Description of document: Title of Thesis: The Race To The Stratosphere: The Operational State Of Worldwide High-Altitude Long Endurance Lighter-Than Air Systems For Communications And Surveillance By 2020. 2009. Released by the Office of The Director of National Intelligence (ODNI)

Requested date: 18-September-2017

Release date: 04-December-2024

Posted date: 23-December-2024

Source of document: FOIA Request
Director, Information Management Office
ATTN: FOIA/PA
Office of the Director of National Intelligence
Washington, D.C. 20511
Email: ODNI_FOIA@odni.gov

OFFICE OF THE DIRECTOR OF NATIONAL INTELLIGENCE
WASHINGTON, DC

3 December 2024

Reference: ODNI Case No. DF-2022-00321

This letter provides an interim response to your Freedom of Information Act (FOIA) request to the Defense Intelligence Agency (DIA), dated 18 September 2017, requesting 18 specific theses written by students at the National Intelligence University. As previously noted by DIA, DIA transferred these cases to the Office of the Director of National Intelligence (ODNI) in 2022.

ODNI processed this request under the FOIA, 5 U.S.C. § 552, as amended and located 17 of the theses requested. Note, despite a thorough search, "Rationing the IC: The Impact of Private American Citizens on the Intelligence Community" was not located.

This interim response provides a response on ten of the theses. During the review process, we considered the foreseeable harm standard and determined that certain information must be withheld pursuant to the following FOIA exemptions:

- (b)(3), which applies to information exempt from disclosure by statute. Specifically, the National Security Act of 1947, as amended:
  - Section 102A(i)(l), 50 U.S.C. § 3024(i)(1), which protects information pertaining to intelligence sources and methods; and
  - Section 102A(m), as amended, 50 U.S.C. § 3024(m), which protects the names and identifying information of ODNI personnel.
- (b)(6), which applies to information that, if released, would constitute a clearly unwarranted invasion of personal privacy.

Be advised, we continue to process your request. If you are not satisfied with this response, a number of options are available. You may contact me, the FOIA Public Liaison, at ODNI_FOIA_Liaison@odni.gov, or the ODNI Requester Service Center, at ODNI_FOIA@odni.gov or (703)-275-1313. You may also submit an administrative appeal to the Chief FOIA Officer, c/o Chief, Information Management Office, Office of the Director of National Intelligence, Washington, DC 20511 or emailed to ODNI_FOIA@odni.gov. The appeal correspondence should be clearly marked "Freedom of Information Act Appeal of Adverse Determination" and must be postmarked or electronically transmitted within 90 days of the date of this letter.

Lastly, the Office of Government Information Services (OGIS) of the National Archives and Records Administration is available with mediation services and can be reached by mail at 8601

Adelphi Road, Room 2510, College Park, MD 20740-6001; telephone (202) 741-5770; toll-free (877) 684-6448; or email at ogis@nara.gov.

Sincerely,

Erin Morrison
Chief, Information Review and Release Group
Information Management Office

THE RACE TO THE STRATOSPHERE: THE OPERATIONAL STATE OF WORLDWIDE HIGH-ALTITUDE LONG ENDURANCE LIGHTER-THAN-AIR SYSTEMS FOR COMMUNICATIONS AND SURVEILLANCE BY 2020

by

Major, USAF
NDIC Class 2009

Submitted to the faculty of the
National Defense Intelligence College
in partial fulfillment of the requirements for the degree of
Master of Science of Strategic Intelligence

July 2009

ABSTRACT

TITLE OF THESIS: **The Race to the Stratosphere: The Operational State of Worldwide High-Altitude Long Endurance Lighter-than-Air – Systems for Communications and Surveillance by 2020**

STUDENT: , MSSI, 2009

CLASS NUMBER: NDIC 2009 **DATE:** July 2009

THESIS COMMITTEE CHAIR:

COMMITTEE MEMBER:

This thesis set out to answer the following research question: To what extent will foreign states develop and employ lighter-than-air high-altitude long endurance systems (LTA HALE) systems for communications and surveillance applications by 2020? The thesis concludes that, by 2020, LTA HALE systems will be an emerging operational capability with a few systems that are employed on missions that have limited endurance and restricted operating environments. These LTA HALE systems missions will most likely carry smaller communication payloads. Although countries around the world such as Japan, South Korea, China, Russia and the EU have varying but limited LTA HALE programs, the maturing of necessary technology such as thin-film solar arrays, fuel cells and advanced light-weight materials will enable these systems to be developed. Additionally a growing LTA industrial base that currently caters to low-altitude unmanned airships will push and aid in the development of LTA HALE systems.

A systematic analysis of historic and current LTA programs as well as trends in platform and payload was performed using DoD technology readiness assessment-based process. This assessment identified critical technologies which are explored for capability, maturity, and availability. Additionally, a case study on one of the leaders in LTA HALE development, the Japan Aerospace Exploration Agency (JAXA) LTA HALE program explores the programmatic and technical hurdles.

Foreign LTA HALE systems are a potential threat to U.S. national security missions. These systems can carry multiple dual-use communication and surveillance payloads technologies from cell phone and traffic monitoring to radar surveillance. But even if these systems are advertised for “peaceful purposes”, they are a readily adaptable dual use technology. Their potential large lifting capacity allows them to be integrated with additional covert or overt mission payloads that could be used for military and intelligence applications. LTA HALE systems could provide adversaries with an inexpensive, persistent, and responsive intelligence, surveillance, and reconnaissance (ISR) capability, which could mitigate the United States’ strategic advantage. An understanding of potential adversary LTA HALE capability allows the United States to develop plans and systems to counter adversary capabilities gained through employment of communications and surveillance payload on LTA HALE systems operating in the stratosphere.

Thesis chapters final

This page is for Identification purposes only

Title page and abstract are in a separate file.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

In 1794, a strange spherical shape appeared over the horizon of northern France. Dutch and Austrian forces were engaged with the French army in the Battle of Fleurus. They could not have guessed the bag filled with gas, dubbed *L'Entreprenant,* floating in the distance would lead to their defeat.[1] With this new device, French commanders were able to track the position of the Dutch and Austrian forces. The Austrian commander believed the device was a violation of the "gentlemanly rules of war" and tried to shoot the balloon down, but to no avail.[2] The balloonists raised their fists, shouting back "*Vive la Republique,*" as they simply ascended out of range.[3] Intelligence gathered from the balloon observations is credited with giving the French a victory.[4]

For the next 150 years, lighter-than-air platforms prominently figured in warfare intelligence. However, the end of World War II marked the decline of the lighter-than-air systems. The airplane and space age pushed the need for lighter-than-air systems into near obscurity. Over the last couple of decades, however, interest in these systems has

---

[1] "Balloons in War," *U.S. Centennial of Flight commission*, http://www.centennialofflight.gov/essay/Lighter_than_air/Napoleon%27s_wars/LTA3.htm (accessed July 4, 2009).

[2] L.T.C. Rolt, *The Aeronauts* (New York: Walker and Company, 1966), 162.

[3] Ibid.

[4] "Balloons in War.".

resurged as a solution for missions such as communications, persistent surveillance and heavy cargo lift.

Topic Overview and Justification

Since the dawn of war, military commanders have sought the "high ground" to extend their communication and intelligence capabilities. Surrounding hills were augmented with towers to increase the range and perspective of visual information. From higher vantage points, armies could observe and reconnoiter enemy troop movements and communication signals from greater distances. Balloons and telescopes allowed the vantage point to be pushed ever higher, increasing the field of view without sacrificing detail, providing an artificial, mobile high ground. As this artificial and mobile high ground evolved, commanders demanded more intelligence.

For the past 60 years, aircraft and space systems have reigned supreme over the intelligence and communication high ground. Satellites provided uninhibited strategic access while aircraft enabled operational and tactical flexibility. Nevertheless, countries, commanders, and corporations continue to demand more and now require the ability to continuously monitor and provide coverage over their borders, targets and assets. Persistent surveillance has become the mantra *du jour*. Recent technological advances in power generation, materials science, and electronic miniaturization have led to the development of high-altitude long endurance (HALE) vehicles.[5] These systems offer access to the "middle ground" between traditional air and space environments. This middle ground presents advantages over the traditional mediums for communication and intelligence systems. Compared against traditional aircraft, HALE systems present a larger sensor footprint and increased loiter time over the target area. Unlike satellites, HALE systems are not subject to the laws of orbital mechanics, and payload signals are less affected by atmospheric distortion. These systems also offer an affordable alternative to satellites and can be maintained and upgraded with new payload technology. HALE systems provide persistence akin to a geostationary satellite with payloads that can have improved performance over satellites and increased coverage over lower altitude systems.

In favor of smaller, faster, and more agile systems, designers built their systems around the orbital laws of Johannes Kepler and aerodynamic laws of Daniel Bernoulli, abandoning the buoyancy principles of Archimedes.[6] In an effort to increase the capability of HALE technology, some developers have returned to this principle first used to elevate the high ground.[7] Lighter-than-air systems (LTA) rely on aerostatic lift or

---

[5] These systems are also know by several names: high-altitude platform stations (HAPS), high-altitude long loiter (HALL), and near-space systems.

[6] For a summary of these men and the physical principles they discovered see Clifford Pickover, *Archimedes to Hawking : laws of science and the great minds behind them* (New York: Oxford University Press, 2008).

[7] There are aerodynamic HALE systems such as AeroVironment's Global Observer and QinetiQ's Zephyr system."Stratospheric Persistent Unmanned Aircraft Systems: Global Observer Detail," *AeroVironment.com*, http://www.avinc.com/uas/stratospheric/global_observer/ (accessed July 4, 2009); "QinetiQ's Zephyr UAV exceeds official world record for longest duration unmanned flight," *Qinetiq.com*, http://www.qinetiq.com/home/newsroom /news_releases_homepage/2007/3rd_quarter/qinetiq_s_zephyr_uav.html (accessed July 4, 2009).

buoyancy to give them flight. These LTA HALE systems do not require power or fuel to become and remain airborne.[8] LTA HALE designers also take advantage of the significant lift potential of LTA technology. Scientific balloons can lift payloads in excess of 8000lbs of payload, reach 138,000 feet, and under the right conditions float for months at a time.[9]

HALE systems provide the balance between the operational flexibility of aircraft and the persistence of satellites. LTA HALE has the potential to provide even more lift and endurance over aerodynamic HALE systems. LTA HALE systems can improve cost effectiveness by reducing the number of assets, air or space, needed for persistent coverage. These systems also save on expendable resources such as fuel for aircraft and launch costs for satellites. LTA HALE has the latent ability to provide flexible, cost effective persistent coverage for communications and surveillance missions.

Given this discussion, lighter-than-air HALE systems could provide adversaries with an inexpensive, persistent, and responsive intelligence, surveillance, and reconnaissance (ISR) capability, which could mitigate the United States' strategic advantage. The United States is heavily reliant on its space systems and this reliance creates vulnerabilities. Potential adversaries do not require the same global infrastructure as the United States. They can employ agile technologies, like lighter-than-air systems, to

---

[8] LTA HALE is a generic termed used in this thesis to represent a wide range of systems and operational LTA concepts. LTA HALE includes high altitude airships, stratospheric airships and free floating platforms.

[9] "Scientific Balloons," *NASA Columbia Scientific Balloon Facility*, http://www.csbf.nasa.gov/balloons.html (accessed July 3, 2009). These characteristics do not represent the same balloon system. The altitude a balloon can achieve of a given size and type is dependent on the payload weight.

get inside of the U.S. decision cycle. Adversary employment of HALE systems provides them the opportunity to achieve similar effects even when the high ground of space is compromised. Once deployed, these assets are difficult to detect. Charting adversary capability supports U.S. strategic planning and intelligence collection requirements. An understanding of potential adversary LTA HALE capability allows the United States to develop plans and systems to counter and control the middle ground. Unimpeded foreign access to this capability could degrade the U.S. strategic advantage at the intelligence high ground.

Research Question

To what extent will foreign states develop and employ LTA HALE systems for communications and surveillance applications by 2020?

In the United States, the operational employment of LTA HALE has been a topic of research and discussion since at least the 1960's.[10] The research centered around cost benefit analysis of LTA HALE, technical feasibility studies and prototyping vehicles design. The majority of the research assessed that LTA HALE systems would provide an

[10] Michael S. Smith and Edward Lee Rainwater, "Applications of Scientific Ballooning Technology to High Altitude Airships," in *AIAA's 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Technical Forum* (presented at the AIAA's 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Technical Forum, Denver, CO: American Institute of Aeronautics and Astronautics, 2003), 2.

effective and affordable capability to augment current air and space systems. The same benefits that have attracted the United States to LTA HALE have gained the attention of the international and private communities. Indeed, over the last decade, several countries, (e.g. United States, Japan, South Korea) and corporations (e.g. Space Data, Sanswire Corp, Lindstrand Technologies, RosAeroSystems) have pursued lighter-than-air programs in a quest for persistent wireless communication capabilities.[11] However, characterizing this non-U.S. development and the consequences of employment is conspicuously absent from the literature. This thesis seeks to characterize non-US development and employment by answering the question: "To what extent will foreign states develop and employ LTA HALE systems for communications and surveillance applications by 2020?"

---

[11] Michael Lee, Steve Smith, and Stavros Androulakakis, "The High Altitude Lighter Than Air Airship Efforts at the US Army Space and Missile Defense Command/Army Forces Strategic Command," (presented at the 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, WA: American Institute of Aeronautics and Astronautics, 2009); Kunihisa Eguchi and Yoshio Yokomaku, "2000 Overview of Stratospheric Platform Airship R&D Program in Japan" (Stratospheric Platform Airship Team -National Aerospace Laboratory Japan, 2000), http://lrp2001003.pdf%3Fid%3DNALRP2001003&ei=xahCSpvVKcWEtweixKGYCQ&usg = AFQjCNFJXg9Zw-it0OPbRDbY7VkHvoFw9w&sig2=PmMN23ocNLYD-b1l0sB8gg (accessed June 5, 2009); Chan-Hong Yeom et al., "Development of a Stratospheric Platform in Korea" (presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001); "Space Data," *Space Data.com*, http://www.spacedata.net/ (accessed July 4, 2009); "HALE," *Lindstrand Technologies*, http://www.lindstrandtech.com/hale.html (accessed July 3, 2009).

Hypothesis

By 2020, foreign actors that face mounting regional and border security problems or anticipate a crisis requiring persistent coverage, and have limited access to space, will fully integrate LTA HALE systems into their communications and surveillance infrastructures.

The notion of affordable space launch promised in the 1970s has yet to materialize. Indigenous space lift is limited to a few countries that are geographically advantaged, such as Brazil, and technically capable, such as the United States, EU (multiple countries), Japan, China, and Russia. Even with a launch capability or cooperative partnerships, attaining persistent satellite coverage of a given area requires either geosynchronous orbits or multiple satellites. Furthermore, aircraft are limited in persistence due to factors such as human endurance and fuel consumption. Even aerodynamic HALE platforms, such as Global Hawk, face endurance problems and are expensive to acquire and operate.[12] The buoyant lift provided by LTA HALE systems provides the potential for affordable and persistent communication and surveillance over large regional areas. LTA HALE advocates promise "space-like" capability at a reduced

[12] "RQ-4 Block 20 Global Hawk," *Northrop Grumman Aerospace Systems*, http://www.as.northropgrumman.com/products/ghrq4b/index.html (accessed July 4, 2009).

cost.[13] If the lofty promises of lighter-than-air are genuine, then state actors that have a regional military capability and limited access to space will gravitate to LTA HALE solutions for communication and intelligence applications by 2020. Non-state multinational corporations with similarly competitive business interests will also be attracted to the capabilities promised by LTA HALE, further accelerating the availability of LTQ HALE communications and surveillance solutions.

Key Questions

Several key questions are addressed in order to answer the research question:

1. What is the historical and current development and employment of LTA platforms in both the commercial and military realms? Identifying the actors that are pursuing LTA and how they intend to employ the technology is critical to understanding how these platforms will evolve. This research focuses on identifying technical and operational requirements that drive LTA HALE. Additionally, the research will explore the states that are pursuing LTA HALE systems, as well as, states that have adapted similar LTA technology into their infrastructure.

---

[13] Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship* (Glenn Research Center: National Aeronautics and Space Administration, December 2003), 6, http://ntrs.nasa.gov/search.jsp?N=0&Ntk=all&Ntx=mode%20matchall&Ntt=Initial%20Feasibility%20Assessment%20of%20a%20High%20Altitude%20Long%20Endurance%20Airship (accessed June 5, 2003).

2. What are the major technical challenges to developing and employing an LTA HALE system? LTA HALE systems are still under development. The research will address the maturity and availability of platform and payload technology to be included in operational systems by 2020.

3. What are the programmatic and operational hurdles to developing and employing an LTA HALE system? LTA HALE systems are complex, requiring programmatic and operational structures to manage the acquisition and employment of these systems. This research seeks to identify the challenges and level-of-effort required to develop and employ a system.

Answering these questions will establish the current state of LTA HALE systems and an estimation of their ability to be employed over the next decade.

Methodology

A systematic analysis of historic and current programs was performed to establish the baseline of LTA HALE development. Analysis of current research efforts identified trends in the platform and payload technology. A technology readiness assessment, based on a U.S. Department of Defense process, is performed to identify critical technologies. These technologies are assessed for their current level of maturity. In Chapter 4, a case study on the Japan Aerospace Exploration Agency (JAXA) LTA HALE program explores the programmatic and technical hurdles addressed by a program that is considered one of the more promising to develop an LTA HALE capability.

The primary sources of data for the thesis include documents from the NASA balloon library, the American Institute of Aeronautics and Astronautics (AIAA) conferences and journals, the JAXA technical library, presentations from international LTA conferences, and the United States Naval Academy Library.[14] Interviews were conducted by the author with members of the international community at the 18th AIAA International Lighter-than-Air Conference, 5-7 May 2009, to identify perceived challenges and expectations for the operational employment of lighter-than-air HALE concepts.

Definitions, Scope and Classification

The following definitions are provided to clarify terms used in the research question and hypothesis:

"Communications" includes any system used to deliver voice and data services including, hand held radio, cell phone, and wireless network connectivity.

[14] The United States Naval Academy's library has an excellent collection of balloon and airship documents dating from the early 20th century to the present.

"Surveillance" is generically used to mean payloads that collect data through remote sensing such as radar and optical imagers. These systems could be used for intelligence collection or civilian applications such as traffic monitoring or forest fire detection.

The thesis focuses primarily on LTA HALE systems for communications and intelligence. LTA technology designed for heavy lift is reviewed in the research and is considered only for its impact on LTA HALE technology. The analysis relied on data that is published or previously translated into English.

The thesis is unclassified. The data, analysis and conclusions were derived from unclassified sources and methods.

Overview of Thesis

Chapter 2 presents an overview of LTA history, concepts and technology. A history is presented of LTA and its use in communications and intelligence applications. Next, fundamental LTA principles and technology are reviewed. Requirements and advantages driving the development of LTA HALE are explored. Finally the world-wide activities in LTA are explored to identify countries working on LTA HALE systems, what their operational requirements are for developing them, and whether they have adopted similar technology.

Chapter 3 examines the technology for an LTA HALE system. Critical platform and payload technologies are identified and assessed against the requirements derived from feasibility studies and LTA HALE designs. Technology maturity, challenges, and availability are used to assess the potential of these systems to be incorporated into LTA HALE systems by 2020.

Chapter 4 provides a case study of the JAXA's LTA HALE program. The program is used to explore the programmatic challenges and level-of-effort required to develop an LTA HALE system. The case study also provides context to the viable LTA HALE programs evaluated in Chapter 5.

Chapter 5 examines programs within countries that have demonstrated viable LTA HALE potential. The programs are reviewed within the context of the technology challenges and case study investigated in Chapter 3 and Chapter 4. These examinations are used to assess the potential employment of lighter-than-air HALE systems by 2020. A discussion of the implications for U.S. intelligence and defense capabilities completes the thesis.

CHAPTER 2

HISTORY AND BACKGROUND ON LIGHTER-THAN-AIR SYSTEMS

> In Truth, I hope these new mechanic meteors will prove only playthings for the learned and idle, and not be converted into new engines of destruction to the human race, as is often the case of refinements or discoveries in science. The wicked wit of man always studies to apply the results of talents to enslaving, destroying or cheating his fellow creatures.
>
> \- Horace Walpole 1894

The chapter begins with a historical review of lighter-than-air flight to examine their application in intelligence and warfare. The review also extracts technical and programmatic challenges that have plagued lighter-than-air systems since their inception. The history is followed by a review of the fundamentals of LTA, discussing how LTA vehicles work and why they are sought to be employed for communications and surveillance operations. Then discussion is then focused on deriving requirements that drive the foreign development of LTA HALE systems. Finally, a review of select countries is performed to investigate LTA HALE activities around the world and to identify missions and problems the countries intend to address.

History of Lighter-than-Air Systems as Tools of Intelligence and Warfare

Throughout history, birds were the inspiration behind human attempts to fly. Humans, however, would first fly like embers rising from a fire rather than soaring on wings like Daedalus. As early as 1250, Roger Bacon postulated flight could be achieved by filling thinly wrought metal spheres with aethereal air or liquid fire. [15] These spheres, having been launched above the earthly air, would float on the atmosphere as a ship does on the water.[16] Bacon's vision of flight would have to wait 500 years for two brothers from France.

On June 5, 1783, Joseph and Etienne Montgolfier publicly launched a hot air balloon over Annonay, France.[17] Their spectacle sparked a race for the first manned balloon flight. Not to be out done by "Amateurs," a team from the Parisian Academy of Science, led by Professor Jacques Alexander C. Charles, launched the first hydrogen-filled balloon in August of the same year.[18] After achieving an impressive altitude of over 3000 ft, the balloon landed forty-five minutes later, where local residents of Gonoesse attacked it with pitchforks as it writhed on the ground.[19] Despite the success of the Charles' hydrogen balloon, the Montgolfier brothers won the manned-balloon race on 21

---

[15] Deng, *Ancient Chinese inventions: 3,000 years of science and technology* (Beijing: China Intercontinental Press, 2005), 112-113. Chinese lore describes egg shell floating on hot air in the 2nd century b.c.e and of the Kongming hot air balloon (lantern) around 200 AD.

[16] Edwin Kirschner, *Aerospace Balloons: From Montgolfiere to Space* (Fallbrook: Aero Publishers, 1985), 10.

[17] Charles Gillispie, *The Montgolfier Brothers and the Invention of Aviation* (New Jersey: Princeton University Press, 1983), 21-23. At the time, Montgolfier believed it was some component of the smoke that caused the balloon to rise.

[18] Charles is more commonly known of for the gas laws named after him.

[19] Basil Collier, *The Airship : A History* (New York: G.P. Putman's, 1974), 17.

November 1783 with a 500-foot hot-air flight that lasted 21 minutes.[20] Just 11 days later, Professor Charles flew his hydrogen-filled balloon for over two hours achieving altitudes in excess of 10,000 feet. While history relegates Professor Charles to second place, the gas-filled balloon proved vastly superior in performance and dominated ballooning for the next 200 years.[21]

Balloons in War

Well before the first balloon ascended, people were envisioning the balloon as an instrument of war. Montgolfier believed that if a balloon could be made large enough, "it [would] be possible to introduce an entire army, which borne by the wind, will enter right over the heads of the English" and attack the forces holding onto Gibraltar.[22] He also used the balloon warfare idea to justify the enormous costs of the balloon to his investors.[23] Benjamin Franklin, who happened to be attending the balloon flights in November 1783, quickly surmised the military potential. Although when asked of what use were these balloons, he famously quipped, "Of what use is a baby?"[24] He refrained

[20] Hugh Allen, *Story of the Airship*, Third. (Ohio: R.R. Donnelly and Sons Company, 1943), 22. The first animals to take flight were a rooster, a duck, and a sheep on a Montgolfier balloon,. These animals became symbols on the insignia of the U.S. Army Air Corps lighter-than-air division.

[21] John Christopher, *Balloons at War: Gasbags, Flying Bombs & Cold War Secrets* (Stroud: Tempus, 2004), 13.

[22] Ibid., 10.

[23] Charles Gillispie, *The Montgolfier Brothers and the Invention of Aviation*, 19.

[24] A.F.L. Deeson, *Illustrated History of Airships* (Bourne End: Spurbook Limited, 1973), 15.

from voicing his greater concerns, but was quick to relay them back to his peers in the United States.

> The invention of the balloon appears to be a discovering of great import and what may possibly give a new turn to human affairs. Convincing sovereigns of the folly of wars may perhaps be one effect of it. Since it will be impractical for the most potent of them to guard his dominions, five thousand balloons capable of raising two men each could cost no more than five ships of the line; and where is the prince who could afford so to cover his country with troops for its defense that 10,000 men descending from the clouds might not in many places do an infinite mischief before a force could be brought to repel them.[25]

In a single statement, Franklin portends the international relations theories of defensive realism, the security dilemma, deterrence, and mutually assured destruction. He even foreshadows the airpower theories of Guillermo Douhet. The underlying hope of peace in his statement failed to be realized due to limitations in balloon technology and the revolutionary fervor of the time.

Napoleon's army was the first to use balloons as an instrument of warfare. In 1794 they created the world's first air force, the Compaigne d'Ae'rostiers, to observe troop movements from above, providing tactical and operational intelligence. The balloons even had an unintended, yet beneficial, effect: psychological warfare. The English nervously scanned the skies in fear of a balloon-borne invasion. After L' Entreprenant led to the defeat of the Austrians and Dutch at the Battle of Fleurus, the balloon enjoyed ten years of intermittent success before Napoleon dismantled the units. Although gas generation in the field was problematic, the balloon corps was eventually dismantled for unstated reasons. There are several speculations as to why, such as cost-

[25]As quoted in Kirschner, *Aerospace Balloons: From Montgolfiere to Space*, 11.

saving measures or the inability to adapt to the technology, remaining reliant on cavalry reconnaissance.[26] Napoleon, however, had a hatred of the balloons possibly driven by "Bonaparte's inflated self opinion of his own talents as a military tactician" and the fact that an errant balloon created a stir at his coronation ceremony.[27]

During the first half of the 19th century, several countries explored the possibilities of the use of balloons during conflict. Many countries used balloons to drop propaganda over neighboring countries. By the middle of the century, innovations in military ballooning had moved across the Atlantic to the United States. The Union and the Confederacy used balloons throughout the Civil War developing concepts such as the in-flight telegraph and the "aircraft" carrier.[28] Notwithstanding the success of balloons as instruments of war, bickering between the two major proponents of balloons kept the concept from fully meeting its potential during the Civil War. One interesting anomaly was that photography from balloons was never used for reconnaissance, despite Mathew Brady's wide use of photography to document the war and Felix Nadar's use of cameras on balloons since the late 1850s.[29] Perhaps the most important outcome of the Civil War

---

[26] Christopher, *Balloons at War: Gasbags, Flying Bombs & Cold War Secrets*, 27.

[27] *L' Entreprenant* is French for Enterprise.

[28] For an account the T.S.C Lowe and the Civil war balloon see Steve Poleskie, *The Balloonist : the story of T.S.C. Lowe-- inventor, scientist, magician, and father of the U.S. Air Force*, 1st ed. (Savannah GA: Frederic C. Beil, 2007).

[29] Christopher, *Balloons at War: Gasbags, Flying Bombs & Cold War Secrets*, 28-38.

efforts was Count Von Zeppelin's trip to the United States to observe the balloon's wartime employment.[30]

The Franco-Prussian War saw an expanded application. During 1870, Paris was held under siege. Beginning in September of that year, the French enacted an airlift. Over the course of the siege, 66 balloons evacuated 102 people and carried over 2.5 million letters to maintain communications with the rest of France.[31] By the end of the 19th century, over a dozen countries maintained a balloon corps including China, Japan, Prussia, France, and England.

By the turn of the century, balloons had become a regular feature on the battlefield. Germany, France and England employed the kite balloon for surveillance. The German variant, known as the *drachen,* helped to direct trench warfare and range artillery fire over the eastern and western fronts by radioing down reports from above. Beginning as early as the First World War and progressing through World War II, barrage balloons protected cities by hoisting heavy steel cables to create a curtain of death for incoming bombers. Barrage balloons frequently broke away from their moorings creating havoc and destruction as they dragged their cables through the city streets. These events renewed ideas of offensive balloon applications. Balloon historian John Christopher points out that "balloons have a nasty streak and many offensive and secret tasks were devised for them during the Second World War, including trailing wires, carrying bombs

[30] A.F.L. Deeson, *Illustrated History of Airships*, 31.

[31] Christopher, *Balloons at War: Gasbags, Flying Bombs & Cold War Secrets*, 50.

or incendiary devices, and even delivering propaganda material and agents behind enemy lines."[32]

The Japanese independently developed balloon bombs during WWII. An estimated 10,000 balloon bombs, or Fu-Gos, were launched against the United States. The Japanese intended the Fu-Gos to create massive forest fires across the western United States. Fortunately for the United States, the wind currents required to take the Fu-Gos across the Pacific occurred in the winter months when U.S. western forests were damp rather than in the dry summer months, else the Fu-Go project might have succeeded.[33] Unfortunately, the Fu-Go did succeed in killing the wife of a minister and five children on a church picnic in southern Oregon.[34] These were the only deaths resulting from enemy action on the American continent during WWII.[35] Undetonated Fu-Gos remain a threat to this day in the American Northwest.[36]

Balloon concepts persisted throughout the Cold War; however, they took a turn toward the shadows of conflict. The United States instituted multiple reconnaissance balloon projects including Project Genetrix, 1956, and Operation Melting Pot. These efforts launched hundreds of large balloons over the Soviet Union to collect imagery and

---

[32] Ibid., 116.

[33] Joel Carpenter, "Fu-Go Balloons," *PROJECT 1947*, http://www.project1947.com/gfb/fugo.htm (accessed July 5, 2009).

[34] Ibid.

[35] Ibid.

[36] "Fu-Go Weapon," *Japanese Balloon Bombs*, http://www.japaneseballoonbombs.com/ (accessed July 5, 2009).

other intelligence.[37] The CIA extensively employed balloons to blanket propaganda leaflets over Soviet bloc countries.[38] Harking back to the Siege of Paris, defectors were given instructions for homemade hot air balloons that they used to escape from behind the Iron Curtain. While defectors were floating out, gas balloons ferried spies into Soviet bloc countries.[39] Covert and clandestine balloon applications became so prevalent that one director of the CIA, Walter Bedell Smith grumbled, "If you send me one more project with goddamn balloons, I'll throw you out of here."[40] His antagonism, however, was directed at psychological warfare rather than weariness of balloon operations.

While the days of the barrage balloon are gone, balloons remain integral to defensive applications. Unmanned aerostats concepts, developed in the 1970s, are vital to current border surveillance and base defense systems for many countries. Over 1800 meteorological balloons are launched daily to collect weather information vital to civilian and military activities. While balloons have surged in importance in the scientific community and waned in military applications over the last 50 years, their unique capabilities continue to hold the interest of militaries around the world.

---

[37] Donald Welzenbach, "Observation Balloons and Reconnaissance Satellites," http://www.foia.cia.gov/ 1960 (accessed February 25, 2009).

[38] Hugh Wilford, *The Mighty Wurlitzer : How the CIA Played America* (Cambridge: Harvard University Press, 2008), 39.

[39] Christopher, *Balloons at War: Gasbags, Flying Bombs & Cold War Secrets*, 195.

[40] Wilford, *The Mighty Wurlitzer : How the CIA Played America*, 45-46.

History of Airships

Before a balloon was ever lofted into the air, inventors developed concepts to control the movement and flight of balloons, that is, to make them *dirigible*.[41] Most of the early concepts for making balloons dirigible were borrowed from the nautical world, such as using sails and oars to propel balloon-borne naval vessels. After witnessing the first balloon demonstrations in 1783, Jean Baptiste Meusnier, an officer in the French Army Corps of Engineers, developed concepts for a steerable lighter-than-air vehicle (i.e. an airship). In his paper, "The Equilibrium of Air Machines", he published basic precepts of design that continue to be reflected in modern airships.[42] Despite Meusiner's innovative design, the first flight of a dirigible craft would not take place until seventy years later. With the help of advances in steam power generation, Henri Giffard made the first truly dirigible flight of an airship in 1852. His efforts did not ignite a wider interest in flight. It would take the success of the balloon airlift, during the 1870 Siege of Paris, to generate a concentrated effort to produce a dirigible craft.[43] Even with the renewed vigor, the viability of the airship was not established until 1901 when Alberto Santos-Dumont, a Brazilian living in France, flew his airship from St Cloud to the Eiffel tower and back.[44]

[41] Dirigible is French for directable or steerable.

[42] A.F.L. Deeson, *Illustrated History of Airships*, 18.

[43] Edward Horton, *The Age of the Airship* (Chicago: Henry Regnery Company, 1973), 15.

[44] Ibid., 21.

Although France made the initial contributions to the airship, the Germans mounted a massive effort to develop an airship designed for war. Count Ferdinand von Zeppelin, a member of the German army, feared the advances the French were making in airships throughout the latter part of the 19th century.[45] Von Zeppelin "feared that his army might be left behind in the race for what he foresaw might be a formidable weapon."[46] Count Zeppelin constructed and lost five airships before 1909.[47] However, Count Zeppelin persisted and managed to create a German industry that led the world. By World War I, the Germans had a formidable capability and embarked on a Zeppelin bombing campaign beginning in 1915. Although the Zeppelin bombing raids killed hundreds of people and created substantial damage, they were largely ineffectual.[48] This is attributed more to poor strategic employment of the systems rather than lack of capability.[49] Nevertheless, the Zeppelins were an effective instrument of psychological warfare.[50]

Germany was not the only employer of Airships. The U.S and Britain used blimps to effectively conduct antisubmarine warfare. Nevertheless, airships struggled to find their place. With stiff competition from aircraft and other naval programs, airship

---

[45] Ibid., 10.

[46] A.F.L. Deeson, *Illustrated History of Airships*, 31.

[47] Hugh Allen, *Story of the Airship*, 17.

[48] Edward Horton, *The Age of the Airship*, 42.

[49] Ibid.

[50] Hugh Allen, *Story of the Airship*, 15.

proponents found themselves writing books to defend their use as a valuable and complementary asset.[51] The arguments were to no avail and the airship faded from the military inventories by the 1960's.

Lighter-than-Air systems have a long and turbulent history as an instrument of warfare and intelligence. LTA use continues to be reinvented to meet the needs of the era. Balloons in the form of aerostats continue to be employed in communications and surveillance infrastructures. Airships have become relatively dormant in the LTA field but they are beginning to make a comeback in new forms of unmanned and persistent surveillance vehicles. Investigation into the historical aspects of balloons and airship reveal recurrent trends in technology and operational challenges. Power and envelope construction are traditionally the most challenging problems in LTA development and wind is an enduring operational concern.

Lighter-than-Air Fundamentals

Buoyancy

Hieron II, ruler of Syracuse had beset Archimedes with a difficult task: Determine whether or not a crown made for the ruler was made of pure gold without destroying it.

[51] For examples of these works see Commander C. E. Rosendahl, *What About The Airship?* (New York: Charles Scribner's Sons, 1938); Hugh Allen, *The Story of The Airship (Non-Rigid)* (Akron, Ohio: The Lakeside Press, R. R. Donnelley & Sons Company, 1943); P. W. Litchfeld and Hugh Allen, *Why? Why Has America No Rigid Airships?* (Cleveland, Ohio: The Corday & Gross Co., 1945).

As Archimedes sat in a bath contemplating the problem, he noticed the water rise and fall as he entered and left the bath. Inspiration struck and Archimedes ran naked through the streets shouting "Eureka!" His understanding of relative densities and displacement led to what is referred to as the Archimedes Principle. Published in 240 b.c.e. in his book *On Floating Bodies*, Archimedes describes the hydrostatic force of buoyancy as the upward force acting on a body is equal to the weight of the fluid displaced by that body. This is the same principle that allows steel ships weighing thousands of tons to float on water. Bacon made the leap in 1250 to apply the same concepts to air, which explains why he wanted to launch his spheres on "top" of the heavier atmosphere.[52]

All lighter-than-air systems follow this same basic principle to achieve flight. Large, free-floating scientific balloons use the concept of buoyancy to carry thousands of pounds of payload to the stratosphere. The balloons can achieve this height, in excess of 40 km (25 miles) by using lightweight polyethylene material to enclose large volumes of gas (generally helium) that is less dense than the surrounding atmosphere. The balloon is partially inflated on the ground and as it rises, the helium expands filling large volumes of the polyethylene envelope. The envelope can be as large as 40 million cubic feet.[53] There are a variety of balloon technologies from the "zero-pressure" balloons described above that float for hours to days to ultra long duration balloons that can float for several

[52] Kirschner, *Aerospace Balloons: From Montgolfiere to Space*, 8.

[53] "Scientific Balloons," NASA - Columbia Scientific Balloon Facility, http://www.csbf.nasa.gov/balloons.html (accessed July 6, 2009).

months.[54] These balloons are generally limited to scientific explorations. These balloons require delicate handling and special launch conditions that will need to be overcome before such systems can be operationalized for reliable commercial or military employment.

Smaller latex balloons are launched over 1800 times a day for weather applications.[55] Generally these balloons carry significantly smaller payloads than their scientific cousins and only persist on the order of hours or a couple of days with added buoyancy control systems. Even with this limited capability, businesses and universities around the world are adopting this technology to supply communication to rural areas and to perform scientific research on a variety of interests, such as micro-gravity.[56] Space Data Corporation, a Phoenix, Arizona based company, has developed communication systems by employing an array of these free-floating systems to provide persistent coverage through replenishment of balloon constellations.[57] Their current product line includes systems that monitor remote oil rigs, extend cell phone networks and augment land mobile radio systems.

[54] "NASA's Scientific Ballooning Program," *NASA Goddar Space Flight Center*, http://astrophysics.gsfc.nasa.gov/balloon/ (accessed July 6, 2009).

[55] "Weather Balloons," *National Weather Service Forecast Office - El Paso*, http://www.srh.noaa.gov/epz/kids/balloon.shtml (accessed July 8, 2009).

[56] "Expendable Stratospheric Platforms," *Venture Itch.com*, April 24, 2008, http://www.ventureitch.com/?p=526 (accessed July 8, 2009).

[57] "Space Data."

Airship Basics

Airships fall into two basic categories: rigid and pressurized.

Rigid airships have a lightweight frame that provides a skeletal structure for the airship. The outer cover provides structure and protection and is not used to contain the lifting gas. The concept is similar to an ocean liner. The airship is divided into bays that contain bags filled with lifting gas. The physical characteristic of this design allow the airship to be built larger to maximize lift characteristics.[58] This tendency is reflected in the monstrous airships of the early 20th century such as the Graf Zeppelin and the Hindenburg.[59] These rigid airships required large infrastructures and hundreds of people, especially for launch and landing operations. Although these airships are obsolete, they are about the same size as some contemporary LTA HALE designs (e.g. over 200 m long). Modern operations could not afford to employ hundreds of people just to help launch and land the systems. LTA HALE systems will require new operational concepts and technology to handle "Hindenburg" sized systems.

Pressurized airships represent the technology that is currently employed for airship design (e.g. the Goodyear Blimp) and was the airship as envisioned by Meusnier.[60] Also referred to as non-rigid airships, the structure and aerodynamic shape is

---

[58] G. A. Khoury and J. D. Gillett, *Airship Technology* (Cambridge University Press, 2004), 11.

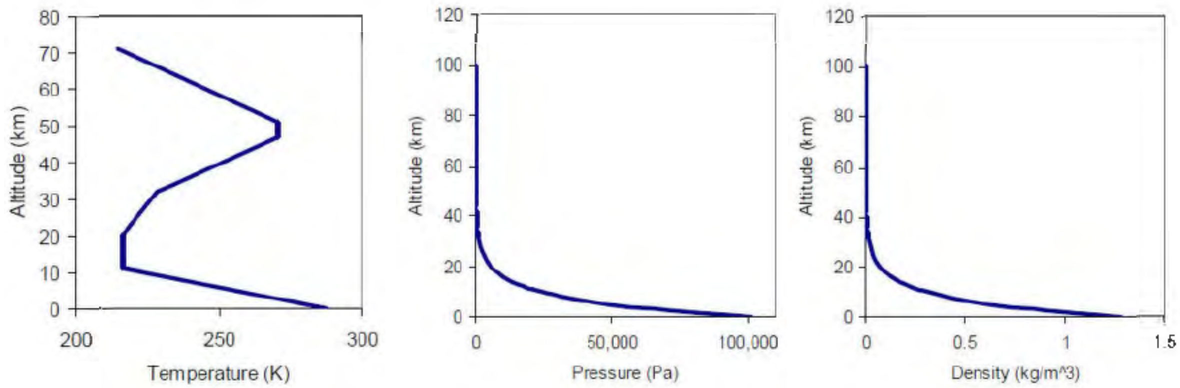
[59] Ibid.

[60] A.F.L. Deeson, *Illustrated History of Airships*, 18; Hugh Allen, *Story of the Airship*, 25. The blimp is the airship originally envision by Muesnier. The term blimp is derived from British nicknames for the two types of airships: "rigid" and "limp." During the First World War, a "Type B" airship was employed and the contraction of "B, limp" evolved into "Blimp."

achieved by fully inflating the system. An airship cannot be fully inflated with lifting gas on the ground or it would burst open due to the drop in surrounding atmospheric pressure as it ascends (see Figure 2.1). In order to adjust to the internal pressure without having to vent lifting gas, as structure known as a ballonet is installed inside of the envelope (see Figure 2.2).[61] The ballonet is simply an airtight bag that can be inflated with surrounding air. The ballonet is fully inflated when the airship is on the ground and just enough helium to give the airship shape and make it buoyant is added to the envelope. As the airship ascends, air is let out of the ballonet to allow the helium to expand. When the ballonet is completely deflated the airship has reached it maximum altitude. This is known as the "pressure height." If the airship ascends higher it will have to vent helium causing it to lose lift.

[61] For an in depth technical discussion on airships see Khoury and Gillett, *Airship Technology*.

Figure 2.1 Temperature, pressure and density vs. altitude.

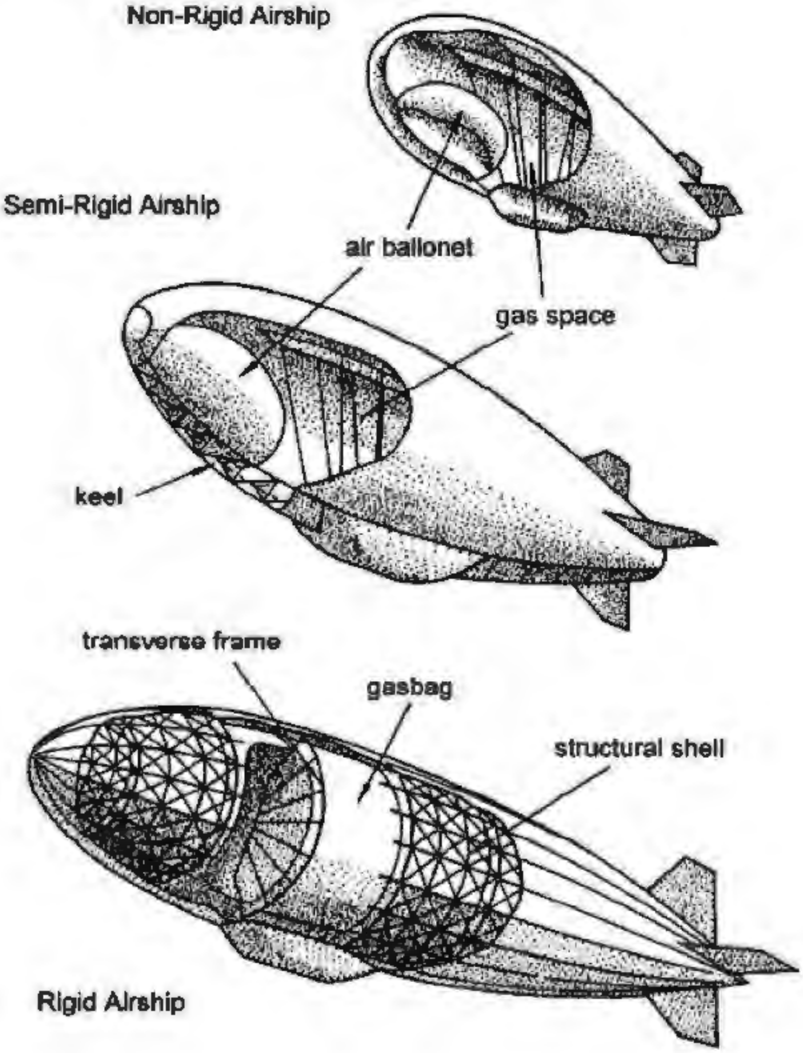


Source: Charles W. Vogt, Jr., "Operating in the Near Space Regime" (Air Force Institute of Technology, 2006), 19.

A subset of the pressurized airship is the semi-rigid airship which used additional structures to increase the strength of the envelope. Although modern envelope materials have made these structures largely unnecessary, semi-rigid airships are making a minor comeback with the modern Zeppelin NT system.[62]

[62]The company that built the Zeppelin NT is directly related to the original Zeppelin company. NT is an acronym for New Technology. Santos-Dumont flew a semi-rigid airship on his historic trip around the Eifel tower "Zeppelin NT - History," *Zeppelin NT*, http://www.zeppelinflug.com/zeppnt_histo.htm (accessed July 4, 2009).

Figure 2.2 Airship design and internal configuration



Source: Khoury and Gillett, *Airship Technology*, 12.

The LTA HALE system will be a pressurized airship with extremely large ballonets (usually more than one is installed to give the airship added control and balance). LTA HALE ballonets and envelopes will have to endure conditions (e.g. cold temperatures) that are beyond those experienced by modern airships (see **Error! Reference source not found.**). LTA HALE concepts also gain inspiration from the monstrous rigid airship of the past, the thought being that if the "quaint" early 20th century technology could build such large airships, then modern technology should be able to build similar sized systems today. Most LTA HALE systems are based on the concept that pressurized airships could employ modern materials to build a system the size of a Graf Zeppelin to reach and operate at high altitudes. But what requirements drive LTA HALE concepts to be considered? The next section explores this question by looking at derived requirements.

Derived Requirements for Lighter-than-Air High-Altitude Long Endurance

Through the first two sections of this chapter, the need for LTA HALE systems was assumed. But, what need is driving high altitude long endurance concepts? If this thesis focused on a U.S. application, a requirements analysis would be performed to identify capability gaps. After capability gaps were identified, various systems or concepts would be analyzed to see if they could meet the stated requirements. The focus of this thesis however, is the foreign development and employment of these systems. Their rubric for adopting these systems is not strictly a requirements-driven process and may be influenced by other factors, such as market forces. The operational advantages of LTA HALE systems are explored to derive the requirements of these systems.

LTA HALE Persistent Capability

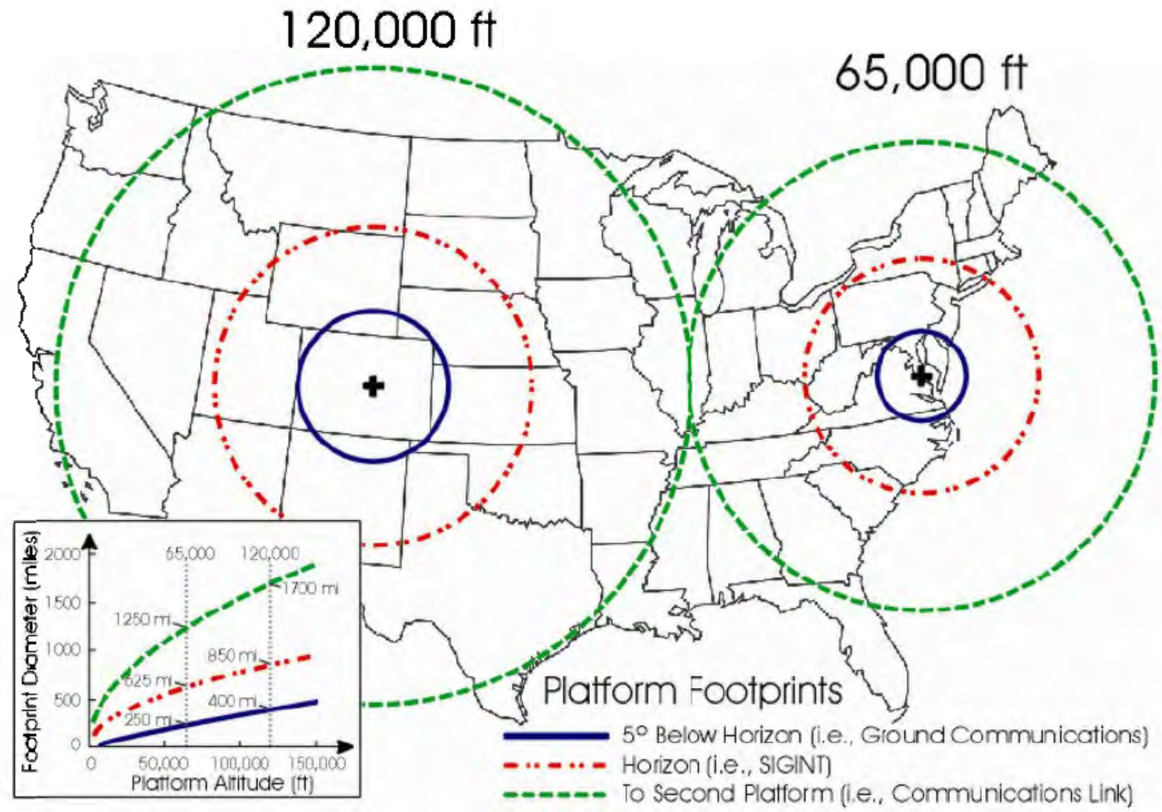
The term 'high-altitude long endurance' (HALE) describes physical attributes of the system. The intent of these systems is not to simply fly for long periods of time at extreme heights, but to provide an operational capability. The combination of high-altitude and long endurance forms a system that has the ability to deliver cost effective, persistent coverage. LTA provides the means to enable and enhance HALE capability. The need for persistent systems is addressed in the last section of this chapter entitled "Foreign LTA Activities for Communications and Surveillance."

Persistence is a term that is nebulously employed for many military and civilian surveillance applications. For the purposes of this thesis, persistence will be defined as continuous operational coverage over a defined area or of a target. The first step to deriving LTA HALE requirements is to dissect HALE into its component parts. The advantage of higher altitude is explored first, followed by long endurance.

High-Altitude Aspects of Persistence

A higher altitude equates to a larger ground footprint. As a platform rises in altitude, the area visible to the platform increases, allowing onboard sensor packages to collect data over a greater area (see Figure 2.3). Based on the collection system, the sensor field of view may not collect data from the entire footprint simultaneously, but the sensor suite can collect anywhere within the footprint without having to reposition the platform. This is known as Instantaneous Access Area (IAA).[63] The increased IAA of high-altitude platforms allows sensor payloads to maintain persistent contact with targets, especially moving targets. The larger coverage area also allows the HALE platform to drift without losing significant coverage.

Figure 2.3 Footprint Sizes for Platforms at 65,000 and 120,000 Feet for Three Look-Angle Restrictions



Source: Lt Col Edward B. Tomme, *The Paradigm Shift to Effects-Based Space: Near-Space as a Combat Space Effects Enabler* (Maxwell AFB, AL: Airpower Research Institute, 2005), 11.

[63] Wiley Larson, *Space Mission Analysis and Design*, 3rd ed. (El Segundo Calif.: Microcosm Springer, 2006), 164.

Lower flying, unmanned aerial systems (UAS) have less IAA available.[64] To achieve the same coverage as a higher platform, the lower flying system must move across the target area which causes the system to lose persistence over the target. Multiple systems could be employed with overlapping footprints to maintain an equal persistence; however, this would entail higher costs, additional personnel, and increased system complexity to manage multiple platform, sensor and information feeds. Satellites operate in the "ultimate" high ground with large footprints and IAAs but they have inherent limitations related to endurance issues addressed in the next section.

Scientific balloons regularly achieve altitudes above 30km (100,000 ft) which motivates airship and sensor designers to develop operational systems to reach similar heights. Other systems operate at this altitude include the U-2 Dragon Lady, the RQ-4 Global Hawk, the now-retired SR-71 Blackbird along with developing systems, such as AeroVironment's Global Observer and QinetiQ's Zephyr system.[65] All of these systems, along with satellites, must contend with limited endurance to varying extents.

---

[64] Although these systems could be airships, the term here is used to represent aerodynamically lifted aircraft for clarity in the discussion.

[65] "QinetiQ's Zephyr UAV exceeds official world record for longest duration unmanned flight," *Qinetiq.com*, http://www.qinetiq.com/home/newsroom/news_releases_homepage/2007/3rd_quarter/qinetiq_s_zephyr_uav.html (accessed July 4, 2009); "Stratospheric Persistent Unmanned Aircraft Systems: Global Observer Detail," *AeroVironment, Inc.*, http://www.avinc.com/uas/stratospheric/global_observer/ (accessed June 22, 2009); "RQ-4 Block 20 Global Hawk," *Northrop Grumman Aerospace Systems*, http://www.as.northropgrumman.com/products/ghrq4b/index.html (accessed July 4, 2009). These assets are considered HALE systems.

Long Endurance Aspects of Persistence

In order to achieve persistence, a platform must be able to maintain a presence or endure over the target Area. The long endurance aspect of HALE systems attempt to maximize this aspect of persistence. Physical factors that limit the endurance of various assets are shown in Table 2.1.

Table 2.1 Limitations to endurance

Type of Asset	Limitations
Manned (e.g. U-2)	Human physiology, fuel, oil
Aerodynamically Lifted UASs (Predator, RQ-4)	Fuel, oil
Low earth orbiting satellites	Time over target area (on the order of minutes)

The high-altitude aspect of persistence was dominated by satellites, providing significantly larger footprints than even the highest altitude balloons. But the nature of satellite orbital mechanics only allows them transient access over a given target area. The persistence provided by satellite coverage has been described as "stroboscopic, dictated by orbital mechanics, which can cause important developments to be missed should they occur during times that the satellite is not overhead. Fielding constellations of satellites to mitigate the gaps in the strobe effect can be prohibitively expensive for short-duration events…." [66] The ground footprint of satellites may be large, but they are fleeting.

[66] Lt Col Edward B. Tomme, *The Paradigm Shift to Effects-Based Space: Near-Space as a Combat Space Effects Enabler* (Maxwell AFB, AL: Airpower Research Institute, 2005), 15, www.au.af.mil/au/awc/awcgate/cadre/ ari_2005-01.pdf (accessed June 5, 2009).

UAS can fly unrestricted over a target, but they must consume fuel and oil to maintain their presence. As with satellites, they can use multiple assets to replenish the coverage but this drives the cost and complexity issues addressed previously. AeroVironments's Global Observer is projected to extend the current single asset maximum endurance from about 35 hrs to 7 days.[67] Although this will prove to be a remarkable capability, the system is limited by the amount of liquid hydrogen fuel it can carry onboard.

LTA HALE systems intend on extending endurance by taking advantage of their substantial and "power free" buoyant lift. The size of these systems is such that renewable energy or large quantities of consumable fuel can be carried on board to power station-keeping and payload systems for several months or longer. LTA HALE concepts have the potential to simultaneously increase high-altitude and long endurance to maximize persistence.

Based on the requirement derived for HALE systems, geosynchronous satellites would serve as the ultimate HALE asset with the largest ground footprints (covers approximately one-third of the earth) and a persistence that is measured in years, constrained only by the life expectancy of the system. However, the enormous range from platform to target (35,786km) limits the effectiveness of geostationary satellites for many communications and intelligence applications.

[67] "RQ-4 Block 20 Global Hawk"; "Stratospheric Persistent Unmanned Aircraft Systems: Global Observer Detail."

Advantage of HALE Operation for Payloads

The high-altitude aspect of a HALE system enables mission payloads to have a larger IAA. But if this were the sole requirement, and cost was not a factor, then all sensors designers would demand that their assets be put on a geosynchronous satellite. LTA HALE operates in an environment that has several advantages for communications and surveillance mission payload.

An increased ground footprint does not come without a corresponding decrease in capability. For imaging applications, as the distance from the target increases, the ability to resolve image detail decreases linearly. To maintain an equivalent resolution capability at a higher altitude, the onboard optical sensor system must correspondingly increase in size (i.e. the aperture of the lens) which leads to increased weight and cost. For signals applications, the problem is more dramatic. The difference in the strength of the received signals diminishes quadratically as distance increases.[68]

Although this appears to diminish the capability achieved by operating at higher altitudes, the effect on an LTA HALE system is not that remarkable. In order to achieve the same resolution as an imaging UAS flying at 10km (~33,000 ft) an LTA HALE imaging system operating a 20km would only need to double the size of the optics. A typical imaging satellite (e.g. Ikonos or GeoEye-1) orbiting at 700km would need to have

[68] This loss of signal is due to free space path loss which is the geometric spreading of a signal as it travels through space.

optics 35-times larger than the LTA HALE system and 70-times larger than the UAS.[69] The comparison between a communications satellite operating in geosynchronous orbit yields striking results. To receive a 2GHz radio signal the LTA HALE system only needs to be 4 times more sensitive than the UAS to receive the signal. The geosynchronous satellites, however, must be 12.6 million times more sensitive.[70]

Atmospheric effects

The earth's atmosphere has deleterious effects on remote sensing and communication applications. The atmosphere absorbs, reflects, and distorts electromagnetic waves as they traverse through it. The ionosphere is particularly problematic for electromagnetic signals. Scintillation effects and solar activity create inconsistencies in the ionosphere that affect space-based applications from communication systems to the Global Positioning System.[71] LTA HALE systems will operate well below the ionosphere.

---

[69] "GeoEye-1 Launch Site--About GeoEye-1," *Geoeye.com*, http://launch.geoeye.com/LaunchSite/about/ (accessed July 7, 2009).

[70] The calculations assumed the transmitter was operating directly beneath all systems. The received strength for each system was calculated as follows: Satellite -193.7dB, LTA HALE system -128.6dB, UAS 122.62. For a more in depth look at comparative sensor technology see Charles R. Ferguson and Douglas A. Harbold, "High Altitude Long Endurance (Hale) Platforms for Tactical Wireless Communications And Sensor Use In Military Operations" Thesis, Naval Postgraduate School 2001, 35.

[71] Tomme, *The Paradigm Shift to Effects-Based Space: Near-Space as a Combat Space Effects Enabler*, 12-13, 42-43.

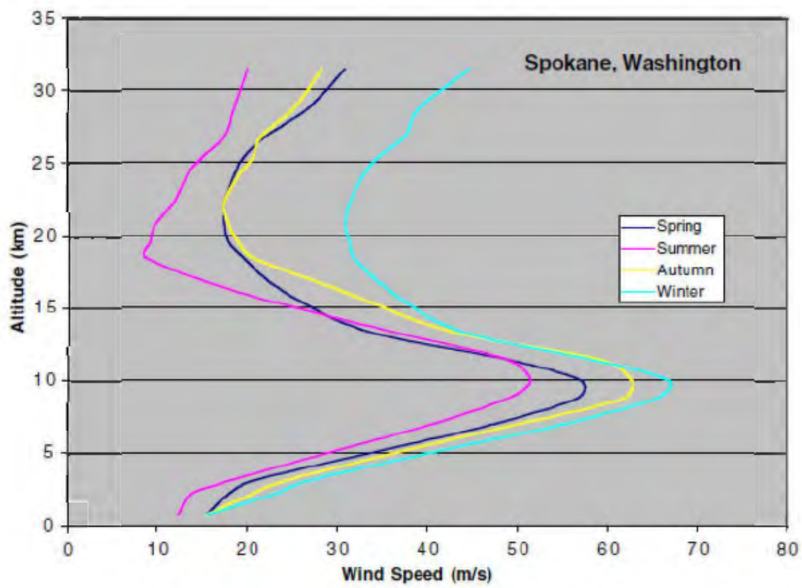
Why fly so High?

So far, the derived requirements have centered on how LTA HALE systems can improve persistence and performance of mission payloads. LTA HALE systems are limited in their choice of operational altitude. Although the airship does not need propulsion to remain airborne, it does need it to perform station keeping over the target area. According to a NASA LTA feasibility assessment "The propulsion system power requirement is the main power draw for the airship"[72] The propulsion system's power requirements are driven by the drag experienced by the surface area of the airship's envelope. The envelope areas on LTA HALE systems are extremely large, on the order of 20,000 m^2 and larger. This presents significant surface drag. This surface drag is proportional to the square of the wind speed. As the wind speed increases, the propulsion power demands dramatically increase. An inspection of a wind profile (average wind speed by altitude) reveals the feasible operating altitudes for LTA HALE systems (see Figure 2.4). A significant increase in wind speed occurs over the middle altitudes (above 5 km). The next viable operational window for LTA HALE systems occurs roughly between 18km to 22km. LTA HALE programs target their design to operate in the pocket of "calm". Although the wind speed is variable across the seasons and with location, the basic shape remains relatively constant across the world. (See China's diagram on LTA HALE operations Figure 2.4). The LTA HALE concepts of Japan, South Korea, EU, and Russia all target the 18-22km altitude.

[72] Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*, 69.

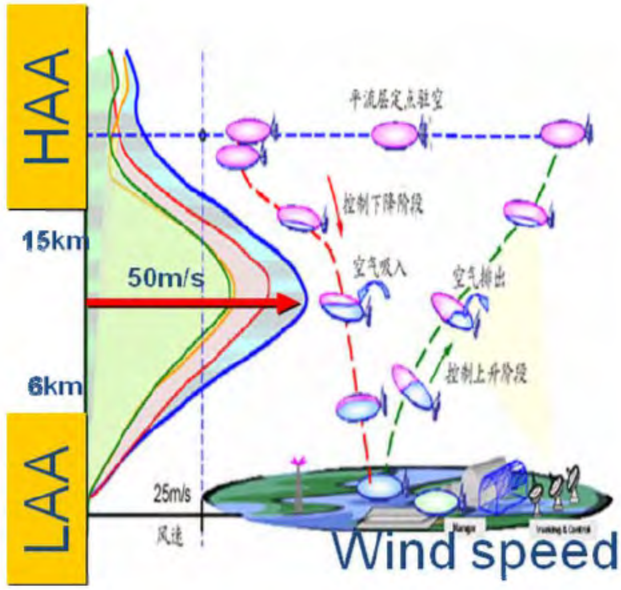
Creating an airship that can operate in the stratosphere is not so much a choice as it is a necessity. While the stratosphere presents a window of opportunity for LTA HALE systems, the wind profile is such that design cannot be "walked up" to this altitude. LTA HALE programs must test on airships that operate below 5km and then leap to the stratosphere.

Figure 2.4 Example wind profile over the United States



Source: Anthony Colozza, Initial Feasibility Assessment of a High Altitude Long Endurance Airship (Glenn Research Center: National Aeronautics and Space Administration, December 2003), 18.

Figure 2.5 Wind speed effects on China's LTA HALE concept



Source:. Zi-Niu Wu and Xiao-Jian Xue, "Civilian Demands Application of Airships in Civil Projects" (presented at the VEATAL 2008 Beijing China Conference, Beijing, CN, April 2008), http://www.veatal.com/pageLibre000115d8.php (accessed July 3, 2009).

Note: HAA stands for high altitude airship; LAA is a low altitude airship.

The final requirement for an LTA HALE system is derived from "optimizing" the factors of the operational and technical considerations discussed above:

- Maintain persistence akin to a geostationary satellite.

- Operate as high as possible to increase your IAA.

- Operate as close to the target as possible to increase resolution/link margin.

- Operate as close to the target as possible to decrease atmospheric effects

- Operate below the ionosphere

- Operate in minimum wind speed conditions

The ultimate objective of LTA HALE systems is to operate like a pseudo geostationary satellite within the atmosphere. A European government policy consortium expressed a need for platforms that meet these derived requirements. The "…EO [electro-optical] market and the foreseen user requirements point to the need for data with a high update rate, high accuracy and high ground resolution but at an affordable cost. This requires the merging of the advantages of both aerial and satellite data without their respective setbacks"[73] The LTA HALE system is born out a desire to optimize payload and platform operational requirements. Nevertheless, these requirements do not address intended employment of these systems. The following section addresses how these LTA HALE systems are projected to be used by various countries.

Foreign LTA Activities for Communications and Surveillance.

The LTA HALE system derived requirements provide insight into why the operational characteristics of these systems may be useful; yet these do not address intended employment. This section provides a brief survey of the foreign LTA HALE and the intended missions of their systems. Current LTA efforts are also explored to see how

[73] D. Fransaer et al., "Pegasus: Business Model for a Stratospheric Long Endurance UAV System for Remote Sensing," 2004, http://www.isprs.org/congresses/istanbul2004/ (accessed July 7, 2009).

these countries are adapting similar systems and to reveal any underlying LTA operational and technical capability that will enable them to develop LTA HALE systems by 2020.

Japan

Over the last decade Japan has emerged as the leader in LTA HALE development. Japan's program is a government backed effort led by their aerospace agency JAXA. Japan has succeeded in taking feasibility studies performed in 1998 beyond the conceptual stage and has had the world's most extensive foreign LTA HALE program over the last decade.[74] Japan's objectives for the program were to develop a station keeping platform, similar to a geostationary satellite that could be used for telecommunication and earth observation programs including digital TV, cell phones, agricultural growth, and traffic monitoring.[75] Japan developed several key LTA HALE technologies and performed two flight test programs, with one of their airships reaching the stratosphere. Japan is also involved in developing low altitude unmanned airships to aid in disaster response. A case study on Japan's LTA HALE program is discussed in Chapter 4.

---

[74] Toyotoshi Kurose, "Japan: Development for SPF Stratospheric Platform Airship," *Gekkan JADI*, May 1, 2008.

[75] Shuichi Sasa, "Stratospheric Platform Program in Japan and Ground-to-Stratosphere Flight Test" (presented at the 9th UAVNET Meeting, Amsterdam, January 27, 2004), http://www.uavnet.com%2FDL%2FDocument_Library%2FAmsterdam_Meeting%2FStratospheric_platform_Sasa.pdf&ei=BCNBSsE7h4m2B7KUiaIJ&usg=AFQjCNGtJz00B_5DNHC9D_QSyCaV-zMZ6Q&sig2=lkpiccUJIccb_PGO1YTOug (accessed June 5, 2009).

South Korea

In 2000, South Korea began a 10-year program to fully commercialize an LTA HALE system.[76] As with Japan, the program is a government sponsored effort that is led by Korea Aerospace Research Institute (KARI). [77]KARI completed the first phase of development in 2005 by developing and flight testing a 50m autonomous airship prototype.[78] South Korea has also performed research on power generation, flight control, envelope technology and a civilian communications payload for their airship.[79] The objective of the program was to develop a system for commercial communication networks (e.g. cell phone, broadband access) and to "establish a good foundation in…broadcasting relay, stratospheric communications, and high precision national intelligence networks." These "intelligence networks" are not defined in open sources. KARI's program is often referred to in the LTA HALE literature as a viable program. An assessment of South Korea's program is performed in Chapter 5.

---

[76] Chan-Hong Yeom et al., "Development of a Stratospheric Platform in Korea."

[77] Ibid.

[78] Sang-Jong Lee et al., "Development of Autonomous Flight Control System for 50m Unmanned Airship," in *Proceedings of the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference, 2004.* (presented at the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference, 2004., Melbourne, Australia, 2004), 457-462, http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1417504 (accessed June 5, 2009).

[79] W. Kang et al., "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope," *Composite Structures* 75, no. 1-4 (2006): 151-155.

European Union

Europe has been a leader in lighter-than-air platforms since the first balloon floated over France in 1783 and the Germans mastered the Zeppelin. Within the EU, several governments, corporations and consortiums have explored and promoted LTA HALE concepts over the last decade. In 1999, the European Space Agency (ESA) contracted with Lindstrand Technologies, a British company, to develop designs for a stratospheric airship.[80] The intended applications of the Lindstrand system include mobile phone links and surveillance radar. [81] A collaboration between Advanced Technologies Group, StratSat Technologies, and SkyCat had plans to develop a "StratSat" beginning in 2001, but the companies are now bankrupt. As recently as 2008, the StratXX program in Switzerland established a collaboration of European aerospace companies and universities to develop a communications LTA HALE system. [82]

Europe has a large LTA community that is using LTA to perform communications and surveillance missions with lower altitude airships. Sweden, France and Britain have world renowned stratospheric balloon programs with which NASA

[80] "HALE."

[81] Ibid.

[82] "StratXX - Near Space Technology," *StatXX.com*, http://www.stratxx.com/ (accessed July 3, 2009).

frequently partners.[83] Manned airships are performing surveillance missions around the world, including Skycruise Switzerland and Zeppelin NT.[84] Skycruise has supported "anti-terror surveillance" at every Olympics since 1996.[85] The EU also has multiple low-altitude unmanned airships that are used for surveillance such as the Skive aviation group. Lindstrand produced the G-22 unmanned airship that was used by the Spanish Government in 2004 for a classified military surveillance operation and is now being developed by BAE Systems for surveillance and defense applications.[86]

Several consortiums supported by governments inside and outside the EU are dedicated to LTA HALE development. The Capanina effort was started in 2004 to develop communications technology and standards for HALE and LTA HALE systems.[87] These cooperatives do not fund or develop LTA HALE systems. The 18-month long EU consortium study defined an extensive list of potential operational missions for LTA

[83] "CNES : A strategic activity," *Centre National d'Etudes Spatiales*, http://www.cnes.fr/web/CNES-en/3642-a-strategic-activity.php (accessed July 6, 2009); "Esrange Space Center," *Swedish Space Corporation*, http://www.ssc.se/esrange (accessed July 8, 2009)(CNES) webpage, http://www.cnes.fr (accessed January 10, 2009); Swedish Space Corporation, "Esrange Space Center" http://www.ssc.se/esrange (accessed January 10, 2008).

[84] "Airships for Passenger Flights - Advertising - Security - Consulting," *Skyship Cruise Switzerland Ltd.*, http://www.skycruise.ch/security.htm (accessed July 8, 2009).

[85] Associated Press, "Athens Readies Airship for Olympic Terror Patrol," *USATODAY*, July 19, 2004, http://www.skycruise.ch/info/medien/USATODAY-040719.pdf.

[86] "Helium Airships," *Lindstrand Technologies*, http://www.lindstrandtech.com/helium_airships.html (accessed July 3, 2009); "BAE Systems Floats Autonomous System At Farnborough International," *BAE Systems*, http://www.baesystems.com/Newsroom/NewsReleases/2008/autoGen_108611183947.html (accessed July 3, 2009).

[87] Milan Lalovic et al., *Strategy Document: Delivering Broadband for All including Commercial and Technical Risk Assessment* (CAPANINA, May 23, 2005).

HALE systems. These missions include telecommunications to support trains and disaster relief efforts, security missions for border control and protection of critical infrastructure, and earth observations missions such as traffic and forest fire monitoring. The study also detailed payload requirements for each of the missions. [88]

China

China is actively engaged in LTA activities and has expressed the desire to build LTA HALE systems. [89] As early as 2001, TsingHua University presented preliminary research on an LTA HALE concept.[90] China also has a growing LTA industrial base and has established an airship association. [91] Several commercial companies in China, including Beijing Losan United, Shanghai Vantage Airship Manufacture Company, and Huajiao Airship, have developed unmanned airships.[92] These companies market the airships for multiple functions including police and surveillance applications.[93] Huajiao Airship even makes the dubious claims that their system "equipped with special

---

[88] Ibid.

[89] Duan Dong Bei, "Airship's R&D in Application Aeronautic and Astronautic in China" (presented at the VEATAL 2008 Beijing China Conference, Beijing, CN, April 2008), http://www.veatal.com/pageLibre000115d8.php# (accessed July 3, 2009).

[90] Zhipeng Tong et al., "R&D of Stratospheric Platform and SP based Information Systems in China" (presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001).

[91] *NASIC Open Source Report: (U) Chinese Airship Research Association* (Wright-Patterson AFB, OH: National Air and Space Intelligence Center (NASIC), June 2, 2009), 4.

[92] "Losan United Sky Technology Dream," *Lonsan*, http://www.lonsan.com.cn/en/research/index.php (accessed July 8, 2009).

[93] "Vantage Airship," *Shanghai Vantage Airship Manufacture Company Limited*, http://www.vantageship.com/index2.htm (accessed July 8, 2009).

facilities…carries special military force to fight against terrorists, riots…and hostage rescue operations."[94] The company also markets a sensor and radar suite for their airship designed for mine sweeping operations.[95]

China has not limited themselves to organic systems. They have procured Russian LTA systems for radar surveillance of the Taiwan Strait.[96] China has established requirements or multiple missions to be executed by low-altitude and high-altitude airships that include: fire monitoring, public security, wireless system concept, next generation cellular phone systems, broadband access, and radiolocation and have indicated that it could be used for military concepts.[97]

Russia

Airship manufacturer RosAeroSystems, has indicated that it is developing the "Berkut" LTA HALE for communications and surveillance using similar equipment installed on geostationary satellites.[98] RosAeroSystems has over 15 years manufacturing

---

[94] "Huajiao Airship," *Huajiao Airship.com*, http://www.hjairship.com/englishwebsite/home.htm (accessed July 8, 2009).

[95] Ibid.

[96] "Lighter than air," *Armada International*, http://www.thefreelibrary.com/Lighter+than+air-a0166350176 (accessed July 8, 2009).

[97] Zi-Niu Wu and Xiao-Jian Xue, "Civilian Demands Application of Airships in Civil Projects" (presented at the VEATAL 2008 Beijing China Conference, Beijing, CN, April 2008), http://www.veatal.com/pageLibre000115d8.php# (accessed July 3, 2009).

[98] "Russia building surveillance and communications airship - agency," *BBC Monitoring Former Soviet Union*, October 13, 2008 (b) (3) [redacted]

LTA, low altitude technology, aerostats for commercial and military missions. LTA HALE objectives have not been articulated, but RosAeroSystems has produced LTA systems for international military and civilian customers. [99]

The Rest of the World

The Middle East has been a staple for testing and developing aerostat systems and the region is showing signs of interest in airships. In 2004, the Israeli Aircraft Industries (IAI) briefly established a solar-powered stratospheric airship program.[100] Although the project only developed initial plans for broadband communications platform, Israel's Ministry of Defense apparently supported the concept "primarily for early warning and missile defense missions." [101] Israel plays an active role in the European LTA HALE consortium efforts.

Other countries in the Middle East, such as Kuwait, Saudi Arabia and the UAE are interested in procuring LTA systems for civil and military missions.[102] The UAE's Abu Dhabi Unmanned Aerial Vehicle Investments, a government investment firm, is

---

[99] "Airship Nazca," *The Airship Nazca Project*, http://www.airshipnazca.com/ (accessed July 3, 2009); "Augur/RosAeroSystems Au-21 Puma," *Jane's Electronic Mission Aircraft*, (b) (3) [redacted]

[100] Barbara Opall-Rome, "Israel Aircraft Industries Promotes Airship Concept," *SpaceNews.com*, February 24, 2004, http://www.space.com/spacenews/archive04/iaiarch_022404.htm (accessed July 8, 2009).

[101] Ibid.

[102] "Lighter than air."

developing several LTA systems to support security and maritime operations.[103] Although Space Data Corporation is a U.S.-based company, they have an international division that is developing similar systems around the world, including for countries in the Middle East. [104]

Both India and Pakistan have expressed interest in airship systems for surveillance activity. India, especially the Indian Institute of Technology, Bombay, is a prominent force in the research and development of novel airship design.[105] Both countries currently use tethered LTA platforms that carry tracking radar systems for border surveillance.[106] Israel has sold several LTA systems to India to support border defense.[107] India has recently expressed renewed interest in an LTA HALE system for civilian applications.[108]

In 2005, Australia and Columbia had agreements with Sanswire to provide Stratellites® for communications infrastructure, but the partnerships are no longer

[103] Wendell Minnick, "Change of UAE Management Doesn't Ground Camcopter", Defense News, http://www.c4isrjournal.com/story.php?F=3176331 (accessed 10 January 2009).

[104] Space Data Corporation website, "International Programs." https://www.spacedata.net (accessed December 28, 2008).

[105] Programme on Airship Design and Development webpage, http://www.aero.iitb.ac.in/~airships/index.html (accessed 28 December 2008).

[106] Defense Industry Daily, "Flying LTTE Tigers, LET Terrorist Boats Help Spur India's Aerostat Radar Buys from Israel," 21 Jan 2009 (accessed 22 January 2009).

[107] Strategy Page, "India Buys Israeli Aerostat Radar," January 23, 2009 http://www.strategypage.com/htmw/htada/articles/20090123.aspx (accessed 23 January 2009).

[108] Luke Brook, e-mail with the author, 30 June 2009.

advertised on Sanswire's website.[109] Turkey's government expressed a desire to buy Lockheed Martin's High Altitude Airship for border defense back in 2005, but they were apparently unaware that it was not an operational system at the time.[110] They have made no efforts to develop a system of their own.

Conclusion

LTA HALE systems and unmanned airships are gaining wider attention among the international community. These systems have the potential to optimize both persistence and performance for communications and surveillance missions. However, these systems do not exist today and must be developed using state-of-the-art technology. Chapter 3 will examine the enabling technologies and identify critical technology challenges that confront the development of LTA HALE systems.

[109] "Sanswire-TAO Stratellite™," *Sanswire.com*, http://www.sanswiretao.com/product-stratellite.htm (accessed July 4, 2009).

[110] Utku Cakirozer, "Turkey Said May Purchase High Altitude Airship for Monitoring PKK Activities," September 26 (b) (3) [redacted]

CHAPTER 3

TECHNOLOGY CHALLENGES FOR LTA HALE SYSTEMS

This Chapter addresses the technology challenges for LTA HALE systems. Critical technologies were identified using a DoD technology assessment process. The technologies were assessed against the requirements derived from multiple feasibility studies and LTA HALE system technical goals. The technology is further assessed for maturity, technology challenges, and availability of the technology to international LTA HALE programs.

Technology Assessment and Methodology

Critical technologies for LTA HALE systems were identified by using the process outlined in the Technology Readiness Assessment (TRA) Deskbook. According to the TRA Deskbook, "a TRA is a systematic, metrics-based process…that assesses the maturity of certain technologies…used in systems."[111] Feasibility studies and program documents from various LTA HALE efforts were examined to identify common

[111] Deputy Under Secretary of Defense for Science and Technology, "Technology Readiness Assessment (TRA) Deskbook" (U.S. Department of Defense, May 2005), 10, https://acc.dau.mil/CommunityBrowser.aspx?id=18545 (accessed June 18, 2009).

technology themes and requirements. Critical technologies of the LTA HALE systems were identified through the TRA process and following its precept that "a technology element is 'critical' if the system being acquired depends on this technology element to meet operational requirements…and if the technology element or its application is either new or novel."[112]

After the critical technologies were identified, they were assessed for their ability to meet LTA HALE requirements based on the current and projected capabilities of the technology. The technology was then assessed a maturity using a technology readiness level (TRL) construct. The TRLs for each of the technologies were derived by answering guide questions from the Air Force Research Laboratory's (AFRL) "TRL calculator."[113] TRLs provide a common language to assess the maturity and risk of developing LTA programs. International programs do not necessarily follow the same development paths as DoD systems, but the TRL provides a sense of the level of effort required to mature the system for operational employment. For most technologies, the TRL level would need to be TRL 5 now or at least a TRL 6 by 2015 in order to be integrated into an operational system by 2020. A full description of the TRA process and TRLs can be found in the TRA Deskbook.[114] Table 3.1 provides a brief explanation of TRLs.

---

[112] Ibid., 26.

[113] William Nolte, "TRL Calculator Upgrade to v 2.2," *Defense Acquisition University*, https://acc.dau.mil/CommunityBrowser.aspx?id=25811 (accessed June 18, 2009) The TRLs assessed in this thesis are based on the authors analysis and should not be cited as official TRLs unless otherwise stated.

[114] Deputy Under Secretary of Defense for Science and Technology, "Technology Readiness Assessment (TRA) Deskbook," 3-16 - 3-20.

Table 3.1 Explanation of TRLs

Level	Explanation
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in an operational (space) environment
TRL 8	Actual system completed and (flight) qualified through test and demonstration
TRL 9	Actual system (flight) proven through successful mission operations

Source: "Technology Readiness Assessment (TRA) Deskbook", 3-16.

Although TRLs provide an indication of maturity, they only reflect the current state of the technology. The level of effort required to adapt these technologies to an LTA HALE system is addressed in the technology challenges section of the assessment. Factors are identified that indicate where substantial research, development, tests, and evaluation (RDT&E) resources need to be expended to develop a technology to meet LTA HALE requirements.

Maturity and technology challenges were considered independent of international origin. The international availability section assesses the accessibility of the technology to be acquired or manufactured by the international community. For example, if LTA HALE vehicles required nuclear technology, the availability would be very limited due to indigenous capabilities, international restrictions, and export control laws.

The TRA assessment revealed that critical technologies for an LTA HALE system centered on power generation and hull construction.[115] The three critical technologies identified were solar arrays, fuel cells, and envelope materials. Developmental challenges for these technologies centered on reducing mass, improving performance, and adapting them to operate at high altitudes for extended periods. Lifting gases were also identified as a key driver[116] for LTA systems. Each of these critical technologies are reviewed and explored for requirements, maturity, challenges, and availability.

As discussed in Chapter 2, wind conditions and drag considerations drive LTA HALE designers to develop vehicles that operate between altitudes of 18 km and 22 km. Feasibility studies developed by NASA and JAXA were used to determine technical capability requirements for LTA HALE systems that operated at these altitudes. Although various design trades can drastically affect the vehicles physical characteristics,

[115] Each of the subsystems of the proposed LTA HALE designs were examined to determine if the technology exists or is being used in a novel way. The technologies identified were compared to technology concerns expressed in the literature by the LTA HALE designers. The critical technologies were also verified by experts interviewed by author at the 18th AIAA Lighter-than-Air Technology conference, Seattle, WA 5-7 May 2009.

[116] A key driver is not a technology challenge, but does effect the technical development and operational employment of the system.

requirements for similarly sized vehicles are relatively stable since they are based on the physics of the system rather than technology choices.

Power

Power is a historic problem for airships. Henri Giffard built the first true dirigible vehicle because he was able to develop a steam engine light enough to be lofted by a balloon.[117] The gasoline engine, with its better power-to-weight ratio, sparked the "age of the airship" in the early twentieth century.[118] The high-altitudes and endurance demands of LTA HALE systems create an even more daunting power challenge than previously tackled.

In Chapter 2, propulsion was identified as the primary driver of power requirements. The propulsion system's power requirements are driven by its station-keeping mission along with the drag experienced by the airship's hull. Thus, as the volume of the airship grows, due to increases in weight or operational altitude, the power requirement also increases. Once the operational altitude is set, which establishes volume, the average power of an airship is determined by the mean wind speed at that altitude.[119]

[117] Edward Horton, *The Age of the Airship*, 15.

[118] Ibid.

[119] Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*, 24.

Researchers at NASA and JAXA have used the 99th percentile wind speed to determine maximum power (see Figure 3.1).[120] Maximum power determined by this method is used as the baseline evaluation reference for power.

The LTA HALE studies and designs performed by NASA, JAXA, and KARI had a wide range of power requirements varying from 200 kW to over 1200 kW maximum power. Most of the Foreign LTA designs fell within 200 kW to 500 kW ranges.[121] Differences were primarily due to varying assumptions on wind speed conditions, payload mass and power, and total airship mass. LTA HALE systems that operated under favorable wind conditions (e.g. summer on the U.S. east coast) require less power than systems that needed to operate during more severe conditions (e.g. winter on the U.S. east coast). By comparing Figure 3.1 and Figure 3.2, the relationship between peaks in maximum wind speed and maximum power becomes apparent. Although the wind conditions vary across the world (even at the same latitude) the U. S. East Coast

---

[120] Masanobu Oogaki, "Overview of Stratospheric Platform Airship R&D Program" (presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001); Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*, 48; Craig L. Nickol et al., *High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development*, NASA/TP-2007-214861 (Hampton, Virginia: National Aeronautics and Space Administration, Dryden Langley Research Center, March 2007), 45, http://ntrs.nasa.gov/search.jsp?N=0&Ntk=all&Ntx=mode%20matchall&Ntt=hale%20aoa (accessed June 5, 2009).

[121] "High Altitude Airship 'Berkut'," *RosAeroSystems*, http://rosaerosystems.pbo.ru/english/projects.html (accessed July 4, 2009); Eguchi and Yoshio Yokomaku, "2000 Overview of Stratospheric Platform Airship R&D Program in Japan"; Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*, 84; Craig L. Nickol et al., *High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development.*

stratospheric wind conditions are representative of those experienced by other nations such as Japan.[122]

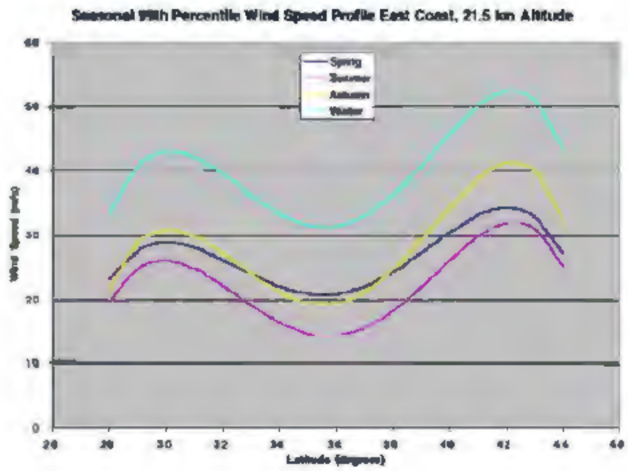
The payload mass of the baseline airships is 2000kg with a 10 kW power capacity. This mass is sufficient capacity to carry payloads that fit on Global Hawk block 20 systems and current foreign aerostat radar systems.[123] This payload mass is also comparable to foreign LTA HALE designs.

Two baseline LTA HALE systems were chosen for this study. The first is a 300kW system that represents the average foreign LTA HALE system and the second is a 1200 kW system that represents an upper end system. These values would allow an airship to conduct a station-keeping mission in moderate to severe conditions expected across a wide range of seasons and latitudes (see Figure 3.2 for example maximum airship power requirements). These baseline power requirements are used to evaluate power generation technologies proposed for LTA HALE systems.

[122] Toshihiko Hirooka, "Observational features of stratospheric winds over Japan related to global circulation changes" (presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001) Accurate wind data is another challenge for LTA HALE systems.

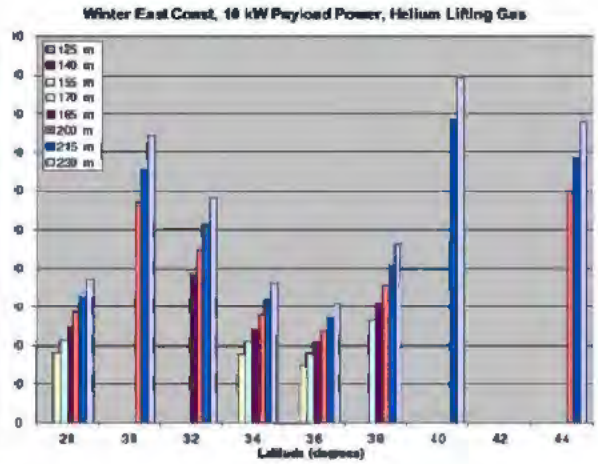
[123] "RQ-4 Block 20 Global Hawk"; "Augur/RosAeroSystems Au-21 Puma."

Figure 3.1 Seasonal 99th percentile wind speed



Source: Colozza, Initial Feasibility Assessment, 23.

Figure 3.2 Maximum power for airship



Source: Colozza, Initial Feasibility Assessment, 84. Note: The different bars represent different size airship. Latitudes that are missing bars represent systems that could not be built based on the design constraints.

Solar Array Technology

Solar energy collected by photovoltaic (PV) arrays is the most common source of power proposed by airship designers. Airships being studied by Japan, South Korea, China, Russia, and the European Union designs all rely on solar energy as their primary power source.[124] The long-endurance requirement drives developers to a renewable source of energy and is a necessary and practical option for concepts that fly longer than

[124] Kunihisa Eguchi and Tsutomu Fujihara, "Research Progress in Solar Power Technology for SPF Airship" (National Aerospace Laboratory Japan, 2003); Chan-Hong Yeom et al., "Development of a Stratospheric Platform in Korea"; Tong et al., "R&D of Stratospheric Platform and SP based Information Systems in China"; "High Altitude Airship 'Berkut'"; John Pattinson, "HALE Airship: Manufacture, Flight and Operation" (presented at the 1st Appleton Space Conference, Rutherford Appleton Laboratory Oxon, UK, December 8, 2005).

a few months.[125] The large surface area of an airship, on the order of 20,000 m^2 and larger, entices developers to use the envelope as a solar energy collection platform. Attaching thin-film solar arrays to the envelope surface is a recurring theme in LTA HALE design.

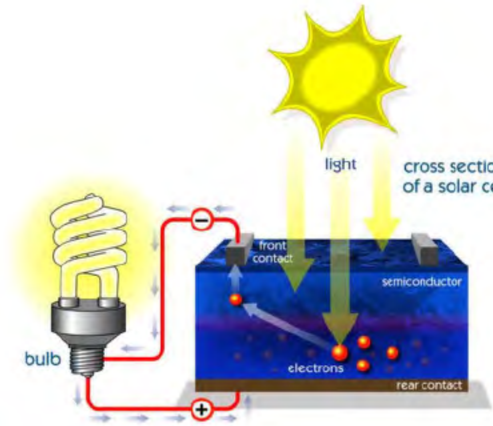
Thin Film Photovoltaic Technology Overview

Photovoltaic (PV) cells convert sunlight directly into electricity. The process begins with a photon striking the PV cell. A photon with the proper energy is absorbed by a semiconductor material (e.g. silicon). The absorbed photon transfers its energy to an electron "knocking it loose" from its atomic bond into the conductive layer of the material. The electron is then free to be transmitted as electric current (see figure 3.3).[126] Modern PV cells come in a variety of forms, characterized by their photoactive material and fabrication technique.

[125] A radioisotope thermoelectric generator could also be used, but such a power source has not been proposed by the foreign LTA HALE systems. These types of devices would provide technical regulatory and public relations limitations that make them impracticable for use.

[126] A more in depth but not overly technical description can be found at the DoE website."Photovoltaic Basics," U.S. DoE Solar Energy Technologies Program, http://www1.eere.energy.gov/solar/pv_basics.html (accessed July 4, 2009).

Figure 3.3 Basic PV cell operation



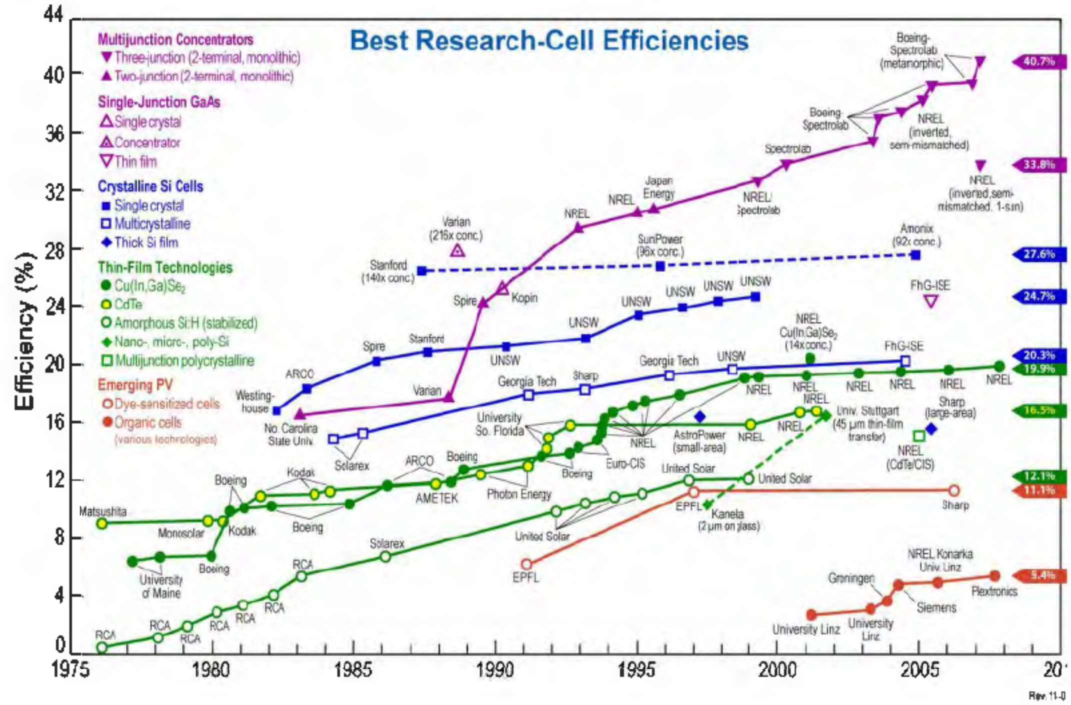
Source: "Using Sunlight More Efficiently," American Institute of Physics, http://www.aip.org/isns/reports/2008/046.html (accessed July 6, 2009).

The familiar crystalline silicon PV cell is a first generation PV technology. While these PV cells can achieve energy conversion efficiencies greater than 20% (see Figure 3.4), they are heavy, rigid, expensive, and need to be "grown" in a slow manufacturing process.[127] Thin-film PV technology was developed to address manufacturing difficulties and high cost of traditional crystalline silicon technology.[128]

[127] Commercial efficiencies are limited by manufacturing limitations.B. von Roedern and H.S. Ullal, "The Role of Polycrystalline Thin-Film PV Technologies in Competitive PV Module Markets," (presented at the 33rd IEEE Photovoltaic Specialists Conference, San Diego, CA: IEEE, 2008).

[128] "Using Sunlight More Efficiently," *American Institute of Physics*, http://www.aip.org/isns/reports/2008/046.html (accessed July 6, 2009).

Figure 3.4 Basic Laboratory Research PV Cell Efficiencies



Source: "Performance and Reliability R&D - Indoor Testing," National Renewable Energy Laboratory, http://www.nrel.gov/pv/performance_reliability/indoor_testing.html (accessed July 6, 2009).

In an effort to reduce the amount of expensive semiconductor material required to make PV cells, thin-film PV technologies were developed. Thin-film refers to the method used to deposit photoactive material onto a substrate during manufacturing rather than the actual "thinness" of the PV device.[129] Thin-film PV technology allows the solar cell to be made with less material, thus enabling it to be lighter weight and less expensive. Amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium

129 "Solar Energy Technologies Program: Polycrystalline Thin Film," *U.S. DOE Energy Efficiency and Renewable Energy*, http://www1.eere.energy.gov/solar/tf_polycrystalline.html (accessed July 6, 2009).

diselenide (CIGS) are the most common thin-film PVcells. Thin-film solar arrays are more cost effective than their crystalline silicon cousins, but they are less efficient, 6%-13% on average, and not as well characterized.[130] Nevertheless, thin-film PV provides airship developers with many advantageous properties.

Requirements for Thin-film Solar Arrays

Airships and satellites share similar solar array requirements and high efficiency is not necessarily the primary characteristic for either system. Many of the LTA HALE proposals refer to the increasing high efficiency of solar arrays, and in fact, solar cells are breaking efficiency records every month. World record laboratory PV cells composed of Gallium Arsenide (GaAS) are achieving efficiencies greater than 40%.[131] However, this higher efficiency comes at the cost of greater mass and increased complexity. According to an AFRL trade study, the primary solar array performance metrics include "specific power (W/kg), areal [surface] power density (W/m2), array stowed volume (kW/m3), cost ($/W) and ultimate power available…."[132] The AFRL study further points out that:

[130] B. von Roedern and H.S. Ullal, "The Role of Polycrystalline Thin-Film PV Technologies in Competitive PV Module Markets."

[131] "World Record: 41.1% efficiency reached for multi-junction solar cells at Fraunhofer ISE," *Fraunhofer ISE*, January 2009, http://www.ise.fraunhofer.de/press-and-media/press-releases/press-releases-2009/world-record-41.1-efficiency-reached-for-multi-junction-solar-cells-at-fraunhofer-ise (accessed July 6, 2009).

[132] John Merrill et al., "Air Force Perspective on Present and Future Space Power Generation," in *2006 IEEE 4th World Conference on Photovoltaic Energy Conference* (presented at the 2006 IEEE 4th World Conference on Photovoltaic Energy Conference, Waikoloa, HI, 2006), 1750, http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4059996 (accessed 25 February 2009).

> In the case of airships designed for high-altitude operation the environmental conditions … are such that space solar cell and array technologies are required. Because of the need for high power-to-lift ratios, the highest possible specific power solar cells are desirable, resulting in the use of lightweight polymer substrates.[133]

German and Swiss engineers are developing ultra-light solar array technologies under the precept that LTA HALE and space "solar cells should be optimized for highest [specific power] rather than for highest efficiency."[134]Thin-film solar arrays use 100-times less semiconductor material than crystalline silicone PV cells, and can be deposited on thin metal foil or a polymer (e.g. plastic) substrate making it lighter and flexible.[135] According to a NASA feasibility study, "an airship will be exposed to numerous stresses and flexing during its ascent and while operating at altitude. A solar array that can flex with the structure and bend without fracturing is of great benefit to the airship."[136]

Current and projected thin-film PV array characteristics were used to develop size and weight estimates of the PV array (see Table 3.2). The analysis reveals that thin-film PV technology is capable of producing solar arrays that could fit within the surface area of the projected envelope structures. The size of the solar arrays was larger than some studies, such as NASA's analysis of alternatives study (AoA). NASA's AoA only

---

[133] Ibid., 1751.

[134] N. Wyrsch et al., "Ultra-Light Amorphous Silicon Cell for Space Applications," in *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on*, vol. 2, 2006, 1.

[135] "The Third Wave of Solar Power," *Nanosolar*, http://www.nanosolar.com/technology.htm (accessed July 6, 2009).

[136] Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*, 36.

required an 891 m^2 solar array that weighed 174kg for their 1200kW systems. RosAeroSystems, on the hand, had solar arrays on the order of 8000 m^2 for their 230 kW system.[137]

Table 3.2 Characteristics of different PV solar array types

				300 kW Vehicle		1200 kW vehicle	
PV Type	PV efficiency (%)	power density (W/m2)	specific power (w/kg)	PV array size (m2)	PV array weight (kg)	PV array size (m2)	PV array weight (kg)
a-Si	9	123	541	2,439	555	9,756	2,218
a-Si Next Generation	11	150	2521	2,000	119	8,000	476
CIGS Current	7	96	322	3,125	932	12,500	3,727
CIGS 2010	12	164	1039	1,829	289	7,317	1,155
CIGS Next Generation	18	246	1299	1,220	231	4,878	924

Source: Adapted from data in AFRL study. J. E. Granata and J. Merrill, Mass and cost comparison of lightweight array and rigid array (Kirtland AFB: Air Force Research Laboratory, Space Vehicles Directorate), 2.

Note: The PV efficiencies represent laboratory PV cells at approximately TRL 4 or TRL 5.

The "current" efficiencies, however, represent PV systems that are available for testing in the laboratory. Additionally, AFRL's estimates of future performance are more aggressive than the National Renewable Energy Laboratory's (NREL) projections (see Table 3.3). Current a-Si manufacturing technology produces PV arrays with only a 6%

[137] Some of the feasibility assessments and airship designs seem to mix characteristics of the crystalline silicon and thin-film technology (e.g. using the higher efficiency of c-SI and the low weight of thin-film PV.

efficiency, a figure that has remained stable for the last 5 years (see Figure 3.5). Efficiencies that could be manufactured for large envelope structures by 2020 are more likely represented by the lower efficiency PV material. Although efficiency may not be the most important factor, solar array shading, caused by the shape and alignment of the LTA HALE vehicle, will decrease the area that can effectively collect energy.[138] Even if the array could be made as large as the envelope, more efficient PV arrays may be required to compensate for solar shading and shorter days during the winter.

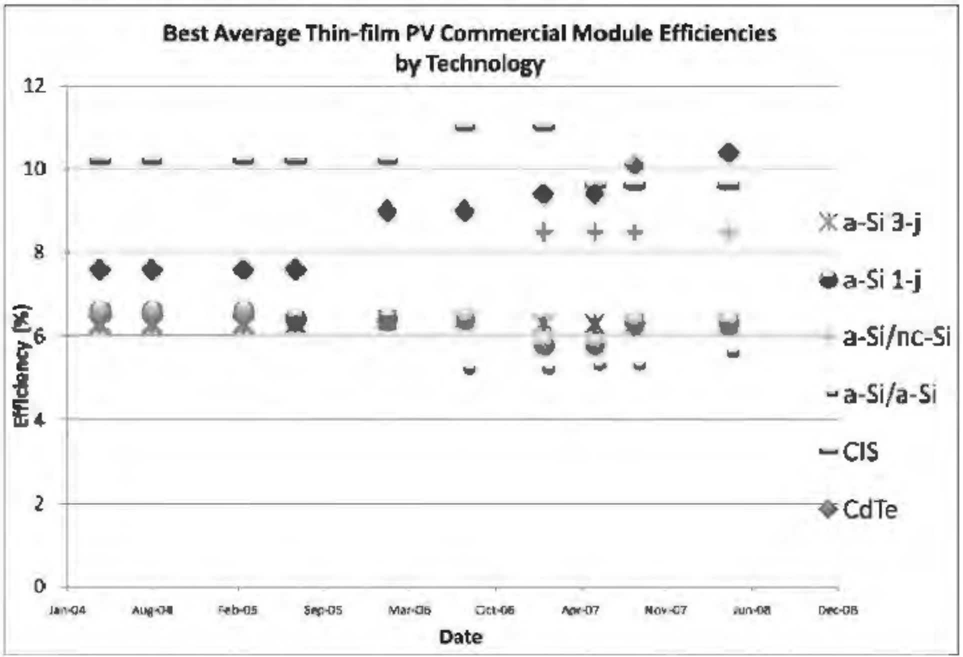
Table 3.3 NREL projected commercial PV performance

Technology	Future commercial module performance (80% of current record cell efficiency)
CIS	15.9%
CdTe	13.2%
a-Si 1-j	8.0%
a-Si 3-j a-Si/nc-Si	9.7%

Source: Adapted from B. von Roedern and H.S. Ullal, "The Role of Polycrystalline Thin-Film PV Technologies in Competitive PV Module Markets," (presented at the 33rd IEEE Photovoltaic Specialists Conference, San Diego, CA: IEEE, 2008), 2.

[138] Even if an LTA HALE is completely covered with PV cells, not all of them would be exposed to sunlight. Even the side fully exposed to the sun would not receive the normal-incidence sunlight that is used to attain the maximum efficiency values quoted in the literature.

Figure 3.5 Best Commercial PV array efficiencies



Source: B. Von Roedern, "Best Production-Line PV Module Efficiency Values: From Manufacturers Websites" (National Renewable Engery Lab, May 11, 2009), 1-2, http://www.nrel.gov/pv/thin_film/pn_techinfo_latest_ updates.html (accessed July 6, 2009) .

Thin-film PV Array Maturity

Thin-film manufacturers started ramping up mass market production of solar arrays in 2003.[139] By 2007, thin-film PV technology had cornered over 55% of the commercial market.[140] New "roll-to-roll" manufacturing techniques allow thin-film PV to be created on large continuous sheets creating the possibility of an integrated

[139] B. von Roedern and H.S. Ullal, "Thin Film CIGS and CdTe Photovoltaic Technologies: Commercialization, Critical Issues, and Applications," (presented at the 22nd European Photovoltaic Solar Energy Conference (PVSEC) and Exhibition, Milan, Italy: IEEE, 2008), 1.

[140] B. von Roedern and H.S. Ullal, "The Role of Polycrystalline Thin-Film PV Technologies in Competitive PV Module Markets," 4.

envelope/PV array.[141] Nevertheless, thin-film PV is considered a relatively new technology and performance has leveled off with manufacturers trading efficiency for producibility.[142] Production and performance issues still exist, such as low yield rates and inadequate degradation characterization (loss of efficiency over time due to exposure to ultraviolet radiation and ozone.)[143]

Thin-film solar arrays are in the early stages of RDT&E for use on satellite and HALE systems. Thin-film cells have been tested on the International Space Station and are currently onboard the research satellite TAC-SAT II.[144] Scientists from several countries have performed preliminary environmental and radiation hardness tests.[145] These thin-film PV arrays, however, are low-powered(less than 60 W) and rigid. Flexible thin-film PV arrays constructed on foil or polymer substrates have yet to be tested in a relevant operational environment.[146] Although thin-film PV is widely available, the

---

[141] "The Third Wave of Solar Power."

[142] B. von Roedern and H.S. Ullal, "The Role of Polycrystalline Thin-Film PV Technologies in Competitive PV Module Markets," 1-4.

[143] Rommel Noufi and Ken Zweibel, *High-Efficiency Cdte and Cigs Thin-Film Solar Cells: Highlights and Challenges* (Golden, CO: National Renewable Energy Laboratory).

[144] "MicroSat Systems, Inc.: Reliable, Affordable, Spacecraft for DoD, NASA and Commercial Markets - Thin Film Arrays," *MicroSat Systems*, http://www.microsatsystems.com/msiProducts/satelliteSubsystems/thinFilmArrays/ (accessed July 6, 2009).

[145] A. Jasenek, et al, "Radiation Response of Cu(In,Ga)Se2 Solar Cells," Proc. 3rd WCPEC, (Osaka, Japan, 2003).

S. Kawakita, M. Imaizumi, S. Matsuda, et al., "SuperRadiation Tolerance of CIGS Solar Cells Demonstrated in Space by MDS-1 Satellite", Proc. 3rd WCPEC, (Osaka, Japan, 2003).

[146] John Merrill and J.E. Granata, *Mass and Cost Comparison of Lightweight Array And Rigid Array* (Air Force Research Laboratory, 2008).

technology for their integration onto LTA HALE applications remains in the laboratory. Additionally the technology required for manufacturing of integrated solar array/envelope concepts remains on the drawing board. Although a couple of patents exist for integrated LTA HALE solar arrays, they have yet to be developed and tested.[147]

Thin-Film PV Array Technology Challenges

LTA HALE vehicles will be able to leverage the considerable commercial and government efforts to develop flexible thin-film PV arrays. Notwithstanding, the technical challenge to LTA HALE is significant. International space programs will push thin-film technology to meet the environmental requirements, but airships will require arrays 7-30 times larger and heavier than the largest projected 400 m^2 thin-film satellite designs.[148] Commercial programs will continue to improve the efficiency and manufacturability of the thin-film technology. The airship's solar array, however, will be equivalent in power and size to the world's largest fixed terrestrial thin-film CIGS solar array.[149]

Using roll-to-roll manufacturing techniques, thin-film PV can now be deposited on flexible polymer substrates and backing structures similar to common airship envelope

[147] Liu, Shengzhoug et al., "Solar cells for stratospheric and outer space use - US Patent Application," http://www.patentstorm.us/applications/20080173349/fulltext.html (accessed July 6, 2009).

[148] J. E. Granata and J. Merrill, *Mass and cost comparison of lightweight array and rigid array* (Kirtland AFB, NM: Air Force Research Laboratory, Space Vehicles Directorate, 2008).

[149] "World's Largest CIGS Thin Film Solar Array Goes Live in Tucson, Arizona," *Global Solar*, May 14, 2009, http://www.globalsolar.com/press/press.php (accessed July 6, 2009).

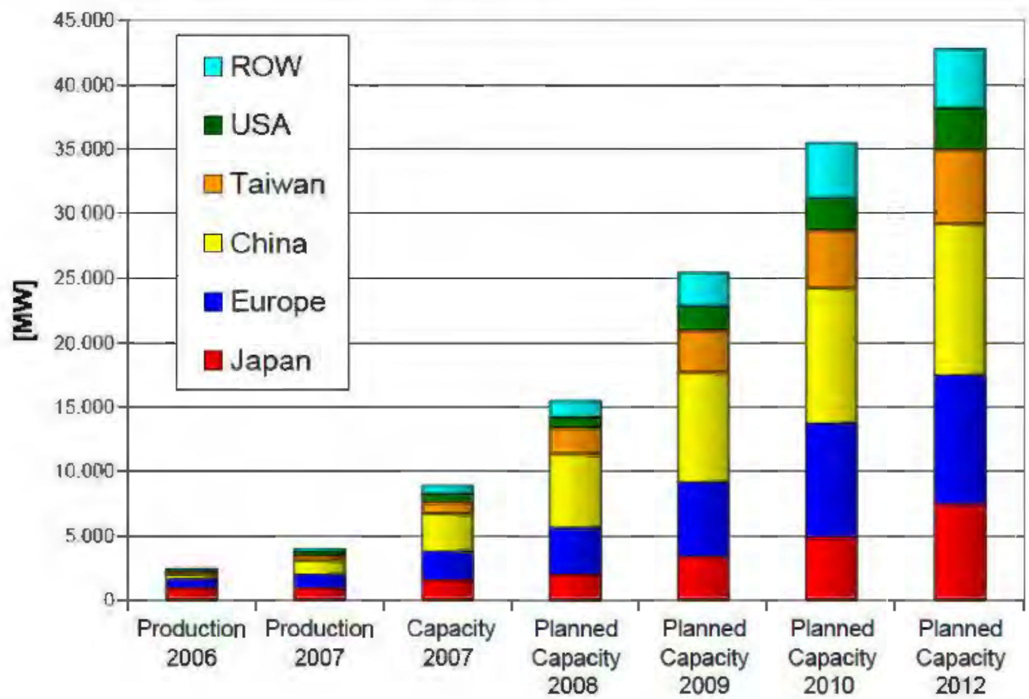
materials (e.g. Tedlar®).[150] But, the ability to integrate, bond, or manufacture large continuous gores of integrated thin-film PV-envelope will be a distinctive problem for LTA HALE systems. LTA HALE engineers will have to invest significant RDT&E in the design and characterization of the PV-envelope aerodynamic performance, material strength, flexibility and durability, and PV array performance under envelope stress. LTA HALE thin-film PV systems face a considerable challenge, requiring the largest, most powerful mobile solar arrays, operating in the most severe environments.

[150] "The Science of Photovoltaic Enegry : DuPont Photovoltaic Solutions," *Dupont.com*, http://www2.dupont.com/Photovoltaics/en_US/science_of/index.html (accessed July 6, 2009); "PowerFilm Technology," *PowerFilm*, http://www.powerfilmsolar.com/about/technology/ (accessed July 6, 2009).

International Availability of Thin-film PV

Thin-film technology is globally available. Japan, China and Germany lead the world in PV production, but the United States and Japan lead thin-film manufacturing (see Figure 3.6). The technology is available without restriction and supported by international cooperatives.[151]

Figure 3.6 Worldwide production of PV cell technology



Source: "Prometheus Institute for Sustainable Development," Prometheus. http://www.prometheus.org/research/pisdresearch (accessed July 8, 2009).

[151] "The International Solar Energy Society (ISES)," *ISES.com*, http://www.ises.org/ises.nsf!Open (accessed July 6, 2009).

Other Considerations

CIGS manufacturing may be limited by feedstock materials. According to the NREL roadmap, "the ultimate impact of CIGS PV technology may be limited by the availability of indium."[152] Cost of the solar array may be another concern. Even though commercial estimates for thin-film solar array are projecting less than $3/W, the requirements of the LTA HALE solar array (e.g. extremely large size, environmentally hardened) will drive a cost comparable to the aggressive cost goal of NASA $200/W. [153] This equates to an LTA HALE PV array that costs $60M- $240M, which may be prohibitively high for some countries to readily adapt to a risky unproven technology such has LTA HALE.[154]

All of the foreign LTA HALE developers (e.g. EU, Japan, South Korea, Russia, and China) believe that solar arrays are essential to meet their endurance requirements and environmental concerns.[155] A global development effort will help improve thin-film PV technology, but unique size, power, and durability requirements will require significant RDT&E from LTA HALE programs to mature the technology for operational

[152] Bolko von Roedern, *National Solar Technology Roadmap: CIGS PV*, Management Report (National Renewable Energy Laboraty, June 2007), 2.

[153] J. E. Granata and J. Merrill, *Mass and cost comparison of lightweight array and rigid array*

[154] This cost is strictly the dollar per watt cost multiplied by the power required for the 300kW and 1200kW system. Other costs such as integration are not included.

[155] Eguchi and Yoshio Yokomaku, "2000 Overview of Stratospheric Platform Airship R&D Program in Japan"; Zi-Niu Wu and Xiao-Jian Xue, "Civilian Demands Application of Airships in Civil Projects."

employment. Thin-film PV technology is feasible for LTA HALE systems, but will remain a high risk area for development.

Assessed LTA HALE technology readiness level: TRL level 4

Fuel Cell Technology

Using solar power as the primary renewable source of energy creates a power-during-darkness problem. Although HALE systems will fly higher than clouds so that daytime operations will be unaffected by weather, night operations will require the LTA HALE system to either store excess solar energy or rely on a secondary source of power. To meet weight and endurance requirements, LTA HALE developers from Japan, South Korea, and the EU are incorporating hydrogen fuel cells into their designs. Using fuel cells to enable high-altitude airships is a theme that has been repeated for several decades.[156]

Fuel Cell Technology Overview

Fuel cells have many features that are advantageous to LTA applications, such as high specific energy, low noise, low vibration, low thermal signature, and low- to zero-polluting emissions.[157] Fuel cells generate power by converting chemical energy directly

[156] Steiner Volker, "How to improve the performance of an LTA-vehicle (balloon or airship)," (presented at the AIAA Lighter-Than-Air Systems Technology Conference, San Francisco, CA: American Institute of Aeronautics and Astronautics, 1997), 2.

[157] Thomas H. Bradley et al., "Design Studies for Hydrogen Fuel Cell Powered Unmanned Aerial Vehicles," (presented at the 26th AIAA Applied Aerodynamics Conference, Honolulu, HI: American Institute of Aeronautics and Astronautics, 2008), 1.

into electricity through an electrochemical reaction, rather than a combustion reaction. A traditional generator requires a combustion reaction to generate heat energy, which is then converted into mechanical energy via a device such as a piston. The mechanical energy can then be converted into electricity. Conversion losses and physical constraints (e.g. Carnot efficiencies) limit the amount of mechanical and electrical energy generated by a combustion reaction.[158] Fuel cells used in transportation applications operate directly on hydrogen, which has a high energy density (see Figure 3-7). The energy efficiency of fuel cells and the energy density of hydrogen enables potential long endurance power for LTA HALE systems.

As with lighter-than-air technology, the fuel cell is not a new invention. Sir William Grove created the fuel cell concept in 1839. Grove reasoned that if electricity could split water into hydrogen and oxygen, then reversing the process would produce electricity and water:[159] $2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat

Fuel cells come in a variety of forms. They are typically characterized by their electrolyte (a substance that transmits ions) and fuel type.[160] The process is analogous to the operation of a battery, except that a fuel cell requires a continuous source of fuel, known as a reactant, to operate. Common fuel cell types are polymer electrolyte

[158] "Carnot Cycle," *Hyperphysics*, http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/carnot.html (accessed June 19, 2009).

[159] "Fuel Cells: Discovering the Science," *Smithsonian Institution American History*, http://americanhistory.si.edu/fuelcells/origins/origins.htm (accessed June 21, 2009).

[160] EG&G Technical Services, Inc., *Fuel Cell Handbook*, 7th ed. (U.S. Department of Energy Office of Fossil Energy, 2004).

membrane (PEM) fuel cell, alkaline fuel cell, phosphoric acid fuel cell, molten carbonate fuel cell, and the solid oxide fuel cell (SOFC).[161] Alkaline fuel cells have been used since the 1960s by NASA for space missions including the Space Shuttle and Apollo missions, but are considered too expensive for most commercial transportation applications.[162] Transportation applications are primarily interested in the SOFC and PEM fuel cell. PEM fuel cells are being developed as the primary power source for automotive and small UAV applications, while the SOFC is used for auxiliary power and a few UAV applications.[163]

The operation of the PEM fuel cell begins with the introduction of pressurized hydrogen gas into the anode side of the cell (see Figure 3.7).[164] A catalyst made of platinum causes the hydrogen to ionize, splitting the negatively charged electron from the positively charged proton. The proton passes through a polymer membrane to the cathode side.[165] The membrane blocks the electron, forcing it to travel around an external circuit to the cathode side. This electron flow around the membrane is the mechanism that generates electrical current. On the cathode side of the membrane, protons and

---

[161] "HFCIT Fuel Cells: Current Technology," *U.S. DOE Energy Efficiency and Renewable Energy*, http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/current_technology.html (accessed June 19, 2009).

[162] "HFCIT Fuel Cells: Types of Fuel Cells," *U.S. DOE Energy Efficiency and Renewable Energy*, http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html#oxide (accessed June 17, 2009).

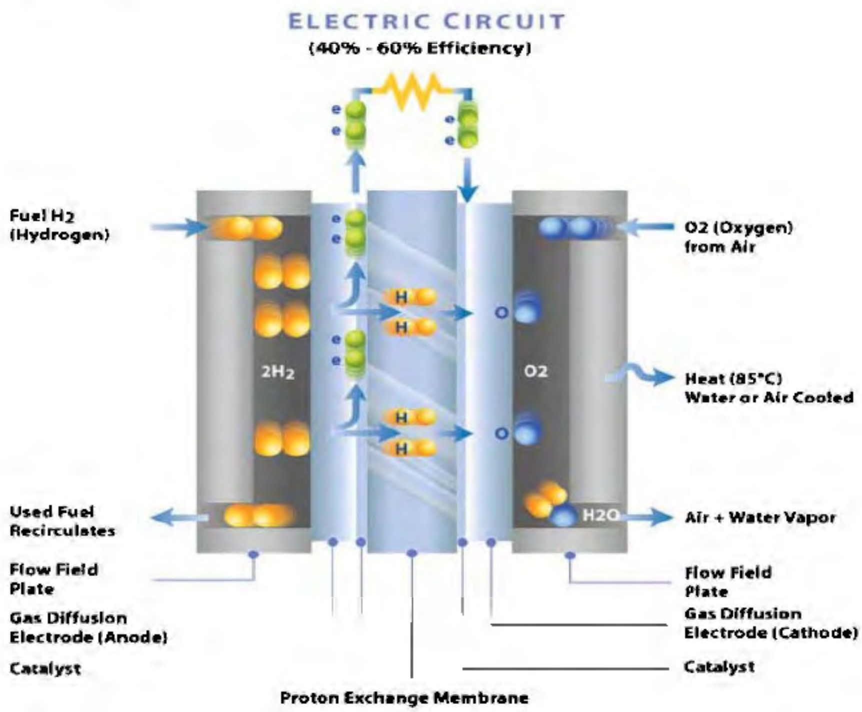
[163] P. Aguiar, D.J.L. Brett, and N.P. Brandon, "Solid oxide fuel cell/gas turbine hybrid system analysis for high-altitude long-endurance unmanned aerial vehicles," *International Journal of Hydrogen Energy* 33, no. 23 (December 2008): 7214-7223.

[164] The other fuel cell types function in similar manner.

[165] The PEM fuel cell is also known as the Proton Exchange membrane fuel cell.

electrons combine with oxygen molecules to form water. The only byproduct of a correctly operating PEM fuel cell is heat and water. The components of a PEM fuel cell (bipolar plates, catalyst, polymer membrane, etc.) are known as a membrane electrode assembly (MEA) (see figure 3.8). A single MEA generates less than one volt of energy and must be connected together in stacks to achieve higher voltages and currents.[166]

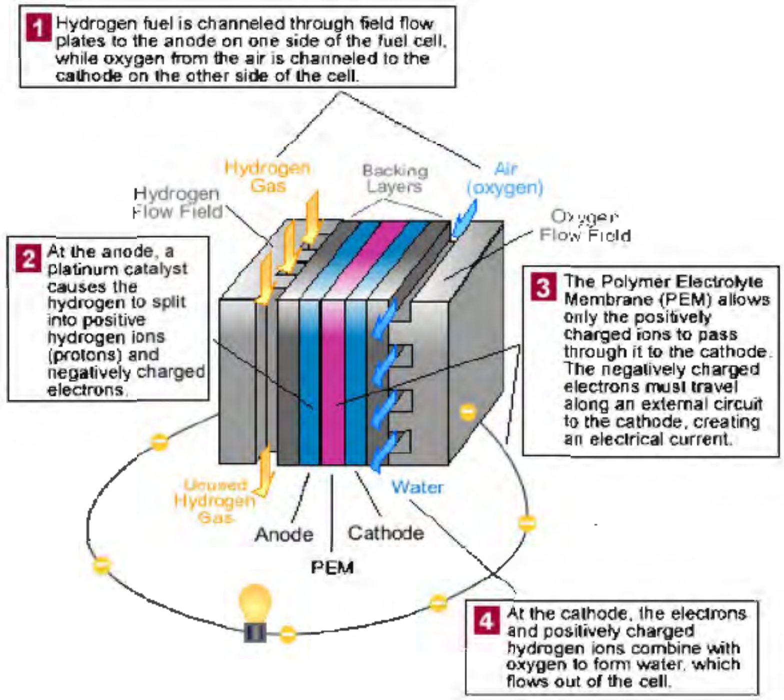
Figure 3.7 Operation of a PEM fuel cell



Source: "How Fuel Cells Work," Ballard Power, http://www.ballard.com/About_Ballard/Resources/How_Fuel_Cells_Work.htm (accessed June 20, 2009).

[166] EG&G Technical Services, Inc., *Fuel Cell Handbook*, 1-4.

Figure 3.8 Membrane electrode assembly



Source "How They Work: PEM Fuel Cells." Fueleconomy.gov, http://www.fueleconomy.gov/feg/fcv_pem.shtml (accessed June 21, 2009).

A PEM fuel cell can use standard hydrocarbon fuels by using a reformer to preprocess the fuel into hydrogen gas. A reformer allows convenient access to common fuels, eliminating the need to store compressed hydrogen; however, reformers degrade fuel cell performance. SOFCs operate at a higher temperature than PEM fuel cells, which allows them to directly use “dirty hydrogen” sources, such as bio-diesel, gasoline, and kerosene.[167]

Fuel Cell Requirements

Fuel cells share the same power and weight requirements as the solar array. Fuel cell engineers concentrate on volumetric power density (W/L or W/m^3) rather than surface power density (W/m^2). The specific power (W/kg) of fuel cell systems is approaching the Department of Energy’s goal for 2015 of 2000 W/kg.[168] The added weight of the balance of necessary components (e.g. pumps, fans) drops the specific power down to 650 W/kg.[169] Automotive and aerospace developers are trying to reduce the size and weight of the system to fit into cars, launch systems, and aircraft. Due to the large size of LTA HALE systems, engineers are less concerned with maximizing power density; however, specific power is a critical issue to minimize total weight. Table 3.14 compares the size of the two reference LTA HALE systems using the 2015 DOE goal. The feasibility studies have widely varying fuel cell mass estimates. The original estimates, made by NASA and JAXA, projected fuel cells to weigh from 2000 to more

[167] “Protonex Awarded $3.3 Million Contract To Develop a Deployable Fuel Cell Power System for Small Unmanned Aerial Vehicles,” *Protonex Technology Corporation*, http://www.protonex.com/products/military.aspx (accessed June 22, 2009).

[168] Monjid Hamdan, “PEM Electrolyzer Incorporating an Advanced Low Cost Membrane,” May 20, 2009, http://www.hydrogen.energy.gov/annual_review09_production.html (accessed June 15, 2008).

[169] Balance of Plant include external components (pumps, fans, etc.) needed to make the fuel cell work Jayanti Sinha, Stephen Lasher, and Yong Yang, “Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications” (presented at the DOE Hydrogen Program: 2009 Annual Merit Review Proceedings - Fuel Cells, Arlington, VA, May 21, 2009), http://www.hydrogen.energy.gov/annual_review09_fuelcells.html#analysis (accessed June 19, 2009).

than 5000kg.[170] Based on the analysis presented in Table 3.4, the 650 W/kg would exceed the initial design estimates.

Table 3.4 Fuel Cell characteristics for baseline LTA HALE systems

LTA HALE system	power density (kW/L)	specific power (kW/kg)	Fuel cell size (L)	Fuel Cell weight (kg)
300 kW	0.650	0.650	462	462
1200 kW	0.650	0.650	1,846	1,846

Source: Author's analysis using DOE fuel cell target goals. Lasher, "Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications."

Fuel Cell Maturity

The fuel cell is an emerging concept that faces multiple performance limitations. Fuel cells are commercially available for an assortment of applications. Ballard and UTC have tested PEM fuel cell systems on mass transit bus programs since the 1990's.[171] Several automakers including Honda, GM, and Daimler Chrysler, are leasing fuel cell

---

[170] Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*, 88; Craig L. Nickol et al., *High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development*, 51; Eguchi and Yoshio Yokomaku, "2000 Overview of Stratospheric Platform Airship R&D Program in Japan"; Yoshitsugu Sone et al., "One kilowatt-class fuel cell system for the aerospace applications in a micro-gravitational and closed environment," *Journal of Power Sources* 157, no. 2 (7, 2006): 886-892; Masahiko Onda, "Design Considerations on Stratospheric LTA Platform," (presented at the 13th AIAA Lighter-than-Air systems technology conference, Norfolk, VA: American Institute of Aeronautics and Astronautics, 1999), 208.

[171] "Bus Fuel Cell Hydrogen Powered," *Ballard Power*, http://www.ballard.com/Motive_Power/Heavy_Duty_Market/Application_Overview.htm (accessed June 22, 2009); "Transportation Fleet Vehicles," *UTC Power*, http://www.utcpower.com/fs/com/bin/fs_com_Page/0,11491,0152,00.html (accessed June 22, 2009).

vehicles to consumers for extended road tests.[172] The major automakers forecast that their fuel cell vehicle will be ready for larger commercial markets by 2015.[173]

The aviation industry is using fuel cells to power a variety of aircraft. SOFC and PEM fuel cells are powering small experimental UAV systems, which are setting new endurance and distance records.[174] A variation of the PEM fuel cell that runs on a water methanol solution, known as the Direct Methanol Fuel Cells (DMFC), is commercially available for portable applications, including small UAVs.[175] AeroVironment's HALE system, Global Observer, uses liquid hydrogen PEM fuel cells.[176] The company has also partnered with Protonex to develop fuel cell versions of their smaller vehicles.[177] Boeing and Intelligent Energy led an international team that designed and flew the first fuel cell powered manned aircraft.[178]

---

[172] "Honda FCX Clarity - Drive FCX," *Honda Worldwide Fuel Cell*, http://automobiles.honda.com/fcx-clarity/drive-fcx-clarity.aspx (accessed June 22, 2009).

[173] Nicole Mordant, "Automakers see no one winner in green car race," *Reuters.com* (June 2, 2009), http://www.reuters.com/article/GCA-BusinessofGreen/idUSTRE5516JD20090602?sp=true (accessed June 22, 2009).

[174] "Protonex Awarded $3.3 Million Contract To Develop a Deployable Fuel Cell Power System for Small Unmanned Aerial Vehicles."

[175] EG&G Technical Services, Inc., *Fuel Cell Handbook.*

[176] "Stratospheric Persistent Unmanned Aircraft Systems: Global Observer Detail."

[177] "Protonex Awarded $3.3 Million Contract To Develop a Deployable Fuel Cell Power System for Small Unmanned Aerial Vehicles."

[178] Adrian Harrington, "Fuel cell plane in aviation first," *Intelligent Energy*, April 3, 208, http://www.intelligent-energy.com/index_article.asp?SecID=8&secondlevel=25&artid=4001%20 (accessed June 20, 2009); "Cool Fuel," *Boeing.com*, http://www.boeing.com/news/frontiers/archive/2003/august/i_atw.html (accessed July 6, 2009).

Foreign navies are currently using PEM fuel cells on their submarines to provide power for "air independent propulsion" systems. The fuel cell allows them to run quieter, longer, and cleaner than diesel powered submarines.[179] German submarines have set record times submerged underwater using PEM fuel cell technology. [180]

Depending on the application, the PEM and SOFC fuel cell has a TRL between 6 and 9. The automotive fuel cell should be a TRL 8-9 by 2015. Although LTA HALE systems will benefit from aerospace and automotive efforts to improve efficiency, reduce size, decrease weight, and increase durability, the LTA HALE system presents endurance and environmental challenges beyond the scope of these programs. A representative fuel cell system has never been tested under LTA HALE operational conditions. The fuel cell faces many technical challenges before it will be mature enough for operational employment.

Fuel Cell Technology Challenges

The limitations that affect automotive applications do not necessarily inhibit airship operations. Automotive applications require a readily accessible hydrogen infrastructure, compact hydrogen storage, and cost effective fuel cells to meet competitive market demands.[181] LTA HALE fuel cell systems face other technical

---

[179] "U212 / U214 Attack Submarines," *Naval Technology.com*, http://www.naval-technology.com/projects/type_212/ (accessed July 6, 2009).

[180] "HYDROGEN SHIPS & SUBS - Are the secrets of fuel cells hidden in top-secret naval research?," hydrogen commerce.com, http://hydrogencommerce.com/index16.htm (accessed July 6, 2009).

[181] "HFCIT Fuel Cells: Fuel Cell Technology Challenges," *U.S. DOE Energy Efficiency and Renewable Energy*, http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_challenges.html (accessed June 19, 2009).

challenges that are beyond the interests of the automotive and aircraft industries, most notably unique durability requiring stratospheric operating requirements, and greater power requirements.

Durability

One of the most significant challenges for LTA HALE fuel cell is durability. The best PEM fuel cells, operating in real world circumstances, last less than 2000 hours with significant degradation beginning at 1000 hrs.[182] In the automotive world, a 2000-hour fuel cell equates to approximately 60,000 miles. However, 2000 hours equates to approximately 80-days of constant LTA HALE operations.[183] Although laboratory fuel cells are now reaching a 5000-hour lifetime, both real-world and laboratory fuel cells receive regular maintenance, which will be less frequent to non-existent for an LTA HALE vehicle. Current fuel cell durability projections and goals would require the entire fuel cell stack to be replaced every LTA HALE mission, reducing the cost effectiveness and operational availability of the system.

A practical LTA HALE fuel cell system represents a leap in durability and performance over automotive and even projected HALE UAV requirements. HALE UAVs, such as AeroVironment's Global Observer, are only expected to fly no longer

---

[182] *Hydrogen and Fuel Cell Activities, Progress, and Plans: Report to Congress* (Department of Energy, January 2009), 20.

[183] Keith Wipke et al., "DOE's Hydrogen Fuel Cell Activities: Developing Technology and Validating it through Real-World Evaluation," (presented at the Alternative Fuels & Vehicles Conference, Las Vegas, NV, 2008).

than 7-days. The current record flight for a fuel cell-powered UAV is just over nine hours.[184] LTA HALE systems must have fuel cells that can operate maintenance-free for several months at a time. Durability also affects development time. To ensure fuel cells systems meet safety and durability requirements, developers would have to test them continuously over several years to ensure they meet statistically significant performance parameters.[185]

Stratospheric Environment

Operating fuel cells at high stratospheric altitudes introduces exceptional challenges. Although PEM fuel cells operate at lower temperatures than other fuel cells, they produce a large amount of heat that will be difficult to dissipate in the thin atmospheric conditions of the stratosphere. PEM fuel cells also require liquid water to operate, which creates cold start and freezing problems. Automotive fuel cell vehicle developers are addressing the freezing issue, but only down to -20 C. [186] LTA HALE fuel

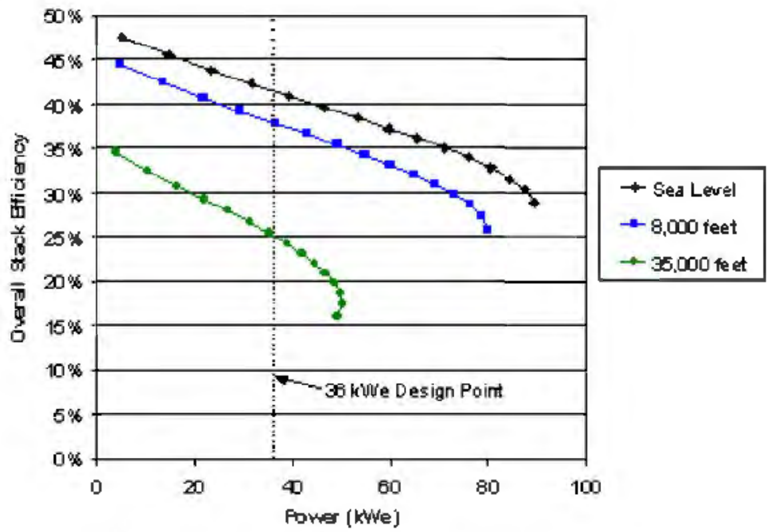
[184] "Protonex Awarded $3.3 Million Contract To Develop a Deployable Fuel Cell Power System for Small Unmanned Aerial Vehicles."

[185] David J. Bents, *Lunar Regenerative Fuel Cell (RFC) Reliability Testing for Assured Mission Success* (Cleveland, Ohio: Glenn Research Center, February 2009), 5, http://ntrs.nasa.gov/ (accessed June 5, 2009)

[186] Amedeo Conti, "Subfreezing Start/Stop Protocol for an Advanced Metallic Open-Flowfield Fuel Cell Stack" (presented at the DOE Hydrogen Program: 2009 Annual Merit Review Proceedings - Fuel Cells, Arlington, VA, May 21, 2009), http://www.hydrogen.energy.gov/annual_review09_fuelcells.html# analysis (accessed June 19, 2009).

cells will have to contend with a dynamic thermal environment with temperatures varying 30 C throughout the day and reaching below -75 C. Research performed by the National Fuel Cell Center also indicates that fuel cell performance degrades significantly at higher altitudes (e.g. lower pressure and temperature) losing both efficiency and power output (see Figure 3.9). [187] Solving this problem may require adding environmental controls to the system, which adds weight and power. The stratospheric environment presents a substantial challenge for engineers.

Figure 3.9 Fuel cell performance vs. altitude



Source: Pratt. "Aerospace Fuel Cell Systems: Proton Exchange Membrane Fuel Cell." kWe is kilowatts of electric power. The "e" just signifies that it is electricity and not some other power like thermal.

Larger Power Requirements

[187] Joe Pratt, "Aerospace Fuel Cell Systems: Proton Exchange Membrane Fuel Cell," 2004, http://www.nfcrc.uci.edu/2/ACTIVITIES/RESEARCH_STUDIES/Aerospace_FC_Systems/Proton_exchange_Membrane_Fuel_Cell/Index.aspx (accessed June 19, 2009).

LTA HALE systems will require greater peak power than other transportation applications. The largest automotive fuel cell will use less than 120kW of power.[188] Small long-endurance UAVs use less than 1kW and HALE UAVs do not require more than 140kW. The aviation industry is not currently interested in using fuel cells to power larger commercial aircraft.[189] The largest submarine fuel cell operates at a peak power of 300kW, which is at the bottom end of the LTA HALE requirements.[190] The 300 kW-1200kW fuel cell system needed to power the LTA HALE system is equivalent to the largest stationary PEM fuel cell power plants currently in operation.[191]

International Availability

Fuel cell technology is readily available to the international community without restriction. Countries around the world have developed fuel cell technology for automotive, maritime, aerospace and stationary power applications. Greece, Italy, Spain, South Korea, and Germany are employing PEM Fuel cell technology in their

---

188 "Hydrogen Bus Fuel Cell Specifications," *Ballard Power*, http://www.ballard.com/Motive_Power/Heavy_Duty_Market/Product_Specifications.htm (accessed July 6, 2009).

189 Ibid.

190 "UTC Power to Design Fuel Cell for Spanish Submarine," *prnewswire.com*, July 19, 2006, http://www.prnewswire.com/cgi-bin/stories.pl?ACCT=104&STORY=/www/story/07-19-2006/0004399622&EDATE= (accessed July 6, 2009); Albert E. Hammerschmidt, "Fuel Cell Propulsion of Submarines," in *Siemens Energy & Automation - Industrial & Residential Products, Solutions, Services* (presented at the Advanced Naval Propulsion Symposium 2006, Arlington, VA, 2006), 1-7, http://www2.sea.siemens.com/NR/rdonlyres/D3201AC8-C746-4EC8-975A-64E607662195/0/SiemensPresentsFuelCellattheAdvanceNavalPropulsionSymposium.pdf. (accessed July 6, 2009).

191 "Power Plants," *Fuel Cell.org*, http://www.fuelcells.org/db/index.php (accessed July 8, 2009).

submarines.[192] Fuel cells benefit from a worldwide research effort backed by international commissions and cooperatives.[193] International fuel cell companies are even providing technology for U.S. military systems.[194]

Other Considerations

PEM fuel cells rely on platinum as a catalyst to ionize the gas. Although programs are underway to find other suitable catalysts, platinum remains the primary option.[195] 90% of the world's platinum comes from South Africa and Russia, creating potential supply chain restrictions and cost escalations.[196] Platinum is already the largest cost driver for PEM fuel cells.[197]

<u>Assessed LTA HALE technology readiness level: TRL 6</u>

---

[192] Albert E. Hammerschmidt, "Fuel Cell Propulsion of Submarines," 1-7.

[193] "Hydrogen Implementing Agreement," *International Energy Agency*, http://www.ieahia.org/ (accessed July 6, 2009).

[194] "Horizon Fuel Cell Powers World Record UAV Flight," http://www.horizonfuelcell.com/news.htm (accessed June 22, 2009).

[195] Yong Wang et al., "Development of Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells" (presented at the DOE Hydrogen Program: 2009 Annual Merit Review Proceedings - Fuel Cells, Arlington, VA, May 18, 2009), http://www.hydrogen.energy.gov/annual_review09_fuelcells.html#analysis (accessed June 21, 2009).

[196] Rebecca Osakwe, "PEM Fuel Cells and Russia's Supply of Platinum," *Stanford's Student Journal of Russian, East European, and Eurasian Studies* 2 (Spring 2006): 18.

[197] Brian James, "Mass-Production Cost Estimation of Automotive Fuel Cell Systems," May 21, 2009, http://www.hydrogen.energy.gov/annual_review09_fuelcells.html (accessed July 8, 2009).

Regenerative Fuel Cell

The persistence of a fuel cell-powered LTA HALE system is ultimately limited by the amount of hydrogen that is stored onboard the vehicle. Additionally, as fuel is consumed the airship becomes lighter creating buoyancy control problems.[198] A solution to this problem is to use an electrolyzer, powered by the solar array, to convert "waste" water back into hydrogen and oxygen. A system that combines a fuel cell and electrolyzer into a single system is known as a regenerative fuel cell (RFC). [199]

Technology Overview

The RFC functions like a bi-directional fuel cell. In the "electrolyzer" mode, the RFC uses electricity generated by the solar array to split water back into hydrogen and oxygen (see Figure 3.10). The most common RFC electrolyzers use the same technology as PEM fuel cell, but optimized to run in reverse.[200] A PEM or SOFC-based RFC can use the same fuel cell stack as both the electrolyzer and fuel cell (see

---

198 Khoury and Gillett, *Airship Technology*, 55.

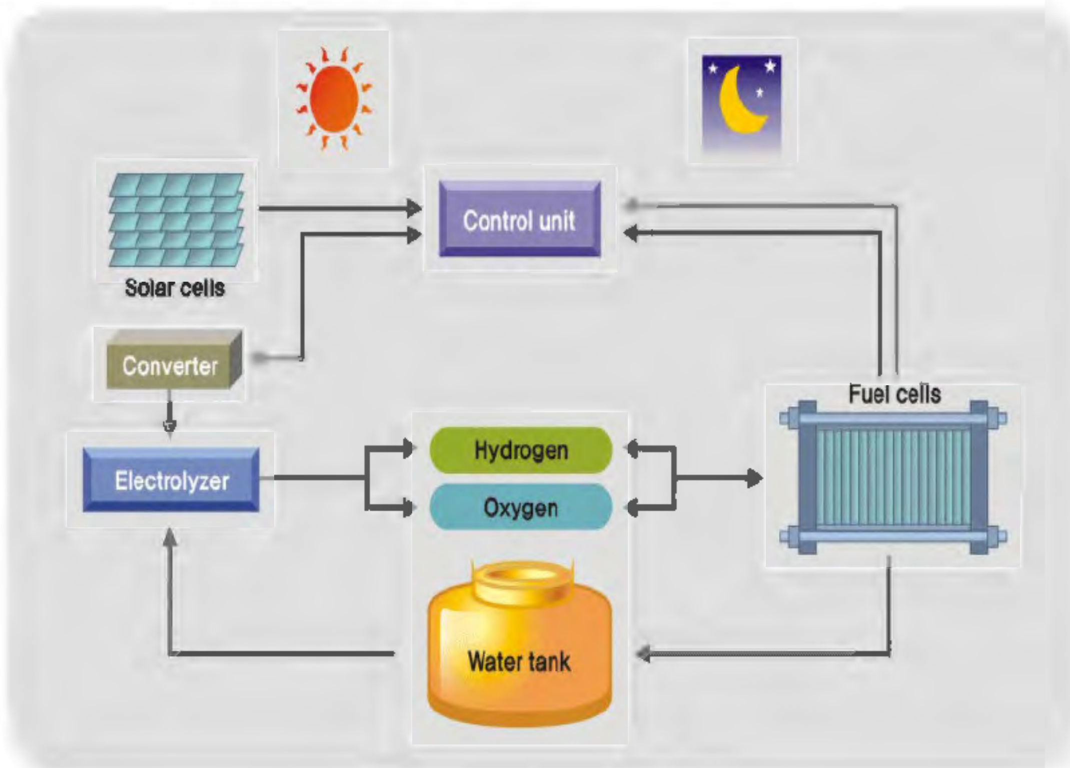
199 Also referred to as reversible fuel cells.

200 Monjid Hamdan, "PEM Electrolyzer Incorporating an Advanced Low Cost Membrane."

Figure 3.11). This "unitized" regenerative fuel cell (URFC) is an attempt to reduce overall component weight, but research indicates that there is not a significant improvement of specific energy over a non-unitized system.[201]

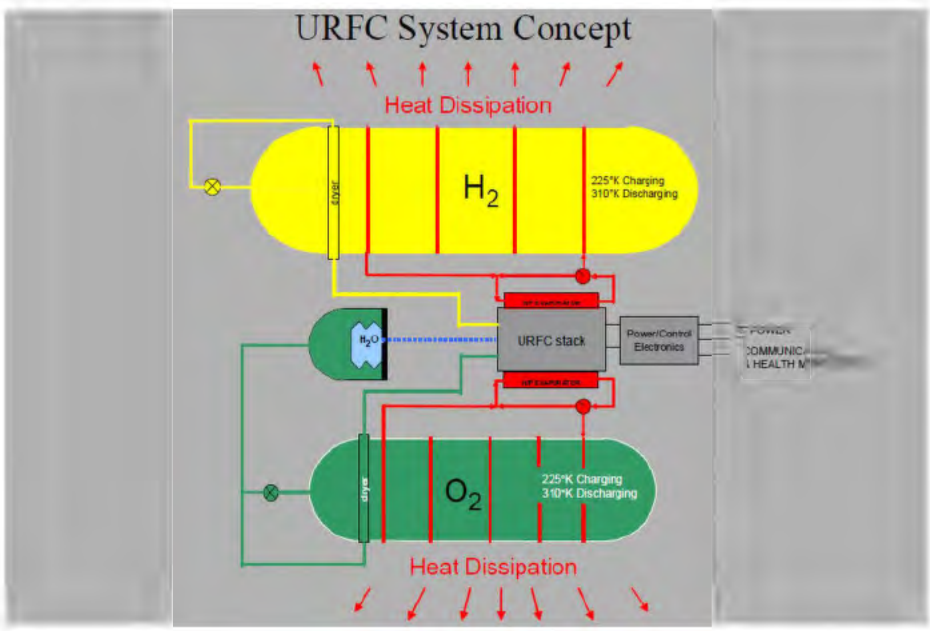
[201] Kenneth A. Burke, *Unitized Regenerative Fuel Cell System Development* (Cleveland, Ohio: Glenn Research Center, December 2003), 2, http://ntrs.nasa.gov/ (accessed June 5, 2009); F. Barbir, T. Molter, and L. Dalton, "Regenerative fuel cells for energy storage: efficiency and weight trade-offs," *IEEE Aerospace and Electronic Systems Magazine* 20, no. 3 (3, 2005): 35-40.

Figure 3.10 Regenerative fuel cell components



Source: "Power Modules," *Fuel Cell Power Inc*,
http://fuelcellpower.co.kr/en/pro/pro_01.asp?m_id=pro&s_id= pro_01 (accessed June 19, 2009).

Figure 3.11 Unitized regenerative fuel cell concept



Source: Kenneth A. Burke, Unitized Regenerative Fuel Cell System Development, 2.

Regenerative Fuel Cell Requirements

LTA HALE developers require a lightweight renewable source power. RFCs have high specific energy densities (W-h/kg) and are not susceptible to problems caused by dynamic charge and discharge cycles.[202] Although specific power density of hydrogen and oxygen is greater than 3600kW-h/kg, when the mass of the component parts are added in, the energy density drops below 1000 W-h/kg.[203] The energy densities of laboratory RFCs are reaching 400 and 600 W-h/kg, which is two to three times better than rechargeable battery technology.[204] While fuel cell requirements are based on maximum power, the average power for the most challenging night mission (e.g. time in darkness, average wind speed) determines the energy storage minimum capacity. Table 3.5 explores the size of the RFC for a winter mission. The mass of the RFC system is less than the projected mass of the feasibility studies.[205]

---

[202] Barbir, Molter, and Dalton, "Regenerative fuel cells for energy storage: efficiency and weight trade-offs," 35.

[203] Ibid., 37.

[204] David J. Bents, *Closed-Cycle Hydrogen-Oxygen Regenerative Fuel Cell at the NASA Glenn Research Center—An Update* (Cleveland, Ohio: Glenn Research Center, April 2008), 2, http://ntrs.nasa.gov/ (accessed June 5, 2009); "Advanced Energy Storage : Technology Overview," *Sion Power Corporation*, http://www.sionpower.com/technology.html (accessed June 20, 2009). Lithium sulfur batteries projected to achieve 500 W-h/kg. 350 W-h/kg batteries were used in the Zypher HALE system.

[205] Craig L. Nickol et al., *High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development*, 53.

Table 3.5 RFC characteristics for baseline LTA HALE systems –winter

LTA HALE system	Energy Density (kW-h/kg)	Averge mission power (kW)	Time in Darkness (h)	Total energy (kW-h)	RFC weight (kg)
300 kW	0.6	30	16	480	800
1200 kW	0.6	100	16	1600	2,667

Source: Analysis based on data from Bents, *Closed-Cycle Regenerative Fuel Cell.*

As with solar arrays, maximizing the efficiency of the system is not necessarily the most important metric. An Institute of Electrical and Electronic Engineers (IEEE) journal article written by a commercial developer of fuel cells points out that "since the efficiency of regenerative fuel cells is 'tradeable' with their size and mass, it is important to size them so that the total energy system mass, not only the portion attributable to energy storage, is minimized for any given required power output and mission profile."[206] While energy density and efficiency are important, they must be balanced to provide the optimal total system mass.

Regenerative Fuel Cell Maturity

The ability to use solar power as an efficient means to generate hydrogen is under intense international study.[207] Current research efforts are creating electrolyzers with

---

[206] Barbir, Molter, and Dalton, "Regenerative fuel cells for energy storage: efficiency and weight trade-offs," 35.

[207] "Abstracts: Production of Hydrogen from Water," *17th World Hydrogen Energy Conference*, June 19, 2008, http://www.whec2008.com/abstractsProductionofHydrogenfromWater.asp (accessed June 19, 2009)

higher efficiencies so that they can generate hydrogen at competitive prices.[208] RFC systems are commercially available, but they do not operate in a closed-loop system where oxygen, hydrogen, and water are conserved.[209] Commercial RFC systems have access to external sources of water, atmospheric oxygen, and multiple sources of electricity. Most RFCs, like the one developed at Savannah River National Laboratory, essentially share a common hydrogen storage tank between the electrolyzer and fuel cell.[210]

Closed-loop regenerative fuel cells are less developed than fuel cell technology. Closed-loop RFCs are on the critical path of planned manned missions to the moon and Mars, implying significant RDT&E resources may be expended by international space programs to mature RFCs. JAXA and KARI have started developing RFC concepts for their LTA HALE systems, but the only closed-loop RFC ever built is at the NASA Glenn Research Center.[211] Although terrestrial efforts are not focused on closed-loop systems, "solar hydrogen" programs will continue to push electrolyzer technology to higher

[208] Monjid Hamdan, "PEM Electrolyzer Incorporating an Advanced Low Cost Membrane."

[209] NASA's RFC only allows electricity in and heat out.

[210] T. Motyka, *Savannah River National Laboratory Regenerative Fuel Cell Project* (Savannah River Site: Savannah River National Laboratory, November 2008), 9, http://www.osti.gov/bridge/purl.cover.jsp?purl=/941112-8jMDpb/.

[211] David J. Bents, *Lunar Regenerative Fuel Cell (RFC) Reliability Testing for Assured Mission Success*, 1; David J. Bents, *Closed-Cycle Hydrogen-Oxygen Regenerative Fuel Cell at the NASA Glenn Research Center—An Update*, 2.

efficiencies and reduced costs. NASA assesses their technology to be at TRL 5 with a goal to be at TRL 6 by 2013.[212]

Regenerative Fuel Cell Technology Challenges

RFCs face the same challenges that fuel cells have with thermal problems, stratospheric conditions, and durability. Commercial research on electrolyzers focuses on improving efficiency and cost effectiveness rather than reducing the mass of the system. Even though international space programs are developing closed-loop RFC technology, they are targeted at lower power levels. The JAXA and KARI RFCs were small 1kW prototypes.[213] NASA's RFC only had a 5kW output with a 60kW storage capacity. [214] Additionally, the system was balanced on a 12-hr daylight cycle using "simulated" solar energy.[215] A significant leap in capability is required to go from the 5 kW in the lab to the 300 kW in stratosphere.

RFCs are critical for LTA HALE systems that intend on operating longer than a few months. An RFC must dynamically balance reactant generation versus consumption. If the electrolyzer does not generate enough reactant during the daylight hours, the airship

[212] David J. Bents, *Closed-Cycle Hydrogen-Oxygen Regenerative Fuel Cell at the NASA Glenn Research Center—An Update*, 1-8.

[213] Tsutomu Fujihara and Kunihisa Eguchi, *Research and Development on Regenerative Fuel Cells for Stratospheric Platform Airship - Ground-based Testing of 1kW RFC System Models*, JAXA Research and Development Memorandum (Unmanned and Innovative Aircraft Team: Japan Aerospace Exploration Agency (JAXA), February 2008), 2 (accessed 25 February 2008).

[214] David J. Bents, *Closed-Cycle Hydrogen-Oxygen Regenerative Fuel Cell at the NASA Glenn Research Center—An Update*, 2.

[215] Ibid., 3.

will eventually deplete its fuel supply. The NASA and JAXA RFC prototypes required significant operator input to control the balance of the system.[216] For some environments like winter at higher latitudes in Japan, short days, long nights, low angle of incident on solar panels, and stronger winds make it difficult to charge the system long enough to get through the night.[217]

[216] Ibid.

[217] Anthony Colozza, *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*, 88.

International Availability

Solar hydrogen programs are being investigated worldwide.[218] Regenerative fuels are currently being used in remote applications, but closed-loop fuel cell research is currently limited to space programs.[219] French, Russian and Australian scientists have started to explore unitized RFC concepts at the university level.[220]

Other Considerations

RFCs use PEM fuel cell technology that relies on platinum as a catalyst to ionize gas. Although programs are underway to find other suitable catalysts, platinum remains the primary option.[221]

Assessed LTA HALE technology readiness level for RFCs: TRL 5

Power Conclusion

Power is the primary challenge preventing LTA HALE systems from becoming a reality.[222] Global efforts are pushing LTA HALE power technology ever closer to a

---

[218] A. Yilanci, H.K. Ozturk, and I. Dincer, "Progress in Energy and Combustion Science : A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications," *Progress in Energy and Combustion Science* 35, no. 3 (June 2009): 231-234.

[219] Asbjørn Strand and Helge Weydahl, "Regenerative Fuel Cell Systems for Satellites," www.prototech.no/doc/PDF%20files/RFCS%20artikkel.pdf. (accessed 8 July 2008).

[220] Arun Doddathimmaiah, "17th World Hydrogen Energy Conference - Modelling and Performance Measurement of Unitised Regenerative Fuel Cells," *WHEC 2008*, June 19, 2008, http://www.whec2008.com/abstract/494.asp (accessed June 20, 2009).

[221] Yong Wang et al., "Development of Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells."

[222] Julian Knott, "Interview at 18th AIAA lighter-than-air Technology Conference," May 5, 2009.

reality, but a concerted RDT&E effort by developers with consistent funding from government and private investors will be required to make the final push.[223] Solar arrays and fuel cells will need to be combined with other power storage devices, such as advanced batteries and super-capacitors to generate the right kind of power when needed.[224] Fuel cell automobiles, aircraft, and marine vessels currently use a combination of power systems.[225] The LTA HALE community will not be able to develop these programs on their own and will require partnerships in cooperation with developers from each of these industries in order to achieve the LTA HALE capability. However, LTA HALE systems have substantial and unique challenges that will not be solved by other industries or by waiting for the technology to mature on its own. A concerted RDT&E investment on the part of a country or corporation in advanced power systems would be an indicator of a serious effort to operationalize LTA HALE systems.

In addition to the necessary success in developing solar array and fuel cell technologies to meet operational LTA HALE requirements, another identified critical technology area is envelope materials.

---

[223] C.R. Luffman, *Aspects to consider for a Lighter-than-air High Altitude Platform Development in Europe*, November 16, 2005, 1, http://www.hapcos.org/papers.php. (accessed July 7, 2009)

[224] Fred Mitlitsky, Blake Myers, and Andrew H. Weisberg, "Regenerative Fuel Cell Systems," *Energy & Fuels* 12, no. 1 (1, 1998): 57.

[225] "Honda's own originally developed ultra capacitor -Higher output, higher efficiency, and increased storage capacity," *Honda Worldwide Fuel Cell*, http://world.honda.com/FuelCell/FCX/ultracapacitor/ (accessed June 20, 2009); Adrian Harrington, "Fuel cell plane in aviation first."

Envelope Materials

The envelope constitutes the primary structure of an airship. The weight of the envelope accounts for over 50% of the airship's mass, and is responsible for containing the lifting gas, providing structure, and supporting loads.[226] The envelope for an LTA HALE system will have significant requirement differences from standard airship material due to colder temperatures, higher ultraviolet and ozone exposure, and lower ambient pressures experienced at their stratospheric employment altitudes.[227] The development of the envelope material is listed as one of Japan's critical challenges for LTA HALE development.[228]

Envelope Material Technology overview

There are two primary material structures required for an LTA HALE vehicle, the envelope (hull) and the ballonet see (figure 2.3 from Chapter 2). The material used for the airship must meet multiple and sometimes competing purposes. According to material engineers from TCOM, a leading airship envelope manufacturer, "the challenge is to develop a very lightweight yet strong material that is capable of containing lifting gas and

[226] Kurose, "Japan: Development for SPF Stratospheric Platform Airship."

[227] Kang et al., "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope," 151-155; Tomme, *The Paradigm Shift to Effects-Based Space: Near-Space as a Combat Space Effects Enabler*, 41. See Lt Col Tomme's paper for more information on ozone and UV effects.

[228] Kurose, "Japan: Development for SPF Stratospheric Platform Airship."

resistant to the environment."[229] Basic material requirements for the envelope and ballonet are provided in Table 3.6.

Table 3.6 Material requirements for envelope and ballonet

Characteristic	**Requirement**
Envelope	
High strength	Determines the maximum size of the envelope
High strength to weight ratio	Minimize airship weight
Resistant to environmental effects/degradation	Drives endurance and maintenance
Tear resistant and damage tolerance	Prevent catastrophic tear propagation
Low gas permeability	Maintain lift and reduce operational costs
Joining and seaming quality	Create strong joints that do not creep*/rupture
Low creep*	Maintain envelope shape
Ballonet	
Low Permeability to air and helium (hydrogen)	Minimize helium contamination or loss
High Flexure and abrasion resistance	Inflates and deflates frequently
Low weight	Reduce total mass

Source: Adapted from Khoury and Gillett, Airship Technology, 142
*Note: Creep is the tendency of material to deform under long-term exposure to stress below yield strength.

[229] Honglian Zhai and Antony Euler, "Material Challenges for Lighter-Than-Air Systems in High Altitude Applications," *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)*, 2005, 2, (accessed June 17, 2009).

Modern envelopes and ballonets are made of compound synthetic materials. No single material is able to meet all of the envelope requirements, so designers combine materials together into laminates to achieve the desired hull performance (see Figure 3.12 and Figure 3.13).[230] The entire envelope cannot be made in a single continuous piece, thus it must be joined together using techniques such as ultrasonic, radio frequency, or thermal welding.[231] The seam strength is critical to the overall structure of the airship and must be at least as strong as the envelope material to prevent failure.[232] The ballonet is a simpler construction, since it does not have to bear any structural loads. The main requirement for a ballonet is to maintain high flexibility and low permeability.[233]

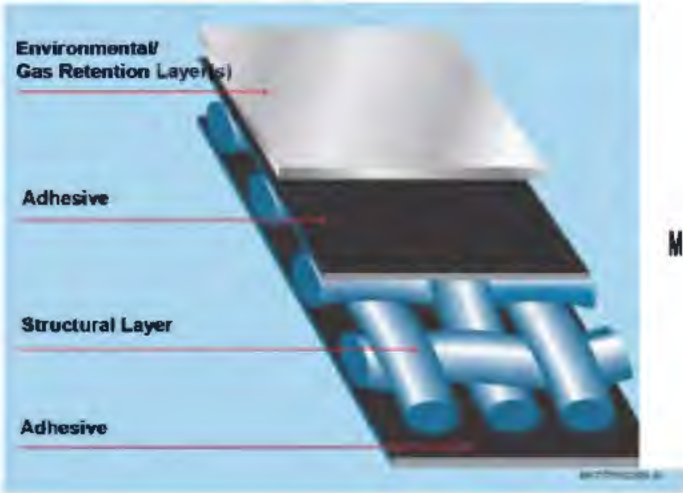
[230] Khoury and Gillett, *Airship Technology*, 145.

[231] T. Miller and M. Mandel, "Airship Envelopes: Requirements, Materials and Test Methods," in *3rd International Airship Convention and Exhibition*, 2000 (accessed June 17, 2009).

[232] Zhai and Euler, "Material Challenges for Lighter-Than-Air Systems in High Altitude Applications," 8.

[233] Miller and Mandel, "Airship Envelopes."

Figure 3.12 Typical hull material layout



Source: Miller and Mandel, "Airship Envelopes."

Figure 3.13 JAXA Zylon® laminate

Source: Zhai, "Material Challenges".

Envelope Requirements

Since the hull is the most massive structure on the vehicle, the weight of the envelope material should be minimized to reach higher altitudes. Additionally the airships will be extremely large, which will put significant strain on the material. According to a study performed by KARI, the airship envelope needs to be at least two-times stronger and lighter than the current polyester (Dacron®) hull technology.[234] LTA HALE developers are investigating modern high performance synthetic materials to see if they can meet the envelope demands. Brand name fabrics such as Zylon®, Spectra®, Vectran®, Kevlar®, and M5® are commonly proposed as envelope base fibers. The

[234] Kang et al., "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope," 153.

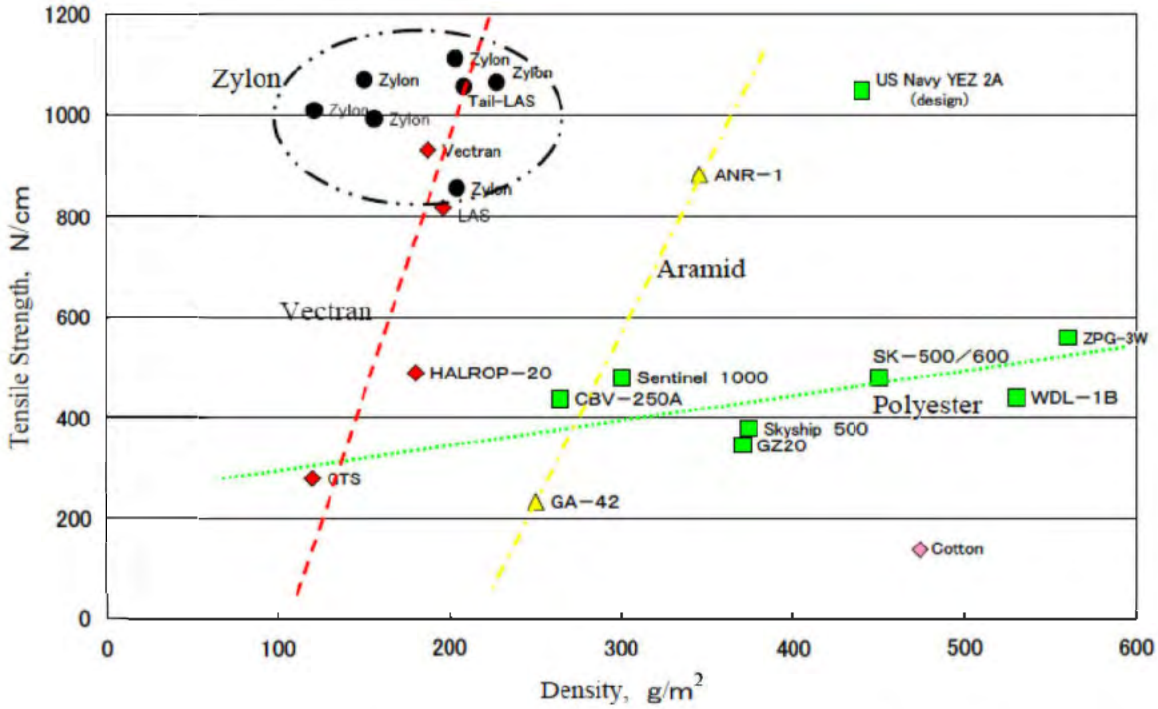
characteristics of each of these materials are shown in Table 3.7. The more experienced LTA HALE developers (e.g. JAXA, KARI, Lindstrand, and TCOM) are exploring Zylon® and Vectran® as their primary envelope material. Figure 3.14 shows that Vectran® and Zylon® meet the strength and weight requirements (i.e. tensile strength ~800 N/cm and density ~200 g/m^2) for the LTA Hull with Zylon® exhibiting superior strength characteristics.

Table 3.7 Characteristics of bigh performance materials

MATERIAL		STRENGTH, g/d	PROs	CONs
M5®	PIPD	> 40	Strong, good compressive properties, excellent weatherability	Limited technical data and not commercially available
Zylon®	PBO	42	Strong	Low flex resistance, poor UV, visible light, and moisture resistance
Spectra®	PE	25-40	Strong, flexible, and good weatherability	Low melting point, poor creep resistance, and difficult to bond
Thornel®	Carbon	30	Strong, high temperature resistance, excellent weatherability	Stiff , low flex resistance, processing difficulty (weave), and very low stretch
Vectran®	LCP	23	Good overall properties and excellent cut resistance	Not as strong as Spectra® or Zylon®, poor UV Resistance
Kevlar®	Aramid	22	Strength comparable to Vectran®	Poor folding and abrasion resistance
Kosa®	PET	7-9	Tough, durable, inexpensive, fully evaluated LTA fiber	low strength

Sources: Zhai and Euler, "Material Challenges," 5.

Figure 3.14 Comparison of envelope materials



Source: Maekawa and Takegaki, "On Structures of the Low-Altitude Stationary Flight Test Vehicle," 5.
Note: The boxes, triangles, and diamonds name airships made with similar material.

JAXA and KARI have performed preliminary tests on Zylon® and Vectran® respectively. The results indicated that Zylon had the highest strength and lowest weight and exceeded the "twice-as-strong and half-the-weight" of polyester requirement. Vectran® was on the "edge" of this requirement, but it was more stable under environmental tests than Zylon®. JAXA created a Zylon® envelope material that had a surface density of 203 g/m2.[235]

[235] Masaaki Nakadate et al., "Reinforcement of an Opening for High Strength and Light Weight Envelope Material Zylon," (presented at the 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, WA: American Institute of Aeronautics and Astronautics, 2009), 1, (accessed June 17, 2009).

Lindstrand designed, but never produced, a material with a surface density of 295 g/m2 that included a built-in PV array (see Figure 3.15).[236] For comparison to the Lindstrand design, the weight of the a-Si PV array calculated for each baseline LTA HALE system (see Table 3.2 in PV array requirements section) was added to the JAXA material to determine the total hull weight (min PV array). The weight of a PV array that encloses the entire envelope (full PV array) is also calculated since the mass of Lindstrand's design includes an envelope sized PV array (see Table 3.8).

Table 3.8 Material plus integrated solar array comparison

System	Tensile Strength (N/cm)	Material density (kg/m2)	300 kW vehicle (20,000 m2)	1200 kW vehicle (30,000 m2)
JAXA	1310	0.203	4060	6090
Lindstrand	1432	0.297	5940	8910
JAXA + min PV array	unknown	N/A	4615	8308
JAXA + full PV array	unknown	0.43	8600	12900

Source: Author's analysis of data from Nakadate, "Reinforcement of Light Weight Envelope,"5; Pattinson, "HALE Airship."

The calculated envelope masses fall within initial feasibility requirements. The Lindstand design results in a heavier structure than the JAXA plus the minimum PV array combination, but the Lindstrand envelope includes a solar array that encompasses the entire LTA HALE system. Further studies are required to explore the design space. Nevertheless, experts in envelope design believe that a lightweight laminate material can

[236] Pattinson, "HALE Airship: Manufacture, Flight and Operation."

be produced that meets the basic strength and weight requirements of an LTA HALE envelope.[237]

Envelope Material Maturity

Vectran® and Zylon® are commercially available materials that have a wide variety of applications. Vectran® has been used in space suits, sails, experimental balloons, and the Mars Pathfinder cushion landing system.[238] Zylon® is found in applications such as sails, sports equipment, and protective clothing for firefighters.[239] The aerospace industry has continued interested in both Zylon® and Vectran® for future missions to Mars, and as part of the structural components for NASA's Ultra-long Duration Balloon Project.[240] Nonetheless, the maturity of the laminate and fabrication techniques for large airship hulls remains low.

KARI and JAXA have performed preliminary laboratory tests to characterize the performance of the material in an LTA HALE environment.[241] JAXA also created a 50m-

---

[237] Luke Brook, e-mail message to author, June 28, 2009.

[238] "Cut Resistant Gloves and Other Applications & General Properties of Vectran Fiber," *Vectran*, http://www.vectranfiber.com/applications.asp (accessed June 18, 2009).

[239] "Zylon Applications," *Zylon*, http://www.toyobo.co.jp/e/seihin/kc/pbo/menu/fra_menu_en.htm (accessed June 18, 2009).

[240] L. Seely, M. Zimmerman, and J. McLaughlin, "The use of Zylon fibers in ULDB tendons," *Advances in Space Research* 33, no. 10 (2004): 1736-1740.

[241] Kang et al., "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope," 152; Nakadate et al., "Reinforcement of an Opening for High Strength and Light Weight Envelope Material Zylon," 36.

scale version of their vehicle using a less capable Zylon® envelope material.[242] Although high performance materials have been available for almost a decade or longer, manufacturing, assembling, and testing the compound laminate material in a relevant LTA environment is still an ongoing effort. Additionally, the characteristics of these fibers and how they behave under various temperature and stresses are not well understood and will require significant RDT&E.[243]

Assessed LTA HALE technology readiness level: TRL 4

Envelope Material Challenges

The high performance materials cost significantly more than standard airship envelopes. Since there is no need to use these materials for current commercial airship systems, technical data and experience working with these materials is nonexistent.[244] The performance of these materials, with respect to stress, creep, fatigue, moisture absorption, UV resistance, and ozone resistance "remains a concern".[245] Additionally, even without allowing for stratospheric considerations, the current airship envelope test methods do not accurately reflect real world performance, requiring new analytical

---

242 Nakadate et al., "Reinforcement of an Opening for High Strength and Light Weight Envelope Material Zylon," 3.

243 Zhai and Euler, "Material Challenges for Lighter-Than-Air Systems in High Altitude Applications," 10.

244 Ibid., 3.

245 Ibid., 10.

methods to be developed. [246] According to material experts from ILC Dover and Zeppelin Luftschifftechnik, "The development of design requirements and compliance to these requirements in airship envelopes continues to be a difficult and labor-some practice."[247]

The characteristics of the material are not well understood at the conditions found at stratosphere. According to studies performed by KARI, the material strength changes in a non-linear fashion across the stratospheric temperature ranges.[248] The low, but highly variable, temperature also creates a challenge for the seams that have to absorb stresses of the envelope.[249] The problem is compounded by the increased temperature ranges encountered during launch and recovery operations. [250] Considering that joining high strength material together "has proven to be a challenge," LTA HALE envelope material requires unique and substantial RDT&E. [251] The more complex integrated PV designs (see Figure 3.15) still need to be develop manufacturing techniques and sample material just to begin basic testing. Additionally, engineers need to develop three-dimensional analysis and manufacturing techniques to construct the complex hull

---

[246] Miller and Mandel, "Airship Envelopes"; Zhai and Euler, "Material Challenges for Lighter-Than-Air Systems in High Altitude Applications," 10.

[247] Miller and Mandel, "Airship Envelopes."

[248] Kang et al., "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope," 155.

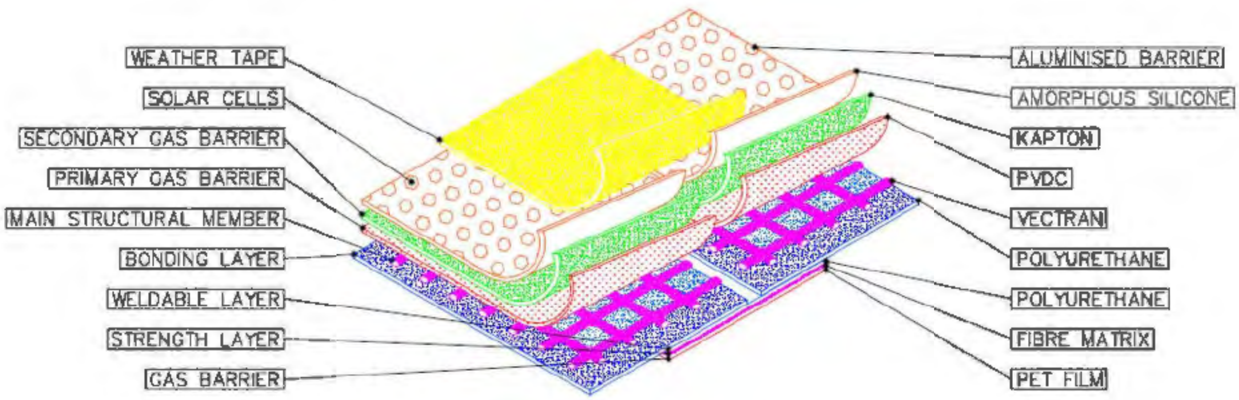
[249] Zhai and Euler, "Material Challenges for Lighter-Than-Air Systems in High Altitude Applications," 10.

[250] Kang et al., "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope," 155.

[251] Zhai and Euler, "Material Challenges for Lighter-Than-Air Systems in High Altitude Applications."

structures. Further compounding the challenge, according to industry experts, "The experience base for the design and analysis of these types of craft remains small."[252]

Figure 3.15 Lindstrand design for integrated solar array envelope laminate



Source: Pattinson, "HALE Airship."

Compliance with international regulatory requirements creates an added design challenge. The LTA HALE system will be classified as an airship, thus "airworthiness regulations must be considered, as these will provide a guideline for the designer." [253] Where no requirement exists the "airship manufacturer must prove equivalent safety to another form of flight."[254] Ultimately, the LTA HALE system will need to develop new

[252] Luke Brooke and Adam Bown, "Design, analysis and patterning of inflated lifting body form LTA vehicle hulls," (presented at the 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, Wa, 2009), 13.

[253] Interview with Per Lindstrand 4 May 2008;Miller and Mandel, "Airship Envelopes," 4.

[254] Pattinson, "HALE Airship: Manufacture, Flight and Operation."

analysis and test techniques to understand performance and conform to regulatory standards that govern physical characteristics, fabrication methods, and statistical performance requirements.[255] This problem is further complicated by the requirement for these systems to operate autonomously. Autonomous UAVs are notoriously difficult to get certified and airships provide and even tougher obstacle because of their unfamiliarity.

Envelope Material Availability

All components of the LTA HALE envelope material are internationally available from multinational corporations, such as DuPont, Kuraray, and Toyobo.[256] However the capability to manufacture large envelopes is limited. Most international airship manufacturers rely on TCOM or ILC Dover to manufacture their standard airship envelopes.[257] U.K. Lindstrand Industries is one of the few international companies that currently has the capability and experience to make larger-than-standard envelopes.[258]

---

[255] Miller and Mandel, "Airship Envelopes," 3.

[256] "DuPont.com: Worldwide," *Dupont.com*, http://www2.dupont.com/Our_Company/en_US/worldwide/index.html (accessed June 18, 2009); "kuraray-Fabrics-Products Infomation," Kuraray.com, http://www.kuraray.co.jp/en/products/fiber/ (accessed June 21, 2009); "TOYOBO-Product-Industrial materail," Toyobo.com, http://www.toyobo.co.jp/e/products/s_sizai.htm (accessed June 21, 2009).

[257] Luffman, *Aspects to consider for a Lighter-than-air High Altitude Platform Development in Europe*, 11.

[258] Ibid.

Other Considerations

Each high performance material is generally produced by only one company: Kuraray manufactures Vectran®, Toyobo manufactures Zylon®, and DuPont manufactures both Kevlar and M5. These materials are in high demand and occasionally experience production bottlenecks.[259] For some materials such as M5, only a limited amount is available for testing.[260]

In addition to challenges involved in the LTA HALE critical technologies of solar arrays, fuel cells, and envelope materials, further unique challenges include communications and surveillance payload integration and generating smart solutions to the LTA HALE key driver- - lifting gases.

Communications and Surveillance Payload Integration

The pursuit of LTA HALE systems is driven by the increased capability that operations in the stratosphere could provide. Although LTA HALE vehicles are built as a platform to carry multiple communication and sensor payloads, these devices must be integrated with platform development from the initial conception of design. The payloads

[259] "Kuraray Expands VECTRAN Superfiber Manufacturing Facilities," http://www.kuraray.co.jp/en/release/2007/070122.html (accessed June 21, 2009).

[260] "About M5," *Magellan Systems International, Inc.*, http://www.m5fiber.com/magellan/about_m5.htm (accessed June 21, 2009).

for an initial LTA HALE system will require tighter integration due to the potentially limited lifting capacity of these systems. The payload technology challenges on a whole are substantially less than the platform technologies. Payload technologies that perform the intended LTA HALE communication and surveillance missions already exist on UAVs, satellites and aerostats. According to a European consortium that researched communication and surveillance payloads LTA HALE systems,

> Most of the payload technologies are common with airborne and spaceborne platforms. Additional developments compared to airborne payloads are mainly necessary with respect to automation, light weight design, small volume and low power consumption. Compared with spaceborne payloads HAAS [LTA HALE and HALE] payloads have the advantage to operate in a less hostile environment and have therefore better growth potential.[261]

In some cases, their complexity, weight, and power can be reduced because they operate closer to the target than satellite systems or they do not have to overcome low altitude, line-of-sight obstructions (e.g. building and trees) as experienced by lower operating systems. China has designed civilian cell phone and broadband LTA HALE communications packages that use less power than the country's analogous satellite and terrestrial systems.[262] The European study also analyzed the regulatory and technical maturity along with the availability of dozens of communication and sensor payloads for

[261] Arie Lavie and Tim Tozer, *Developing a European Research Strategy in the High Altitude Aircraft and Airship Sector*, ACTIVITY ASSESSMENT REPORT (USE HAAS, January 23, 2007), 40.

[262] Zi-Niu Wu and Xiao-Jian Xue, "Civilian Demands Application of Airships in Civil Projects."

an LTA HALE system.[263] Most rated as ready by 2015 and almost all would be ready by 2020.

Even if the payloads can have better operational capability, they face the same environmental and regulatory challenges as the platform systems. Environmental factors such as the ozone effects on equipment performance need to be addressed. According to the same European study, "Electrical power needs, electro-magnetic-compatibility (EMC) and weight/volume limitations all have to be considered when designing a competitive and high performance [LTA HALE] system."[264] In most cases an environmental shelter is employed, but this adds weight that needs to be accounted for in the performance of the system.

Regulatory challenges may be the biggest hurdle these systems need to overcome. The International Telecommunications Union (ITU) is already developing standards that these systems must meet such as approved spectrum allocations (i.e. frequencies and signal characteristics), which will add time and effort to develop the system.[265]

There are multiple ongoing efforts to study and build communications systems that meet these standards and meet the technology challenges of employing

---

[263] Arie Lavie and Tim Tozer, *Developing a European Research Strategy in the High Altitude Aircraft and Airship Sector*, 41-45.

[264] Arie Lavie and Tim Tozer, *Activity Assement Report: Developing a European Research Strategy in the High Altitude Aircraft and Airship Sector*, ACTIVITY ASSESSMENT REPORT (USE HAAS, January 23, 2007), 13.

[265] Milan Lalovic et al., *Strategy Document: Delivering Broadband for All including Commercial and Technical Risk Assessment*, 55.

communication and surveillance systems at high altitudes. The EU has had at least four cooperatives between industry, government and academia geared toward addressing technology and regulatory concerns of HALE and LTA HALE communications systems. These cooperatives are supported by a greater international community that is interested in putting these devices on aerodynamic HALE systems.[266]

LTA HALE mission payloads similar to the ones that could be employed on LTA HALE systems have flown operationally at stratospheric environments for decades on the U-2, Global Hawk, and on scientific balloons around the world.[267] Space Data, which operates free-floating balloon communications in the stratosphere, adapted "off- the-shelf technology" for both its commercial and military systems.[268] An LTA HALE program that is working hand-in-hand with payload developers would be indicative of a serious and viable program. These relationships may even provide an indication of the potential LTA HALE capability that is being developed.

Lifting Gases

[266] "Technical publications HAPCOS," *COST297 - HAPCOS*, http://www.hapcos.org/papers.php (accessed July 6, 2009).

[267] "CNES : A strategic activity"; "NASA's Scientific Ballooning Program"; "Fact Sheets : Near-Space Access Program -- High-Altitude Balloons and Tethered Aerostats : Near-Space Access Program -- High-Altitude Balloons and Tethered Aerostats," *Kirtland Air Force Base*, http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=7890 (accessed July 4, 2009).

[268] "Space Data SkySite," http://www.spacedata.net/ (accessed July 6, 2009).

Lifting gases may not seem like a technological consideration. The physical properties of the gases are static and cannot be improved upon. Despite some proposals that claim to be developing "exotic" lifting gases, there are only two legitimate choices for LTA HALE systems: hydrogen and helium, which are the two lightest gases. Acquiring, refining, and storing these gases is a technological and programmatic consideration for LTA HALE system.

Helium

Helium is the lifting gas of choice for a majority of airship proposals. Unlike its much maligned brother, hydrogen, helium is inert or chemically non-reactive. This means that helium will not combust, thus it is safer to transport and store. Nevertheless, helium has significant trade-offs in terms of performance, price, and availability.

The ubiquitous helium-filled party balloons betray the increasing rarity of this gas. Although it is the second most abundant element in the universe, helium is relatively rare on earth. Helium in the earth's crust is the result of the radioactive alpha decay of uranium and thorium.[269]As helium is "created," it becomes trapped in pockets of impermeable rock mixing with natural gas.[270] Helium is captured as a byproduct of natural gas extraction and refining.[271] Concentrated sources of helium that are

[269] Don L. Anderson, G. R. Foulger, and Anders Meibom, "Helium Fundamentals," *MantlePlumes.org*, http://www.mantleplumes.org/HeliumFundamentals.html (accessed July 8, 2009).

[270] Ibid.

[271] Norbert Pacheco, "US Geological Survey, Mineral Commodity Summaries-Helium" (US Geological Survey, January 2009), 74, minerals.usgs.gov/minerals/pubs/commodity/helium/mcs-2009-heliu.pdf (accessed February 25, 2009).

economically viable for extraction are unevenly distributed around the world. [272] The United States has the largest resource of helium reserves. Helium has many unique properties that make it useful for a variety of applications including cryogenics, pressurizing and purging, and welding cover gas. Cryogenic applications such as magnetic resonance imaging (MRI) and liquid fueled rockets constitute the largest and fastest growing consumers of helium.[273]

Availability and cost is the primary concern for helium. During the early part of the 20th century, to the United States was the world's supplier of helium. At the time, helium was considered a precious resource and was protected by the Helium Act of 1927 which reserved its use primarily the U.S. military.[274] The limited supply of helium forced Germany to fill the Hindenburg with hydrogen, which lead to the historic disaster.[275] The United States is still the leading supplier of helium, producing approximately 80% of the world's supply.[276] In 2008, only four other countries produced helium: Algeria, Poland, Qatar, and Russia. [277] New plants are coming online in Australia, China, India, and Indonesia, but the amount of helium available for extraction in these countries is much

[272] Z. Cai et al., "Modelling Helium Markets" (Cambridge University Judging School, 2006), http://www.jbs.cam.ac.uk/programmes/phd/downloads/conference_spring2007/papers/cai.pdf (accessed February 25, 2009).

[273] "Helium," *U.S. Department of The Interior Bureau of Land Management*, http://www.blm.gov/nm/st/en/prog/energy/helium.html (accessed July 5, 2009).

[274] Charles Rosendahl, *What about the Airship?* (New York: Charles Scribner's Sons, 1938), 93.

[275] Ibid., 94.

[276] Norbert Pacheco, "US Geological Survey, Mineral Commodity Summaries-Helium," 75.

[277] Ibid., 74.

less than the United.[278] Helium is experiencing unprecedented price increases due to shortages in supply. From 2002 to 2007 helium prices doubled. [279] The price for helium increased from 2007 to 2008 by 30% to 50%. [280]

Increasing costs, short supplies, and competing demand against other higher priority applications will levy additional technological, logistical, and cost challenges on LTA HALE systems. New helium conservation techniques such as envelope gas purification will need to be developed.[281] The traditional wasteful (dumping and pumping) technique is no longer an option. A critical concern is that helium is the only option for cryogenic applications that require cooling below -429 F.[282] Countries are investigating advanced extraction techniques to capture helium in traditionally non-viable areas.[283] Collectively, these research thrusts could be an indication that helium may become too valuable to use in LTA applications, forcing these systems to use hydrogen.

[278] Ibid., 75.

[279] Ibid., 74.

[280] Ibid.

[281] D. M. Smith, T. W. Goodwin, and J. A. Schillinger, "Challenges to the Worldwide Supply of Helium in the Next Decade" (Air Products and Chemicals, Inc), https://www.airproducts.com/NR/rdonlyres/E44F8293-1CEE-4D80-86EA-F9815927BE7E/0/ChallengestoHeliumSupply111003.pdf (accessed July 6, 2009).

[282] Ibid.

[283] Ibid.

Hydrogen

Hydrogen is the most abundant element in the universe and is the third most common element on earth.[284] For Airship applications, hydrogen has multiple advantages over helium. Hydrogen is less expensive than helium and has a 7% greater lifting capability.[285] Hydrogen is also a larger molecule, which prevents it from diffusing through the envelope as easily as helium. Using hydrogen as the lifting gas results in a smaller airship with greater lift. Even so, hydrogen has had to apologize for itself ever since the Hindenburg went up in flames. Almost every article that discusses airships, immediately qualifies that they use "non-explosive" helium. Overcoming a bias against hydrogen is a global challenge and will be one of the largest impediments to its employment in LTA HALE systems. Using hydrogen, whether by choice or necessity will require LTA HALE programs to develop new technology to address safety, certification and handling issues.

An additional consideration for hydrogen is its production method. Due to its reactive nature, hydrogen is only found in a combined form, like water and hydrocarbon fuels. While electrolyzers can create hydrogen, this is currently an inefficient and expensive process. Currently, 95% of hydrogen comes from steam reforming of natural

---

[284] Mildred Dresselhaus, *Basic Research Needs for the Hydrogen Economy* (U.S. Department of Energy, May 13, 2003), iii.

[285] Charles P. Burgess, *Airship Desgin* (New York: The Ronald Press Company, 1927), 37.

gas which generates greenhouse gases.[286] For LTA HALE systems that are billed as "zero emission" vehicles, there will need to be an investment in eco-friendly hydrogen product and storage facilities at significant expense.

Lifting gases are the foundation of LTA HALE systems. Although they are not a critical technology challenge that needs to be addressed (like fuel cells), they are a key driver for enabling technologies (e.g. envelopes). The choice of lifting gas also impacts operational parameters such as maintainability, turn-around time, supply chain management, safety and certification. Selection and management of lifting gas affects requirements spanning LTA HALE employment and sustainment.

Technology Assessment Conclusion

The almost quaint nature of the airship masks the complex technical requirements that hide beneath. In the case of solar arrays, fuels cells and material requirements, LTA HALE vehicles not only require the most advanced designs, but will employ the largest and most powerful versions of these technologies in the most extreme conditions. By 2020, the technology will exhibit basic characteristics required to develop and employ an LTA HALE system. These technologies are beginning still immature with TRLs raning from TRL 4 to TRL 5 indicating they are still in laboratory development developement

[286] "Hydrogen - Energy," *Department of Energy Kids Page*, October 2008, http://www.eia.doe.gov/kids/energyfacts/sources/IntermediateHydrogen.html (accessed June 22, 2009).

will need to invest considerable RDT&E resources across all technology areas to increase performance, develop manufacturing techniques, create design and analysis tools, and build high fidelity simulations and prototypes. Because of the unique requirements of LTA HALE systems, an investment in these technology areas, especially envelope materials, will be a leading indicator that an LTA HALE capability is being seriously pursued.

Table 3.9 Assessed LTA HALE technology readiness levels

Technology	Assessed Technology Readiness Levels
Thin-film PV arrays	TRL 4
PEM Fuel Cells	TRL 6
Regenerative Fuel Cells	TRL 5
High Performance Envelope Material	TRL 4

Source: Author.

CHAPTER 4

CASE STUDY ON JAPAN'S STRATOSPHERIC PLATFORM

There are many foreign LTA programs that exist on paper but there are few that have gone past the conceptual stage of development. Of these programs, Japan has had the most focused and extensive foreign LTA HALE program over the last decade. A case study on Japan's LTA HALE program is reviewed in this chapter. The object of the case study is to examine the programmatic challenges and the level-of-effort required to produce an LTA HALE system and to assess Japan's progress toward developing an operational system.

Program Overview

Japan began feasibility studies and preliminary efforts to develop an LTA HALE system in 1998.[287] Japan's objectives for the program were to develop a stationkeeping platform, similar to a geostationary satellite that could be used for telecommunication and earth observation programs.[288] Japan established the Stratospheric Platform Development

[287] Kurose, "Japan: Development for SPF Stratospheric Platform Airship."

[288] Shuichi Sasa, "Stratospheric Platform Program in Japan and Ground-to-Stratosphere Flight Test."

Council that included members of the government, academia and industry, such as Kawasaki Heavy Industries.[289] The council was jointly directed by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the Ministry of Internal Affairs and Communications (MIC).[290] The Japan Aerospace Exploration Agency (JAXA), which falls under MEXT, was charged with developing the airship platform components and payload technology for earth observation (see figure 4.1). [291] The National Institute for Information and Communications Technology (NICT) was responsible for developing communications, tracking, and air traffic control systems for the project.[292]

---

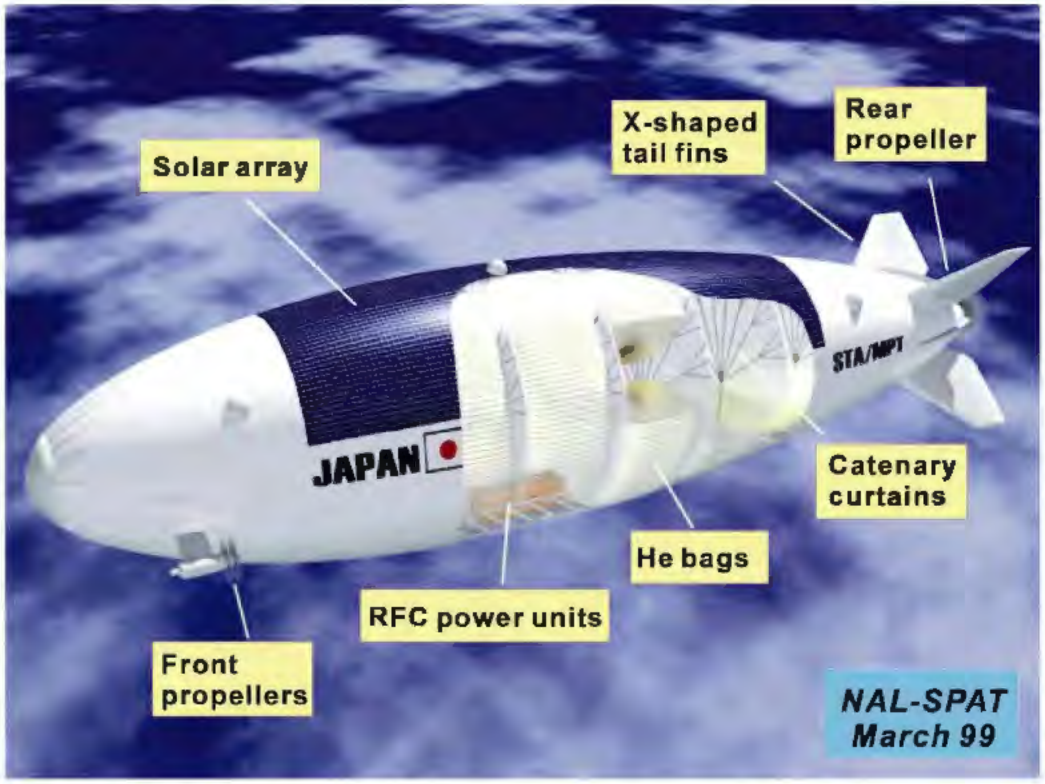
[289] Kurose, "Japan: Development for SPF Stratospheric Platform Airship" Kawasaki Heavy Industries was the prime contractor for vehicle development.

[290] Ibid.

[291] Masaaki Nakadate, "Development and Flight Test of SPF-2 Low Altitude Stationary Flight Test Vehicle," in *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)* (presented at the 16th AIAA Lighter-Than-Air Systems Technology Conference, Arlington, VA: American Institute of Aeronautics and Astronautics, 2005), 2; "JAXA History," *JAXA- Japan Aerospace Exploration Agency*, http://www.jaxa.jp/about/history/index_e.html (accessed June 24, 2009) The National Aerospace Laboratory of Japan (NAL) was in charge of the airship program before it merged with JAXA in 2003.

[292] "R&D of Stratospheric Wireless Platforms," http://www2.nict.go.jp/q/q262/3107/end101/ENG/main.html (accessed June 24, 2009) Telecommunications Advancement Organization of Japan (TAO) and the Communications Research Laboratory (CRL) are frequently referred to in the literature. TOA and CRL merged under the NICT in April of 2004. TOA and CRL had separate responsibilities for developing tracking and communication technology respectively.

Figure 4.1 Japan's Stratospheric Platform concept



Source: Eguchi and Yokomaku, "2000 Overview of Stratospheric Platform."

In 1998, the Stratospheric Platform Development Council began to direct efforts to produce and test platform and payload components and operational concepts for, what they termed, the practical Stratospheric Platform (SPF).[293] Under this effort, Japan was to develop and test risk reduction technologies and perform actual flight test.[294] The flight test program was funded as one of Japan's "Millennium Projects" and as JAXA's

[293] Nakadate, "Development and Flight Test of SPF-2 Low Altitude Stationary Flight Test Vehicle," 3.

[294] "Studies on the Stratospheric Platform," *Sora to Sora*, 2004, http://www.ard.jaxa.jp/eng/info/prm/2004/001/04.html (accessed June 24, 2009).

aeronautical applications director Toru Shimizu expressed, "the Stratosphere Platform Project was launched with high expectations…by the Cabinet Office."[295]

The SPF program was designed to support multiple mission applications. The initial goal of the program according to Kawasaki manager Toyotoshi Kurose was to be able to use SPFs to do the following:

> …instantly construct an ultra-highspeed telecommunications infrastructure that enables this network to achieve complete coverage of the Japanese archipelago and surrounding skies and seas. Moreover, even when a disaster or the like causes problems in terrestrial communications systems, this SPF airship network will continue to operate independently oblivious to the effects of this disaster, making continued service provision possible.[296]

Although the mission of JAXA and NICT is to develop technology for "peaceful purposes", industry partners have recognized the capability of the SPF airships " to provide heretofore unexcelled services in defense-related applications…enabling ongoing monitoring of potentially threatening aircraft and marine vessels in air and seas …[and] at the same time, they will also be able to provide…data communication services to Japan ground, maritime and air self defense forces'…."[297] This application of the SPF airship has not been found in the government literature.

---

[295] "Toru Shimizu - Expectations soar for our huge new airship," *JAXA- Japan Aerospace Exploration Agency*, http://www.jaxa.jp/article/interview/no11/index_e.html (accessed June 23, 2009).

[296] Kurose, "Japan: Development for SPF Stratospheric Platform Airship."

[297] Ibid.

In addition to the communication and earth monitoring, the SPF has gained increasing attention for disaster warning and response. NICT has developed operational and technical designs for a Tsunami warning system and continues to refine communications packages for disaster response.[298] High-level members on a panel discussing the strategic vision of Japan's aerospace program lamented that an SPF was not in place to help recover from the Niigata Chuetsu Earthquake in 2005.[299] Japan intends on using the system as both a stable long term platform and a dynamic response system.

Technology Risk Reduction and Flight Test Programs

Japan identified from their feasibility assessment that the program was completely different from a traditional airship and would present a significant challenge. As Mr. Shimizu points out "every aspect of the airship, ranging from materials for the outer film, the structure, and flight control...[and] we have to strive to make achievements by challenging the unknown world while paying the utmost attention to ground and flight

[298] Noboru Koyama et al., "Tsunami Monitoring System by Stratospheric LTA Platform," in *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)* (American Institute of Aeronautics and Astronautics, 2005), 1-8.

[299] "JAXA 2025 Panel Discussion "Aerospace: a Contributor to Society"," *JAXA- Japan Aerospace Exploration Agency*, 2005, http://www.jaxa.jp/about/2025/p4_3_e.html (accessed June 25, 2009).

safety."[300] The program was broken down into three phases, technology risk reduction and the Millennium Project flight test, the 150m demonstrator system, and finally the practical SPF.[301] The first phase began in 2000 and lasted for six years. The follow on phases have not been scheduled but were to commence after the results of the first phase were studied. Japan's technology demonstration concentrated on performing risk reduction on the envelope material, hull structure, power sources, and operation and system control.[302] The goal of the Millennium Project was to build and test two prototype vehicles to evaluate SPF technology that would lead to the development of the 150m demonstrator program (see Figure 4.2).[303]

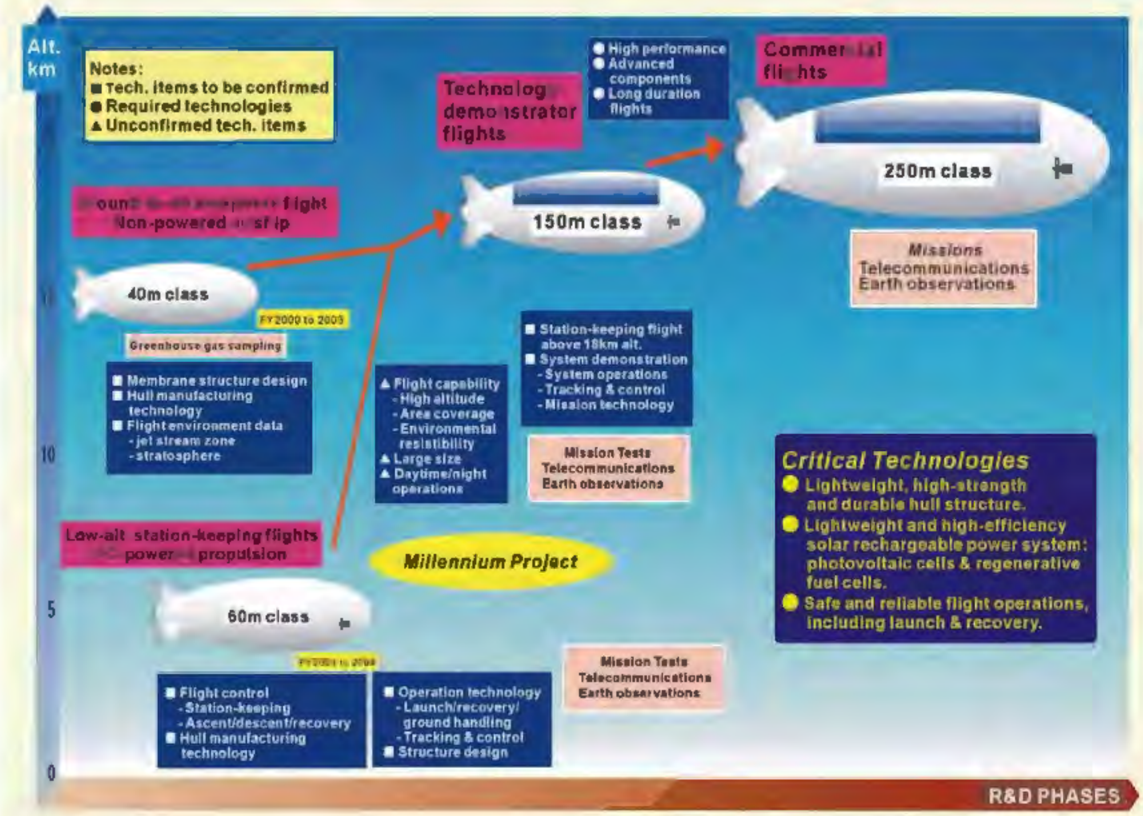
[300] "Toru Shimizu - Expectations soar for our huge new airship."

[301] Eguchi and Yoshio Yokomaku, "2000 Overview of Stratospheric Platform Airship R&D Program in Japan."

[302] Shuichi Sasa, "Stratospheric Platform Program in Japan and Ground-to-Stratosphere Flight Test."

[303] Eguchi and Yoshio Yokomaku, "2000 Overview of Stratospheric Platform Airship R&D Program in Japan."

Figure 4.2 Japan's SPF development Program



Source: Shuichi Sasa, "Stratospheric Platform Program in Japan and Ground-to-Stratosphere Flight Test.

Technology Demonstration and Risk Reduction

The program began by developing and testing component technologies of the system. Top priority was given to ensure that the SPF program did not generate environmentally damaging emissions.[304] JAXA also recognized that mass is a primary issue for airships and gave priority to reducing the weight of the components.[305] To address these issues, JAXA began R&D on envelope materials, solar array, and regenerative fuel cells.

Envelope Material

Developing a lightweight envelope material is a primary concern for Japan. In 2000, JAXA constructed three versions of a laminate material, two with a Zylon core and one with a Vectran core. [306] JAXA measured multiple physical properties (e.g. weight, thickness, permeability) and performed over a dozen mechanical tests (e.g. tensile strength, joint strength, and creep) on each material.[307] Vectran was further tested for thermal and electrical properties. JAXA subjected each material to accelerated environmental exposure tests. JAXA was intent on using the Zylon laminate for the

[304] Ibid.

[305] Kurose, "Japan: Development for SPF Stratospheric Platform Airship."

[306] Nakadate et al., "Reinforcement of an Opening for High Strength and Light Weight Envelope Material Zylon," 2.

[307] Soji Maekawa and Atsushi Takegaki, "On Structures of the Low-Altitude Stationary Flight Test Vehicle," in *AIAA 5th Aviation, Technology, Integration, and Operations Conference (ATIO)* (presented at the 16th AIAA Lighter-Than-Air Systems Technology Conference, Arlington, VA: American Institute of Aeronautics and Astronautics), 5.

flight test vehicles, but it did not meet specifications during testing. [308] Ultimately, the flight test vehicles were constructed of Vectran.[309] Testers placed strips of Zylon and Vectran next to each other on various surfaces of one of the flight test vehicles hull to compare degradation characteristics.[310] Although two test vehicles were constructed with a Vectran laminate hull, Japan is determined to use Zylon for their 150m demonstrator and commercial envelopes, as evidence by their continued testing of the material.[311]

Solar Arrays

JAXA carried out experiments on SPF solar arrays in 2003. The purpose of the test was to collect basic design data on array installation, power management functions, solar shading effects, and thermal affects on the envelope.[312] JAXA built a 35m tethered airship that was fitted with 14 solar panels made of mono-crystalline silicon.[313] This is a departure from other LTA HALE programs that plan to use thin-film solar array, but these tests were conducted in 2003 and the solar panels were most likely the lightest and most efficient panels that were readily available. Japan concluded that the solar array

[308] Ibid., 4.

[309] Nakadate, "Development and Flight Test of SPF-2 Low Altitude Stationary Flight Test Vehicle," 6.

[310] Maekawa and Takegaki, "On Structures of the Low-Altitude Stationary Flight Test Vehicle," 6.

[311] Nakadate et al., "Reinforcement of an Opening for High Strength and Light Weight Envelope Material Zylon," 7; Shoji Maekawa et al., "Tear Propagation of a High Performance Airship Envelope Material," (presented at the 17th AIAA Lighter-Than-Air Systems Technology Conference, Belfast, Northern Ireland: American Institute of Aeronautics and Astronautics, 2007), 1-9.

[312] Eguchi and Tsutomu Fujihara, "Research Progress in Solar Power Technology for SPF Airship.".

[313] Ibid.

system provided sufficient power, but more research was required to characterize solar shading and to find efficient, environmentally resistant, low cost UV arrays that could be massed produced for the airship. These requirements would drive a design to use thin-film PV, but JAXA has not further investigated solar arrays for their airship.

Regenerative Fuel Cells

Japan investigated several forms of power generation, including microwave and laser power beamed from the ground.[314] Regenerative fuel cells, however, were selected to meet power and weight requirements, long endurance objectives, and environmental concerns.[315] In 2002, JAXA constructed a 1kW RFC testbed, which was used to develop a prototype system that could fit on a test vehicle. [316] The objective of the program was to develop an onboard version of an RFC that could meet the environmental and lightweight demands of the SPF.[317] The RFC system was tested in a simulated closed-loop for 1100 hours, but was never hooked up to an actual solar array or flown on a flight test

---

[314] Masahiko Onda, "Design Considerations on Stratospheric LTA Platfrom," in *A Collection of the 13th AIAA Lighter-Than-Air Systems Technology Conference Technical Papers* (presented at the 13th AIAA Lighter-Than-Air Systems Technology Conference, Norfolk, VA: American Institute of Aeronautics and Astronautics, 1999), 208.

[315] Eguchi and Yoshio Yokomaku, "2000 Overview of Stratospheric Platform Airship R&D Program in Japan."

[316] Tsutomu Fujihara and Kunihisa Eguchi, "Experimental Work on Solar Regenerative Fuel Cells for SPF Airship" (Stratospheric Platforms Project Center-JAXA, 2002), http://send.chofu.jaxa.jp%2Fsend%2Feng%2Fdlpdf.php3%2Fnalrp2002004.pdf%3Fid%3DNALRP2002004&ei=xJxCSpCOG8K5lAek_vj5CA&usg=AFQjCNE48efRa6TKZcEi6D3Y25vWHn7CLA&sig2=ZgvicFwQ16imuz9ceJ9oMQ (accessed June 5, 209).

[317] Ibid.

vehicle.[318] JAXA's preliminary test provided them with positive results and data for a 15kW fuel cell system, but to date this system remains in the concept phase.[319] The RFC is being further developed for Japan's space program, with continued attention toward airship design.[320]

Millennium Project Flight Test Program

The culmination of the Millennium project was the construction and testing of two LTA flight test vehicles. The first flight test vehicle was constructed to test the ability to get to the stratosphere. The second flight test vehicle focused on airship flight operations, payload mission equipment testing, and command and control systems.[321]

The Ground-to-Stratosphere Vehicle

The Ground-to-Stratosphere (GTS) vehicle was 47m long and composed of a Vectran envelope. [322] The system was used for a non-powered flight test that demonstrated vehicle construction, vertical launch, buoyancy measurements, pressure

[318] Sone et al., "One kilowatt-class fuel cell system for the aerospace applications in a micro-gravitational and closed environment," 890-891.

[319] Tsutomu Fujihara and Kunihisa Eguchi, *Research and Development on Regenerative Fuel Cells for Stratospheric Platform Airship - Ground-based Testing of 1kW RFC System Models.*

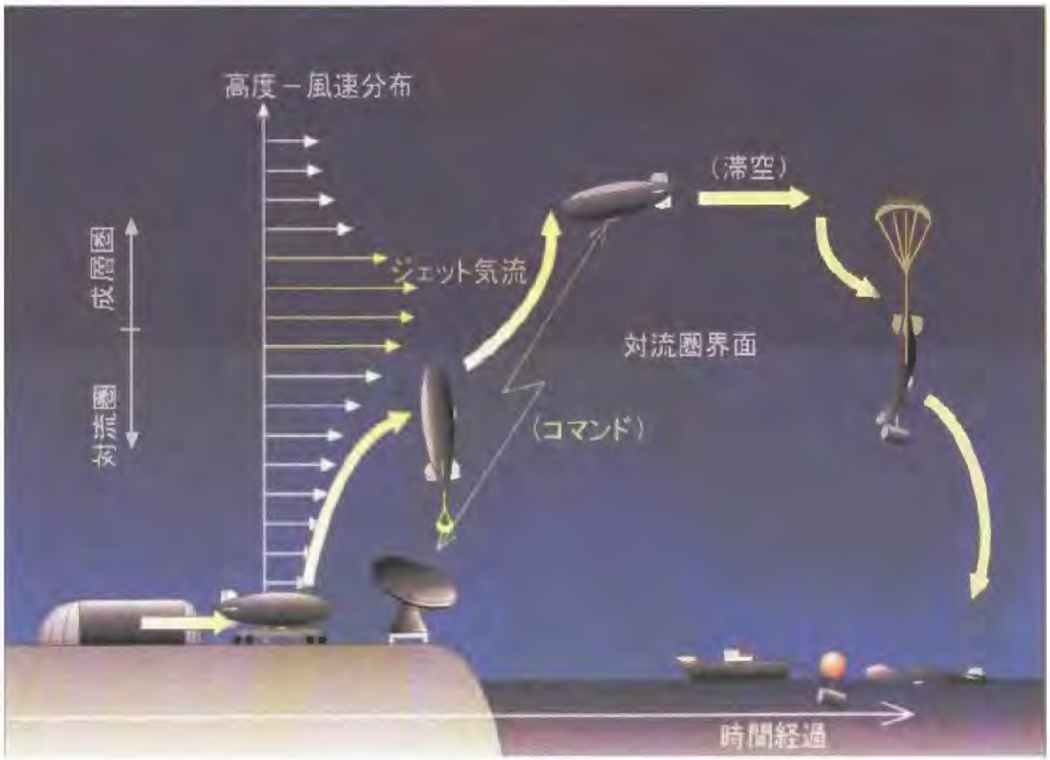
[320] Sone et al., "One kilowatt-class fuel cell system for the aerospace applications in a micro-gravitational and closed environment," 891.

[321] Shuichi Sasa, "Stratospheric Platform Program in Japan and Ground-to-Stratosphere Flight Test."

[322] Ibid. The GTS is also referred to as SPF-1.

control, and the flight path estimation software.[323] Minimized use of personnel to minimize safety hazards and operational cost were key considerations.[324] The GTS flew to an altitude of 16km where it was leveled-off and tested for 30 min correctly demonstrating all flight objectives (Figure 4.3).

Figure 4.3 GTS operational test concept



Source: The access reads "time" along the bottom axis and Tropsphere/Stratosphere along the y axis. The other labels read (from left to right) Windspeed vs Altitude, Jet Steam, Command, Tropopause, Gas Sampling. Fujihara and Eguchi, Ground to Stratosphere Flight Test, 5.

---

[323] Ibid.

[324] Tsutomu Fujihara and Kunihisa Eguchi, *Ground to Stratosphere Flight Test-Development Test Vehicles*, JAXA Researh and Development Memoradum (Japan Aerospace Exploration Agency (JAXA), January 6, 2005), 5.

The Low-Altitude Test Vehicle

The second 60m flight test vehicle, dubbed SPF-2, was used for more extensive tests performed at lower altitudes below 4km. JAXA conducted nine low-altitude stationary flight tests from May to November 2004. [325] According to Mr. Masaaki Nakadate, a manager and senior researcher on the effort, the objective of the low altitude flight test was "…to prove key technologies for SPF airships, manufacturing of a huge hull envelope, safe operations with buoyancy control and thermal management, and flight control; to conduct mission experiments for earth environment and traffic observations, and telecommunications and broadcasting."[326] The SPF-2 also verified simulations and performed experiments that could not be fully performed in the lab, such as ballonet sloshing. [327] As the airship maneuvers, the air inside the ballonets "sloshes" around which could affect the controllability of the airship. JAXA modeled this phenomenon in the lab, but validation of the model through flight test was required.

The vehicle took 4-years to design and build, during which time JAXA and NICT developed scale models and simulations for all aspects of the airship.[328] NICT created an

[325] Nakadate, "Development and Flight Test of SPF-2 Low Altitude Stationary Flight Test Vehicle," 3.

[326] Ibid., 2.

[327] Nakadate, "Development and Flight Test of SPF-2 Low Altitude Stationary Flight Test Vehicle." As the airship maneuvers, the air inside the ballonets "sloshes" around which could affect the controllability of the airship. JAXA modeled this phenomenon in the lab, but validation of the model through flight test was required.

[328] Ibid., 2.

integrated control system that included tracking, meteorological data, flight control, and mission simulators.[329] The three phases of low altitude test culminated with an autonomous station keeping flight at the highest achieved altitude of four km.[330] The low-altitude test program successfully demonstrated the key technologies including test of electric motor prolusion, autonomous ascent/decent and geostationary, and flight operations designed for future SPF vehicles.[331]

Payload Research and Development

JAXA's Earth Observation Research Center (EORC) and the NICT developed payloads that were integrated into the flight test programs. Multiple payload experiments were performed using the SPF-2 vehicle test flight. JAXA's Earth Observation Research Center (EORC) conducted experiments on a wide-angle multispectral imager used to take surface measurements on vegetation growth. A high resolution camera was also tested

[329] Takashi Kohno and Shuichi Sasa, "Control and Guidance of Low Altitude Stationary Flight Test Vehicle," in *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)* (presented at the 16th AIAA Lighter-Than-Air Systems Technology Conference, Arlington, VA: American Institute of Aeronautics and Astronautics, 2005), 1-9.

[330] Nakadate, "Development and Flight Test of SPF-2 Low Altitude Stationary Flight Test Vehicle," 8.

[331] Ibid., 6.

that could be used in a future SPF traffic control system.[332] EORC investigated payloads that could support remote sensing missions for agriculture, forestry, fishery, and traffic monitoring. The NICT successfully conducted experiments on digital broadcasting, antenna design, modeling algorithms, mobile terminal position estimation, and optical communications.[333] The NICT also tested communications payloads on NASA's solar powered Pathfinder-Plus program.[334] The payload experiments evaluated technical capability as well as the ability to meet mission requirements and to meet ITU standards.

Current Status

Although the Millennium Project concluded in 2005 with vehicle flight tests, JAXA and NICT continue to work on research and development on a few system components. JAXA has focused their effort on continued testing of Zylon, producing reports on reinforcement and tear propagations.[335] NICT has continued work with NASA

---

[332] "EORC Seen from Space - Landscape of Taiki-cho Region Observed from Airship," *JAXA-Japan Aerospace Exploration Agency*, http://www.eorc.jaxa.jp/en/imgdata/topics/2005/tp050222.html (accessed June 25, 2009).

[333] Derek Gray, Mamoru Nagatsuka, and Mikio Suzuki, "Posthumous Numerical Study of DTV Broadcast Antenna Integration with Prototype Stratospheric Airship Gondola," *EURASIP Journal on Wireless Communications and Networking* 2008 (2008): 1-12.

[334] M. Oodo et al., "Experiments on IMT-2000 Using Unmanned Solar Powered Aircraft at an Altitude of 20 km," *IEEE Transactions on Vehicular Technology* 54, no. 4 (7, 2005): 1278-1294

[335] Nakadate et al., "Reinforcement of an Opening for High Strength and Light Weight Envelope Material Zylon"; Shoji Maekawa et al., "Tear Propagation of a High Performance Airship Envelope Material."

and other organizations to refine modeling of SPF and HALE communication systems.[336] NICT has also continued work modeling the most energy efficient method for SPF station keeping.[337] Nevertheless, today the SPF program appears to have stalled. Neither JAXA nor NICT have briefed plans about future tests beyond the on-going low-level technology experiments described above. A future flight test schedule has not been published or briefed at any conference attended by JAXA since 2005. According to Mr. Nakadate, as of May 2009, no funding had been allocated to proceed with the technology demonstrator phase of the program.[338]

Japan continues to maintain a presence in international LTA journals and conferences, but their publications are centered on further material testing and exploring lower altitude unmanned airship systems for disaster response. Their most recent efforts have focused on adapting the SPF-2 flight control and simulation software to a smaller 14m airship that will have autonomous takeoff and landing capabilities.[339] Although these vehicles do not provide the capability of the SPF, they meet a basic operational need and

---

[336] Derek Gray, Mamoru Nagatsuka, and Mikio Suzuki, "Posthumous Numerical Study of DTV Broadcast Antenna Integration with Prototype Stratospheric Airship Gondola"; Oodo et al., "Experiments on IMT-2000 Using Unmanned Solar Powered Aircraft at an Altitude of 20 km."

[337] Masaaki Sano and Masahiko Onda, "Stratospheric LTA Platform with Variable Flight Altitude Control," in *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)* (presented at the 16th AIAA Lighter-Than-Air Systems Technology Conference, Arlington, VA: American Institute of Aeronautics and Astronautics, 2005), 9.

[338] Masaaki Nakadate, interview by author, Seattle, WA, May 6, 2009.

[339] Takashi Kohno, Masaaki Nakadate, and Masahiro Okuyama, "On-going UAV R&D at JAXA's Aviation Program Group - Second Report with Emphasis on LTA Flight Control," (presented at the 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, WA: American Institute of Aeronautics and Astronautics, 2009), 2, http://pdf.aiaa.org/.

help to maintain the knowledge acquired during the SPF development. While JAXA and NICT are maintaining personnel and skills through these smaller programs, without a consistent funding source, it will only be a matter of time before the experience and lessons-learned will begin to grow stale.

The SPF program employed the entire range of operations from manufacturing to launch and recovery procedures. Manufacturers, operators, aviation regulators, platform developers, and payload producers were all required and included in the effort to meet Japan's basic objectives. Japan was able to meet the original schedule outlined in 2000 by incorporating the diverse government, academic institutions and private industry. The case study of Japan's SPF program reveals the complexity of developing and employing an LTA HALE system. Japan had all of the parts in place to develop and transition an LTA program into operational status. Government, industry, and academic teams worked to demonstrate and reduce technology risk, obtain government certifications and approvals, and develop flight worthy LTA vehicles that also performed missions.

Japan has proven that it has the capability to develop airships made of high performance material, autonomously controlled, with integrated ground control systems. The lower-altitude SPF-2 system was able to integrate a variety of communications and remote sensing payloads and test operational capability. The SPF-1 program proved SPF vehicle design and explored operational launch and recovery options. The SPF program integrated a diverse body of experts and institutions to design, build, and test LTA vehicles. Nevertheless, according to Mr. Nakadate, another ten years of development would be required to produce a commercial SPF after additional funding is received.[340] Although the component pieces of the SPF have been separately evaluated, significant design and testing is needed before these subsystems and payloads can be integrated into the 150m demonstrator ship, which is 2.5 times bigger than the SPF-2.[341] To date, no reason has been publicly provided for the continued lack of program funding, other than that the airship is competing for limited funds against other higher priority programs. Until funding becomes available, Japan is relegated to doing small academic research such as Cyclopeidal propellers experiments for propulsion.[342]

Japan's SPF program provides an illustration of the complex programmatic and operational structures that are required to develop and employ an LTA HALE system. An LTA HALE program requires an established well-defined program with specific objectives and consistent resources. Organizational constructs and relationships that manage platform development, and payload integration, launch systems, command and control, and operational concept development are required. An LTA HALE program that will be fully operational by 2020 will need to exhibit a similar effort put forth by Japan's SPF program. In Chapter 5 countries with viable LTA HALE capabilities will be

[340] Masaaki Nakadate, interview by author, Seattle, WA, May 6, 2009.

[341] Sone et al., "One kilowatt-class fuel cell system for the aerospace applications in a micro-gravitational and closed environment," 10.

[342] Hirohito Nozaki, Yuya Sekiguchi, and Kazuo Matsuuchi, "Research and Development on Cycloidal Propellers for Airships," (presented at the Air Systems Technology Conference, Seattle, WA: AIAA, 2009), 2, http://pdf.aiaa.org/.(accessed February 3, 2009)

assessed in the context of the SPF case study for their ability to develop an LTA HALE system within the 2020 timeframe.

CHAPTER 5

THE FUTURE OF LIGHTER-THAN-AIR SYSTEMS WORLDWIDE

To what extent will foreign actors develop and employ LTA HALE systems for communications and surveillance applications by 2020?

This chapter briefly investigates viable programs reviewed in Chapter 2 within the context of the technology challenges identified in Chapter 3 and the Japanese SPF case study reviewed in Chapter 4. The state of each country's efforts is assessed for its ability to produce and employ an LTA HALE system by 2020. These country assessments are factored into a final assessment of the worldwide LTA HALE employment. Factors that could affect this assessment, either by inhibiting or enabling LTA HALE development, are also explored.

Chapters 3 and 4 revealed that LTA HALE systems are a complex technical and programmatic effort. While the basic technology components should be available for vehicle development, these systems will not be available as "off-the-shelf" ready, and will require significant RDT&E to evolve the technologies to meet LTA HALE requirements. These state-of-the-art technologies will be pushed to their limits of size and performance, generating increased cost and risk that must be accepted and mitigated by investors, customers, and developers through an RDT&E program like the one employed by Japan. Technologies, especially in the areas of power and envelope material, will continue to remain primary hurdles to LTA HALE development through 2020.

Japan's SPF program highlighted the intense programmatic and technical effort required just to perform the first phase of technology and operational development. The SPF program involved the coordination of multiple government agencies, industries, and institutions that was monitored by a joint government council. Japan established a well-defined program with specific objectives, and applied consistent resources. They established new organizational constructs and relationships to manage platform, payload integration, launch system, command and control, and operational concept development and integration. They began to establish other aspects of an operational system such as simulators for pilot training. They performed a deliberate RDT&E effort that enabled them to prototype and test key technologies and operational concepts within a 5 year time frame (2000-2005). Since the end of the first phase with the flight test completed at the end of 2004, Japan has continued to perform analysis on the flight test results and low-level RDT&E on a few critical technologies (e.g. envelope material). Until additional funding is received for their SPF program, Japan's efforts remain limited to low-altitude unmanned airships.

Assessment of Foreign LTA HALE Systems

To complete the assessment, viable programs from Chapter 2 are reviewed within the context of the technology and programmatic challenges. Aspects, including program organization, LTA experience, and external partnerships are analyzed for each country. Even though many of the programs are private or commercial efforts, the LTA programs tend to be aligned by country.

South Korea

South Korea's program is commonly referred to, along with Japan and the United States, as one of the most promising to develop an LTA HALE capability. In 2000, South Korea began a 10-year program to fully commercialize a system.[343] The program was sponsored by South Korea's Ministry of Commerce, Industry, and Energy and used a similar programmatic setup as Japan. The Ministry assigned KARI to develop platform technology, and the Electronics and Telecommunications Research Institute (ETRI) to develop the communications payload.[344] The program was divided into 3 phases: 1) basic technology development and prototyping, 2) 200m long vehicle that station keeps at 20km, and 3) commercialization of the system.[345] During the first phase, KARI

---

[343] Chan-Hong Yeom et al., "Development of a Stratospheric Platform in Korea."

[344] Jonghwa Kim et al., "Is HAPS Viable for the Next-Generation Telecommunication Platform in Korea?," *EURASIP Journal on Wireless Communications and Networking* 2008 (2008): 3.

[345] Chan-Hong Yeom et al., "Development of a Stratospheric Platform in Korea."

developed an autonomous flight control system that was tested in a 50m prototype vehicle.[346] South Korea did not possess an organic LTA capability, so they contracted with Worldwide Aeros, a U.S company, to build the prototype airship and consulted on the effort.[347] The first phase concluded in 2005 with an autonomous flight test of the 50m airship that performed basic station keeping capability.[348] South Korea began the second phase of the program by researching regenerative fuel cells, Vectran envelopes, additional flight control and an exploration of a civilian communications payload.[349]

The second phase of their program was reported as "well-funded" for development; however, only preliminary research on flight control systems and envelope materials has been published as of 2007.[350] Until 2007, South Korea was an active participant in international journals and conferences, but the country's participants have been silent for the last two years. According to Mr. Luke Brooke, who consulted for the project, he "believes that the programme no longer exists."[351] Although this has not been

---

[346] Sang-Jong Lee et al., "Development of Autonomous Flight Control System for 50m Unmanned Airship."

[347] "Aeros Wins Contract with Korea Aerospace Research Institute (KARI)," April 2002, http://www.aerosml.com/Archive%20PR.asp (accessed July 3, 2009).

[348] Sang-Jong Lee, Dong-Min Kim, and Hyo-Choong Bang, "Feedback Linearization Controller for Semi Station Keeping of the Unmanned Airship," *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)* (Arlington, VA: American Institute of Aeronautics and Astronautics, 2005), 2.

[349] Kang et al., "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope."

[350] Milan Lalovic et al., *Strategy Document: Delivering Broadband for All including Commercial and Technical Risk Assessment*, 36 KARI briefed the CAPANINA project and members of the effort were consultants for KARI.

[351] Luke Brooke, e-mail message with author, September 29, 2009.

verified by the South Korean government, a search for the program on their website yielded no results.[352] The objective of the South Korean program was aggressive, ten years from no capability to commercialization of LTA HALE, but they had set up substantial programmatic constructs and a robust RDT&E effort. Nevertheless, after seven years, they had progressed less than Japan's program. As with Japan, the international LTA community looked to South Korea as a leader in LTA HALE systems, but the program appears to have been reduced to a minimal effort at best with no indication of future LTA progress.

Russia

Russia does not currently have a national effort, like Japan or Korea, but the sole airship manufacturer RosAeroSystems, has indicated that it is developing the "Berkut" LTA HALE for communications and surveillance using similar equipment installed on geostationary satellites.[353] The plan is to integrate payloads; RosAeroSystems has over 15 years experience developing and manufacturing LTA, low-altitude technology, including unmanned airships and aerostats for commercial and military missions. They have successfully integrated surveillance and communication payloads onto its systems to support low-flying target detection and border patrol missions.[354] RAS has partnerships with Russian aerospace companies, including Lavochkin Design Bureau and the Moscow

[352] "KARI- Korea Aerospace Research Institute," http://www.kari.re.kr/ (accessed July 3, 2009).

[353] "Russia building surveillance and communications airship - agency."

[354] "Augur/RosAeroSystems Au-21 Puma"; "PUMA Tethered Aerostat," *RosAeroSystems*, http://rosaerosystems.pbo.ru/english/products/puma.html (accessed July 3, 2009).

Aviation Institute, as well as multiple international airship partners.[355] RAS has produced LTA systems for international military and civilian customers. [356] The Berkut system has a preliminary operational concept that employs three versions of the platform to meet different mission requirements and has an innovative launch concept.[357] The Berkut is a feasible concept, backed by RosAeroSystem's experience and capability to develop LTA systems. However, the research suggests that the program has not gone beyond the conceptual stage and RDT&E has not been performed on any of the key LTA HALE technologies. If investors provided sufficient funding, the experience and infrastructures exist that could produce a limited LTA HALE system with payloads similar to their low-altitude aerostat systems by 2020. As of today, the Berkut remains in RosAeroSystems conceptual development.

China

China has a growing and diverse LTA capability with intentions to build an LTA HALE system. As discussed in Chapter 2, multiple LTA programs have emerged in China over the last decade and they have had an indigenous capability to manufacture certified airships since 2004.[358] China has readily adapted foreign LTA technology to support missions, such as radar surveillance of air and maritime activity along the Taiwan

355 "RosAeroSystems Company profile," *RosAeroSystems*, http://rosaerosystems.pbo.ru/english/company.html (accessed July 3, 2009).

356 "Airship Nazca"; "Augur/RosAeroSystems Au-21 Puma."

357 "High Altitude Airship 'Berkut'."

358 Zi-Niu Wu and Xiao-Jian Xue, "Civilian Demands Application of Airships in Civil Projects."

Strait, and has studied using the same technology on board LTA HALE systems.[359] The Hunan Astronautic Industry Corporation (HAIC), Aufair Aerostat Systems, and TsingHua University are leading China's LTA HALE research efforts. In 2001, TsingHua University presented initial plans and preliminary research on China's LTA HALE concepts.[360] HAIC has more recently become involved in the research and development of these systems. HAIC is a part of China Aerospace Science and Industry Corporation (CASIC), which is a state-owned company that reports to the Chinese government through the Commission of Science, Technology, and Industry for National Defense.[361] To facilitate cooperation among these diverse groups, the Chinese Airship Research Association was formed in 2007. Members of this association have been actively involved in the international airship community and they hosted an international airship conference in 2008.[362] During the 2008 conference in Beijing, HAIC articulated a position that stratospheric airships are a priority for China to be used for multiple applications from forest fire and traffic monitoring to terrorist surveillance.[363] HAIC has identified institutions to research the technology challenges identified in Chapter 3, but

---

[359] "Chinese aerostat surveillance system (China)," *Jane's Electronic Mission Aircraft*, October 9, 2003, http://www.janes.com/articles/Janes-Electronic-Mission-Aircraft/Chinese-aerostat-surveillance-system-China.html (accessed July 3, 2009); "Stratospheric Platform Air Reconnaissance and Radar Signal Detection Analysis," *Chinese Airship Association*, http://www.ltachina.cn/bencandy.php?fid=26&id=120 (accessed July 8, 2009).

[360] Tong et al., "R&D of Stratospheric Platform and SP based Information Systems in China."

[361] "China Aerospace Science and Industry Corporation (CASIC) (China)," *Jane's Space Systems and Industry*, May 29, 2009, http://www.janes.com/articles/Janes-Space-Systems-and-Industry/China-Aerospace-Science-and-Industry-Corporation-CASIC-China.html (accessed July 4, 2009).

[362] *NASIC Open Source Report: (U) Chinese Airship Research Association*, 4.

[363] Duan Dong Bei, "Airship's R&D in Application Aeronautic and Astronautic in China."

they are self-admittedly only at the preliminary "stage of technology scheme verification, key technology breakthrough and principle demonstration."[364] Even though China's airship industry is young, they have a growing experience and industrial base. China has the intent to develop the system, especially to improve the infrastructure of their western frontier. Although a specific program with identified objectives and schedules has not been established, China has the potential to develop an emerging LTA HALE capability by 2020.

The European Union

The European Union boasts a diverse LTA community, the most famous of which is the Deutsche Zeppelin Reederei. As shown in Chapter 2, many EU companies have produced manned and unmanned LTA systems for communications and reconnaissance missions. Lindstrand produced the G-22 unmanned airship that was used by the Spanish Government in 2004 for a classified military surveillance operation and is now being developed by BAE Systems for surveillance and defense applications.[365]

Many of the EU companies have presented LTA HALE concepts, but the most notable was the one designed by Lindstrand. In 1999, the European Space Agency commissioned Lindstrand to develop a concept for an LTA HALE communications system.[366] Lindstrand developed designs for all aspects of the LTA HALE system,

[364] Ibid.

[365] "Helium Airships"; "BAE Systems Floats Autonomous System At Farnborough International."

[366] "HALE."

including power systems and envelope materials. However, the effort never progressed past this conceptual phase and remains on Lindstrand's website as a future project.[367] In 2008, the StratXX program in Switzerland established a collaboration of European aerospace companies and universities, but it has yet to produce any significant efforts. [368]

Although a fully funded LTA HALE program does not currently exist in the EU, it has several consortiums supported by governments inside and outside the EU dedicated to LTA HALE development. The High Altitude Platforms for Communications and Other Services (HAPCOS) cooperative and the French Pôle Pégase are the most recent and prominent efforts. These cooperatives do not fund or develop LTA HALE systems. However, they provide a forum to publish research and set strategic vision for platform and payload development, integration and certification. According to the HAPCOS webpage, the main objective of the initiative is "to increase knowledge and understanding of the use of High Altitude Platforms (HAPs) for delivery of communications and other services, by exploring, researching and developing new methods, analyses, techniques and strategies for developers, service providers, system integrators and regulators."[369] The most active component of these groups has performed substantial RDT&E for payloads to be used for communication systems that meet ITU standards. Even though the LTA HALE programs are at the preliminary stages of development for commercial

---

[367] Pattinson, "HALE Airship: Manufacture, Flight and Operation"; "HALE."

[368] "StratXX - Near Space Technology."

[369] "COST297 - High Altitude Platforms for Communications and Other Services," HAPCOS, http://www.hapcos.org/ (accessed July 4, 2009).

applications, the EU has the experience, resources and government backed cooperatives that are pushing for this capability in the communications field. The EU could develop an emerging LTA HALE capability for communications systems by 2020.

Assessment of Foreign LTA HALE Capability by 2020

The thesis sought to address "To what extent will an international LTA HALE capability be developed and employed for communications and surveillance missions by 2020?"

Operating in the stratosphere remains a complex technical challenge. With the exception of two experimental flights (separated by over 40 years), the stratosphere remains unconquered by powered airships.[370] Furthermore, the suspension of the LTA HALE programs in Japan and Korea leaves the non-US efforts without a government funded program to achieve specific objectives or perform basic RDT&E. In 2009, JAXA officials estimated that it would take another ten years for them to build an operational

[370] Michael S. Smith and Edward Lee Rainwater, "Applications of Scientific Ballooning Technology to High Altitude Airships," 1; Michael Lee, Steve Smith, and Stavros Androulakakis, "The High Altitude Lighter Than Air Airship Efforts at the US Army Space and Missile Defense Command/Army Forces Strategic Command," 12.

system once funding was available.[371] This is supported by the fact that a less complex airship effort, the Zeppelin NT, took 12 years to go from preliminary design to flight certification.[372] Nevertheless, an LTA HALE capability is gaining international attention, and is supported in concept with limited funding by international organizations and governments. Although the current efforts are minimal, members of the European Union are pushing for HALE communication systems and China has increased its focus on LTA HALE systems for internal and border surveillance. Additionally the increasing LTA industrial base and experience operating smaller airship systems coupled with the advancement of power and material technology creates a higher potential to develop these systems. The high potential, yet limited efforts, leads to the assessment that by 2020, LTA HALE systems will be an emerging operational capability with a few systems that are employed on missions that have limited endurance and restricted operating environments (e.g. latitude, season). These LTA HALE systems missions will most likely be limited to smaller communication payloads.

The hypothesis from Chapter 1 put forth that countries with mounting regional security problems would develop and employ LTA HALE systems by 2020. The evidence examined in Chapter 2 and earlier in this chapter lend some limited support for the hypothesis. Although countries with limited access to space were expected to be pursuing these systems, the traditional space faring nations had the most viable programs. These countries have larger internal and border security problems, and have the inherent

[371] Masaaki Nakadate, interview by author, Seattle, WA May 6, 2009.

[372] "Zeppelin NT - History."

capability to develop a complex system. With the exception of South Korea, the data indicates that these other interested countries (e.g. Turkey and Columbia) are passively waiting to purchase these systems when they are made available.[373] Smaller unmanned airships, such as those now being pursued in the EU, Japan, China, and Brazil, are more indicative of the current LTA communications and surveillance efforts that are being exported around the world.[374] There are many factors that could affect this assessment, factors that could both inhibit or enable LTA HALE development

.

Factors that Inhibit LTA HALE Systems

Dramatic Change in Perception of Risk and Effort

The level of perceived effort and risk of an LTA HALE program dramatically shifts from low to high during the initial stages of development. This shift in risk assessment causes investors to abandon programs before substantial development can begin. A study performed by a European cooperative laid the blame on developers indicating that they caused "skepticism and uncertainty of expectation, partly as a result

[373] Utku Cakirozer, "Turkey Said May Purchase High Altitude Airship for Monitoring PKK Activities."

[374] Fábio Pereira Benjovengo et al., "Sliding Mode Control Approaches for an Autonomous Unmanned Airship," (presented at the 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, WA: American Institute of Aeronautics and Astronautics, 2009), 1, http://pdf.aiaa.org/ (accessed November 11, 2008).

of unrealistic promises and uncoordinated start-up activities."[375] Overeager developers are not completely to blame. The "free lift" and "free energy" claims attract would-be inventors and purveyors of perpetual motion to the LTA community.[376] Armed with eye-catching slides, these peddlers seduce investors with their presentation skills and promises of affordable and environmentally friendly capabilities. Newspapers and blogs cover these efforts to hawk clean and affordable airships.[377] These salesmen create investor confusion and prevent legitimate ideas from progressing. Investors are also responsible for these problems. They delude themselves by underestimating the complexity of LTA HALE: After all "it's just a balloon." This complacency quickly shifts during RDT&E to the other extreme, creating an over-exaggerated sense of risk causing investors to cancel or transfer LTA HALE efforts. As a result of these developer and inventor dynamics, the LTA HALE programs tend to suffer a lack of consistent funding and programmatic focus.

---

[375] Arie Lavie and Tim Tozer, *Developing a European Research Strategy in the High Altitude Aircraft and Airship Sector*, 17.

[376] For examples of inventors see Kothmann Airship and for an example of a perpetual motion vehicle see the gravity plane. Both were presented at AIAA conferences. K. Kothmann, "Kothmann Multi-Use Airship," (presented at the 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, WA: American Institute of Aeronautics and Astronautics, 2009), http://pdf.aiaa.org/; G. Leavitt, "A Project Overview of High Altitude Reduced Gravity Vehicle Experiments," (presented at the 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, WA: American Institute of Aeronautics and Astronautics, 2009), http://pdf.aiaa.org/ (accessed July 8, 2009).

[377] For an example of a fanciful airship that is prevalent in the general and niche media see,"Giant Turtle Airship Concept is the Green Gadgety Transport of the Future," Wired.com, July 7, 2008, http://www.wired.com/gadgetlab/2008/07/concept-giant-t/ (accessed July 5, 2009); "Giant Flying Turtles to Revolutionize Global Aviation with Solar Power," *Clean Technology and Sustainable Industries Organization*, July 3, 2008, http://www.ct-si.org/news/press/item.html?id=2599 (accessed July 5, 2009).

Organizational culture

This problem is more particular to government programs that divide their assets between air and space organizations. The LTA HALE system is an air vehicle that functions and produces effects like a satellite. LTA HALE programs are forced to battle against cultural perceptions and for their own identity. In a thesis for the School of Advanced Air and Space Studies, Major Peter Flores concluded, "The near-space concept exists within a series of seams. As such, no matter how valid the need for responsive space-like services, and no matter how viable the near-space technologies, this concept will struggle until it finds an organizational advocate who is willing to knit together the many seams near-space presents."[378]

Competition for Resources

Representatives from Japan and China regularly brief that LTA HALE systems bridge the gap between air and space and complement the missions of these domains; nevertheless, a competition for limited resources does exist.[379] Due in part to the organizational culture problems addressed above, LTA HALE does not have the history, presence, or bureaucracy to successfully compete against the substantial air and space establishments.

[378] Peter J. Flores, "Untapped Potential: The Influence of International Regimes and Organizational Culture on The Near-Space Concept" (School of Advanced Air and Space Studies, 2007), 47.

[379] Kurose, "Japan: Development for SPF Stratospheric Platform Airship"; Duan Dong Bei, "Airship's R&D in Application Aeronautic and Astronautic in China."

Taking Too Large of a Leap

The leap to stratospheric operations is daunting enough, but many projects seem to make it even harder by trying to achieve too many objectives too soon. Even with the phased programs of Japan and Korea, they jumped to 150m+ sized ships that performed station keeping at 20km rather than smaller airships that simply function in the stratosphere. An AIAA paper by Michael Smith and Edward Lee Rainwater, outlines “recipes for disaster” based on past experiences attempting to develop an LTA HALE system:

- Start with over 1,000 pounds for the target payload
- Set the station altitude above 80,000 feet
- Set the initial duration requirement at more than two weeks
- Require that the system station-keep inside an area the size of a football field
- Set payload power requirements equal to that of a small city
- Require the system to carry people
- Schedule a full-scale demonstration flight in two years (with any of the above requirements) [380]

These “ingredients” are reflected in the international designs and programs, for example Japan, Korea, and Russia each plan on initial payloads in excess of 1000kg.[381]

There are multiple factors that inhibit the development of LTA HALE systems: unrealistic and drastically changing expectations, cultural barriers, competition for resources, and setting initial objectives too high. These problems lead to LTA HALE systems that do not have consistent funding or stable programmatic structure. This

[380] Michael S. Smith and Edward Lee Rainwater, “Applications of Scientific Ballooning Technology to High Altitude Airships,” 7.

[381] Eguchi and Yoshio Yokomaku, “2000 Overview of Stratospheric Platform Airship R&D Program in Japan”; Chan-Hong Yeom et al., “Development of a Stratospheric Platform in Korea”; “High Altitude Airship 'Berkut'.”

funding instability causes them to stagnate in the concept and prototype stage. Overcoming these barriers is critical to the success of future LTA HALE systems.

Factors that Enable LTA HALE Development

Although the assessment of this thesis posits that LTA HALE systems will only be an emerging capability by 2020, a number of factors could push and broaden the development and employment of these systems. Technology is one example of a challenge that is aided by other industries, independently improving the necessary power technologies. Several additional factors will facilitate the development of programmatic and operational structures that could be used by LTA HALE systems.

The Drive to Fulfill Requirements

As discussed in Chapter 2, the numerous requirements that could be solved by LTA HALE systems continue to go unfulfilled. These requirements will drive countries to continue seeking solutions for them. A large set of these unfulfilled requirements revolves around surveillance and communication over remote areas, such as China's western frontier, Canada and Russia's northern tiers and Brazil's Amazon rain forests. Additionally, the consortiums, such as HAPCOS and Pôle Pégase continue to push applications, requirements and strategic vision for HALE and LTA HALE systems.

Adoption of Similar Systems: Small Unmanned Airships and Aerostats

Countries and private organizations are readily adapting low-altitude airships and aerostats into their infrastructures. Small remotely piloted and autonomous airships are being developed around the world to meet communication and remote sensing requirements. Aerostats are increasingly employed for coastal surveillance and border patrol. Unmanned airships and aerostats generate the command and control systems, industrial base, and LTA employment and sustainment experience that could enable LTA HALE systems. These systems also create the programmatic and organizational structures that could support or advocate for increased capabilities like LTA HALE. The widespread adoption of aerostats by international militaries also builds a wider acceptance of LTA systems.

Heavy lift cargo transport airships also serve to build the industrial base and operational resources. China, Russia and the EU are investigating airships to transport extremely large "out-sized" payloads such as oil and gas equipment and to reach remote areas that lack transportation infrastructure.[382] They are also under serious study and development by international commercial efforts led by Boeing and DHL.[383] In addition to the programmatic advantages, endeavors to increase the endurance of these unmanned systems could help push enabling technology for higher altitude systems.

[382] Additional information on these effort can be found at the VEATAL website."VEATAL Conference Proceedings," *VEATAL Airship Project*, http://www.veatal.com/pageLibre0001187e.php#I0006972f (accessed July 3, 2009).

[383] "VEATAL Conference Proceedings"; "SkyHook International Inc.-JHL-40 Boeing," *SkyHook HLV International*, http://www.skyhookintl.com/ (accessed July 3, 2009).

Influence of International Programs

Successful development and employment of an operational LTA HALE system would reduce actual and perceived risk, sparking the development of other programs. The LTA HALE literature frequently refers to other international programs to provide either program justification or a sense that the competition is getting ahead.[384] Many of these non-U.S. programs rely on U.S. companies to provide guidance and support for their LTA systems. Although the U.S. has had its share of setbacks in LTA HALE development, successful employment by one of the U.S. programs, such as DARPA's Integrated Sensor is Structure (ISIS) program, or even the U.S Army's less ambitious Long Endurance Multi-INT Vehicle program, could ignite international development efforts.[385]

Conclusion

[384] Examples of these references can be found in the following sources: Jonghwa Kim et al., "Is HAPS Viable for the Next-Generation Telecommunication Platform in Korea?"; Duan Dong Bei, "Airship's R&D in Application Aeronautic and Astronautic in China."

[385] "STO: Integrated Sensor is Structure," *Defense Advanced Research Agency: Strategic Technology Office*, http://www.darpa.mil/sto/space/isis.html (accessed July 3, 2009); "A--Modification to Sources Sought W91260-LEMV, posted 22 Apr 09. Draft Statement of Objectives(SOO) for the Long Endurance Multi-INT Vehicle (LEMV) is posted for Industry comment.," *- Federal Business Opportunities: Opportunities*, April 22, 2009, https://www.fbo.gov/index?s=opportunity&mode=form&id=8a9576adda671991e001a322c98a6a44&tab=core&_cview=1 (accessed July 3, 2009); Graham Warwick, "Staying Up, Staring Down - LEMV Airship," Aviation Week.com, *Ares: A Defense Technology Blog*, June 8, 2009, http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckScript=blogScript&plckElementId=blogDest&plckBlogPage=BlogViewPost&plckPostId=Blog%3A27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3A3c0ec60a-4bb5-43d4-b0ff-fefdf0733cb6 (accessed July 3, 2009).

Foreign LTA HALE systems are a potential threat to U.S. national security missions. These systems can carry multiple payload technologies from cell phone and traffic monitoring to radar surveillance. But even if these systems are advertised for "peaceful purposes," they are a readily adaptable dual use technology. Their potential large lifting capacity allows them to be integrated with additional covert or overt mission payloads that could be used for military and intelligence applications. These systems can also operate outside of terrestrial and space networks. LTA HALE systems are substantial efforts that will have visible development and operational characteristics (e.g. large hangers, launch and recovery systems). Charting LTA HALE capability supports U.S. strategic planning and intelligence collection requirements. An understanding of potential adversary LTA HALE capability allows the United States to develop plans and operational capability to counter these systems. Even without attaining LTA HALE, the increasing number of lower altitude assets, such as autonomous airships, needs to be considered by U.S. national security and intelligence communities.

Since the 1960's, stratospheric airships have been perpetually over-the-horizon, just beyond the technological capability of the time. The enabling technologies continue to remain in this elusive state. However, the global interest in LTA HALE continues to grow with an ever expanding list of unmet communications and surveillance requirements and missions. Serious attempts to conquer the stratosphere with airships will not likely decline with the continued improvement and availability of lightweight and efficient power technology. There are many hurdles blocking the realization of stratospheric airships; nevertheless, a growing international LTA community will ensure the concept persists. For over 40 years, stratospheric airships have existed on the horizon of possibility. If foreign stratospheric airships have not been operationalized by 2020, the quest to do so will most likely strengthen and proliferate across the globe.

BIBLIOGRAPHY

A. Yilanci, H.K. Ozturk, and I. Dincer. "Progress in Energy and Combustion Science : A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications." *Progress in Energy and Combustion Science* 35, no. 3 (June 2009): 231-244.

A.F.L. Deeson. *Illustrated History of Airships*. Bourne End: Spurbook Limited, 1973.

"About M5." *Magellan Systems International, Inc.* http://www.m5fiber.com/magellan/about_m5.htm (accessed June 21, 2009).

"Abstracts: Production of Hydrogen from Water." *17th World Hydrogen Energy Conference*, June 19, 2008. http://www.whec2008.com/abstractsProductionofHydrogenfromWater.asp (accessed June 19, 2009).

Adrian Harrington. "Fuel cell plane in aviation first." *Intelligent Energy*, April 3, 208. http://www.intelligent-energy.com/index_article.asp?SecID=8&secondlevel=25&artid=4001%20 (accessed June 20, 2009).

"Advanced Energy Storage : Technology Overview." *Sion Power Corporation*. http://www.sionpower.com/technology.html (accessed June 20, 2009).

"Aeros Wins Contract with Korea Aerospace Research Institute (KARI)," April 2002. http://www.aerosml.com/Archive%20PR.asp (accessed July 3, 2009).

"Airship Nazca." *The Airship Nazca Project*. http://www.airshipnazca.com/ (accessed July 3, 2009).

"Airships for Passenger Flights - Advertising - Security - Consulting." *Skyship Cruise Switzerland Ltd.* http://www.skycruise.ch/security.htm (accessed July 8, 2009).

Albert E. Hammerschmidt. "Fuel Cell Propulsion of Submarines." In *Siemens Energy & Automation - Industrial & Residential Products, Solutions, Services*. Arlington, VA, 2006. http://www2.sea.siemens.com/NR/rdonlyres/D3201AC8-C746-4EC8-975A-4E607662195/0/SiemensPresentsFuelCellatthe AdvanceNavalPropulsionSymposium.pdf. (accessed July 6, 2009).

Amedeo Conti. "Subfreezing Start/Stop Protocol for an Advanced Metallic Open-Flowfield Fuel Cell Stack" presented at the DOE Hydrogen Program: 2009 Annual Merit Review Proceedings - Fuel Cells, Arlington, VA, May 21, 2009. http://www.hydrogen.energy.gov/annual_review09_fuelcells.html#analysis (accessed June 19, 2009).

"A--Modification to Sources Sought W91260-LEMV, posted 22 Apr 09. Draft Statement of Objectives(SOO) for the Long Endurance Multi-INT Vehicle (LEMV) is posted for Industry comment.." - *Federal Business Opportunities: Opportunities*, April 22, 2009. https://www.fbo.gov/index?s=opportunity&mode=form&id=8a9576adda671991e001a322c98a6a44&tab=core&_cview=1 (accessed July 3, 2009).

Anthony Colozza. *Initial Feasibility Assessment of a High Altitude Long Endurance Airship*. Glenn Research Center: National Aeronautics and Space Administration, December 2003. http://ntrs.nasa.gov/search.jsp?N=0&Ntk=all&Ntx=mode%2matchall&Ntt=Initial%20Feasibility%20Assessment%20of%20a%20High%20Altitude%20Long%20Endurance%20Airship (accessed June 5, 2003).

Arie Lavie, and Tim Tozer. *Activity Assement Report: Developing a European Research Strategy in the High Altitude Aircraft and Airship Sector*. ACTIVITY ASSESSMENT REPORT. USE HAAS, January 23, 2007.

———. *Developing a European Research Strategy in the High Altitude Aircraft and Airship Sector*. ACTIVITY ASSESSMENT REPORT. USE HAAS, January 23, 2007.

Arun Doddathimmaiah. "17th World Hydrogen Energy Conference - Modelling and Performance Measurement of Unitised Regenerative Fuel Cells." *WHEC 2008*, June 19, 2008. http://www.whec2008.com/abstract/494.asp (accessed June 20, 2009).

Asbjørn Strand, and Helge Weydahl. "Regenerative Fuel Cell Systems for Satellites." www.prototech.no/doc/PDF%20files/RFCS%20artikkel.pdf.

Associated Press. "Athens Readies Airship for Olympic Terror Patrol." *USATODAY*, July 19, 2004. http://www.skycruise.ch/info/medien/USATODAY-040719.pdf.

"Augur/RosAeroSystems Au-21 Puma." *Jane's Electronic Mission Aircraft*. (b) (3) [redacted]

B. von Roedern, and H.S. Ullal. "The Role of Polycrystalline Thin-Film PV Technologies in Competitive PV Module Markets." San Diego, CA: IEEE, 2008.

———. "Thin Film CIGS and CdTe Photovoltaic Technologies: Commercialization, Critical Issues, and Applications." Milan, Italy: IEEE, 2008.

"BAE Systems Floats Autonomous System At Farnborough International." *BAE Systems*. http://www.baesystems.com/Newsroom/NewsReleases/2008/autoGen_108611183947.html (accessed July 3, 2009).

"Balloons in War." *U.S. Centennial of Flight commission*. http://www.centennialofflight.gov/essay/Lighter_than_air/Napoleon%27s_wars/LTA3.htm (accessed July 4, 2009).

Barbara Opall-Rome. "Israel Aircraft Industries Promotes Airship Concept." *SpaceNews.com*, February 24, 2004. http://www.space.com/spacenews/archive04/iaiarch_022404.htm (accessed July 8, 2009).

Barbir, F., T. Molter, and L. Dalton. "Regenerative fuel cells for energy storage: efficiency and weight trade-offs." *IEEE Aerospace and Electronic Systems Magazine* 20, no. 3 (3, 2005): 35-40.

Basil Collier. *The Airship : A History*. New York: G.P. Putman's, 1974.

Benjovengo, Fábio Pereira, Ely Carneiro de Paiva, Samuel Siqueira Bueno, and Paulo Augusto Valente Ferreira. "Sliding Mode Control Approaches for an Autonomous Unmanned Airship." Seattle, WA: American Institute of Aeronautics and Astronautics, 2009. http://pdf.aiaa.org/.(accessed February 3, 2009)

Brian James. "Mass-Production Cost Estimation of Automotive Fuel Cell Systems" presented at the DOE Hydrogen Program: 2009 Annual Merit Review Proceedings - Fuel Cells, May 21, 2009. http://www.hydrogen.energy.gov/annual_review09_fuelcells.html (accessed July 8, 2009).

Brooke, Luke, and Adam Bown. "Design, analysis and patterning of inflated lifting body form
LTA vehicle hulls." Seattle, Wa, 2009.

"Bus Fuel Cell Hydrogen Powered." *Ballard Power*. http://www.ballard.com/Motive_Power/Heavy_Duty_Market/Application_Overview.htm (accessed June 22, 2009).

"Carnot Cycle." *Hyperphysics*. http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/carnot.html (accessed June 19, 2009).

Chan-Hong Yeom, Dong-Min Kim, Cheol-Ho Lim, and Wang-Gu Kang. "Development of a Stratospheric Platform in Korea" presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001.

Charles Gillispie. *The Montgolfier Brothers and the Invention of Aviation*. New Jersey: Princeton University Press, 1983.

Charles P. Burgess. *Airship Desgin*. New York: The Ronald Press Company, 1927.

Charles Rosendahl. *What about the Airship?* New York: Charles Scribner's Sons, 1938.

"China Aerospace Science and Industry Corporation (CASIC) (China)." *Jane's Space Systems and Industry*, May 29, 2009. http://www.janes.com/articles/Janes-Space-Systems-and-Industry/China-Aerospace-Science-and-Industry-Corporation-CASIC-China.html (accessed July 4, 2009).

"Chinese aerostat surveillance system (China)." *Jane's Electronic Mission Aircraft*, October 9, 2003. http://www.janes.com/articles/Janes-Electronic-Mission-Aircraft/Chinese-aerostat-surveillance-system-China.html (accessed July 3, 2009).

Christopher, John. *Balloons at War: Gasbags, Flying Bombs & Cold War Secrets.* Stroud: Tempus, 2004.

"CNES : A strategic activity." *Centre National d'Etudes Spatiales.* http://www.cnes.fr/web/CNES-en/3642-a-strategic-activity.php (accessed July 6, 2009).

Commander C. E. Rosendahl. *What About The Airship?* New York: Charles Scribner's Sons, 1938.

"Cool Fuel." *Boeing.com.* http://www.boeing.com/news/frontiers/archive/2003/august/i_atw.html (accessed July 6, 2009).

"COST297 - High Altitude Platforms for Communications and Other Services." HAPCOS. http://www.hapcos.org/ (accessed July 4, 2009).

Craig L. Nickol, Mark D. Guynn, Lisa L. Kohout, and Thomas A. Ozoroski. *High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development.* NASA/TP-2007-214861. Hampton, Virginia: National Aeronautics and Space Administration, Dryden Langley Research Center, March 2007. http://ntrs.nasa.gov/search.jsp?N=0&Ntk=all&Ntx=mode%20matchall&Ntt=hale%20aoa (accessed June 5, 2009).

"Cut Resistant Gloves and Other Applications & General Properties of Vectran Fiber." *Vectran.* http://www.vectranfiber.com/applications.asp (accessed June 18, 2009).

D. Fransaer, N. Lewyckyj, F. Vanderhaegehen, and J. Everaerts. "Pegasus: Business Model for a Stratospheric Long Endurance UAV System for Remote Sensing," 2004. http://www.isprs.org/congresses/istanbul2004/ (accessed July 7, 2009).

D. M. Smith, T. W. Goodwin, and J. A. Schillinger. "Challenges to the Worldwide Supply of Helium in the Next Decade." Air Products and Chemicals, Inc. https://www.airproducts.com/NR/rdonlyres/E44F8293-1CEE-4D80-86EA-F9815927BE7E/0/ChallengestoHeliumSupply111003.pdf (accessed July 6, 2009).

David J. Bents. *Closed-Cycle Hydrogen-Oxygen Regenerative Fuel Cell at the NASA Glenn Research Center—An Update*. Cleveland, Ohio: Glenn Research Center, April 2008. http://ntrs.nasa.gov/ (accessed June 5, 2009).

———. *Lunar Regenerative Fuel Cell (RFC) Reliability Testing for Assured Mission Success*. Cleveland, Ohio: Glenn Research Center, February 2009. http://ntrs.nasa.gov/ (accessed June 5, 2009).

Deng. *Ancient Chinese inventions : 3,000 years of science and technology*. Beijing: China Intercontinental Press, 2005.

Deputy Under Secretary of Defense for Science and Technology. "Technology Readiness Assessment (TRA) Deskbook." U.S. Department of Defense, May 2005. https://acc.dau.mil/CommunityBrowser.aspx?id=18545 (accessed June 18, 2009).

Derek Gray, Mamoru Nagatsuka, and Mikio Suzuki. "Posthumous Numerical Study of DTV Broadcast Antenna Integration with Prototype Stratospheric Airship Gondola." *EURASIP Journal on Wireless Communications and Networking* 2008 (2008): 1-12.

Don L. Anderson, G. R. Foulger, and Anders Meibom. "Helium Fundamentals." *MantlePlumes.org*. http://www.mantleplumes.org/HeliumFundamentals.html (accessed July 8, 2009).

Duan Dong Bei. "Airship's R&D in Application Aeronautic and Astronautic in China" presented at the VEATAL 2008 Beijing China Conference, Beijing, CN, April 2008. http://www.veatal.com/pageLibre000115d8.php# (accessed July 3, 2009).

"DuPont.com: Worldwide." *Dupont.com*. http://www2.dupont.com/Our_Company/en_US/worldwide/index.html (accessed June 18, 2009).

Edward Horton. *The Age of the Airship*. Chicago: Henry Regnery Company, 1973.

EG&G Technical Services, Inc. *Fuel Cell Handbook*. 7th ed. U.S. Department of Energy Office of Fossil Energy, 2004.

Eguchi, Kunihisa, and Tsutomu Fujihara. "Research Progress in Solar Power Technology for SPF Airship." National Aerospace Laboratory Japan, 2003.

Eguchi, Kunihisa, and Yoshio Yokomaku. "2000 Overview of Stratospheric Platform Airship R&D Program in Japan." Stratospheric Platform Airship Team -National Aerospace Laboratory Japan, 2000. http://lrp2001003.pdf%3Fid%3DNAL RP2001003&ei=xahCSpvVKcWEtweixKGYCQ&usg= AFQjCNFJXg9Zw-it0OPbRDbY7VkHvoFw9w&sig2=PmMN23ocNLYD-b1l0sB8gg (accessed June 5, 2009).

"EORC Seen from Space - Landscape of Taiki-cho Region Observed from Airship." *JAXA- Japan Aerospace Exploration Agency*. http://www.eorc.jaxa.jp/en/imgdata/topics/2005/tp050222.html (accessed June 25, 2009).

"Esrange Space Center." *Swedish Space Corporation*. http://www.ssc.se/esrange (accessed July 8, 2009).

"Expendable Stratospheric Platforms." *Venture Itch.com*, April 24, 2008. http://www.ventureitch.com/?p=526 (accessed July 8, 2009).

"Fact Sheets : Near-Space Access Program -- High-Altitude Balloons and Tethered Aerostats : Near-Space Access Program -- High-Altitude Balloons and Tethered Aerostats." *Kirtland Air Force Base*. http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=7890 (accessed July 4, 2009).

"Fuel Cells: Discovering the Science." *Smithsonian Institution American History*. http://americanhistory.si.edu/fuelcells/origins/origins.htm (accessed June 21, 2009).

"Fu-Go Weapon." *Japanese Balloon Bombs*. http://www.japaneseballoonbombs.com/ (accessed July 5, 2009).

Fujihara, Tsutomu, and Kunihisa Eguchi. "Experimental Work on Solar Regenerative Fuel Cells for SPF Airship." Stratospheric Platforms Project Center-JAXA, 2002. http://send.chofu.jaxa.jp%2Fsend%2Feng%2Fdlpdf.php3%2Fnalrp2002004.pdf%3Fid%3DNALRP2002004&ei=xJxCSpCOG8K5lAek_vj5CA&usg=AFQjCNE48efRa6TKZcEi6D3Y25vWHn7CLA&sig2=ZgvicFwQ16imuz9ceJ9oMQ (accessed June 5, 209).

"GeoEye-1 Launch Site--About GeoEye-1." *Geoeye.com*. http://launch.geoeye.com/LaunchSite/about/ (accessed July 7, 2009).

"Giant Flying Turtles to Revolutionize Global Aviation with Solar Power." *Clean Technology and Sustainable Industries Organization*, July 3, 2008. http://www.ct-si.org/news/press/item.html?id=2599 (accessed July 5, 2009).

"Giant Turtle Airship Concept is the Green Gadgety Transport of the Future." Wired.com, July 7, 2008. http://www.wired.com/gadgetlab/2008/07/concept-giant-t/ (accessed July 5, 2009).

Graham Warwick. "Staying Up, Staring Down - LEMV Airship." Aviation Week.com. *Ares: A Defense Technology Blog*, June 8, 2009. http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckScript=blogScript&plckElementId=blogDest&plckBlogPage=BlogViewPost&plckPostId=Blog%3A27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3A3c0ec60a-4bb5-43d4-b0ff-fefdf0733cb6 (accessed July 3, 2009).

"HALE." *Lindstrand Technologies*. http://www.lindstrandtech.com/hale.html (accessed July 3, 2009).

"Helium." *U.S. Department of The Interior Bureau of Land Management*. http://www.blm.gov/nm/st/en/prog/energy/helium.html (accessed July 5, 2009).

"Helium Airships." *Lindstrand Technologies*. http://www.lindstrandtech.com/helium_airships.html (accessed July 3, 2009).

"HFCIT Fuel Cells: Current Technology." *U.S. DOE Energy Efficiency and Renewable Energy*. http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/current_technology.html (accessed June 19, 2009).

"HFCIT Fuel Cells: Fuel Cell Technology Challenges." *U.S. DOE Energy Efficiency and Renewable Energy*. http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_challenges.html (accessed June 19, 2009).

"HFCIT Fuel Cells: Types of Fuel Cells." *U.S. DOE Energy Efficiency and Renewable Energy*. http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html#oxide (accessed June 17, 2009).

"High Altitude Airship 'Berkut'." *RosAeroSystems*. http://rosaerosystems.pbo.ru/english/projects.html (accessed July 4, 2009).

Hirohito Nozaki, Yuya Sekiguchi, and Kazuo Matsuuchi. "Research and Development on Cycloidal Propellers for Airships." Seattle, WA: AIAA, 2009.

"Honda FCX Clarity - Drive FCX." *Honda Worldwide Fuel Cell*. http://automobiles.honda.com/fcx-clarity/drive-fcx-clarity.aspx (accessed June 22, 2009).

"Honda's own originally developed ultra capacitor -Higher output, higher efficiency, and increased storage capacity." *Honda Worldwide Fuel Cell*. http://world.honda.com/FuelCell/FCX/ultracapacitor/ (accessed June 20, 2009).

"Horizon Fuel Cell Powers World Record UAV Flight." http://www.horizonfuelcell.com/news.htm (accessed June 22, 2009).

"Huajiao Airship." *Huajiao Airship.com*. http://www.hjairship.com/englishwebsite/home.htm (accessed July 8, 2009).

Hugh Allen. *Story of the Airship*. Third. Ohio: R.R. Donnelly and Sons Company, 1943.

———. *The Story of The Airship (Non-Rigid)*. Akron, Ohio: The Lakeside Press, R. R. Donnelley & Sons Company, 1943.

"Hydrogen - Energy." *Department of Energy Kids Page*, October 2008. http://www.eia.doe.gov/kids/energyfacts/sources/IntermediateHydrogen.html (accessed June 22, 2009).

Hydrogen and Fuel Cell Activities, Progress, and Plans: Report to Congress. Department of Energy, January 2009. (accessed June 1, 2009).

"Hydrogen Bus Fuel Cell Specifications." *Ballard Power*. http://www.ballard.com/Motive_Power/Heavy_Duty_Market/Product_Specifications.htm (accessed July 6, 2009).

"Hydrogen Implementing Agreement." *International Energy Agency*. http://www.ieahia.org/ (accessed July 6, 2009).

"HYDROGEN SHIPS & SUBS - Are the secrets of fuel cells hidden in top-secret naval research?." Hydrogen commerce.com. http://hydrogencommerce.com/index16.htm (accessed July 6, 2009).

J. E. Granata, and J. Merrill. *Mass and cost comparison of lightweight array and rigid array*. Kirtland AFB, NM: Air Force Research Laboratory, Space Vehicles Directorate, 2008.

"JAXA 2025 Panel Discussion "Aerospace: a Contributor to Society"." *JAXA- Japan Aerospace Exploration Agency*, 2005. http://www.jaxa.jp/about/2025/p4_3_e.html (accessed June 25, 2009).

"JAXA History." *JAXA- Japan Aerospace Exploration Agency*. http://www.jaxa.jp/about/history/index_e.html (accessed June 24, 2009).

Joe Pratt. "Aerospace Fuel Cell Systems: Proton Exchange Membrane Fuel Cell," 2004. http://www.nfcrc.uci.edu/2/ACTIVITIES/RESEARCH_STUDIES/Aerospace_FC_Systems/Proton_exchange_Membrane_Fuel_Cell/Index.aspx (accessed June 19, 2009).

Joel Carpenter. "Fu-Go Balloons." *PROJECT 1947*. http://www.project1947.com/gfb/fugo.htm (accessed July 5, 2009).

John Merrill, and J.E. Granata. *Mass and Cost Comparison of Lightweight Array And Rigid Array*. Air Force Research Laboratory, 2008.

Jonghwa Kim, Deokjoo Lee, Jaekyoung Ahn, and Do-Seob Ahn. "Is HAPS Viable for the Next-Generation Telecommunication Platform in Korea?." *EURASIP Journal on Wireless Communications and Networking* 2008 (2008): 8.

Julian Knott. "Interview at 18th AIAA lighter-than-air Technology Conference," May 5, 2009.

Kang, W., Y. Suh, K. Woo, and I. Lee. "Mechanical property characterization of film-fabric laminate for stratospheric airship envelope." *Composite Structures* 75, no. 1-4 (2006): 151-155.

"KARI- Korea Aerospace Research Institute." http://www.kari.re.kr/ (accessed July 3, 2009).

Keith Wipke, Sam Sprik, Jennifer Kurtz, and John Garbak. "DOE's Hydrogen Fuel Cell Activities: Developing Technology and Validating it through Real-World Evaluation." Las Vegas, NV, 2008.

Kenneth A. Burke. *Unitized Regenerative Fuel Cell System Development*. Cleveland, Ohio: Glenn Research Center, December 2003. http://ntrs.nasa.gov/ (accessed June 5, 2009).

Khoury, G. A., and J. D. Gillett. *Airship Technology*. Cambridge University Press, 2004.

Kirschner, Edwin. *Aerospace Balloons: From Montgolfiere to Space*. Fallbrook: Aero Publishers, 1985.

Kohno, Takashi, and Shuichi Sasa. "Control and Guidance of Low Altitude Stationary Flight Test Vehicle." In *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)*, 1-10. Arlington, VA: American Institute of Aeronautics and Astronautics, 2005.

Kothmann, K. "Kothmann Multi-Use Airship." Seattle, WA: American Institute of Aeronautics and Astronautics, 2009. http://pdf.aiaa.org/.

Koyama, Noboru, Masahiko Onda, Yasunori Sasaki, Ryu Miura, and Wakoto Akinaga. "Tsunami Monitoring System by Stratospheric LTA Platform." In *AIAA 5 th Aviation, Technology, Integration, and Operations Conference(ATIO)*, 1-8. American Institute of Aeronautics and Astronautics, 2005.

"Kuraray Expands VECTRAN Superfiber Manufacturing Facilities." http://www.kuraray.co.jp/en/release/2007/070122.html (accessed June 21, 2009).

"kuraray-Fabrics-Products Infomation." Kuraray.com. http://www.kuraray.co.jp/en/products/fiber/ (accessed June 21, 2009).

Kurose, Toyotoshi. "Japan: Development for SPF Stratospheric Platform Airship." *Gekkan JADI*, May 1, 2008.

L.T.C. Rolt. *The Aeronauts*. New York: Walker and Company, 1966.

Larson, Wiley. *Space Mission Analysis and Design*. 3rd ed. El Segundo Calif.: Microcosm Springer, 2006.

Leavitt, G. "A Project Overview of High Altitude Reduced Gravity Vehicle Experiments." Seattle, WA: American Institute of Aeronautics and Astronautics, 2009.

Lee, Sang-Jong, Dong-Min Kim, and Hyo-Choong Bang. "Feedback Linearization Controller for Semi Station Keeping of the Unmanned Airship." In *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)*, 1-8. Arlington, VA: American Institute of Aeronautics and Astronautics, 2005.

"Lighter than air." *Armada International*. http://www.thefreelibrary.com/Lighter+than+air-a0166350176 (accessed July 8, 2009).

Liu, Shengzhoug, Beernink, Kevin, Banerjee, Arindam, Yang, Chi-Chung, and Guha, Subhendu. "Solar cells for stratospheric and outer space use - US Patent Application." http://www.patentstorm.us/applications/20080173349/fulltext.html (accessed July 6, 2009).

"Losan United Sky Technology Dream." *Lonsan*. http://www.lonsan.com.cn/en/research/index.php (accessed July 8, 2009).

Luffman, C.R. *Aspects to consider for a Lighter-than-air High Altitude Platform Development in Europe*, November 16, 2005. http://www.hapcos.org/papers.php.

Maekawa, Soji, and Atsushi Takegaki. "On Structures of the Low-Altitude Stationary Flight Test Vehicle." In *AIAA 5th Aviation, Technology, Integration, and Operations Conference (ATIO)*. Arlington, VA: American Institute of Aeronautics and Astronautics.

Masaaki Sano, and Masahiko Onda. "Stratospheric LTA Platform with Variable Flight Altitude Control." In *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)*, 1-9. Arlington, VA: American Institute of Aeronautics and Astronautics, 2005.

Masahiko Onda. "Design Considerations on Stratospheric LTA Platfrom." In , 204-210. Norfolk, VA: American Institute of Aeronautics and Astronautics, 1999.

———. "Design Considerations on Stratospheric LTA Platfrom." In *A Collection of the 13th AIAA Lighter-Than-Air Systems Technology Conference Technical Papers*, 204-209. Norfolk, VA: American Institute of Aeronautics and Astronautics, 1999.

Merrill, John, Paul Hausgen, Donna Senft, and Jennifer Granata. "Air Force Perspective on Present and Future Space Power Generation." In *2006 IEEE 4th World Conference on Photovoltaic Energy Conference*, 1750-1756. Waikoloa, HI, 2006. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4059996.

Michael Lee, Steve Smith, and Stavros Androulakakis. "The High Altitude Lighter Than Air Airship Efforts at the US Army Space and Missile Defense Command/Army Forces Strategic Command." Seattle, WA: American Institute of Aeronautics and Astronautics, 2009.

Michael S. Smith, and Edward Lee Rainwater. "Applications of Scientific Ballooning Technology to High Altitude Airships." In *AIAA's 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Technical Forum*. Denver, CO: American Institute of Aeronautics and Astronautics, 2003.

"MicroSat Systems, Inc.: Reliable, Affordable, Spacecraft for DoD, NASA and Commercial Markets - Thin Film Arrays." *MicroSat Systems*. http://www.microsatsystems.com/msiProducts/satelliteSubsystems/thinFilmArrays/ (accessed July 6, 2009).

Milan Lalovic, Michael Fitch, Mihael Mohorcic, David Grace, Masayuki Oodo, Paul Mitchell, and George White. *Strategy Document: Delivering Broadband for All including Commercial and Technical Risk Assessment*. CAPANINA, May 23, 2005.

Mildred Dresselhaus. *Basic Research Needs for the Hydrogen Economy*. U.S. Department of Energy, May 13, 2003.

Miller, T., and M. Mandel. "Airship Envelopes: Requirements, Materials and Test Methods." In *3rd International Airship Convention and Exhibition*, 2000. (accessed June 17, 2009).

Mitlitsky, Fred, Blake Myers, and Andrew H. Weisberg. "Regenerative Fuel Cell Systems." *Energy & Fuels* 12, no. 1 (1, 1998): 56-71.

Monjid Hamdan. "PEM Electrolyzer Incorporating an Advanced Low Cost Membrane" presented at the 2009 Hydrogen Program Annual Merit Review Meeting, May 20, 2009. http://www.hydrogen.energy.gov/annual_review09_production.html (accessed June 15, 2008).

Mordant, Nicole. "Automakers see no one winner in green car race." *Reuters.com* (June 2, 2009). http://www.reuters.com/article/GCA-BusinessofGreen/idUSTRE5516JD20090602?sp=true (accessed June 22, 2009).

Nakadate, Masaaki. "Development and Flight Test of SPF-2 Low Altitude Stationary Flight Test Vehicle." In *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)*, 1-13. Arlington, VA: American Institute of Aeronautics and Astronautics, 2005.

Nakadate, Masaaki, Shoji Maekawa, Toshiyuki Maeda, Makoto Hiyoshi, Takuya Kitada, and Shinya Segawa. "Reinforcement of an Opening for High Strength and Light Weight Envelope Material Zylon." In , 1-9. Seattle, WA: American Institute of Aeronautics and Astronautics, 2009. (accessed June 17, 2009).

"NASA's Scientific Ballooning Program." *NASA Goddar Space Flight Center*. http://astrophysics.gsfc.nasa.gov/balloon/ (accessed July 6, 2009).

NASIC Open Source Report: (U) Chinese Airship Research Association. Wright-Patterson AFB, OH: National Air and Space Intelligence Center (NASIC), June 2, 2009.

Norbert Pacheco. "US Geological Survey, Mineral Commodity Summaries-Helium." US Geological Survey, January 2009. minerals.usgs.gov/minerals/pubs/commodity/helium/mcs-2009-heliu.pdf (accessed February 25, 2009).

Oodo, M., H. Tsuji, R. Miura, M. Maruyama, M. Suzuki, Y. Nishi, and H. Sasamoto. "Experiments on IMT-2000 Using Unmanned Solar Powered Aircraft at an Altitude of 20 km." *IEEE Transactions on Vehicular Technology* 54, no. 4 (7, 2005): 1278-1294.

Oogaki, Masanobu. "Overview of Stratospheric Platform Airship R&D Program" presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001.

Osakwe, Rebecca. "PEM Fuel Cells and Russia's Supply of Platinum." *Stanford's Student Journal of Russian, East European, and Eurasian Studies* 2 (Spring 2006): 7-36.

P. Aguiar, D.J.L. Brett, and N.P. Brandon. "Solid oxide fuel cell/gas turbine hybrid system analysis for high-altitude long-endurance unmanned aerial vehicles." *International Journal of Hydrogen Energy* 33, no. 23 (December 2008): 7214-7223.

P. W. Litchfeld and Hugh Allen. *Why? Why Has America No Rigid Airships?* Cleveland, Ohio: The Corday & Gross Co., 1945.

Pattinson, John. "HALE Airship: Manufacture, Flight and Operation" presented at the 1st Appleton Space Conference, Rutherford Appleton Laboratory Oxon, UK, December 8, 2005. (accessed June 5, 2009).

Peter J. Flores. "Untapped Potential: The Influence of International Regimes and Organizational Culture on The Near-Space Concept." School of Advanced Air and Space Studies, 2007.

"Photovoltaic Basics." U.S. DoE Solar Energy Technologies Program. http://www1.eere.energy.gov/solar/pv_basics.html (accessed July 4, 2009).

Pickover, Clifford. *Archimedes to Hawking : laws of science and the great minds behind them*. New York: Oxford University Press, 2008.

Poleskie, Steve. *The Balloonist : the story of T.S.C. Lowe-- inventor, scientist, magician, and father of the U.S. Air Force*. 1st ed. Savannah GA: Frederic C. Beil, 2007.

"Power Plants." *Fuel Cell.org*. http://www.fuelcells.org/db/index.php (accessed July 8, 2009).

"PowerFilm Technology." *PowerFilm*. http://www.powerfilmsolar.com/about/technology/ (accessed July 6, 2009).

"Protonex Awarded $3.3 Million Contract To Develop a Deployable Fuel Cell Power System for Small Unmanned Aerial Vehicles." *Protonex Technology Corporation*. http://www.protonex.com/products/military.aspx (accessed June 22, 2009).

"PUMA Tethered Aerostat." *RosAeroSystems*. http://rosaerosystems.pbo.ru/english/products/puma.html (accessed July 3, 2009).

"QinetiQ's Zephyr UAV exceeds official world record for longest duration unmanned flight." *Qinetiq.com*. http://www.qinetiq.com/home/newsroom/news_releases_homepage/2007/3rd_quarter/qinetiq_s_zephyr_uav.html (accessed July 4, 2009).

"R&D of Stratospheric Wireless Platforms." http://www2.nict.go.jp/q/q262/3107/end101/ENG/main.html (accessed June 24, 2009).

Roedern, Bolko von. *National Solar Technology Roadmap: CIGS PV*. Management Report. National Renewable Energy Laboraty, June 2007.

Rommel Noufi, and Ken Zweibel. *High-Efficiency Cdte and Cigs Thin-Film Solar Cells: Highlights and Challenges*. Golden, CO: National Renewable Energy Laboratory.

"RosAeroSystems Company profile." *RosAeroSystems*. http://rosaerosystems.pbo.ru/english/company.html (accessed July 3, 2009).

"RQ-4 Block 20 Global Hawk." *Northrop Grumman Aerospace Systems*. http://www.as.northropgrumman.com/products/ghrq4b/index.html (accessed July 4, 2009).

"Russia building surveillance and communications airship - agency." *BBC Monitoring Former Soviet Union*, October 13, 2008.

(b) (3) [redacted]

Sang-Jong Lee, Seong-Pil Kim, Tae-Sik Kim, Hyoun-Kyoung Kim, and Hae-Chang Lee. "Development of Autonomous Flight Control System for 50m Unmanned Airship." In *Proceedings of the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference, 2004.*, 457-462. Melbourne, Australia, 2004. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1417504.

"Sanswire-TAO Stratellite™." *Sanswire.com*. http://www.sanswiretao.com/product-stratellite.htm (accessed July 4, 2009).

"Scientific Balloons." *NASA Columbia Scientific Balloon Facility*. http://www.csbf.nasa.gov/balloons.html (accessed July 3, 2009).

"Scientific Balloons." NASA - Columbia Scientific Balloon Facility. http://www.csbf.nasa.gov/balloons.html (accessed July 6, 2009).

Seely, L., M. Zimmerman, and J. McLaughlin. "The use of Zylon fibers in ULDB tendons." *Advances in Space Research* 33, no. 10 (2004): 1736-1740.

Shoji Maekawa, Kouichi Shibasaki, Toyotoshi Kurose, Toshiyuki Maeda, Yoshitaka Sasaki, and Tatsuya Yoshino. "Tear Propagation of a High Performance Airship Envelope Material." In , 1-9. Belfast, Northern Ireland: American Institute of Aeronautics and Astronautics, 2007.

Shuichi Sasa. "Stratospheric Platform Program in Japan and Ground-to-Stratosphere Flight Test" presented at the 9th UAVNET Meeting, Amsterdam, January 27, 2004. http://www.uavnet.com%2FDL%2FDocument_Library%2FAmsterdam_Meeting%2FStratospheric_platform_Sasa.pdf&ei=BCNBSsE7h4m2B7KUiaIJ&usg=AFQjCNGtJz00B_5DNHC9D_QSyCaV-zMZ6Q&sig2=lkpiccUJIccb_PGO1YTOug (accessed June 5, 2009).

Sinha, Jayanti, Stephen Lasher, and Yong Yang. "Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications" presented at the DOE Hydrogen Program: 2009 Annual Merit Review Proceedings - Fuel Cells, Arlington, VA, May 21, 2009. http://www.hydrogen.energy.gov/annual_review09_fuelcells.html#analysis (accessed June 19, 2009).

"SkyHook International Inc.-JHL-40 Boeing." *SkyHook HLV International*. http://www.skyhookintl.com/ (accessed July 3, 2009).

"Solar Energy Technologies Program: Polycrystalline Thin Film." *U.S. DOE Energy Efficiency and Renewable Energy*. http://www1.eere.energy.gov/solar/tf_polycrystalline.html (accessed July 6, 2009).

Sone, Yoshitsugu, Mitsushi Ueno, Hitoshi Naito, and Saburo Kuwajima. "One kilowatt-class fuel cell system for the aerospace applications in a micro-gravitational and closed environment." *Journal of Power Sources* 157, no. 2 (7, 2006): 886-892.

"Space Data." *Space Data.com*. http://www.spacedata.net/ (accessed July 4, 2009).

"Space Data SkySite." http://www.spacedata.net/ (accessed July 6, 2009).

"STO: Integrated Sensor is Structure." *Defense Advanced Research Agency: Strategic Technology Office*. http://www.darpa.mil/sto/space/isis.html (accessed July 3, 2009).

"Stratospheric Persistent Unmanned Aircraft Systems: Global Observer Detail." *AeroVironment.com*. http://www.avinc.com/uas/stratospheric/global_observer/ (accessed July 4, 2009).

"Stratospheric Persistent Unmanned Aircraft Systems: Global Observer Detail." *AeroVironment, Inc.* http://www.avinc.com/uas/stratospheric/global_observer/ (accessed June 22, 2009).

"Stratospheric Platform Air Reconnaissance and Radar Signal Detection Analysis." *Chinese Airship Association*. http://www.ltachina.cn/bencandy.php?fid=26&id=120 (accessed July 3, 2009).

"StratXX - Near Space Technology." *StatXX.com*. http://www.stratxx.com/ (accessed July 3, 2009).

"Studies on the Stratospheric Platform." *Sora to Sora*, 2004. http://www.ard.jaxa.jp/eng/info/prm/2004/001/04.html (accessed June 24, 2009).

T. Motyka. *Savannah River National Laboratory Regenerative Fuel Cell Project*. Savannah River Site: Savannah River National Laboratory, November 2008. http://www.osti.gov/bridge/purl.cover.jsp?purl=/941112-8jMDpb/ (accessed July 8, 2009.

Takashi Kohno, Masaaki Nakadate, and Masahiro Okuyama. "On-going UAV R&D at JAXA's Aviation Program Group - Second Report with Emphasis on LTA Flight Control." Seattle, WA: American Institute of Aeronautics and Astronautics, 2009.

"Technical publications HAPCOS." *COST297 - HAPCOS*. http://www.hapcos.org/papers.php (accessed July 6, 2009).

"The International Solar Energy Society (ISES)." *ISES.com*. http://www.ises.org/ises.nsf!Open (accessed July 6, 2009).

"The Science of Photovoltaic Enegry : DuPont Photovoltaic Solutions." *Dupont.com*. http://www2.dupont.com/Photovoltaics/en_US/science_of/index.html (accessed July 6, 2009).

"The Third Wave of Solar Power." *Nanosolar*. http://www.nanosolar.com/technology.htm (accessed July 6, 2009).

Thomas H. Bradley, Blake A. Moffitt, Thomas F. Fuller, Dimitri Mavris, and David E. Parekh. "Design Studies for Hydrogen Fuel Cell Powered Unmanned Aerial Vehicles." Honolulu, HI: American Institute of Aeronautics and Astronautics, 2008.

Tomme, Lt Col Edward B. *The Paradigm Shift to Effects-Based Space: Near-Space as a Combat Space Effects Enabler*. Maxwell AFB, AL: Airpower Research Institute,

2005. www.au.af.mil/au/awc/awcgate/cadre/ari_2005-01.pdf (accessed June 5, 2009).

Tong, Zhipeng, Youshou Wu, Hongwen Zhu, Zhisheng Niu, Gongyi Fu, and Cheng He. "R&D of Stratospheric Platform and SP based Information Systems in China" presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001.

"Toru Shimizu - Expectations soar for our huge new airship." *JAXA- Japan Aerospace Exploration Agency*. http://www.jaxa.jp/article/interview/no11/index_e.html (accessed June 23, 2009).

Toshihiko Hirooka. "Observational features of stratospheric winds over Japan related to global circulation changes" presented at the Third Stratospheric Platform Systems Workshop, Tokyo, Japan, October 1, 2001.

"TOYOBO-Product-Industrial materail." Toyobo.com. http://www.toyobo.co.jp/e/products/s_sizai.htm (accessed June 21, 2009).

"Transportation Fleet Vehicles." *UTC Power*. http://www.utcpower.com/fs/com/bin/fs_com_Page/0,11491,0152,00.html (accessed June 22, 2009).

Tsutomu Fujihara, and Kunihisa Eguchi. *Ground to Stratosphere Flight Test-Development Test Vehicles*. JAXA Researh and Development Memoradum. Japan Aerospace Exploration Agency (JAXA), January 6, 2005.

———. *Research and Development on Regenerative Fuel Cells for Stratospheric Platform Airship - Ground-based Testing of 1kW RFC System Models*. JAXA Research and Development Memorandum. Unmanned and Innovative Aircraft Team: Japan Aerospace Exploration Agency (JAXA), February 2008.

"U212 / U214 Attack Submarines." *Naval Technology.com*. http://www.naval-technology.com/projects/type_212/ (accessed July 6, 2009).

"Using Sunlight More Efficiently." *American Institute of Physics*. http://www.aip.org/isns/reports/2008/046.html (accessed July 6, 2009).

"UTC Power to Design Fuel Cell for Spanish Submarine." *prnewswire.com*, July 19, 2006. http://www.prnewswire.com/cgi-bin/stories.pl?ACCT=104&STORY=/www/story/07-19-2006/0004399622&EDATE= (accessed July 6, 2009).

Utku Cakirozer. "Turkey Said May Purchase High Altitude Airship for Monitoring PKK Activities," September 26, (b) (3) [redacted]

(b) (3) [redacted]

"Vantage Airship." *Shanghai Vantage Airship Manufacture Company Limited.* http://www.vantageship.com/index2.htm (accessed July 8, 2009).

"VEATAL Conference Proceedings." *VEATAL Airship Project.* http://www.veatal.com/pageLibre0001187e.php#I0006972f (accessed July 3, 2009).

Volker, Steiner. "How to improve the performance of an LTA-vehicle (balloon or airship)." San Francisco, CA: American Institute of Aeronautics and Astronautics, 1997.

"Weather Balloons." *National Weather Service Forecast Office - El Paso.* http://www.srh.noaa.gov/epz/kids/balloon.shtml (accessed July 8, 2009).

Wilford, Hugh. *The Mighty Wurlitzer : How the CIA Played America*. Cambridge: Harvard University Press, 2008.

William Nolte. "TRL Calculator Upgrade to v 2.2." *Defense Acquisition University.* https://acc.dau.mil/CommunityBrowser.aspx?id=25811 (accessed June 18, 2009).

"World Record: 41.1% efficiency reached for multi-junction solar cells at Fraunhofer ISE." *Fraunhofer ISE*, January 2009. http://www.ise.fraunhofer.de/press-and-media/press-releases/press-releases-2009/world-record-41.1-efficiency-reached-for-multi-junction-solar-cells-at-fraunhofer-ise (accessed July 6, 2009).

"World's Largest CIGS Thin Film Solar Array Goes Live in Tucson, Arizona." *Global Solar*, May 14, 2009. http://www.globalsolar.com/press/press.php (accessed July 6, 2009).

Wyrsch, N., D. Dominé, F. Freitas, L. Feitknecht, J. Bailat, C. Ballif, G. Poe, K. Bates, and K. Reed. "Ultra-Light Amorphous Silicon Cell for Space Applications." In *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on*, 2: Vol. 2, 2006.

Yong Wang, Jun Liu, Vilayanur Viswanathan, Rong Kou, Yuehe Lin, Sheng Dai, Stephen Campbell, Jingguang Chen, and Brian Willis. "Development of Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells" presented at the DOE Hydrogen Program: 2009 Annual Merit Review Proceedings - Fuel Cells, Arlington, VA, May 18, 2009. http://www.hydrogen.energy.gov/annual_review09_fuelcells.html#analysis (accessed June 21, 2009).

Z. Cai, R. Clarke, N. Ward, W. J. Nuttall, and B. A. Glowacki. "Modelling Helium Markets." Cambridge University Judging School, 2006.

http://www.jbs.cam.ac.uk/programmes/phd/downloads/conference_spring2007/papers/cai.pdf (accessed February 25, 2009).

“Zeppelin NT - History.” *Zeppelin NT*. http://www.zeppelinflug.com/zeppnt_histo.htm (accessed July 4, 2009).

Zhai, Honglian, and Antony Euler. “Material Challenges for Lighter-Than-Air Systems in High Altitude Applications.” In *AIAA 5th Aviation, Technology, Integration, and Operations Conference(ATIO)*, 1-12, 2005. (accessed June 17, 2009).

Zi-Niu Wu, and Xiao-Jian Xue. “Civilian Demands Application of Airships in Civil Projects” presented at the VEATAL 2008 Beijing China Conference, Beijing, CN, April 2008. http://www.veatal.com/pageLibre000115d8.php# (accessed July 3, 2009).

“Zylon Applications.” *Zylon*. http://www.toyobo.co.jp/e/seihin/kc/pbo/menu/fra_menu_en.htm (accessed June 18, 2009).