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14. ABSTRACT
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Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept Development

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Boeing Research and Technology, Huntington Beach, California

May 2012

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Abstract

This final report documents the work of the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team on Task 1 of the Phase II effort. The team consisted of Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech.

Using a quantitative workshop process, the following technologies, appropriate to aircraft operational in the N+4 2040 timeframe, were identified: Liquefied Natural Gas (LNG), Hydrogen, fuel cell hybrids, battery electric hybrids, Low Energy Nuclear (LENR), boundary layer ingestion propulsion (BLI), unducted fans and advanced propellers, and combinations. Technology development plans were developed.

The team generated a series of configurations with different combinations of some of these technologies. The higher heating value of LNG reduces the weight of fuel burned, but because of heavier aircraft systems, more energy is used for a given flight. LNG fueled aircraft have the potential for significant emissions advantages and LNG enhances the integration of fuel cells into the aircraft propulsion and power system.

An unducted fan increases propulsive efficiency and reduces fuel burn. Adding a fuel cell and electric motor into the propulsion system also leads to improvements in emissions and fuel burn. An aft fuselage boundary layer propulsor also resulted in a fuel burn benefit.

Foreword

Part of the mission of Boeing Research & Technology, as the company's advanced, central research and technology organization, is to help create the long-term future of aerospace by identifying and maturing new technologies.

However, while Boeing is interested in developing environmentally progressive vehicles, it would be premature to conclude that any of the concepts studied under this contract will replace any of Boeing's commercial products.

This is an advanced concept and technology study that examines a wide variety of alternative fuel and energy technologies and is not an offer, commitment or promise on the performance or capabilities of any future Boeing product.

Acknowledgments

This project and report reflect the combined efforts of the SUGAR Task 1 team. The team members for this task are Boeing Research and Technology, Boeing Commercial Airplanes, GE Aviation, and the Georgia Institute of Technology. The coordinated effort of this team has produced this report.

The team would like to thank Erik Olson and Mark Guynn of the NASA Langley Research Center for their guidance as the NASA Contracting Officer Technical Representative (COTR), and task technical advisor (TA), respectively. The team would also like to thank Gerry Brown, a NASA subject matter expert, for his contribution.

Additionally, other experts from NASA, the Department of Energy, the Air Force Research Lab, the Federal Aviation Administration, and Virginia Tech contributed during the N+4 technology workshop or made suggestions for the Energy Study Outline.

Table of Contents

- All concepts discussion and ranking
- Identification of most promising concept/technology to take forward in the analysis
- Workshop wrap up and next steps

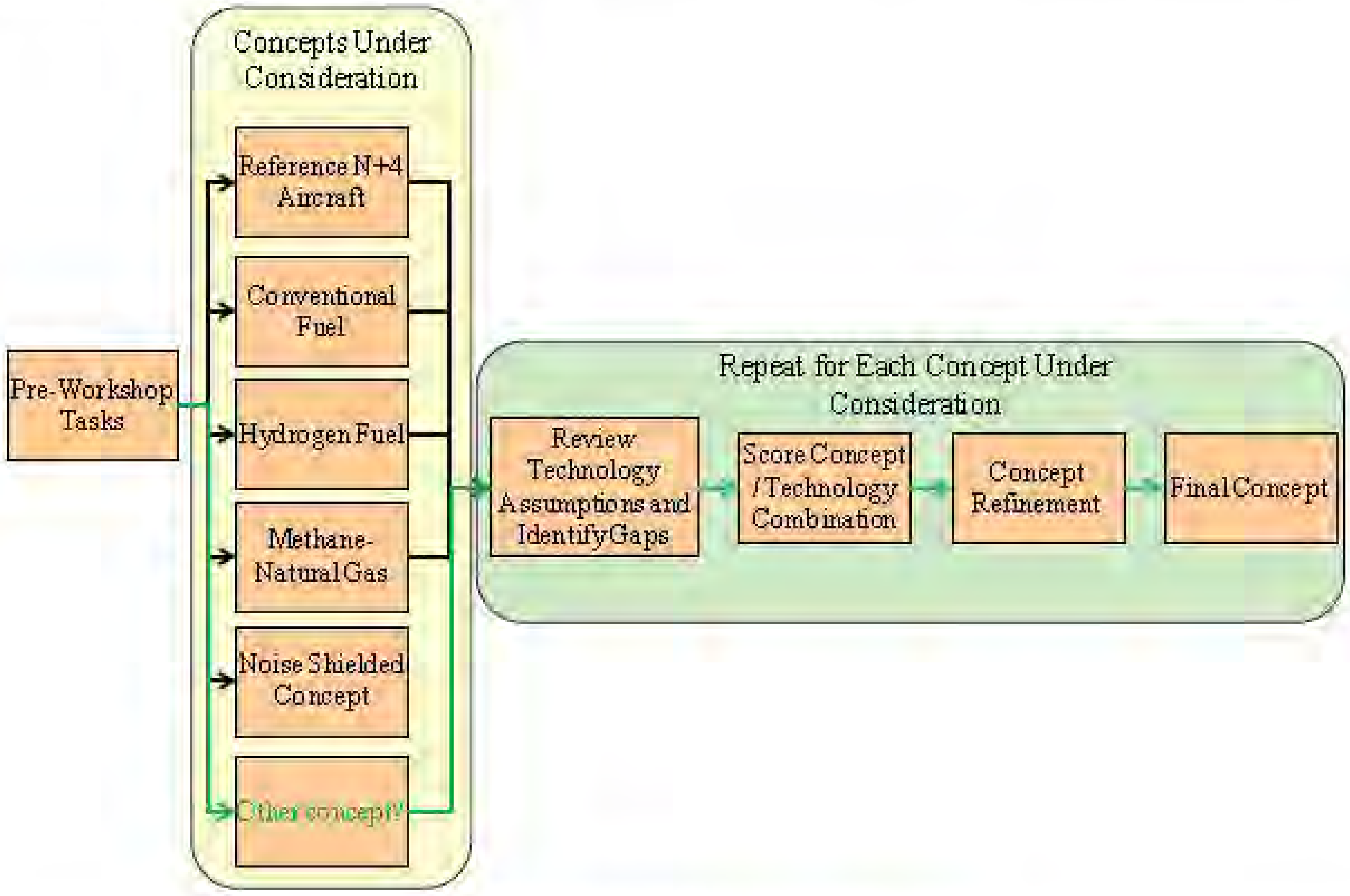


Figure 2.4 – N+4 Workshop Process Diagram

To facilitate the sub-team scoring, a spreadsheet template was developed and included a qualitative scale for the metrics under consideration and each team would independently score each concept. A snapshot of the template is depicted in Figure 2.5. Each team was instructed to score each concept against the metrics. The scales utilized for the metrics were developed by the whole team prior to the workshop and are defined in Table 2.1. The concepts to be scored included:

0. Scoring is relative to SUGAR Free Baseline (737NG Equivalent)
1. Reference airplane
2. Conventional fuel/hybrid electric concept
3. Hydrogen fuel concept (H_2 Burning)
4. Methane-natural gas concept (CH_4 Burning)
5. Fuel cell concept (H_2/FC Battery Hybrid)
6. Team selected alternate concepts, including:
    a. Distributed Propulsion
    b. Low Energy Nuclear Reactor (LENR)
    c. H2/FC Gas Turbine Hybrid
    d. Dual fuel H2/Jet-A burner

Virtual West, the members of each are listed in Table 2.2. The Onsite team was facilitated by Jimmy Tai (GT), the Virtual East by Marty Bradley (Boeing) and Michelle Kirby (GT), and the Virtual West by Blaine Rawdon (Boeing).

Table 2.2 – N+4 Workshop Teams

On Site Team	Virtual West Team	Virtual East Team
Bradley, Marty (Boeing)	Allen, Timothy (Boeing)	White, Edward (Boeing)
Daggett, David (Boeing)	Cotes, Dwaine (Boeing)	Gowda, Srini (GE)
Droney, Christopher(Boeing)	Guo, Yueping (Boeing)	Brown, Gerald (NASA)
Hoisington, Zachary (Boeing)	Foist, Brian (Boeing)	Wahls, Richard (NASA)
Kirby, Michelle (GT)	Rawdon, Blaine (Boeing)	Wells, Doug (NASA)
Murrow, Kurt (GE)	Wakayama, Sean (Boeing)	Jeffries, Rhett (FAA)
Ran, Hongjun (GT)	Dallara, Emily (Boeing)	Felder, James (NASA)
Nam, Teawoo (GT)	Kowalski, Ed (Boeing)	Schetz, Joe (VT)
Tai, Jimmy (GT)	Wat, Joe (Boeing)	Burley, Casey (NASA)
Hammel, Jeff (GE)	Robbana, Ismail (Boeing)	Sequiera, Christopher (FAA)
Perullo, Chris (GT)	Barmichev, Sergey (Boeing)	Martin, John (NASA)
Guynn, Mark (NASA)	Fink, Larry (Boeing)	Kapania, Rakesh (VT)
Olson, Erik (NASA)	Sankrithi, Mithra (Boeing)	
Leavitt, Larry (NASA)		

The workshop began with an overview of the process that would be used for its duration and to put everyone on the same page as to what their roles and expectations for participation were. A review of the definitions of the metrics to score was discussed and clarification questions were asked by a few participants to gain a clear understanding of what each metric implied. Subsequently, to facilitate an understanding of the concepts to score in the workshop, Boeing reviewed the general assumptions of the N+4 reference concept (Figure 2.6) and then each of the advanced concepts to be scored within the workshop. This information provided a common understanding for each team and an opportunity to ask any clarification questions before the larger group broke into sub-team activities.

        - Conversion of electricity to shaft power (50% at gate then 50% on shaft)
    - Advantages
        - Pumping system in place at gate
        - Easier averaging of the power load on grid: off peak storage – cheaper
        - Less technology risk once we know how to store safely on airplane
        - If electricity were green and free, this might be the best?
- Fuel cell concept (H2/FC Battery Hybrid)
    - Concerns:
        - Battery life time
        - Battery performance (can it be achieved)
        - Weight
        - Requires development of two different energy source technologies
    - Advantages
        - Easier averaging of the power load on grid (using H2): off peak storage – cheaper
        - Easier to capture water at altitude

The group continued the discussion of the individual scoring for additional concepts added by group members: Concepts 7, 8, and 9, which were the distributed propulsion (DP), low energy nuclear reactor (LENR), and the turboprop concepts respectively. For Concept 7, the group assumed incremental improvements over the N+4 reference concept and identified that there may exist some technical risks associated with the DP implementation. Consensus was drawn on the key technologies to enable and/or enhance the concept and included:

- BLI – Some concern over technology risk (how well will it really work?)
- Wing tip propulsor integration to reduce induced drag
- Low loss mechanical or electrical power distribution

Concept 8 (LENR) had the same issue with being able to draw the boundary on energy. The group identified that the LENR concept could have tremendous benefits, but the technical risks are extremely high. Lastly, Concept 9 (turboprop) also showed some benefit over the N+4 reference concept, but the group identified that a low noise propeller design was needed. The team then compared the three concepts side by side and concluded:

- LENR nuclear has important advantages, but extremely high risk – if it works, revolutionary to World energy
- DP distributed propulsion is enhancing to multiple concepts if it works as advertised
- TP turboprop scorers were worried about noise

Table 2.3 – Virtual West Team Technologies per Concept

Concept	Technologies
N+4 Reference Airplane	Composite structure Laminar flow Riblets Efficient engines Quiet landing gear and high lift system
Conventional fuel/hybrid electric concept	N+4 Reference technologies Strut braced wing Batteries Hybrid-electric-gas-turbine engines Use more battery power for takeoff noise & LTO emissions
Hydrogen fuel concept (pure H2 burner)	N+4 Reference technologies Hydrogen propulsion system Clean, large-scale hydrogen production Could be strut-braced high wing
Methane-natural gas concept (pure CH4 burner)	N+4 Reference technologies Methane-natural gas propulsion system Methane storage infrastructure Could be strut-braced high wing
Fuel cell concept (H2/FC Battery Hybrid)	N+4 Reference technologies Hydrogen propulsion system Fuel cells Electric motors Batteries Clean, large-scale hydrogen production Could be strut-braced high wing
SUGAR High TurboProps with Jet A	N+4 Reference technologies High-speed propellers Quiet propellers Efficient turboshaft engine Strut-braced wing
SUGAR High TurboProps with Pure H2 burner	SUGAR High Turboprop technologies Hydrogen Fuel Concept technologies
SUGAR High TurboProps with H2/FC Battery Hybrid	Hydrogen Fuel Cell Concept technologies SUGAR High Turboprop technologies Variable speed propellers because of electric motor drive*
SUGAR High TurboProps with Pure battery-electric	SUGAR High Turboprop technologies Electric motors Batteries (especially important for this concept) Variable speed propellers because of electric motor drive*
LENR-powered via heat turbines	LENR Flight weight Conversion of heat to mechanical power Electric generation via gas or steam turbine? Hot fluid transfer to heat exchanger in core? Possible need for radioactive shielding

Concept	Technologies
Distributed Propulsion Hybrid-Electric	Hybrid Electric Concept Propulsion integration Efficient flight weight electric generator Explore more battery power to reduce LTO emissions and noise Explore reduced fan pressure ratio Explore reduced mixing length from small diameter nacelles
Dual Fuel H2/Jet-A	N+4 Reference technologies Hydrogen / Jet-A propulsion system Clean, large-scale hydrogen production

* propulsive efficiency and acoustic benefit

The Virtual West team also identified the same general issues as the Virtual East team in the understanding of the control volume for the block energy scoring. The West team also identified that a life cycle energy study should be conducted for the various energy sources.

As a result of the Virtual West breakout team, the group provided the scores and rankings (with risk included) of each concept to the larger group as depicted in Figure 2.9. Concepts that had only 1 scorer were eliminated since there was insufficient input. As with the Virtual East team, the West team identified that the LENR concept provided the highest payoff.

Person 1	Concept Names	Block Energy	Global Emissions	LTO Emissions	Noise	Cost	Technology Maturity Risk	Final Score with risk
Concept #	Weighting factor	3	3	1	1	1	0.666666667	
0	Sugar Free							0
1	N+4 Reference Airplane	4.50	5.05	5.38	1.13	2.17	10.33	44.22
2	Conventional fuel/hybrid electric concept	6.03	6.62	6.33	1.55	0.75	6.33	50.91
3	Hydrogen fuel concept (pure H2 burner)	4.22	5.80	8.42	1.68	1.32	5.17	44.91
4	Methane-natural gas concept (pure CH4 burner)	4.37	5.17	8.12	1.58	2.22	6.67	44.56
5	Fuel cell concept (H2/FC Battery Hybrid)	3.80	5.33	9.00	1.88	-0.35	3.67	40.38
6	**SUGAR High TurboProp (Jet A)**	6.00	6.00	7.00	2.00	2.67	8.67	52.33
7	**LENR-powered via heat turbines**	5.50	8.50	8.00	2.50	0.00	5.50	57.50
8	**(6a DP) Distributed propulsion**	6.50	7.00	6.50	2.00	2.00	4.00	48.50

Figure 2.9 – Virtual West Team Scoring

2.4.3 Onsite Team Summary

The participants of the Onsite Team conducted a group scoring of each of the concepts and then added other concepts as they saw fit and then compiled as an average score for each concept against the metrics. Subsequently, the participants discussed the ranking results for each concept.

As a result of the Onsite breakout team, the group provided the scores and rankings (with risk included) of each concept to the larger group as depicted in Figure 2.10. During the outbrief, the Onsite team suggested the possibility of a hybrid between concepts 4, 7, and 8 might be a viable option. The Onsite team also identified the LENR concept as the highest payoff, but with an associate high risk.

	Concept Names	Block Energy	Global Emissions	LTO Emissions	Noise	Cost	Technology Maturity Risk	Final Score
Concept #	Weighting factor	2	10	5	4	8	0	
0	Sugar Free	0	0	0	0	0	15	0
1	N+4 Reference Airplane	5	5	6	2	3	9	122
2	Conventional fuel/hybrid electric concept	7	8	7	3	3	5	165
3	Hydrogen fuel concept (pure H2 burner)	5	6	9	2	3	5	147
4	Methane-natural gas concept (pure CH4 burner)	5	5	9	2	4	9	145
5	Fuel cell concept (H2/FC Battery Hybrid)	5	6	10	3	1	3	140
6	**Low Energy Nuclear Reactor**	2	10	10	3	5	1	206
7	**GT w/ SOFC Topping Cycle**	6	7	9	2	3	3	159
8	**Noise Optimized Propeller**	6	6	7	4	3	9	147

Figure 2.10 – Onsite Team Scoring

2.5 N+4 Workshop General Observations, Recommendations, and Inspirations

After each sub-team conducted the breakout sessions and then presented the outbriefs to the whole group, the group identified some common themes amongst the sub-team observations that evolved into general observations of the entire concept scoring activity, specifically:

- Hybrid electric scored high from each team, which confirmed the selection of the concept for the current work scope in Phase II, Task 2.2
- General concern over the definition of control volume with block energy
- LENR high payoff, but high risk
- Methane concept identified as a low risk by all groups
- Participants identified that a struggle of the scoring of the concepts really revolved around:
    - Source of power
    - How it is converted
    - How to use that power

As a result of the group discussion, the workshop focus shifted the expected outcome to picking a concept and then subsequently identifying what power application should be used; a summary of the result and recommendations from the group is outlined below:

1) LENR – Very high payoff/very high risk. Recommend small study to set goals and watch tech feasibility and development
2) Positive consensus on Hybrid Electric – validation of Phase I selection. Already covered in SUGAR Tasks 2.2 and 3.3 (except see energy study)
3) Energy study – Life Cycle source to use (H2 or electricity). Estimate electricity use at typical airport. Supports both electric battery charging and H2 production.
4) Hydrogen – Significant benefits and challenges
    - Because H2 aircraft have been studied extensively in the past, we recommend expanding other areas of the technology space
    - H2 infrastructure and some technologies should be worked outside of this study

- Many H2 cryo aspects will be covered in recommended LNG/methane work below
- See also energy study above

5) Methane – Low cost and possible early deployment of cryo techs
    - Methane GT SOFC driving a generator with variable speed pitch low noise props ... or ... Methane GT SOFC Hybrid with low noise turboprop
    - Methane as first step on a roadmap for a cryo fuel / superconducting
    - GE to check on providing Methane GT and Methane GT SOFC cycle for N+4 task
6) Combined Approach to N+4 technology/config assessment:
    - Adv. Tech Configuration with integrated synergistic technologies
        - Aft fuselage BLI integration – synergy with methane GT SOFC to drive aft electric fan (Goldschmied-like device)
    - Technologies that are evaluated separately and could be combined into the Adv. Tech Configuration (or others)
        - Low noise props – investigate variable RPM and shape memory alloys, plasma actuators?

As a result of the workshop recommendations, a number of side studies were identified to help the group conclude on a possible N+4 concept to pass to the higher fidelity analysis. The group called these inspiration ideas that composed a wish list of research that could possibly be conducted within the scope of the current SOW:

1) LENR
    - Study to set goals
    - Watch tech feasibility and development
    - Investigate system architecture options
    - Develop baseline system design and system performance targets
2) Hybrid Electric
    - Life cycle energy study
    - Follow and encourage battery tech and system community
    - Multiple parallel battery technology developments
3) Methane – Low cost and possible early deployment of cryo techs
    - Gas turbine design issues
    - Aircraft system issues & techs
    - Infrastructure issues & techs
    - Synergistic technologies
        - Methane GT SOFC driving a generator
        - Methane GT SOFC Hybrid
        - Cryo fuel / superconducting

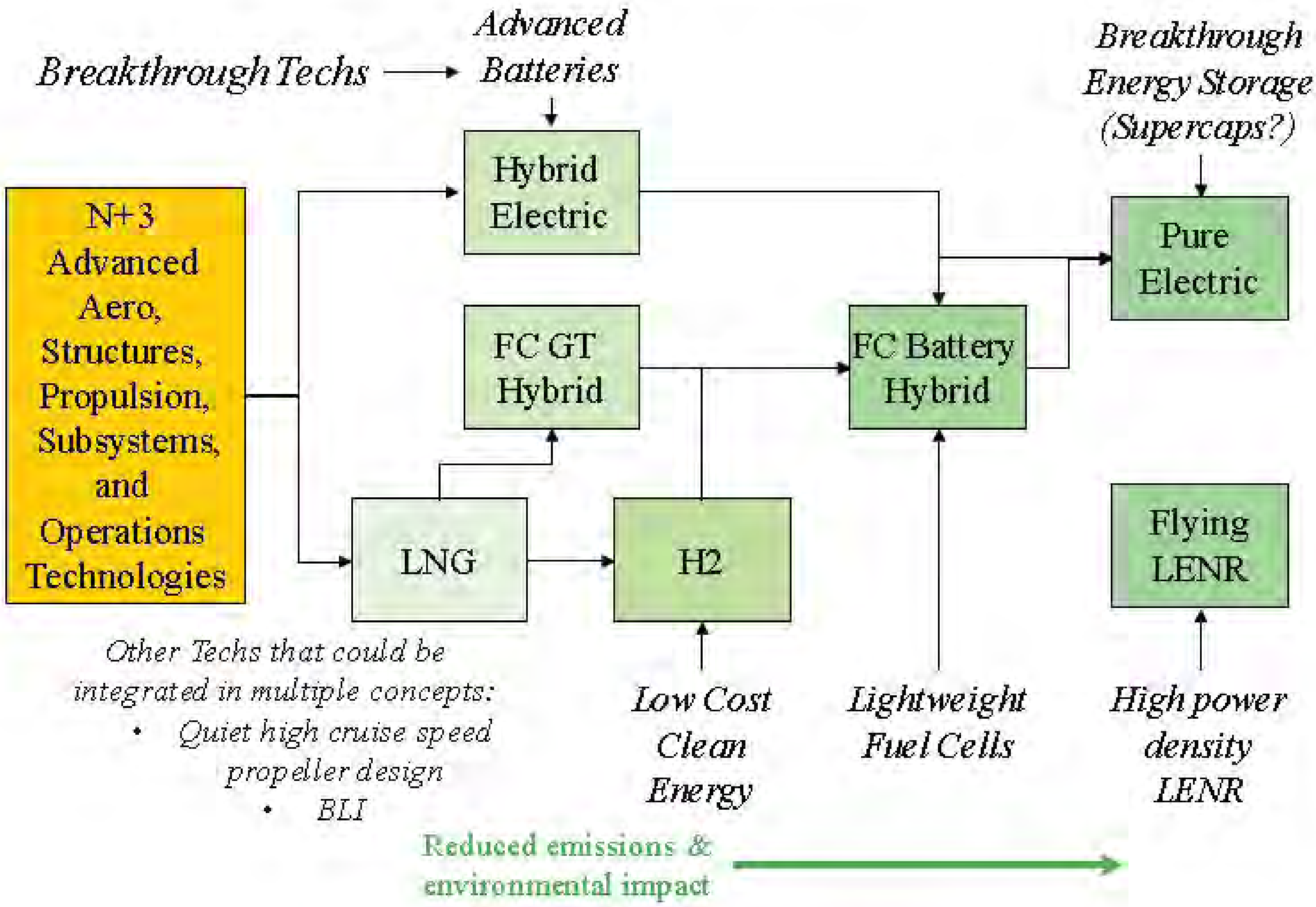


Figure 2.11 – Relationship of N+4 Workshop Technologies

3.0 LENR Requirements Analysis

The idea of using a Low Energy Nuclear Reactor (LENR) was discussed at the N+4 Workshop, both as a ground-based source of energy to create electricity or hydrogen, and an aircraft-carried power source for primary propulsion. Given the potential of clean zero-emissions energy, further work was identified for both applications. Nuclear energy is a potential source of clean low cost energy that should be considered in a detailed energy study (see Section 4.0). In this section we will discuss the potential and requirements for a flying LENR application for aviation.

Since a LENR is essentially a source of heat, a heat engine of some kind is needed to produce useful work that can create an integrated propulsion system for an aircraft. It was decided to do a relatively simple study to determine the range of LENR and heat engine performance that would produce an aircraft competitive to a conventional fueled aircraft.

Some potential heat engine cycles with representative engine power to weight ratios are shown in Figure 3.1. Heat engine power to weight is a strong function of delta temperature from the LENR. Achievable LENR delta temperature is not known at this time and is beyond the scope of this current investigation. Nevertheless, we decided to parametrically vary the LENR and heat engine power per weight and apply a top level operating cost model. Even though we do not know the specific cost of the LENR itself, we assumed a cost of jet fuel at $4/gallon and weight based aircraft cost. We were able to calculate cost per mile for the LENR equipped aircraft compared to a conventional aircraft (Figure 3.2). Looking at the plots, one could select a point where the projected cost per mile is 33% less than a conventionally powered aircraft (Heat engine > 1 HP/lb & LENR > 3.5 HP/lb). Since the power requirements are significantly different at cruise compared to takeoff and climb, we also investigated a hybrid case where batteries and an electric motor are used to supplement the heat engine + LENR at takeoff. This yielded significantly improved results (Figure 3.3) which required lower LENR and heat engine performance levels (Heat engine > 0.4 HP/lb, LENR > 1 HP/lb, & Batteries > 225 Wh/kg).

These numbers are illustrative only, as other combinations could yield useful propulsion and power systems, and the results are dependent on cost and performance assumptions. However, the numbers should be useful in establishing initial system goals for LENR concepts.

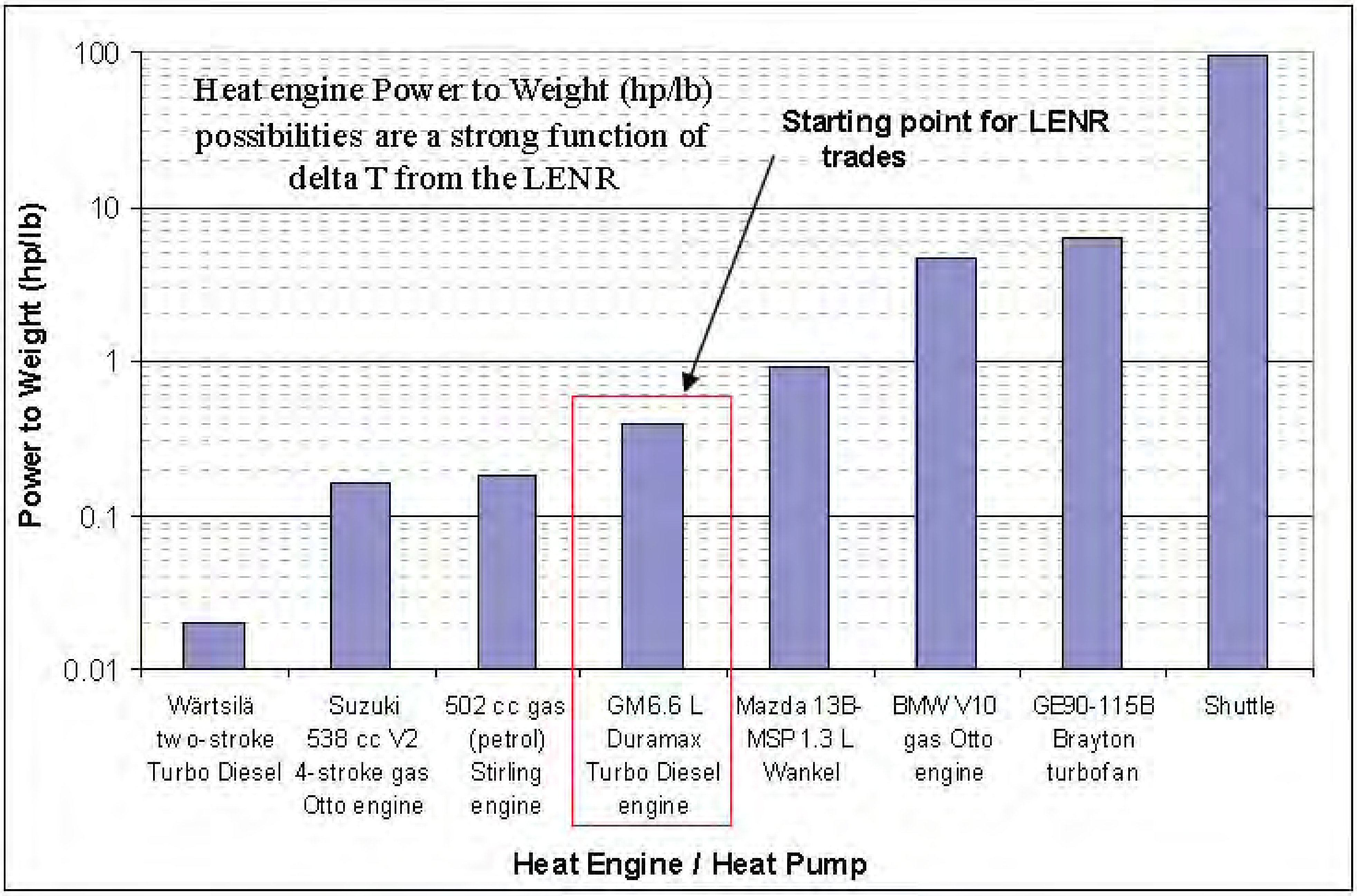


Figure 3.1 – Potential Heat Engines for LENR Systems

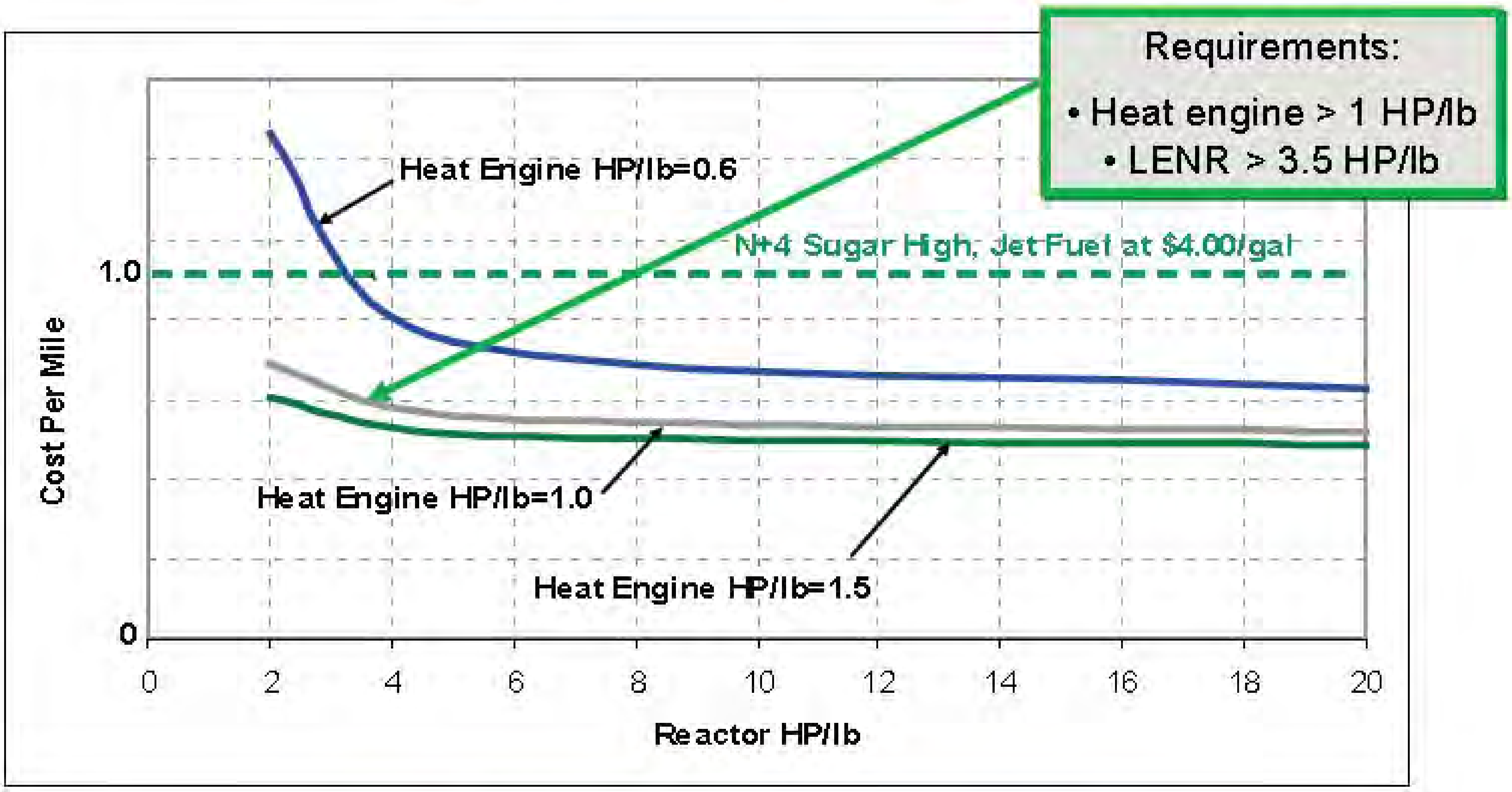


Figure 3.2 – Parametric LENR and Heat Engine Performance Parameters

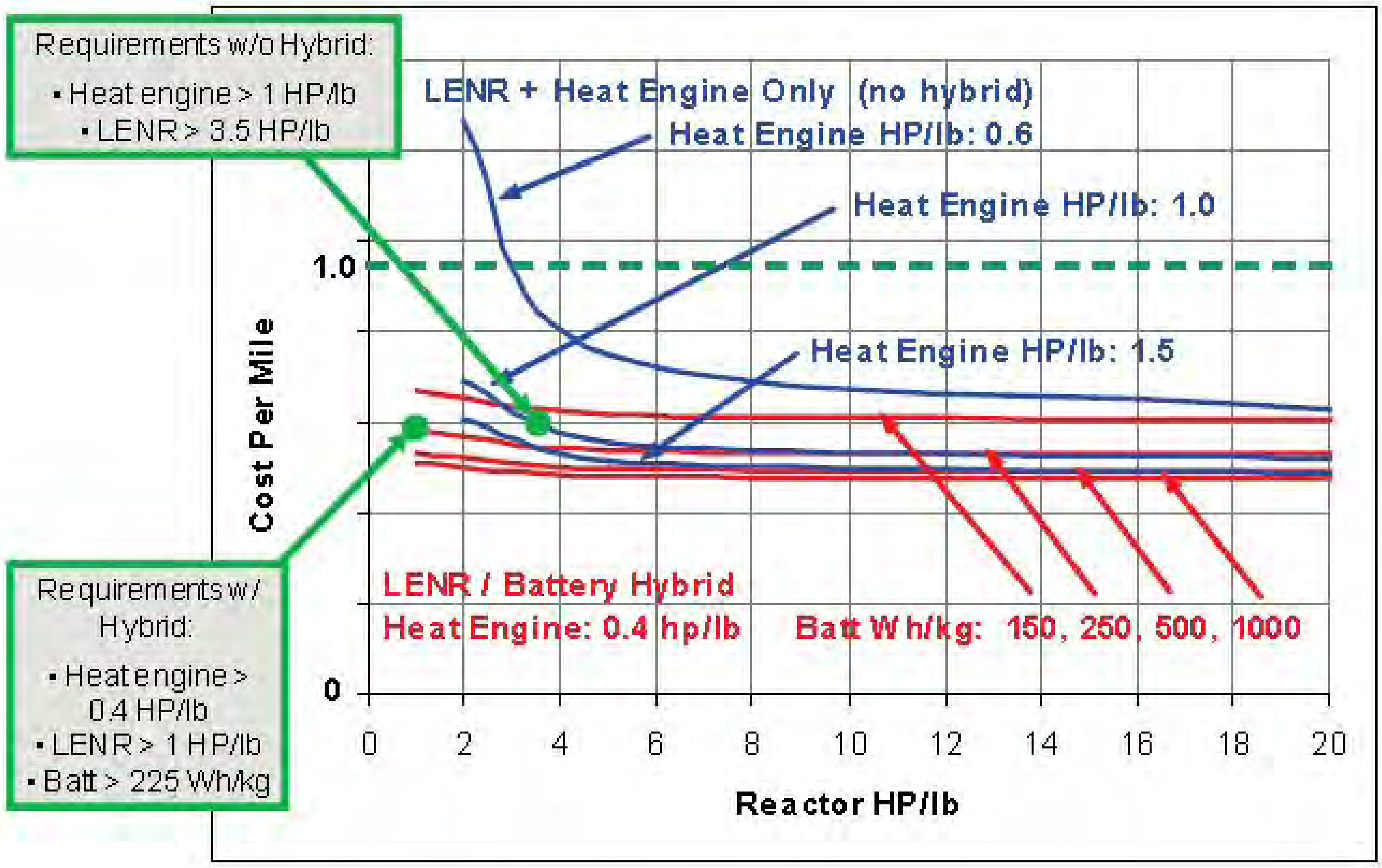


Figure 3.3 – Hybrid LENR + Battery Performance Parameters

6.2.3 Low Energy Nuclear Reactor Technologies

Goals and Objectives:

Develop technologies for Low Energy Nuclear Reaction (LENR) propulsion systems.

Performance Area and Impact:

Traditional fuel burn and emissions will be reduced or eliminated by using LENR energy.

Noise may be reduced by using LENR heat instead of combustion in the engines.

Technical Description:

LENR energy has the potential to eliminate traditional fuel burn and associated emissions. In the current concept, a LENR reactor generates heat that is distributed to heat engines that use the LENR heat instead of combustion. This concept is dependent on successful development of LENR technology, which has reportedly had some success in generating heat in a catalytic process that combines nickel (Ni) with hydrogen (H) gas(8). This process is reported to produce safe byproducts, such as copper, with no radioactive materials used and no long-lasting radioactive byproducts generated. Upon further investigation, it is thought that low level radiation may be generated during active energy cycles, but that it could be easily shielded and would stop quickly after reactor shutdown. Further development of LENR would be required to produce heat at a high enough temperature to support heat engines in a flight-weight installation. LENR physics analysis and evidence of high temperature pitting in LENR metal substrates indicate that temperatures appropriate for heat engines may have been achieved. It is thought that LENR would use very small amounts of fuel.

Initial LENR testing and theory have suggested that any radiation or radio-isotopes produced in the LENR reactions are very short lived and can be easily shielded. In addition, some prototypes(9) that may be harnessing the LENR process can be controlled safely within designed operating parameters and the reaction can be shut down in acceptable time frames. This heat generating process should reduce radiological, shielding and hazardous materials barriers to entry of aviation LENR systems.

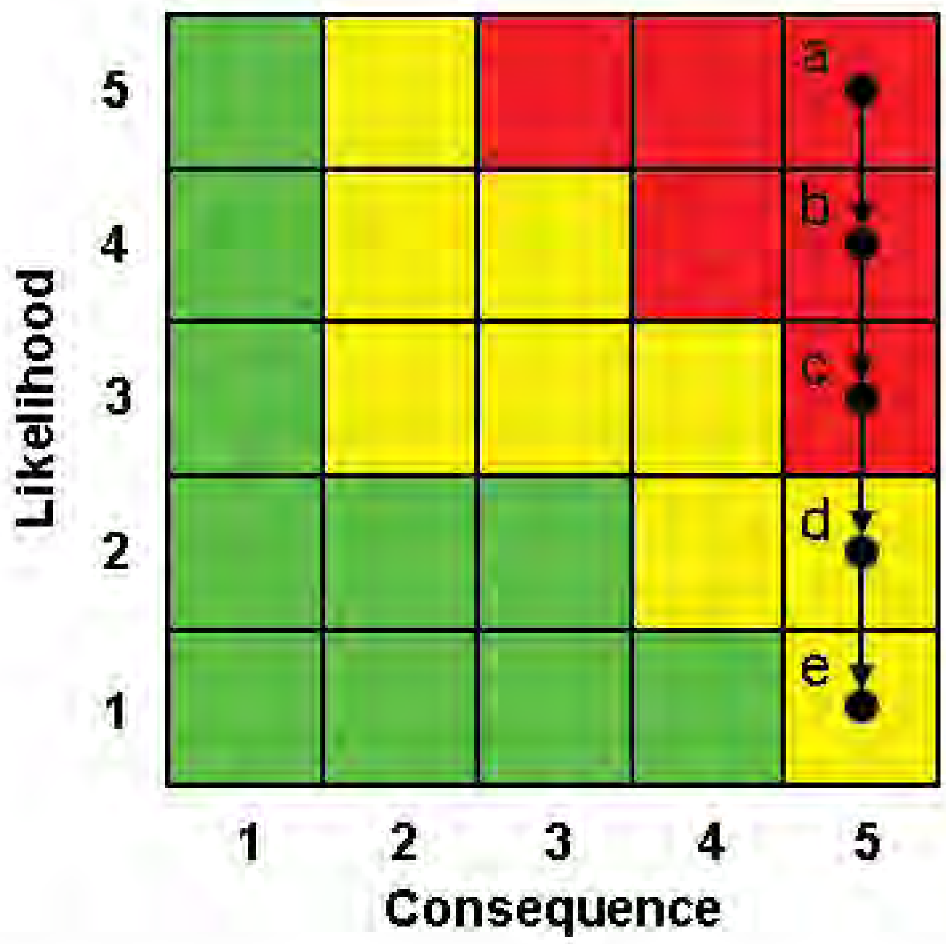
Should LENR development prove successful, a few technology components will need to be developed for LENR-based aircraft propulsion. Heat engines, which run a thermodynamic cycle by adding heat via heat transfer instead of combustion, need to be developed. A system for distributing heat from the LENR core to the heat engines also needs to be developed. Additional systems may need to be developed for supporting the LENR core, including systems to deliver reactants and remove byproducts. The Ni-H LENR system would use pure hydrogen and a proprietary nickel and catalyst substrate. Hydrogen usage would be small compared to systems that combust hydrogen. Initially, hydrogen storage might involve cryogenics. The cold liquid hydrogen (LH_2) fluid might be used in a regenerative system whereby cooling is supplied to super-conducting generators, electric feeders, and motors while the gas would be used as a fuel in the LENR reactor. The primary LENR byproducts that would require periodic removal from the aircraft are the catalyst and nickel that are contained within the reactor core. Through thoughtful design of the reactor core, preliminary information suggests that these can be easily removed and replaced. The reactor core might then be recycled at low cost, due to the absence of toxic products in the core.

Technology Status:

Multiple coherent theories that explain LENR exist which use the standard Quantum Electrodynamics & Quantum Chromodynamics model. The Widom-Larson[10] theory appears to have the best current understanding, but it is far from being fully validated and applied to current prototype testing. Limited testing is ongoing by NASA and private contractors of nickel-hydrogen LENR systems. Two commercial companies (Leonardo Corp. & Defkalion) are reported to be offering commercial LENR systems. Those systems are advertised to run for 6 months with a single fueling cycle. Although data exists on all of these systems, the current data in each case is lacking in either definition or 3rd party verification. Thus, the current TRL assessment is low.

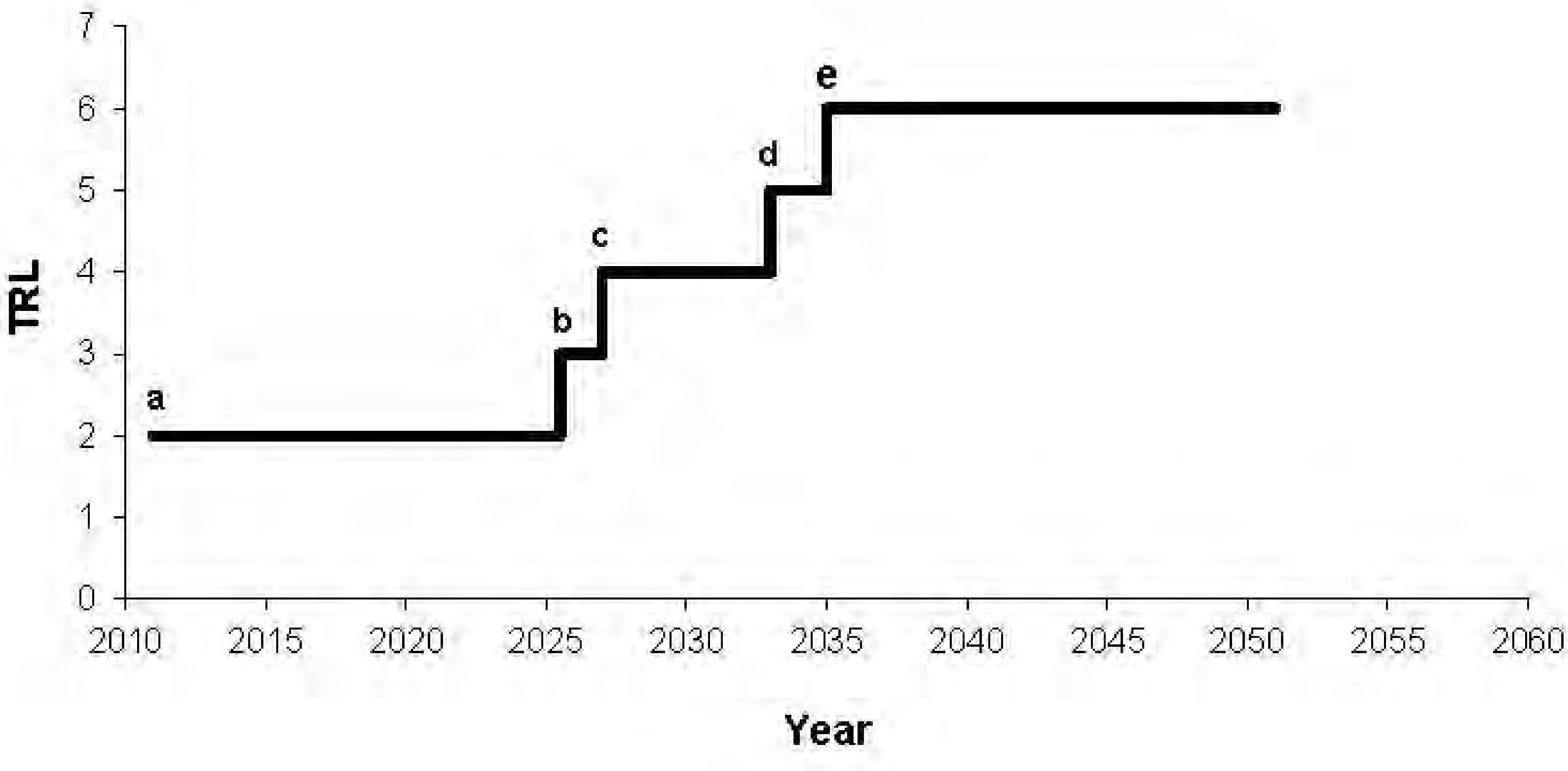
In this study the SUGAR Team has assumed, for the purposes of technology planning and establishing system requirements that the LENR technology will work. We have not conducted an independent technology feasibility assessment. The technology plan contained in this section merely identifies the steps that would need to take place to develop a propulsion system for aviation that utilizes LENR technology.

Risk Assessment:



If development of LENR, heat engines, or heat distribution systems is not successful, this technology will not contribute the projected benefits in fuel burn or emissions.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

A concept for a LENR propulsion system has been generated
Basic principles of LENR are reported to have been demonstrated

TRL 3 (b)

Definitive laboratory test data released and validated showing that the concept works
System level goals (power/weight, etc.) for LENR and heat engine established using a sensitivity study
A conceptual design of a LENR propulsion aircraft and its systems will be performed
Heat engine will be designed and analyzed, based on expected LENR temperature differential achievable
Heat distribution system will be designed and analyzed
Design and analysis will be performed on other systems to support LENR

TRL 4 (c)

A basic heat engine will be built and tested
A basic heat distribution system will be built and tested
Supporting LENR system components will be built and tested
LENR core reactor technology is demonstrated (external development)

TRL 5 (d)

LENR propulsion components will be integrated in a working system
LENR propulsion system will be demonstrated in ground test
Critical LENR propulsion system components will be tested in flight

TRL 6 (e)

LENR propulsion system will be demonstrated in flight

Dependency:

Development of LENR reactor technology is assumed to be developed successfully in an external program. An initial requirements assessment indicates that it is beneficial to develop a hybrid system to augment thrust at takeoff, so as not to oversize the LENR system for cruise conditions

Success Criteria:

Table 6.3 – LENR Technologies Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows LENR propulsion system can meet aircraft propulsion requirements (including safety)	Switch to alternative technology option or abandon concept if feasibility cannot be clearly established.
4	Tests of LENR propulsion system components show performance and weight consistent with successful system operation and safety	Redesign components with shortfalls Switch to alternative technology option
5	LENR propulsion system components integrated and successfully tested	Redesign system for successful operation Switch to alternative technology option
6	LENR propulsion system demonstrates successful in-flight operation	Switch to alternative technology option

Notes:

Alternate technologies include other types of self contained nuclear reactors such as thorium, cold fusion, traveling wave, etc.

Alternate heat engines include Sterling, Diesel, Wankel, Otto, and Brayton cycles.

If a safe flight-weight system is not judged to be achievable, the alternative approach is to keep the reactor on the ground and use it to produce electricity or hydrogen for use in aircraft (see other roadmaps).

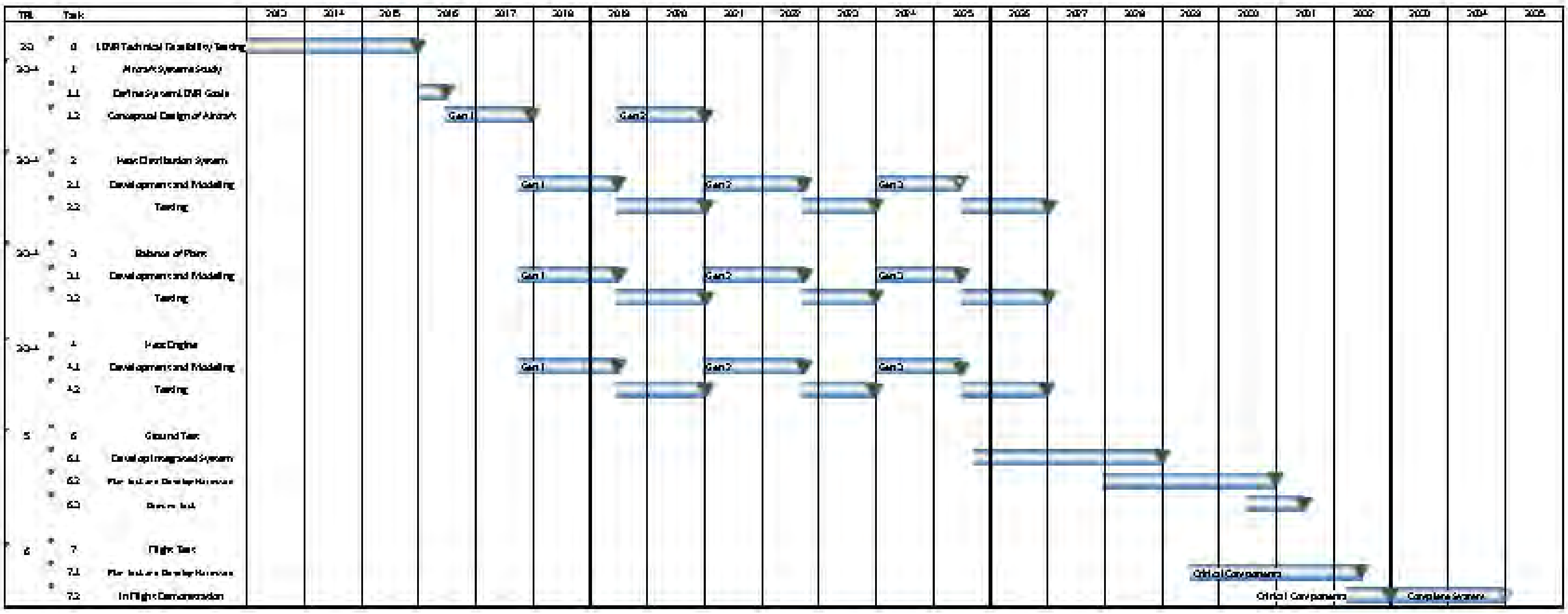


Figure 6.3 – LENR Technologies Roadmap

6.3 Technology Plans Discussion

As we project technologies further into the future, all dates become more uncertain. Additionally, many non-technical outside factors, such as research funding levels, competing energy prices, government actions and incentives, and even public acceptance could have significant influences on the pace and success of technology development.

Generally, we have used a TRL 6 date of 2025 with a corresponding operational date of 2030-2035 for N+3 technologies and a TRL 6 date of 2030-2035 with a corresponding operational date of 2040-2050 for N+4 technologies. We also have assumed that technologies are developed as soon as practical and with robust funding. Therefore, the development plans will tend to be optimistic compared to what will actually occur. The technology plans that have resulted from this effort indicate both N+3 and N+4 timeframes.

Hybrid electric propulsion was identified in Phase I as an N+3 technology and a technology plan was developed. This plan has been updated in this report and adds a specific development plan for the needed high performance modular batteries. Depending on the pace of battery development, they could be an N+3 or an N+4 technology. Also, because of their modularity, it may be possible to develop an aircraft with one kind of battery technology and replace it with another generation of batteries or even a different battery technology during the operational lifetime of the system. Even if batteries of sufficient performance are not ready in the N+3 timeframe for the assumed medium sized commercial airliner, there are likely to be other aircraft applications. Smaller general aviation, business jets, and even regional jets will likely benefit from hybrid electric technologies even at lower battery performance levels.

LNG gas turbine technology could be developed for the N+3 timeframe. The aviation infrastructure change required is very significant and likely to be the dominant influence on the timeline which could stretch into the N+4 timeframe. Hydrogen technology development is essentially similar to LNG technology development, but includes somewhat more difficult technology challenges due to lower cryogenic temperatures, material compatibility issues, and greater leakage potential. Additionally, successful development of hydrogen requires improvements in hydrogen production technology to reduce cost and environmental impact before it is a viable option for aviation. So, it is likely hydrogen is an N+4 technology, even though the hydrogen gas turbine could be developed earlier.

The general viability of LENR technology is still an issue of active research. A breakthrough in nuclear technology would have a significant impact on the entire worldwide energy structure. The technology plan assumes a reasonable "waiting period" to establish viability before beginning development of the technology for aviation.

All concepts in this report also assume the use of various N+3 technologies that were identified in Phase I. Technology plans for these other propulsion, structures, noise, and aerodynamic technologies can be found in the Phase I final report[1].

7.0 Conclusions and Recommendations

Using a quantitative workshop process, the following promising technologies were identified in the N+4 study: Methane/LNG, Hydrogen, Fuel Cell Hybrids, Battery Electric Hybrids, Low Energy Nuclear Reactors (LENR), Boundary Layer Ingestion (BLI), unducted fans and advanced propellers, and combinations. Technology development plans have been developed for these promising technologies and for the required systems and infrastructure development for cryogenic propellants.

An aviation specific life cycle energy study is needed, so the team developed an outline and recommend conducting the full study.

As an advanced technology aircraft for more detailed analysis, the team selected an LNG fueled gas turbine fuel cell hybrid configuration with an aft fuselage boundary layer ingestion propulsor.

The team then generated weight, aerodynamic, and propulsion data for a series of configurations with different combinations of N+4 technologies. Performance and sizing has been conducted for these configurations to allow comparisons on a common basis. Looking at the differences between the configurations allows quantification of the payoff of many of the N+4 technologies identified during the workshop (LNG, fuel cell topping cycle, aft fuselage boundary layer propulsor, and unducted fan).

- LNG fueled aircraft require heavier aircraft systems and larger propellant tankage compared to conventionally fueled aircraft. The higher heating value of LNG reduces the weight of fuel burned (-5.8%), but the heavier aircraft requires more total energy (+5.6%) for a given flight.
- LNG fueled aircraft have the potential for significant emissions advantages over conventionally fueled aircraft. LTO and cruise NOx are lower and less carbon dioxide is produced when it is burned.
- Use of an unducted fan increases propulsive efficiency and reduces fuel burn (-11.6%).
- Adding a topping cycle fuel cell and an aft fuselage boundary layer propulsor driven by an electric motor leads to reductions in emissions and fuel burn (-8.6%).
- The best performing architecture analyzed used LNG, a fuel cell topping cycle, an unducted fan, and an electric motor augmenting fan shaft power. Relative to the SUGAR Free Baseline aircraft, this configuration achieved a 64.1% reduction in fuel burn, beating the 60% N+3 goal. The 59.8% reduction in total energy used, effectively meets the 60% energy reduction goal. This architecture is also estimated to beat the N+3 LTO and cruise NOx emissions goals.

A summary of the technologies investigated in this study is shown in Table 7.1.

Table 7.1 – Task 1 Technology Summary

Technology	Impact	Goals	Relationships	Major Concerns
LNG	Very Significant	Fuel Burn, Emissions, (Fuel Cost), (Fuel Supply)	Enabling to Fuel Cells and Low Emission Combustors	Methane Emissions, Safety, Infrastructure
Unducted Fan	Very Significant	Fuel Burn	Enhancing	Noise, Safety
Engine Fuel Cell	Significant	Fuel Burn, Emissions	Enhancing, Dependent on LNG or Hydrogen	
BLI Aft Propulsor	Significant	Fuel Burn, Emissions, Noise	Enhancing, Dependent on power source (fuel cell or batteries) for electric motor	
LENR	Game Changing	Fuel Burn, Energy Use, Emissions, Noise	Dependent on Hybrid Technology (gas turbine or electric hybrid)	Feasibility, Safety, Weight, Customer Acceptance
Hydrogen	Very Significant	Fuel Burn, Emissions	Enabling to Fuel Cells and Low Emission Combustors, Dependent on Production Technology	Low Cost Green Production, Safety, Customer Acceptance, Infrastructure

LNG technologies should continue to be investigated as there are significant potential emissions advantages, as well as advantages in cost and energy availability. However adding LNG to the aviation propellant infrastructure would be a significant challenge. Also, active research into methane leakage during natural gas extraction, processing, storage, and use should be monitored, as this could have an additional negative environmental impact.

Unducted fans, fuel cells, and BLI are potential enhancing technologies that offer significant improvements.

LENR technology is potentially game-changing to not just aviation, but the worldwide energy mix as well. This technology should be followed to determine feasibility and potential performance.

Hydrogen technology also has potential benefits, but widespread aviation use of hydrogen requires large infrastructure changes as well as significant improvements to produce hydrogen in a low cost environmentally friendly process.

As identified in Phase I, hybrid electric propulsion with high performance batteries offers significant fuel burn, energy, and emissions advantages if large battery technology improvements occur and the technology can be adapted to aviation requirements. Hybrid electric technologies are potentially synergistic with fuel cell, BLI, and LENR technologies. Additionally, using superconducting, the cryogenic characteristics of LNG and hydrogen could be synergistic with hybrid electric technology.