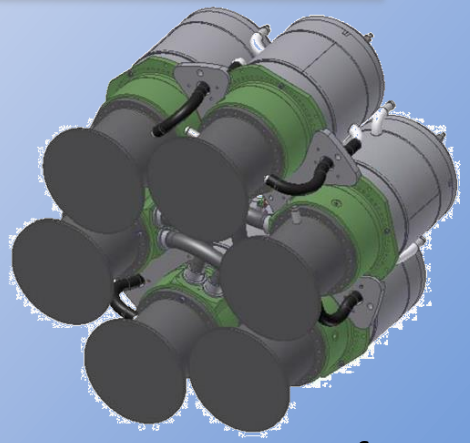


Figure 5: Infinia Stirling engine[6]

Figure 6: NASA ASRG[7]

[6]Qiu, S., "30kW Maintenance Free Stirling Engine for Concentrating Solar Power", US DOE Solar Energy Technologies Program Peer Review, 2010.

[7]"Advanced Stirling Radioisotope Generator (ASRG)", NASA Facts, 2013.

[8]"Fact Sheet: 1903 Wright Brothers Engine Tests", Experimental Aircraft Association, 2013.

Propulsion Systems

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_{LENR} and T_{LENR}

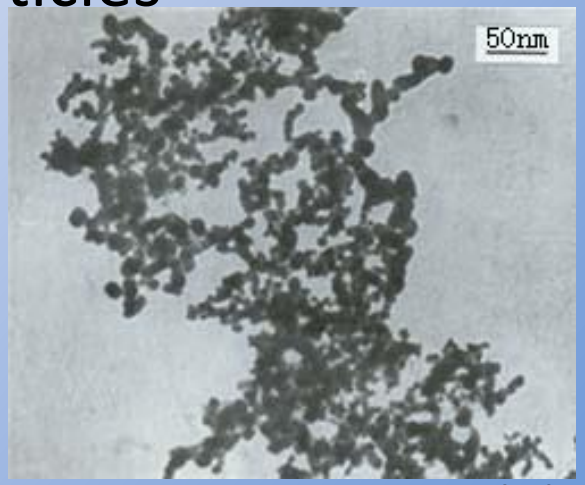


Figure 7: Nickel Nanoparticles[9]

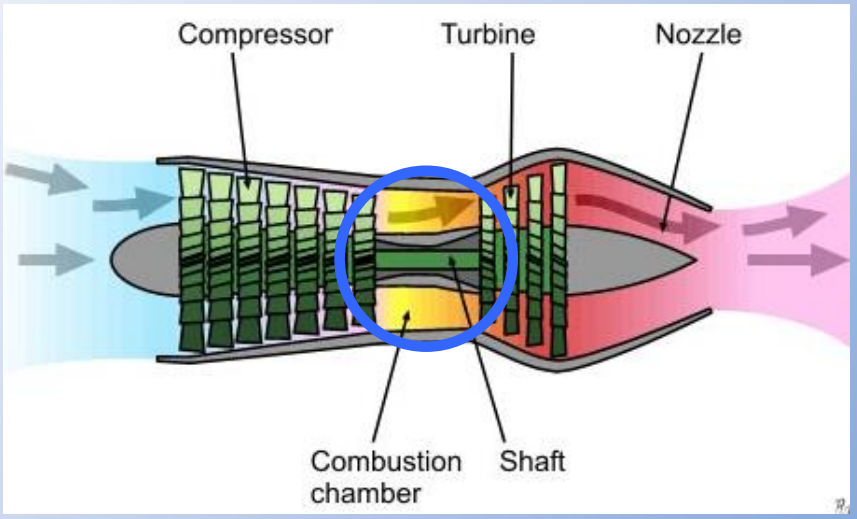


Figure 8: Schematic diagram of the operation of a axial flow turbojet engine[10]

- Compressor and turbine stay the same

[9]"Nanoparticles: Nickel [Ni]", Applied Nanotech Holdings, Inc., [internet catalog], 2013.
[10]Drawn 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

Propulsion Systems

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

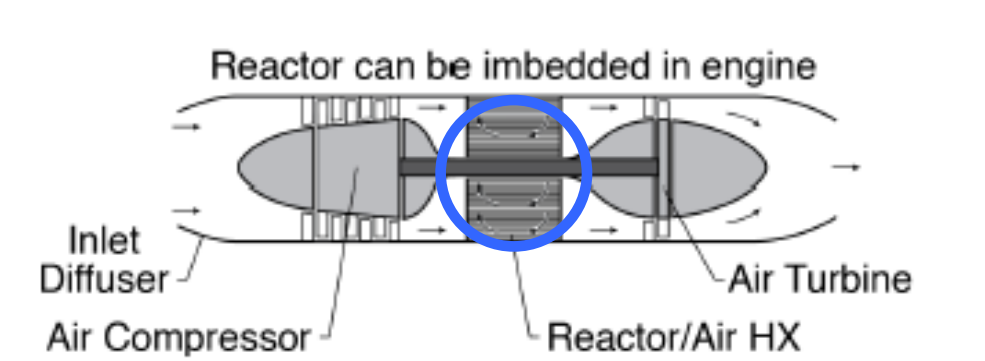


Figure 9: Schematic diagram of turbojet engine with heat exchanger[11]

[11]Wachtl, W., and Rom, F., "Analysis of Liquid-Metal Turbojet Cycle Propulsion of Nuclear Powered Aircraft", NACA Research Memorandum E51D30, Nov. 1951.

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[12]	
Reactor Power Level (MW)	230
Rated Thrust (lb)	84,800
Bypass Ratio	8.4
Turbine Inlet Temperature, Cruise (deg. F)	1600
Total Nuclear System (lb)	391,400
Core Lifetime (hr)	10,000
Coolant	Lithium

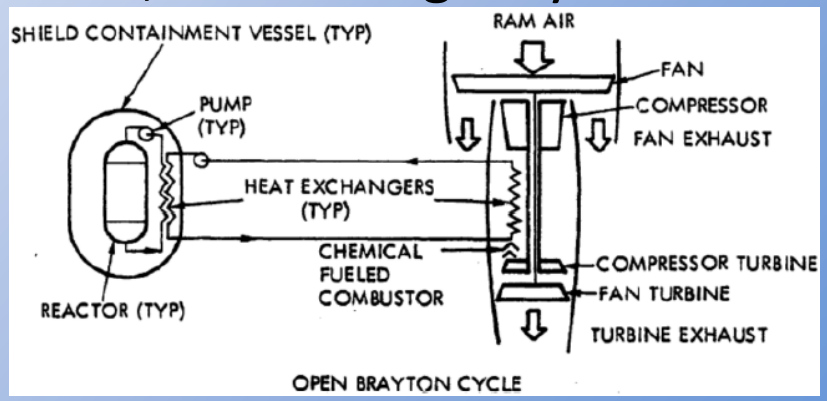


Figure 10: Open Brayton Cycle nuclear aircraft propulsion system schematic from 1977 Lockheed-Georgia report[12]

[12]Muehlbauer, J. C., Byrne, D. N., Craven, E. P., Randall, C. C., Thompson, S. G., Thompson, R. E., Pierce, B. L., Ravets, J. M., and Steffan, R. J., "Innovative Aircraft Design Study, Task II: Nuclear Aircraft Concepts", ADB017795, April 1977, Lockheed-Georgia Company, Marietta, GA.

Propulsion Systems

Brayton Cycle Engine Model:

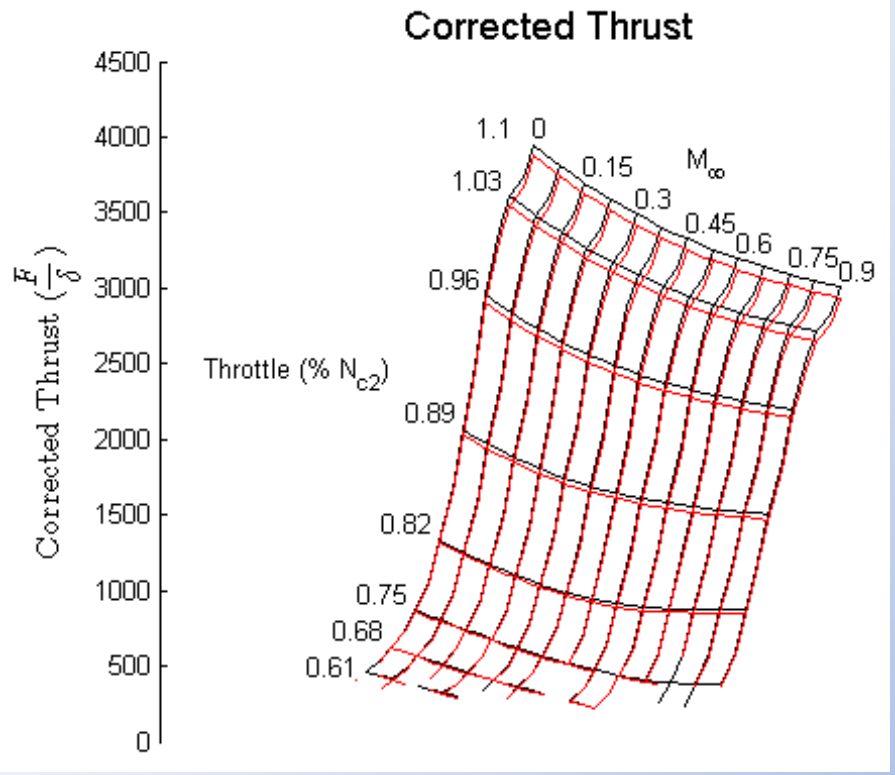
- Built a turbojet model - based off GE J85
- On design
  - Scaled compressor and turbine maps to desired performance
- Off design
  - Built operating lines for each Mach number
  - Mach and altitude engine performance for mission analysis
- Heat exchanger design
  - On design solves for engine and heat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

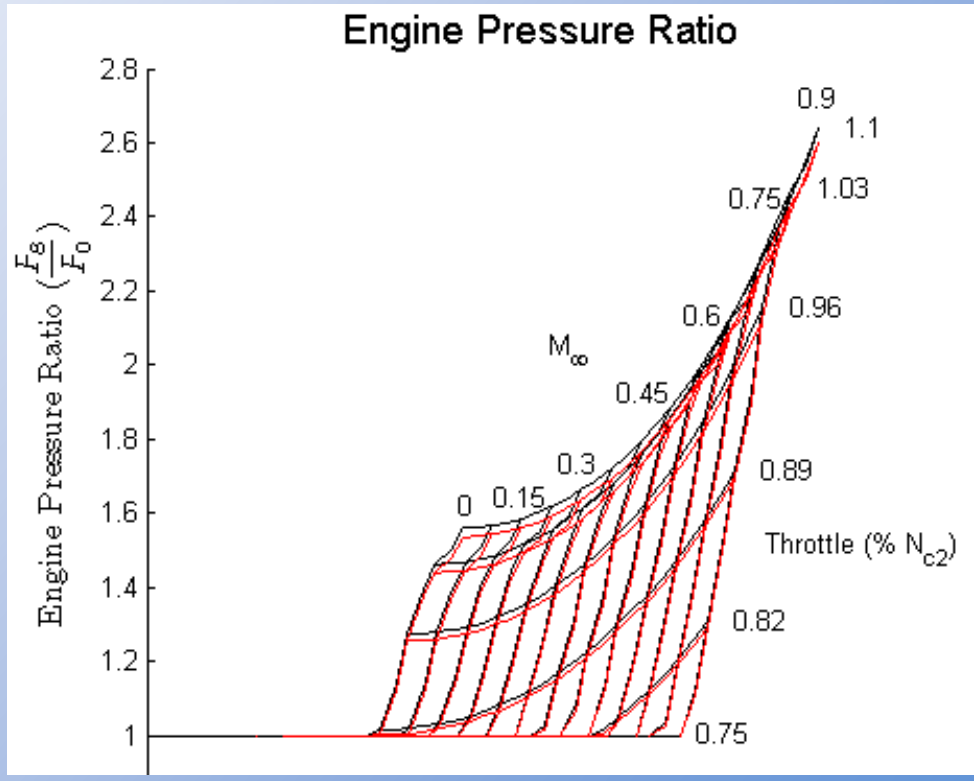
Propulsion Systems

Engine Model with Heat Exchanger Design Point:

	Gas Turbine	Heat Exchanger
Mach	0	0
Altitude (ft)	0	0
Mass Air Flow (lbm/sec)	50	50
T_{04} (R)	1,970	1,970
Engine Output		
Thrust (lb)	3,462	3,325
A_2 (ft^2)	1.36	1.36

Propulsion Systems





Combustor Engine

Heat Exchanger

- 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

Propulsion Systems

6. Brayton Cycle - Ramjet

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

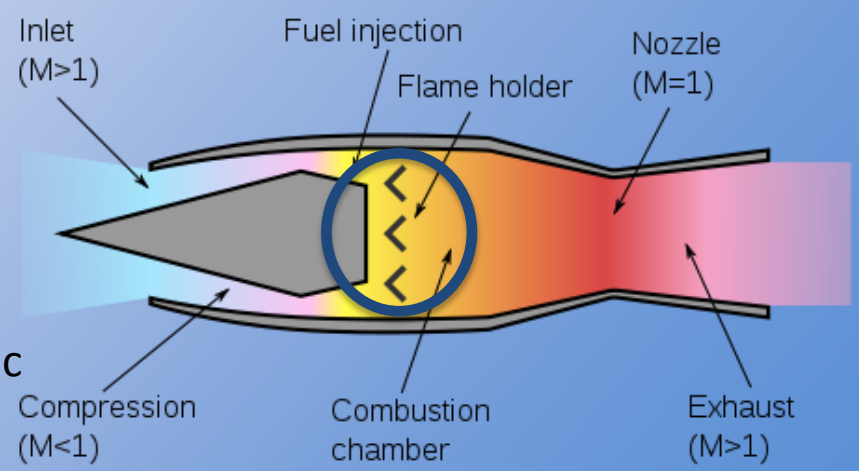


Figure 11: Schematic diagram of a ramjet engine[13]

[13]Vector image made by Cryonic07. Source png-drawing was made by Emoscopes and later slighly modified by Wolfkeeper, 2008.

Propulsion Systems

Brayton Cycle - Ramjet

- Lippisch P13[14]
  - 1944 ramjet powered interceptor
  - Liquid fuel rocket to altitude
  - Powder coal fed ramjet
- Leduc 0.10[16]
  - 1946 liquid fueled ramjet
  - Carried to altitude by Sud-Est SE-161 Languedoc transport

Figure 12: Lippisch P.13a ramjet powered interceptor[15]

Figure 13: Leduc 0.10 ramjet aircraft[16]

[14]Johnson, D., "Li P.13a", http://www.luft46.com/lippisch/lip13a.html, [internet database], 2014.

[15]"A Lippisch P13a szuperszonikus vadászgép", http://www.jetfly.hu/rovatok/jetfly/cikkiropalyazat/palyazat_04.10.25./, [internet database], 2014

[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[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

Figure 14: Mounted on a railroad car, Tory-IIC is ready for its highly successful May 1964 test[17]

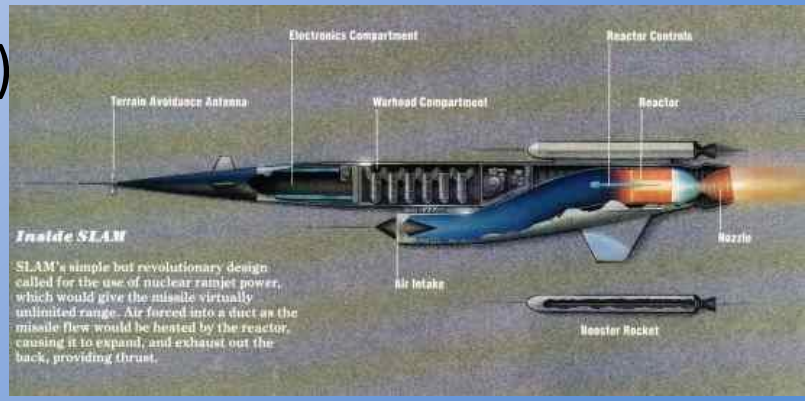


Figure 15: SLAM schematic[17]

[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[16]

- High level aircraft system exploration
- Aid in propulsion system selection for a given mission

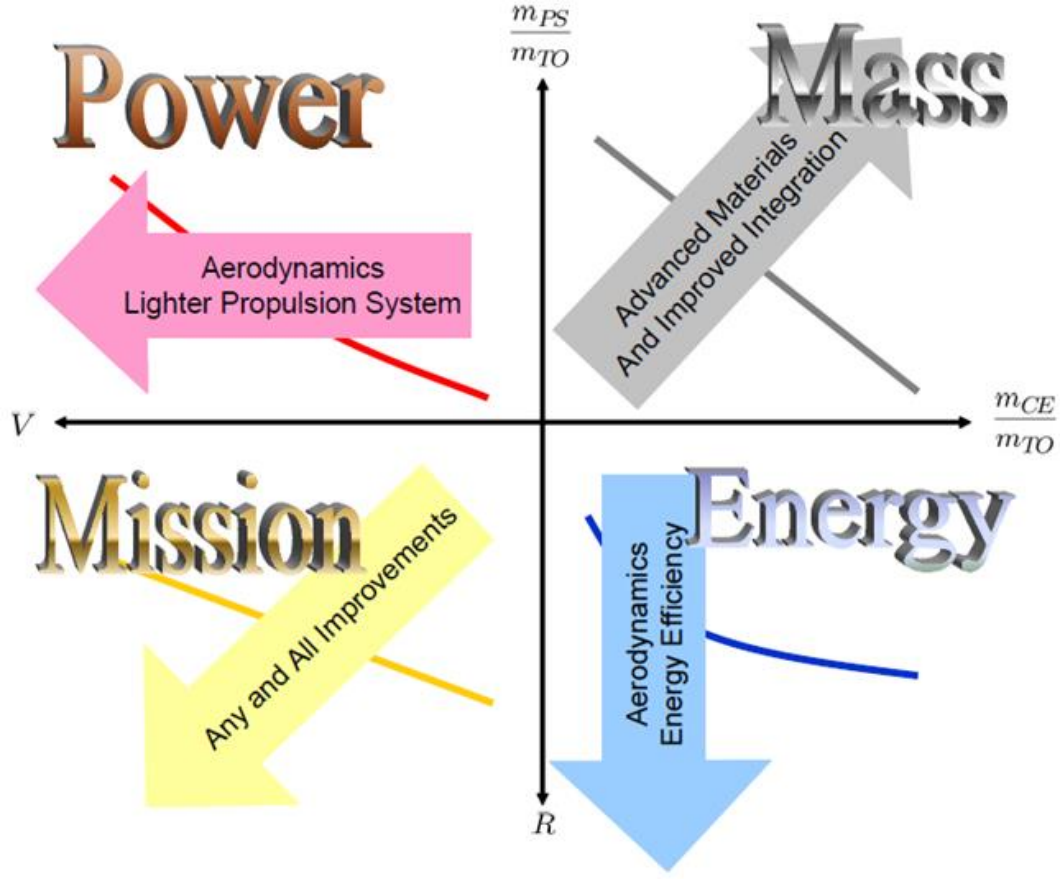


Figure 16: Illustration of a notional NAM ratio diagram[18]

[18]Nam, T., "A Generalized Sizing Method for Revolutionary Concepts Under Probilistic Design Constraints", Ph.d. Diss., May 2007.

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

[19]Nickol, C. L. , Guynn, M. D. , Kohout, L. L. , and Ozoroski, T. A., "High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development", TP-2007-214861, March 2007, NASA, Langley, VA.

Design Space Exploration

NASA Aeronautics Research Institute

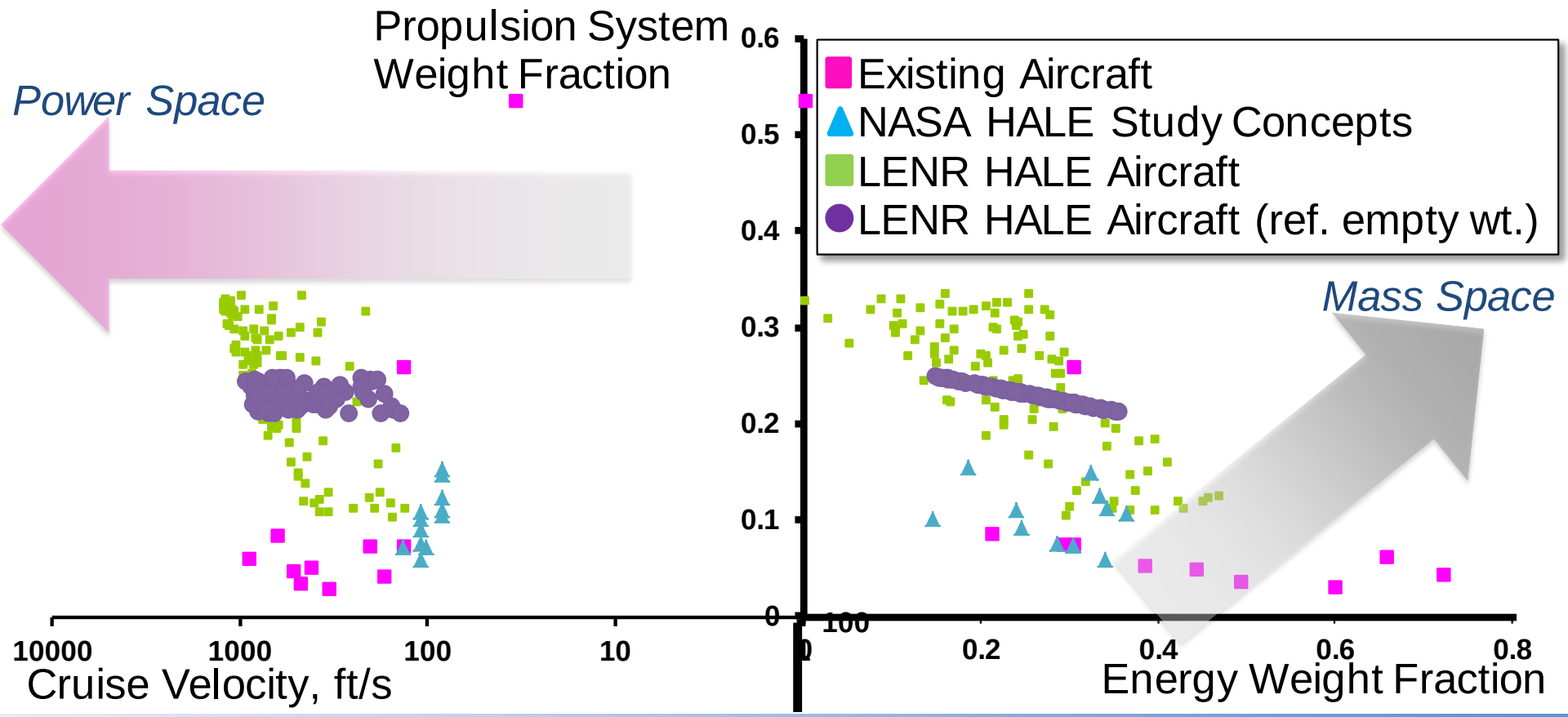


Figure 17: NAM ratio diagram of existing high altitude and long endurance vehicles, solar regenerative aircraft from a NASA study, and notional LENR powered aircraft[20]

[20]Wells, D., "The Application of LENR to Synergistic Mission Capabilities", Submitted for publication and presentation at AIAA Aviation 2014 Conference.

Design Space Exploration

NASA Aeronautics Research Institute

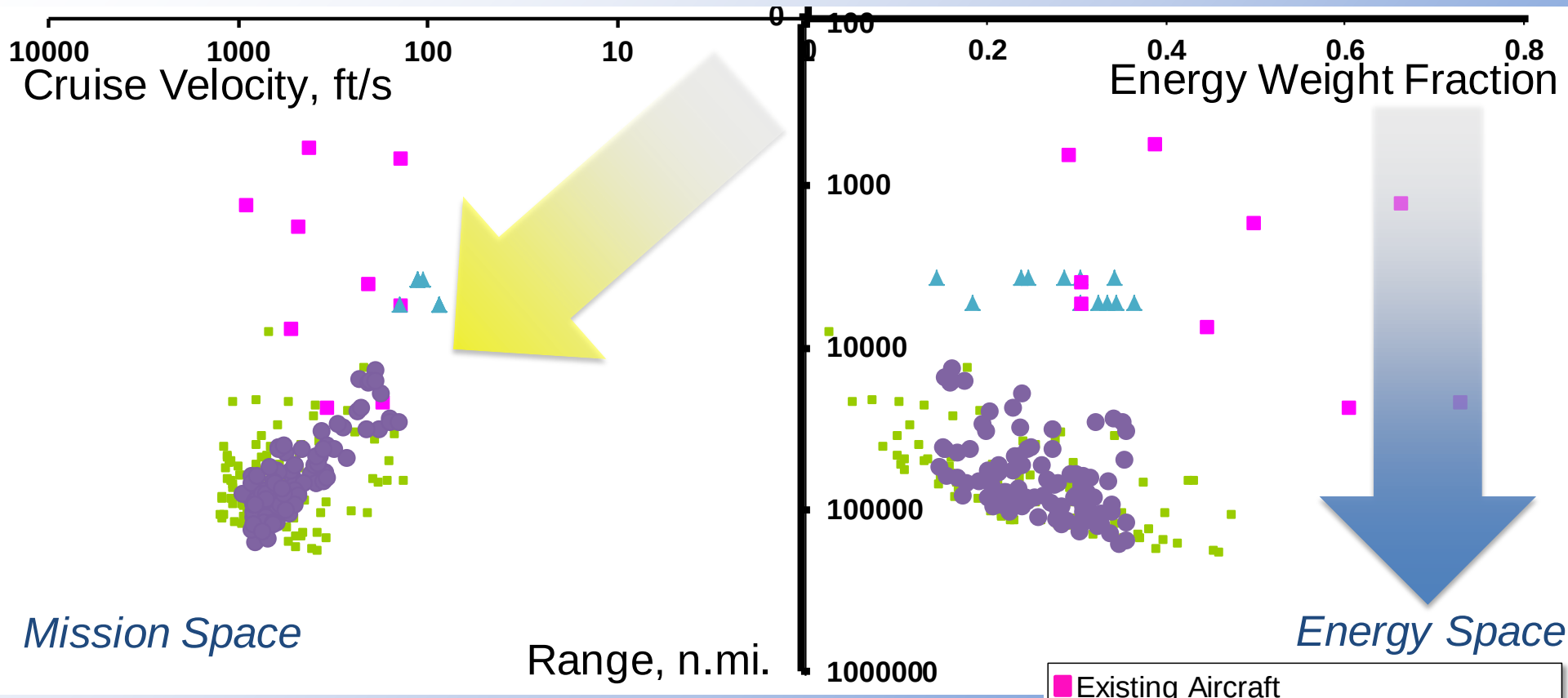


Figure 18: NAM ratio diagram of existing high altitude and long endurance vehicles, solar regenerative aircraft from a NASA study, and notional LENR powered aircraft[20]

[20]Wells, D., "The Application of LENR to Synergistic Mission Capabilities", Submitted for publication and presentation at AIAA Aviation 2014 Conference.

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[19]

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

[19]"Phantom Eye", http://www.boeing.com/boeing/bds/phantom_works/phantom_eye.page, [internet database], 2014.

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

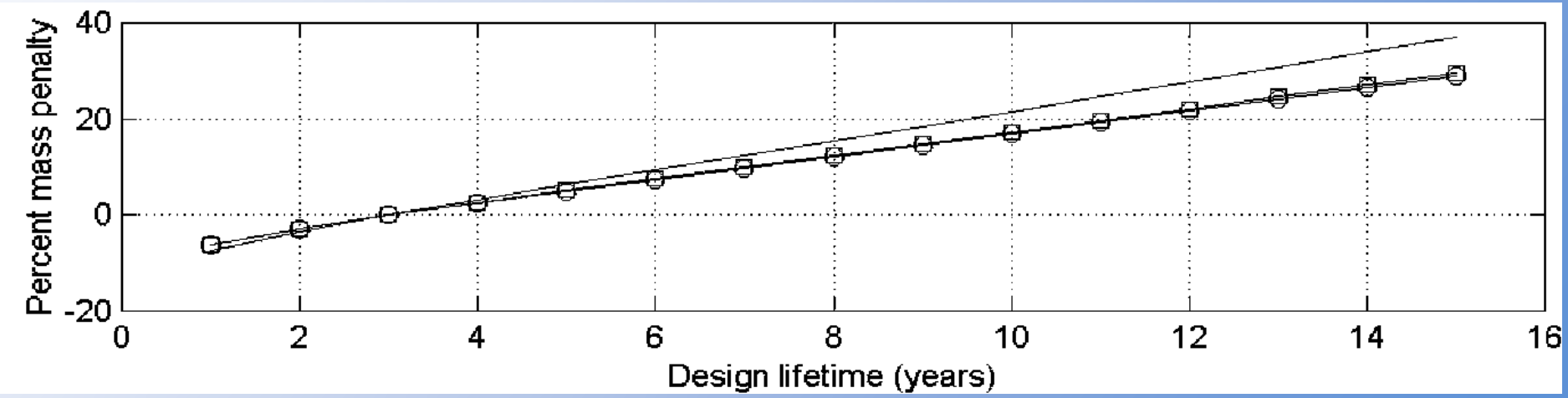


Figure 19: Spacecraft percent mass penalty as a function of the design lifetime[21]

[21]Saleh, J. H., Hastings, D. E., and Newman D. J., "Spacecraft Design Lifetime", AIAA Journal of Spacecraft and Rockets, Mar. 2002.

Aircraft

Cluster Wing

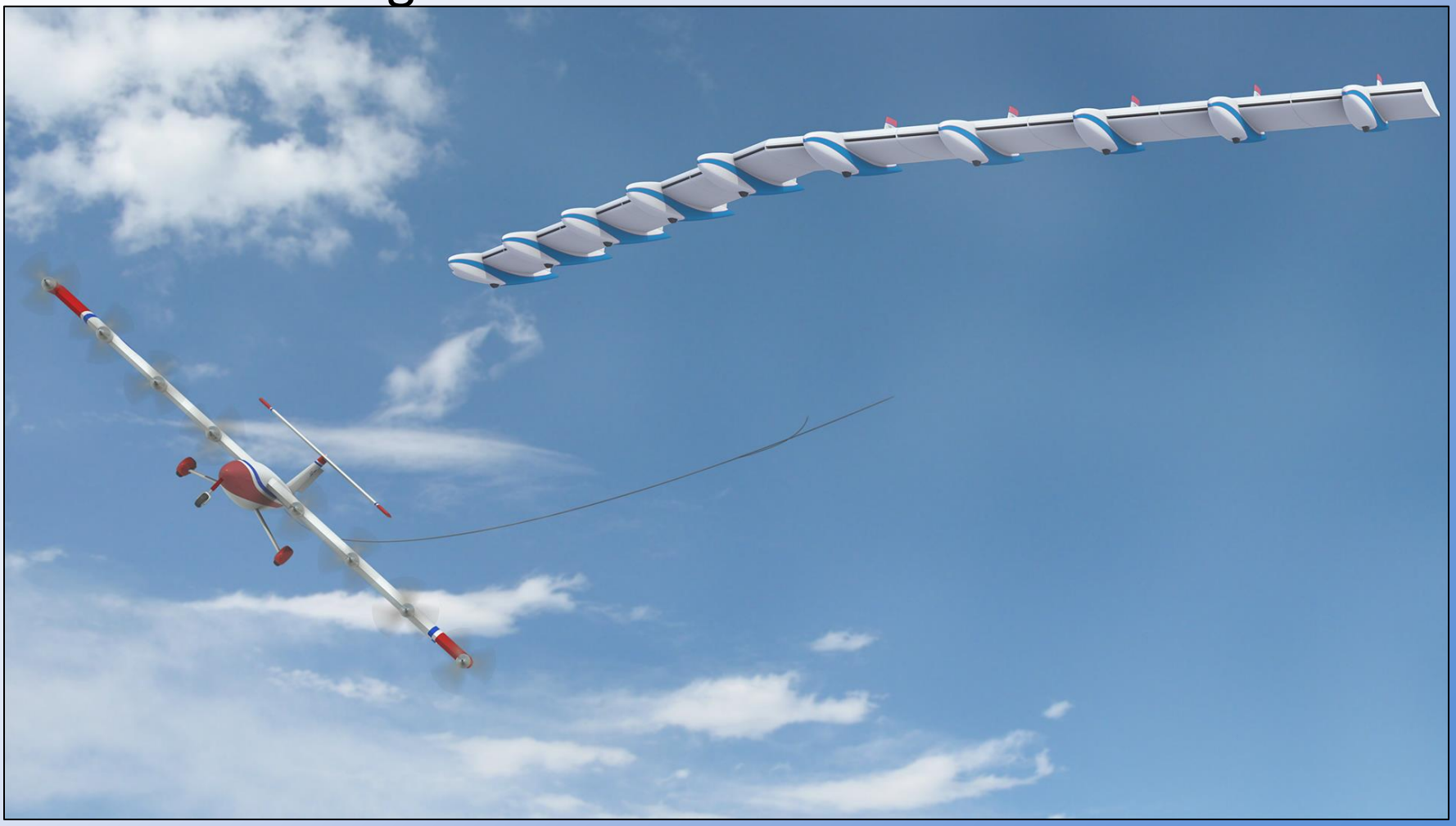
- Reduced induced drag when together
- Distributed sensor network, ordinance delivery, environmental missions
- ~ 0.5 Mach

Aircraft

Cluster Wing

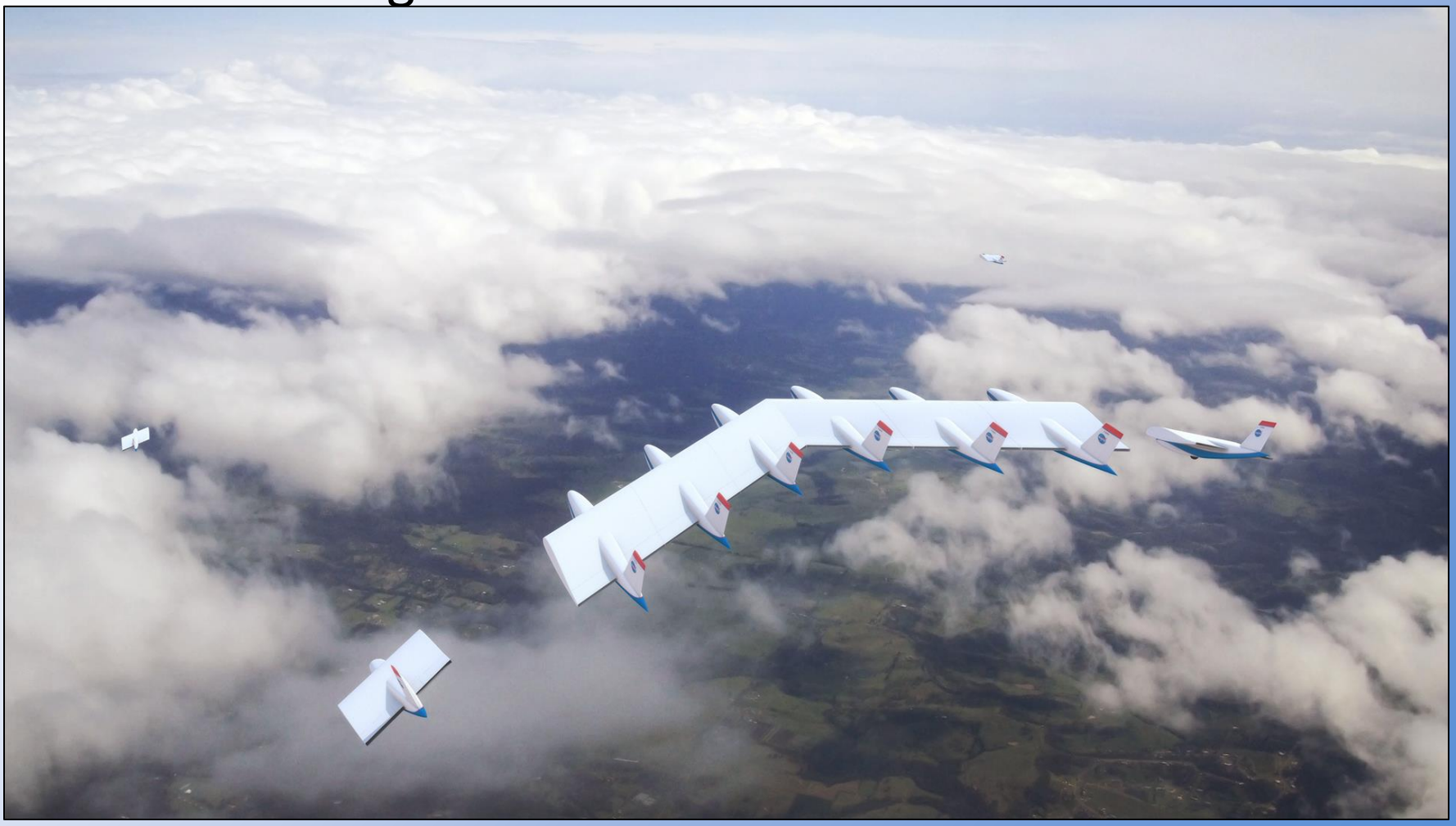
Aircraft

Cluster Wing



Aircraft

Cluster Wing



Missions

Low Supersonic[22,23]

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

[22]Nisen, M., "Elon Musk Admits There's A Much Better Way Of Moving People Long Distances Than The Hyperloop", Business Insider, Aug. 2013.
[23]Welge, H. R., Bonet, J., Magee, T., Tompkins, D., Britt, T. R., Nelson, C., Miller, G., et al., "N+3 Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period", NASA CR-2011-217084, April 2011.

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
- ~ 10,000 nm mission (4-5 days)
- > 150 kt cruise

[24]Cole, W., "The Pelican: A big bird for the long haul," Boeing Frontiers online, Vol. 1, No. 5, Sept. 2002.

Aircraft

Wing-in-Ground Effect

- ~ Panamax dimensions (965 ft x 106 ft)[25]

	Design Goals
Payload Capacity	32 Containers
TOGW (lb)	4.65 M
Wing Loading (lb/ft^2)	130
Wing Area (ft^2)	35,700
Wing Span (ft)	490

[25] "Vessel Requirements," Autoridad Del Canal De Panama, MR NOTICE TO SHIPPING No. N-1-2005, Jan. 2005.

Aircraft

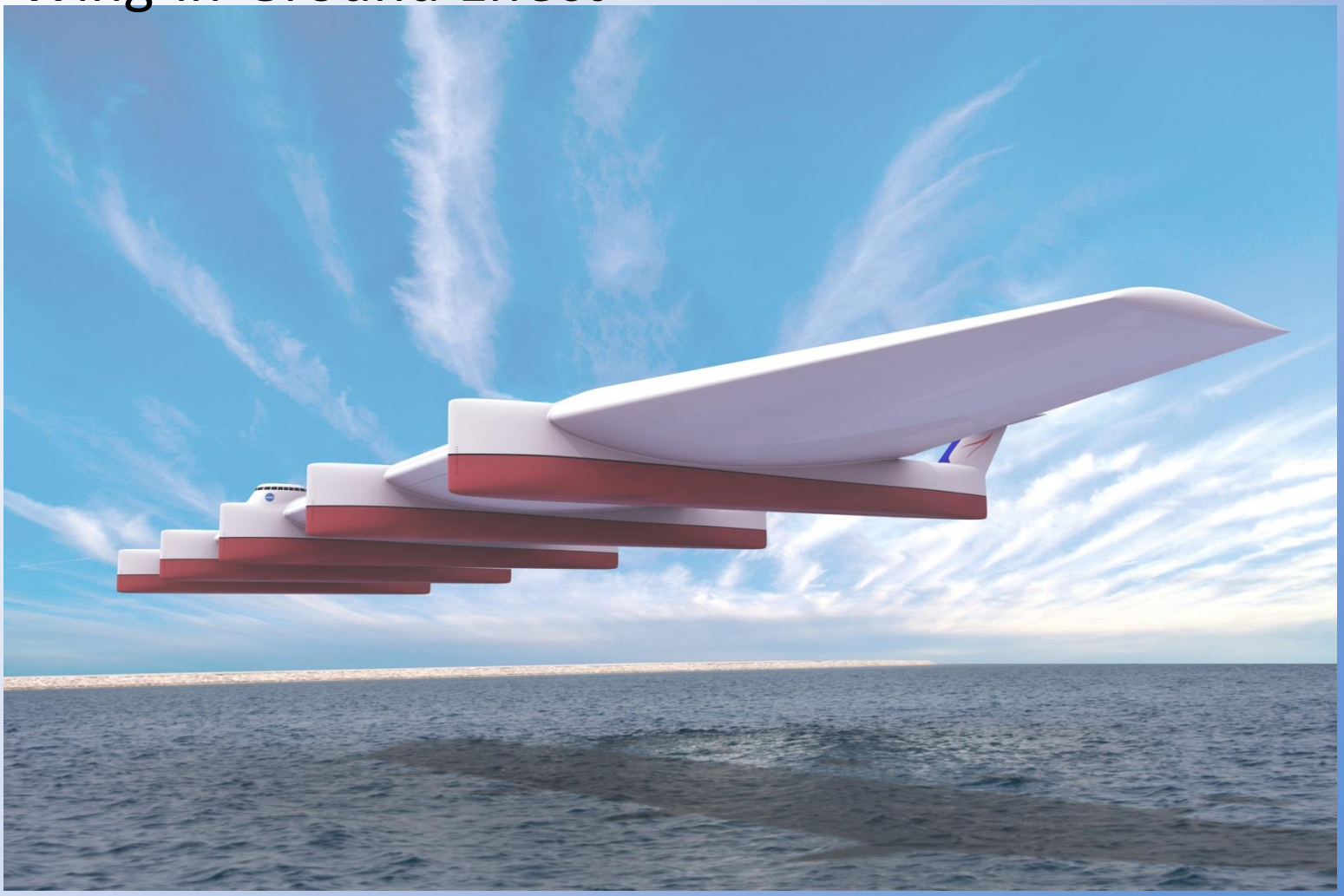
Wing-in-Ground Effect

Aircraft

Wing-in-Ground Effect

Aircraft

Wing-in-Ground Effect



Missions

Small Runway Independent (RI) Transport[2]

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

Comfortable Global Transport[2]

- Disruptive change to transportation business model
- Global range : 12,500 miles
- Subsonic/transonic
- Level of comfort based on ft^2/passenger metric

[2]McDonald, R. A., "Impact of Advanced Energy Technologies on Aircraft Design", AIAA Conference Paper 2014-0538, Jan. 2014.

Aircraft

Cargo

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

	Design Goals[25]
Payload (lb)	600,000
Nuclear Subsystem (lb)	446,290
TOGW (lb)	2,154,392
Wing Loading (lb/ft^2)	120
Wing Area (ft^2)	17,351

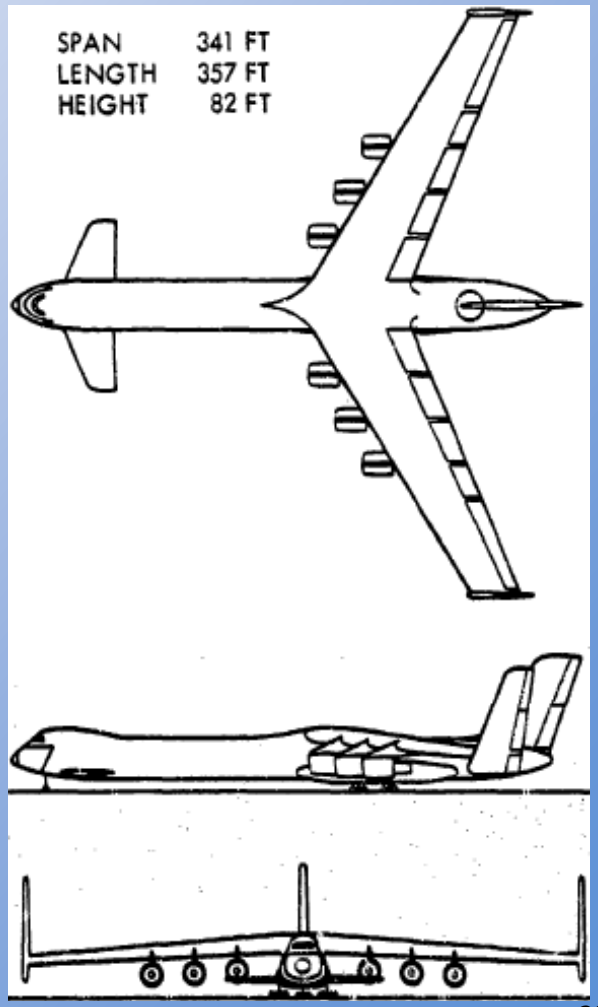


Figure 20: Refined Canard Configuration from 1977 Lockheed-Georgia report[25]

[25]Muehlbauer, J. C., Byrne, D. N., Craven, E. P., Randall, C. C., Thompson, S. G., Thompson, R. E., Pierce, B. L., Ravets, J. M., and Steffan, R. J., "Innovative Aircraft Design Study, Task II: Nuclear Aircraft Concepts", ADB017795, April 1977, Lockheed-Georgia Company, Marietta, GA.

Aircraft

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

	Design Goals
Payload	150 passengers
Cargo System Weight (lb)	100,000
TOGW (lb)	637,000
Feeder Aircraft	
Payload	8 passenger
TOGW (lb)	8,000

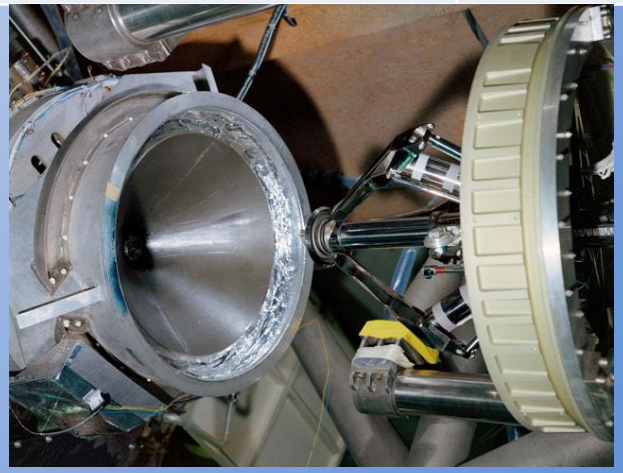
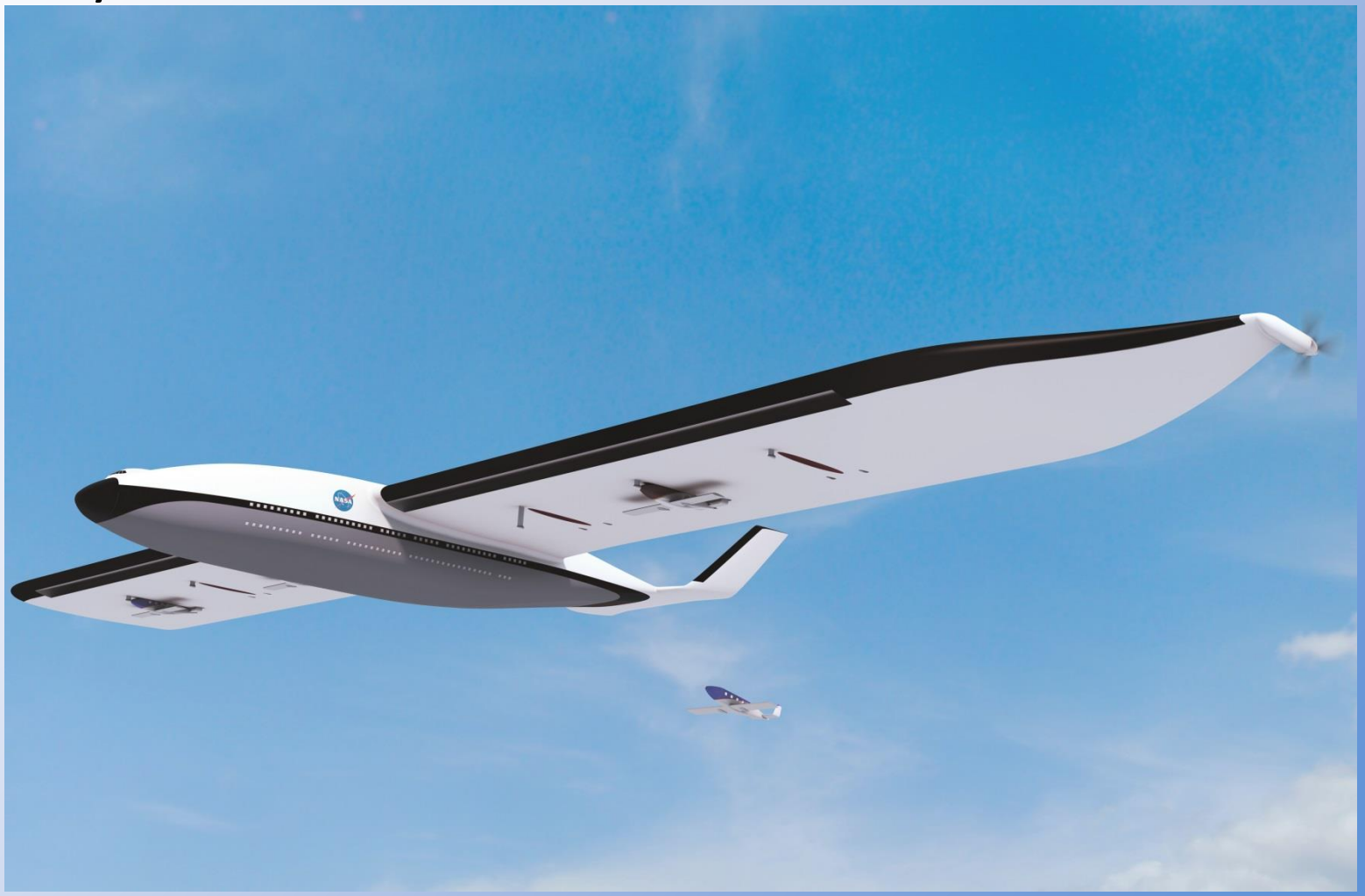


Figure 21: Docking system of the Apollo spacecraft[26]

[26]"Apollo Imagery: S68-50869 (1968)", http://spaceflight.nasa.gov/gallery/images/apollo/apollo9/html/s68-50869.htmls, 2014.

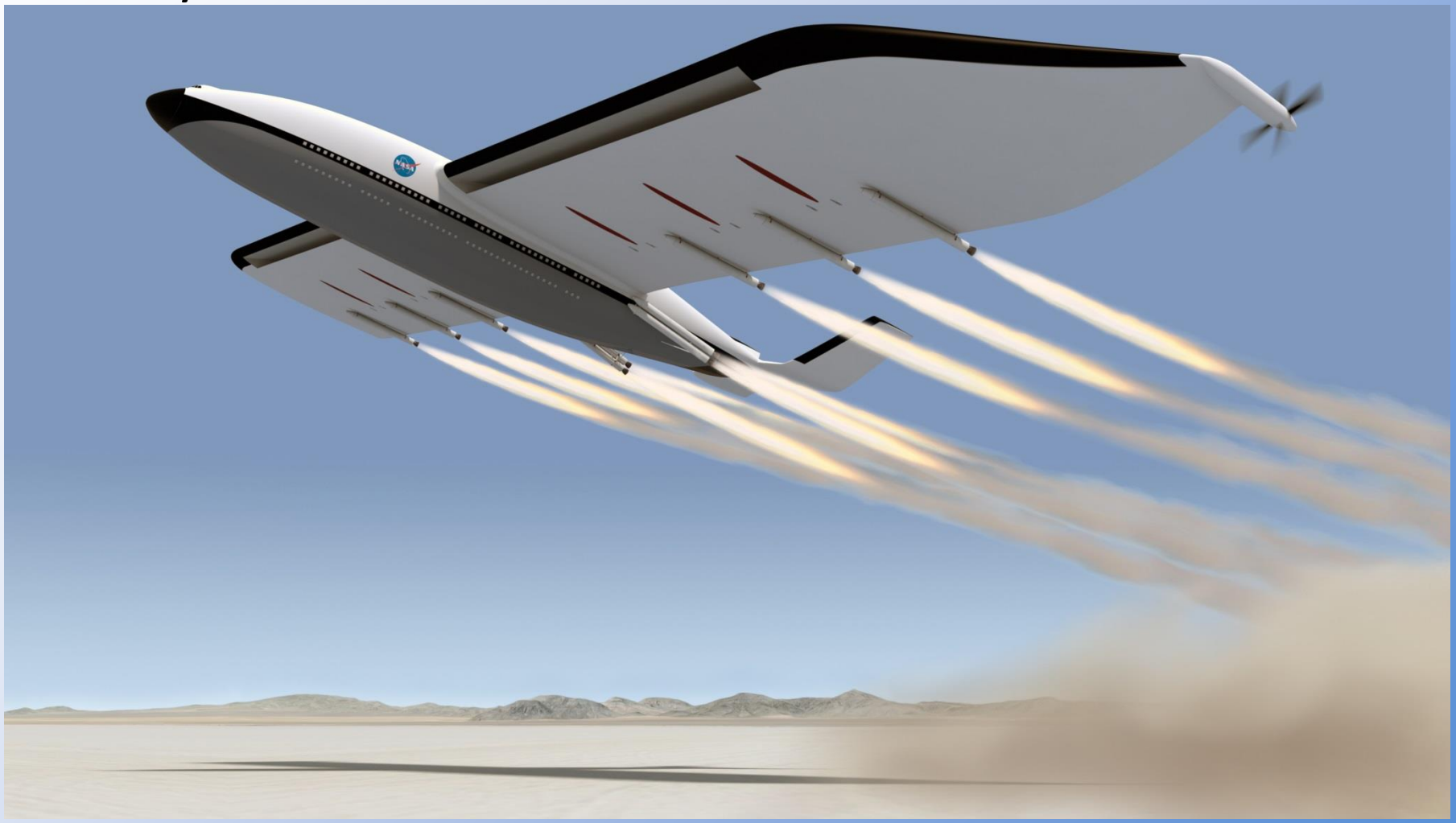
Aircraft

Sky Train



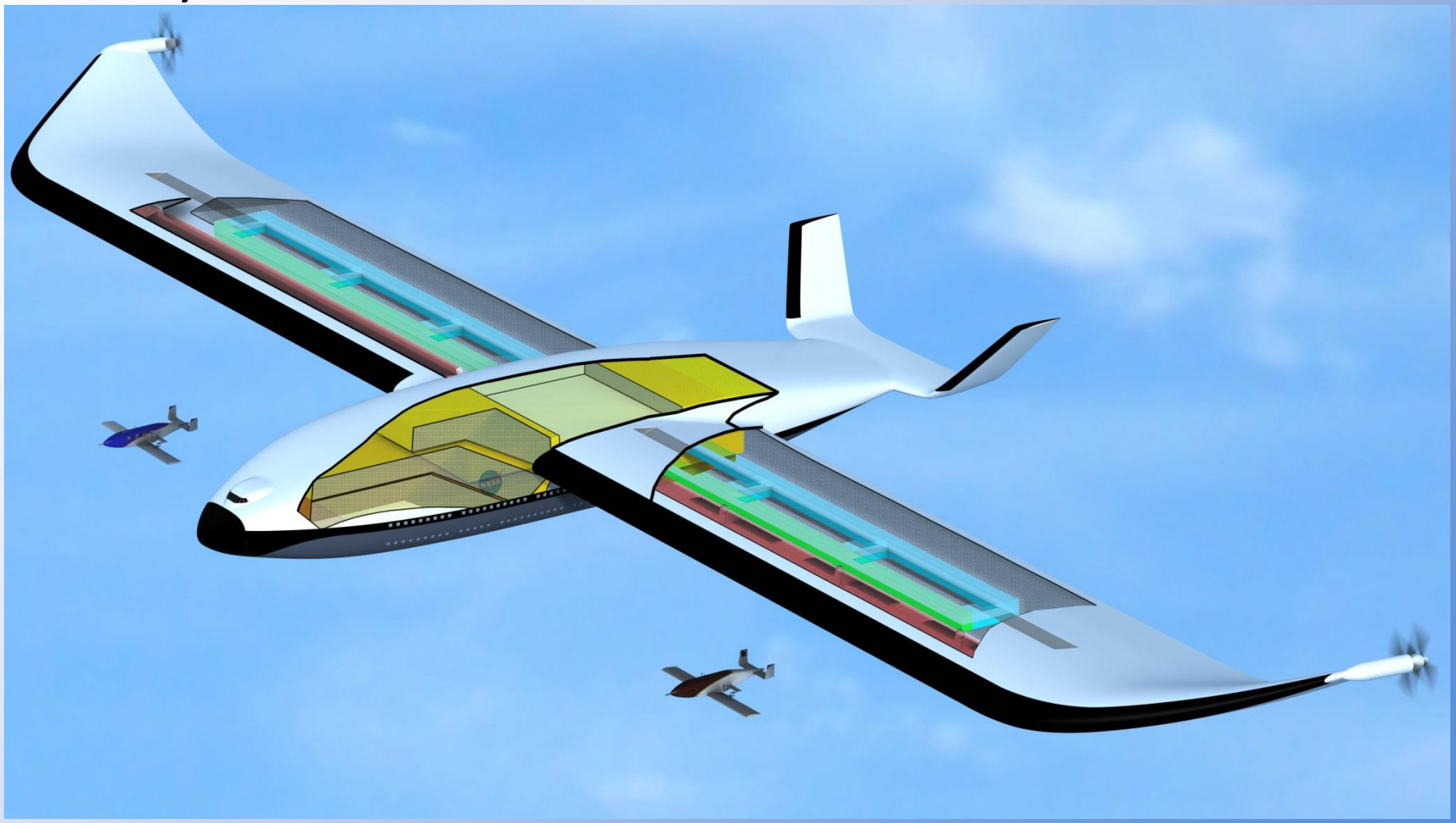
Aircraft

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
- McDonald, R. A., “Impact of Advanced Energy Technologies on Aircraft Design”, AIAA Conference Paper 2014-0538, Jan. 2014.
- 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