AMC'S HYDROGEN FUTURE:
SUSTAINABLE AIR MOBILITY

GRADUATE RESEARCH PROJECT

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AFIT/IMO/ENS/09-13

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Adam D. Reiman, BS, MBA

Major, USAF

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Abstract

The purpose of this research is to compare the costs associated with the transition to hydrogen aircraft for Air Mobility Command (AMC) to the costs of continuing using JP-8. Using current technology, air mobility aircraft can be designed to use liquid hydrogen instead of JP-8. This transformation will be capital intensive. A model was built that converted current AMC JP-8 usage to liquid hydrogen usage and calculated the costs of the infrastructure for that transition. The model focused on hydrogen production through renewable energy. The model covered the costs and requirements for electricity generation, hydrogen production, hydrogen liquefaction and liquid hydrogen storage. The analysis of hydrogen as a fuel for AMC aircraft covered the history of hydrogen aircraft, previous hydrogen aircraft studies, a comparison of hydrogen to JP-8 and liquid hydrogen to thrust conversion. The three areas of focus for liquid hydrogen to thrust conversion include hydrogen turbojets, hydrogen turbines powering High Temperature Superconducting (HTS) motors and fuel cell powered HTS motors. The results of the research suggest a transition to hydrogen infrastructure is an economically sound decision if the forecast price of oil is expected to exceed $7.50 a gallon within the next 20 years.

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Adam D. Reiman

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I. Introduction

Hydrogen has the potential to solve many of the important energy issues facing the United States. To begin the analysis of the use of hydrogen as an alternate fuel, three questions must be addressed. Does the United States need an oil alternative? If an oil alternative is necessary, where does the transition to an alternate fuel make sense? And which alternate fuels are the best options for future action? The answers to these questions provide the motivation to examine in detail the infrastructure costs associated with the transition to liquid hydrogen aircraft for Air Mobility Command. The most important question of the three is the first. The price of oil and the timing of the movement in the price of oil are the critical components of the answer. Accurately forecasting the future price of oil at any given time is extremely complex, but assessing supply and demand might provide insight that could illustrate the need for alternate fuels.

Problem Statement

The United States is dependent on foreign oil. Oil production and eventual decline historically follow a bell curve skewed to the right. The reason for this skew is the combination of new oil resources being discovered and improved recovery techniques (CERA, 2006). The United States hit peak oil production on this bell curve in 1970 (see Figure 1). From this peak, United States' oil production declined to approximately half of what it was in 1970. Although production declined, consumption continued to grow leading to increased imports. Current oil imports now exceed United States production at its peak. The arrival of peak oil could be forecast utilizing oil production and discovery statistics. The 1970 peak in United States oil production was predicted in 1956 by M. King Hubbert. Using Hubbert's method, Kenneth S. Deffeyes computed world oil production would peak on December 16, 2005 (Deffeyes, 2005).

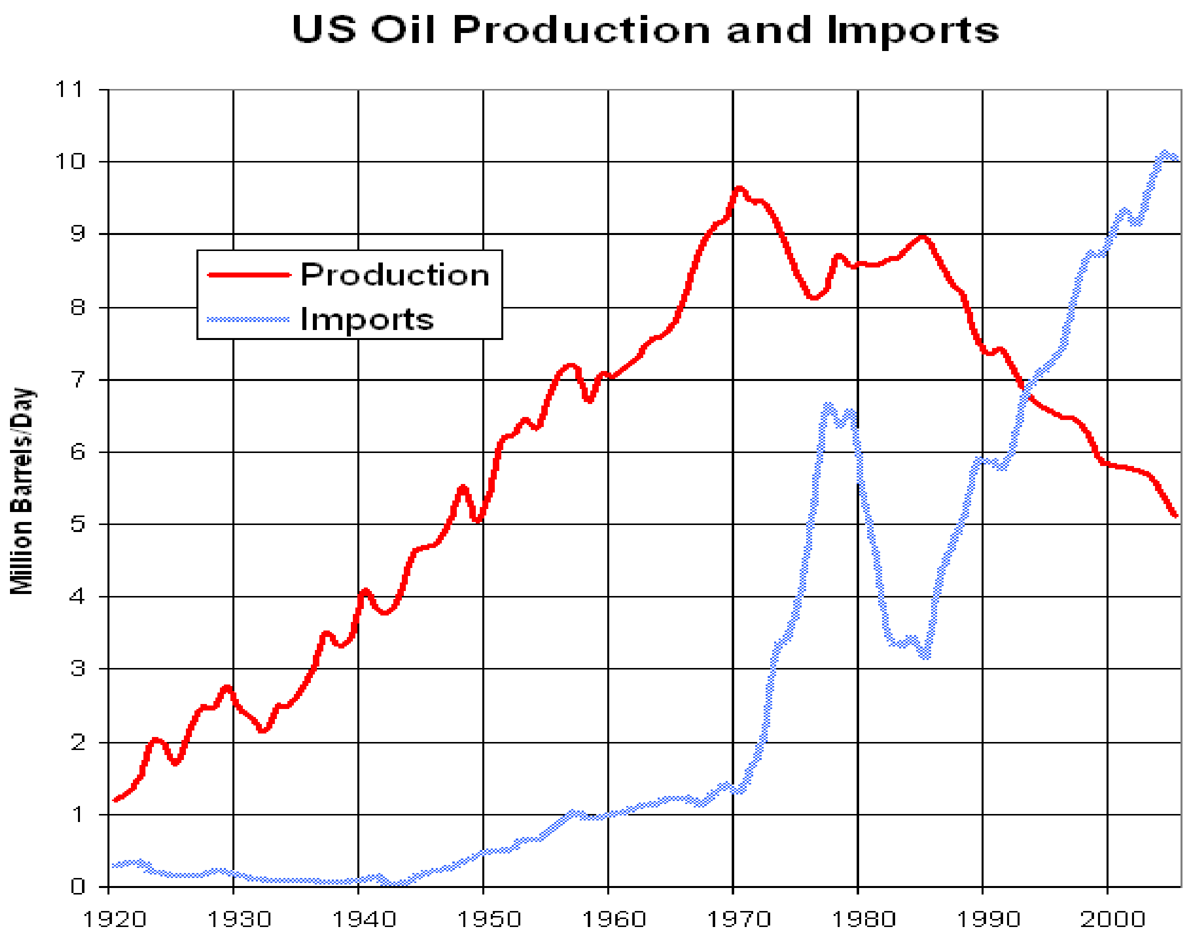

Figure 1
US Production of Crude Oil
(theoildrum, 2008)

Deffeyes based his prediction off of total world reserves of 2.013 trillion barrels. The world has already used over half of these total reserves leaving less than 1 trillion barrels of oil. British Petroleum Statistical Review, the Oil and Gas Journal and World Oil estimate global proven reserves remaining between 1.143 and 1.332 trillion barrels (EIA, 2008). The difference between these totals and Deffeyes' estimate is in the proven reserves of the Organization of Petroleum Exporting Countries (OPEC). Since 1980, total reserves for OPEC have grown by over 300 billion barrels. Most of these reserves have increased without any new discoveries to justify the increase. Every year the proven reserves of OPEC tend to increase despite large scale production from their wells.

The primary reason given for this apparent contradiction in proven reserves is that OPEC sets production quotas based on reported proven reserves. Other reasons for countries overstating their proven reserves include strengthening their international stature, fostering a sentiment of security and stability amongst their populace and increasing the asset base on which they are able to borrow. Sadad al-Huseini, former head of exploration and production at Saudi Aramco, estimates 300 billion barrels of the global 1,200 billion barrels of oil remaining should be categorized speculative (Autobloggreen, 2008). Doctor Ali Samsam Bakhtiari, a former senior expert of the National Iranian Oil Company, has claimed that the top five Middle East proven reserves in size are overstated by 350 billion barrels (Aph, 2006). Even assuming the higher 1.3 trillion barrel estimate, peak oil would only be extended by 5 years.

Of the 65 largest oil producing countries, 54 have already peaked (Thehill, 2008). Even with the vast majority of countries reaching peak oil, Deffeye's prediction of world oil production hitting its peak in 2005 has not held. According to the Energy Information Agency (EIA), world crude oil and natural gas liquids production surpassed the 2005 peak of 82.09 million barrels per day to reach its third quarter of 2008 production at 82.62 million barrels per day. Although this is slightly higher, it is very close to the 2005 level. If ethanol is included, total oil production reached 85.79 million barrels per day. Due to the current recession, the EIA predicts oil production will slightly decline to 84.43 million barrels per day for 2009 (EIA, 2009). Oil production has not followed the IEA 2006 forecast, but has remained above the mean prediction (see Figure 2).

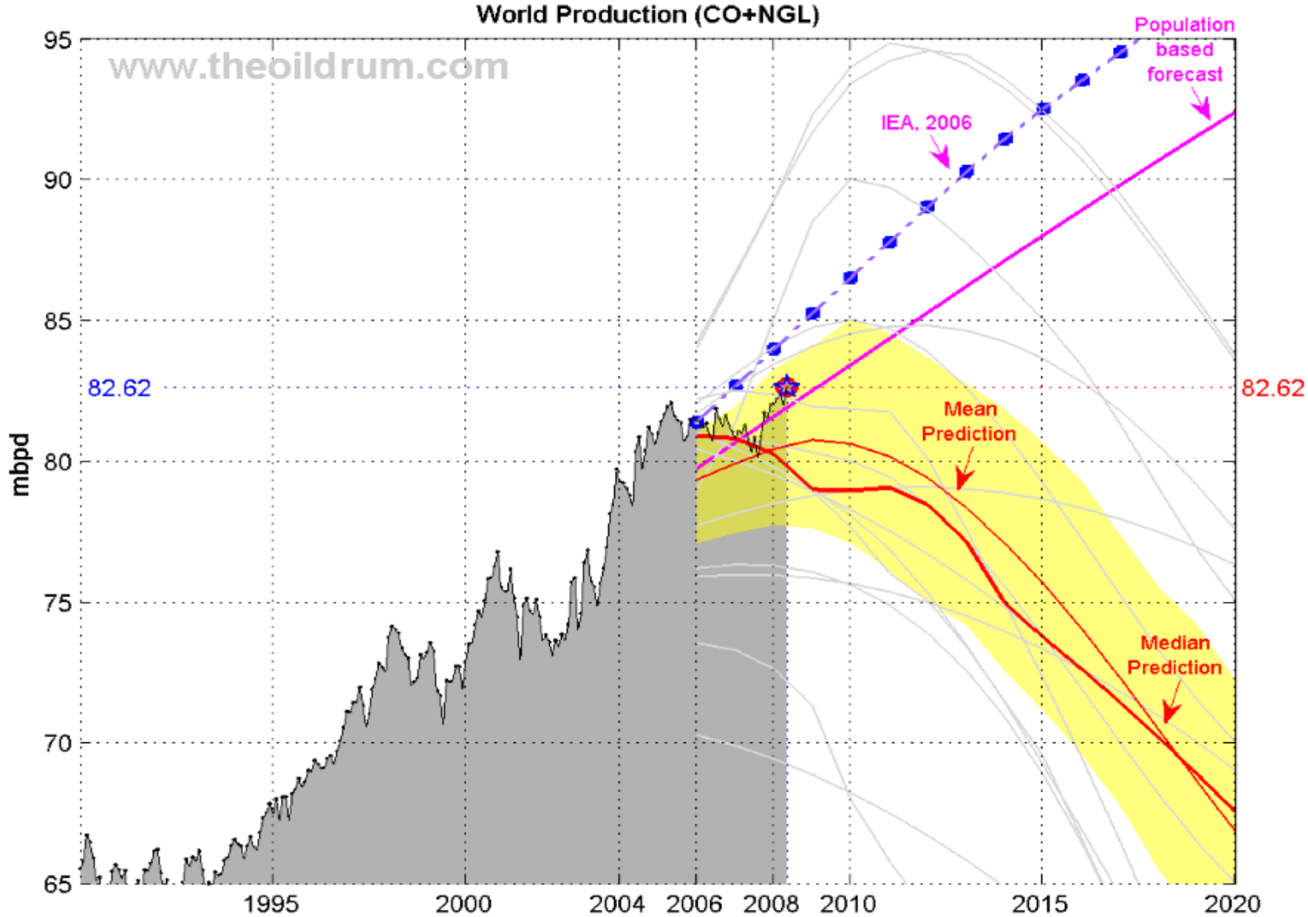

Figure 2
World Production of Crude Oil and Natural Gas Liquids
(theoildrum, 2008)

The EIA in February 2009 predicted global demand will decline to 84.7 million barrels per day in 2009 from the 2008 level of 85.87 million barrels per day. This demand decrease is the expected result of the impact of the global recession (EIA, 2009). Before the recession, prices likely rose on constrained supply concerns. After the global recession impacted demand, prices dropped rapidly (see Figure 3). James Williams of WTRG Economics states, “Oil prices behave like a commodity with wide price swings in times of shortage or oversupply” (Wtrg, 2007). Over the past decade oil prices have more than quadrupled to their peak and then dropped to 2005 levels.

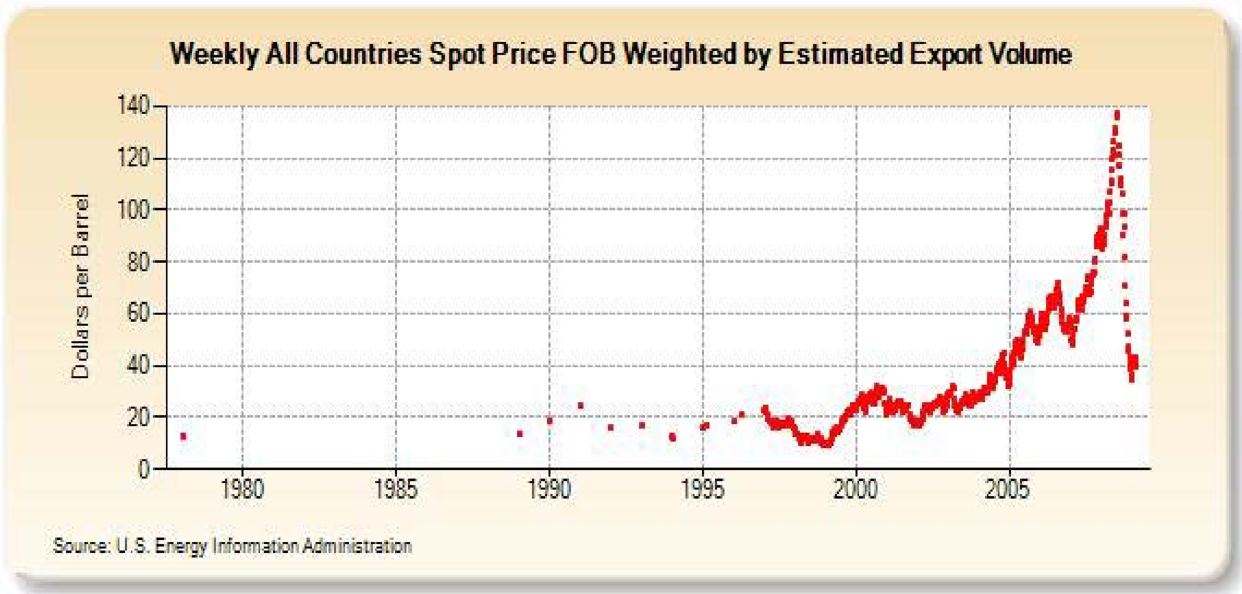

Figure 3
Oil Prices
(Tonto, 2009)

The largest consumer of oil in the world is the United States. The United States consumes roughly a quarter of world oil production. China, the second largest oil consumer, consumes approximately a third of the oil of the United States (see Figure 4). The latest EIA forecast for China's oil consumption growth shows it increasing from 7.98 million barrels per day in 2008 to 8.54 million barrels per day by 2010. The large disparity between US and Chinese consumption makes the United States an extremely important factor to the demand side of the oil supply demand equation. The largest consumer of oil in the United States is the Department of Defense (Farivar, 2007). According to the 2007 CIA World Fact Book, there are only 35 countries in the world consuming more oil than the Department of Defense (Karbuz, 2007).

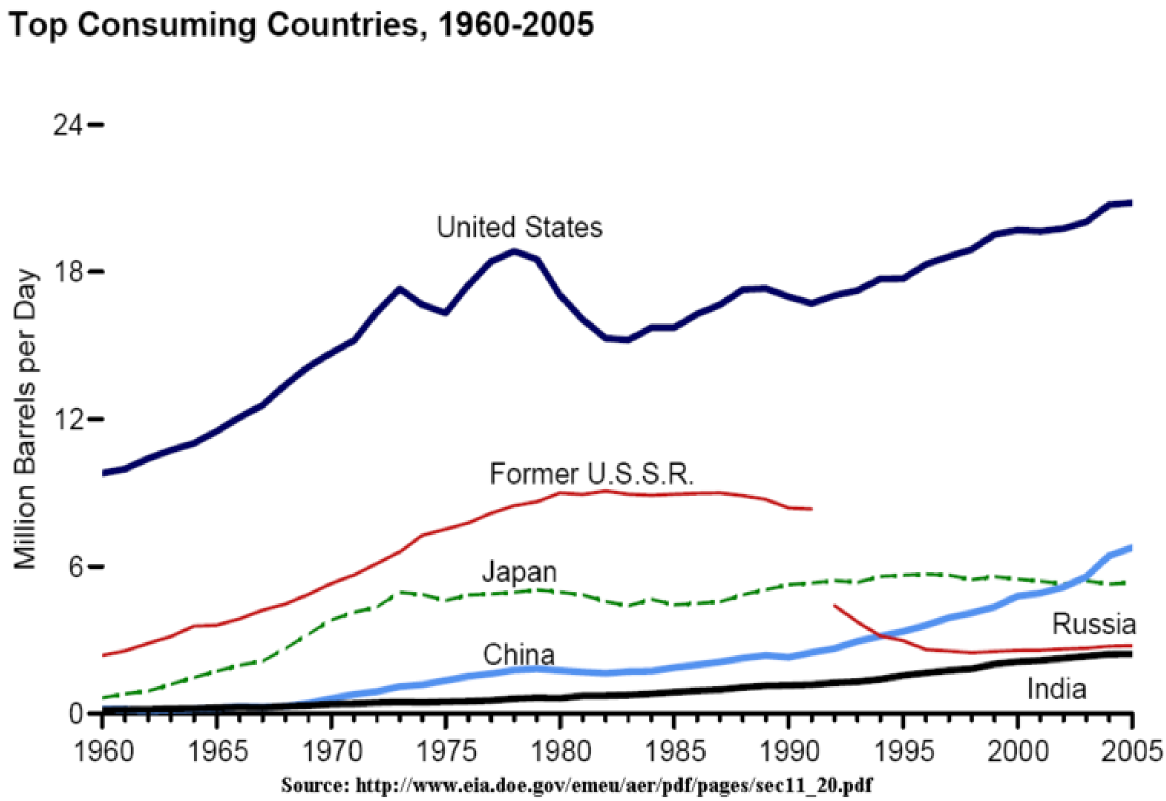

Figure 4
Top Oil Consuming Countries
(eia.doe.gov, 2005)

Since the Department of Defense is a substantial contributor to the United States oil consumption, making a significant reduction on Department of Defense fuel use could result in downward pricing pressure for oil. The easiest area to achieve that reduction is aircraft. The largest consumer of oil in the Department of Defense is the United States Air Force. The United States Air Force consumes more than half of the Department of Defense total oil consumption, with aircraft accounting for almost three fourths of the Department of Defense total (see Figure 5). With such a large percentage of oil consumption in the Department of Defense being utilized by aircraft, an intense focus on alternative aircraft fuels becomes essential.

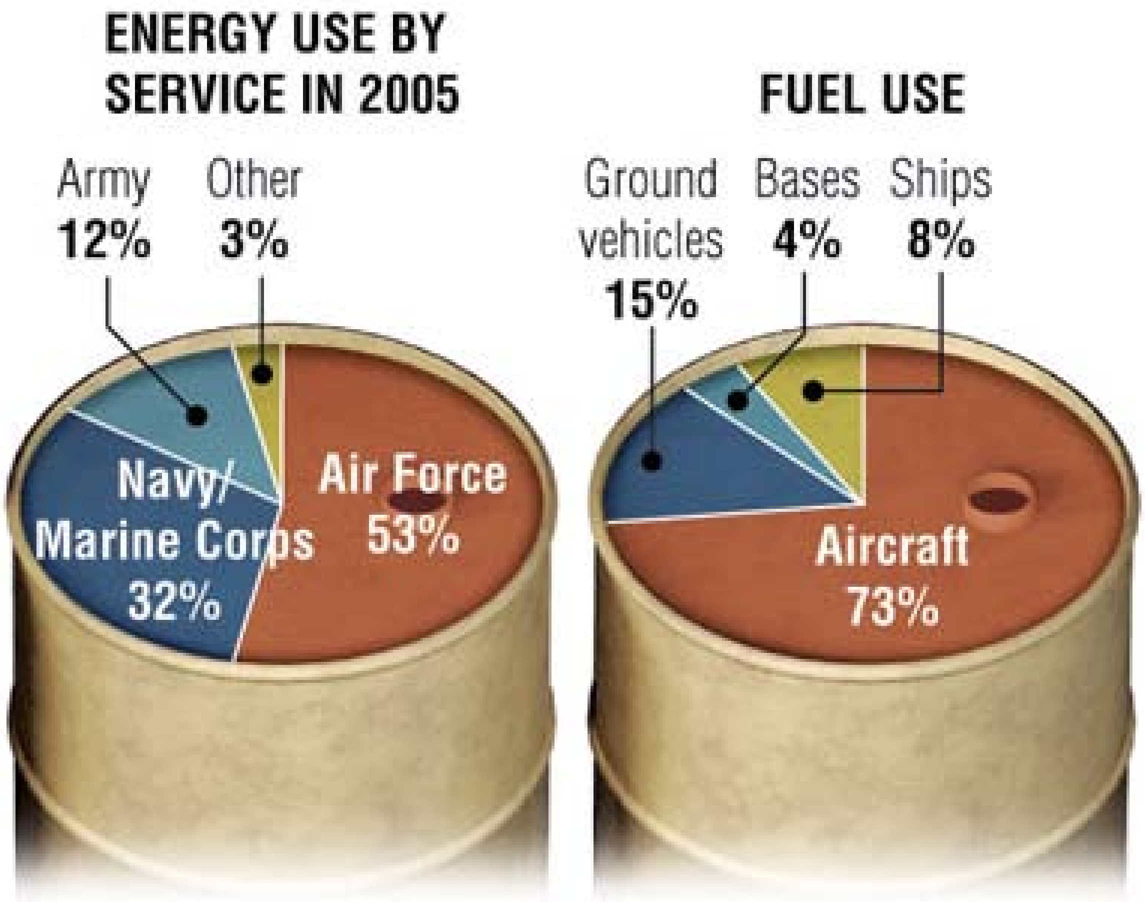

Figure 5
DOD Fuel Usage by Service
(Lugar, 2008)

For the Air Force to obtain the greatest impact from alternative aircraft fuels, they should focus on the largest Air Force consumer, Air Mobility Command. Air Mobility Command aircraft fuel consumption is more than half of the Air Force total (see Figure 6). Fighters come in second in fuel consumption, but their consumption is only half that of mobility aircraft consumption. Within Air Mobility Command, large inter-theater aircraft consume the greatest amount of oil. If new aircraft are proposed to follow the current inter-theater fleet, then utilizing alternative fuels in those aircraft could have a significant impact on oil consumption.

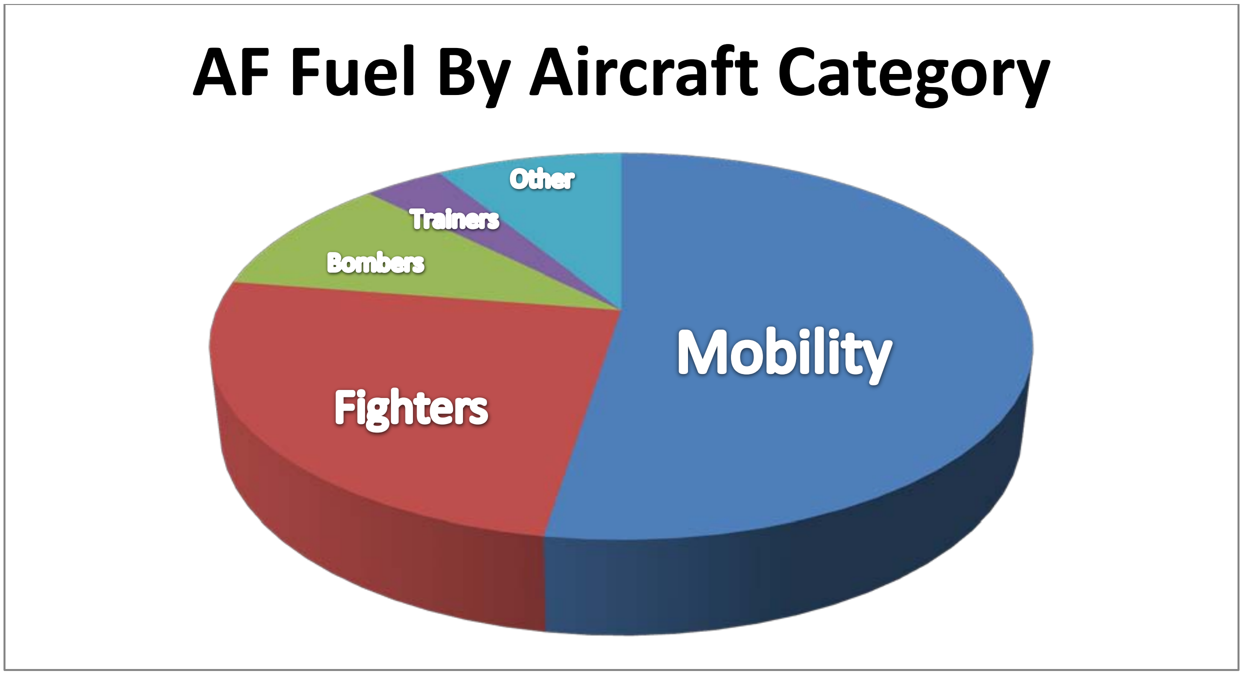

Figure 6
Air Force Fuel Usage by Aircraft Category (Sega, 2007)

It should be noted that some opponents of peak oil theory, such as the Cambridge Energy Research Associates (CERA) believe the remaining global resources base to be 3.74 trillion barrels (Cera, 2006). Yet, these analyses include oil sources beyond conventional oil. The impact of these alternative sources of oil could have a significant impact on the timing of peak oil and the rate of decline in oil supply. These alternative sources of oil are more expensive to obtain. They include oil sands, heavy oil and oil shale. The biggest deposit of oil sands is the Athabasca reserve in Alberta, Canada estimated at over 1.7 trillion barrels with 173 billion barrels estimated as recoverable (Environment, 2008). Oil sands of interest are surface or near surface oil deposits. Being close to the surface, natural gas and lighter oil molecules tend to evaporate. Bacteria at the surface modify the oil leaving ring compounds. This causes the oil to become more viscous than conventional oil. To obtain the oil from the oil sands, it has to be mined or extracted through boreholes. Mining is both an energy and capital intensive process.

For the boreholes, steam is usually injected to move the viscous oil through the rocks which is also an energy and capital intensive process. Once the oil is liberated from the sands, it has to be refined to a viscosity that enables it to travel through pipelines. This is a very hydrogen intensive process. Reducing the large carbon molecules to smaller ones requires hydrogen for chemical stability. Producing oil from oil sands requires a lot of natural gas to create both the steam and the hydrogen (Deffeyes, 2005). The production cost per barrel of oil from oil sands is $26.52 per barrel (Reuters, 2009). Production costs from Saudi conventional oil are less than $2 per barrel (Papastraighttalk, 2008).

The biggest deposit of heavy oil in the world is the Orinoco heavy oil field in Venezuela estimated at over 1.2 trillion barrels with 267 billion barrels recoverable (Mommer, 2004). The difference between the oil sands and heavy oil is the degree to which the oil has been degraded by bacteria. The Orinoco heavy oil has been degraded less than the Canadian oil sands making it easier to extract. The Orinoco oil contains 300 parts per million of vanadium. If vanadium rich oil is combusted it forms deposits that can accumulate. Vanadium also acts as a catalyst converting the sulfur in the oil to sulfuric acid which corrodes metal parts. Fuel additives must be included to resolve the vanadium problems (Deffeyes, 2005). More difficult extraction of heavy oil and vanadium concentration in heavy oil increase the production costs of heavy oil relative to conventional oil.

In addition to being more expensive, both of these solutions fail to solve the United States trade deficit issue. One source of oil in abundance in the United States is oil shale, but recovering oil from oil shale has several drawbacks. These include the expense involved, paraffin crystallization, the use of water in the processing, and the volume increase from the shale retort process. These issues are not insurmountable and need to be looked into in depth as possible solutions to the oil supply problem. There are 1.5 trillion barrels of oil available in United States' oil shale. That amount of oil could last under current United States' consumption for over a century. Yet, despite extensive efforts, oil from oil shale has yet to become commercially attractive (Deffeyes, 2005).

Other options for increasing production include offshore oil drilling and drilling in the Alaska National Wildlife Refuge (ANWR). There are 86 billion barrels estimated offshore with 18 billion barrels under a moratorium on drilling. The available drilling sites are not being drilled due to the economics of deep water drilling (Wangsness, 2008). With world demand of 85 million barrels a day, removing the moratorium would extend the forecast for peak oil by only 7 months. ANWR is expected to hold approximately 10 billion barrels, which is even less than that expected from offshore drilling (MSNBC, 2004). ANWR and offshore drilling could reduce United States' oil imports in the short term, but would only slightly delay the arrival of world peak oil.

The failure of the United States to address peak oil in 1970 has led to a rising trade deficit. Oil now accounts for 449 billion dollars of the United States 717 billion dollar trade deficit (time-blog, 2008). The United States' trade deficit is particularly vulnerable to the price of oil (see Figure 7). With constrained global supply and growing global demand, the United States' trade deficit would be negatively impacted by rising oil prices. The United States' economy is strongly coupled to the price of oil.

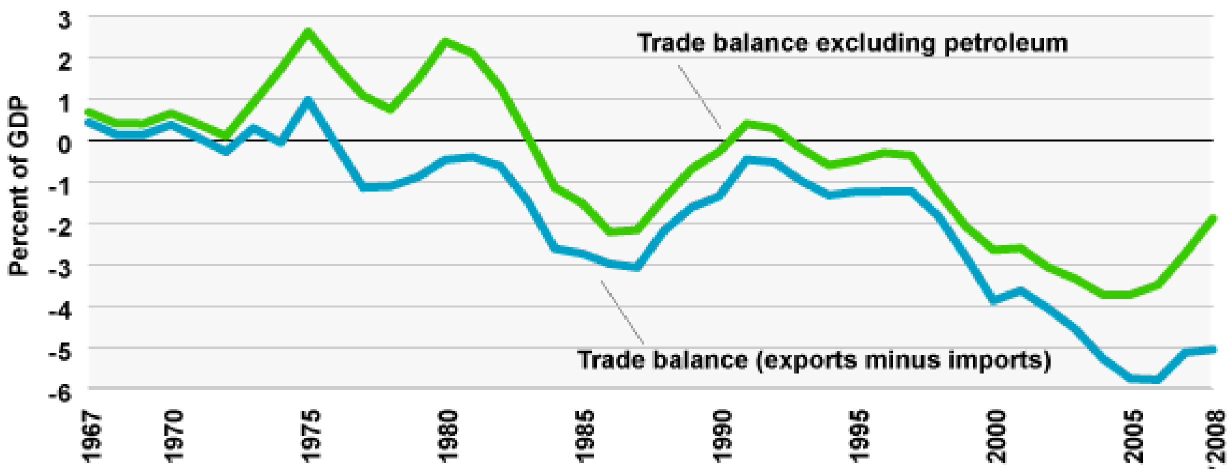

Figure 7
Trade Deficit and Oil (time-blog, 2008)

In addition to the impact of oil prices on the United States' trade deficit, oil prices impact oil demand. As global oil prices rise, more individuals around the world fall below the poverty line (Korin, 2008). Oil is used in food production and oil price increases put positive pressure on food prices. Higher food prices force more people below the poverty line. Greater poverty increases instability around the globe (Rice, 2006). Rising instability expands the need for stability operations. Increasing stability operations will increase the Air Mobility Command demand for fuel. Rising demand for fuel increases oil prices. This positive feedback loop leads to a cycle of increasing instability. The consumption of oil also has the negative consequence of increasing carbon dioxide production. The fear is that increased carbon dioxide production will lead to rising global temperatures, which could have the negative consequences of rising sea levels, acidification of the oceans, desertification and the increased intensity of hurricanes. Since the United States is the leading consumer of oil by a factor of three, the world might blame the United States for the problems caused by rising global temperatures.

Air Mobility Command needs a fuel to replace JP-8 that will not contribute to the trade deficit. The options available are synjet from biofuels, synjet from coal (e.g., from Fischer-

Tropsch), liquid methane and liquid hydrogen. From studies completed in the 1970's and 80's aircraft were designed to take advantage of the properties of synjet, liquid methane and liquid hydrogen. These aircraft designs were required to meet given capabilities. Daniel Brewer, in his 1991 book *Hydrogen Aircraft Technology*, compared the different fuels based on several factors. Two of the factors highlighted suggest the superiority of liquid hydrogen as a future aircraft fuel. These factors include aircraft gross weight and the energy required to produce the fuel for a given capability. The result of comparing aircraft weight for a given capability favors liquid hydrogen. It is important to note that the relative advantage of hydrogen grows with aircraft capability (see Figure 8). In addition to aircraft gross weight, the economics of fuel production should be taken into account.

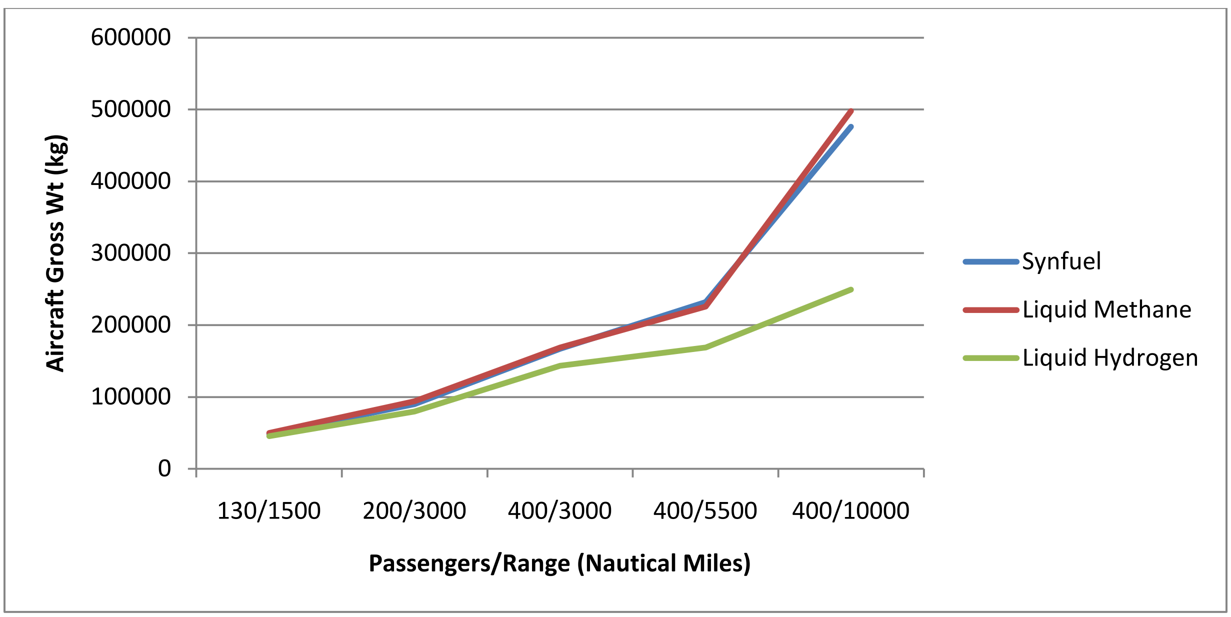

Figure 8
Effect of Fuel on Aircraft Gross Weight for Designed Capability (Brewer, 1991)

To determine the economic feasibility of the different fuels, the energy resources required to produce the fuel for each capability was charted. The energy required was expressed in tons of coal. Similar to the aircraft gross weight chart, the energy required to produce the fuel to achieve a certain capability was the smallest for liquid hydrogen. The advantage for liquid hydrogen increased as the aircraft capability increased (see Figure 9). Since less energy is required to produce liquid hydrogen, liquid hydrogen should be more economically feasible. Both the aircraft gross weight advantage and the energy resources required advantage suggest that liquid hydrogen might have potential as a future JP-8 replacement.

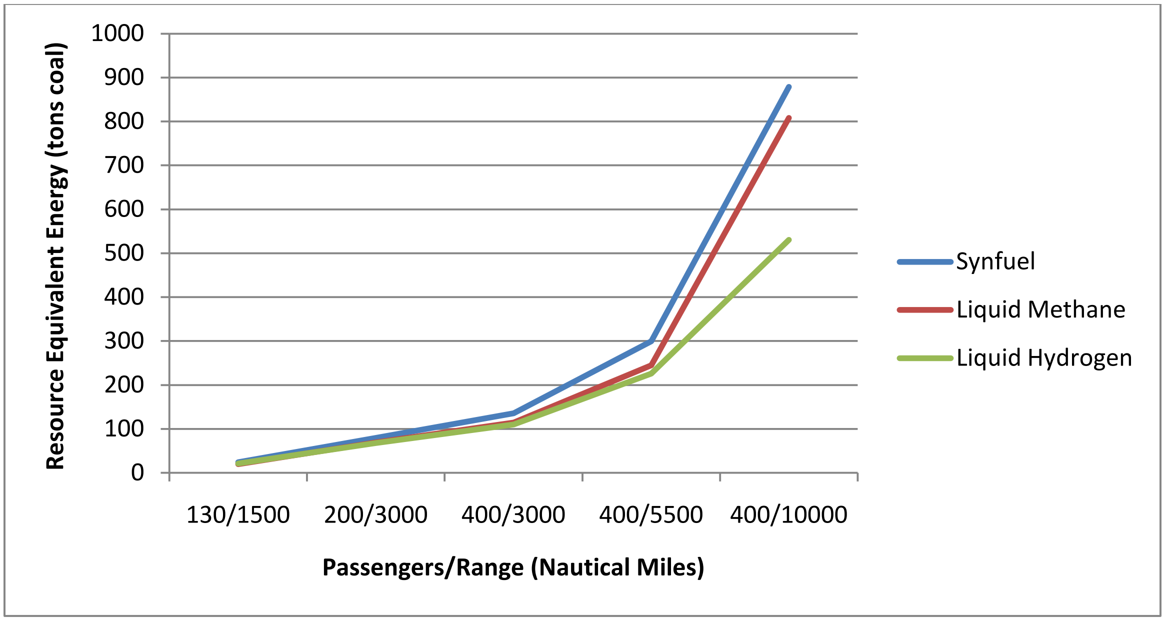

Figure 9
Effect of Fuel on Resource Energy Equivalent (Brewer, 1991)

There are two huge benefits to synfuel. The first is that current aircraft systems do not need to be modified to use it. The second is that the infrastructure is currently set up around the world to transport and deliver synfuel. Yet, synfuel is a heavier fuel than hydrogen as can be seen by the effect of fuel on aircraft gross weight. Synfuel requires more energy to produce the same capability than hydrogen, especially for larger aircraft. Synfuel is an excellent solution in the short term to help reduce the trade deficit, but it does not solve the greater problem of sustainability and is detrimental to the environment. Methane is a middle of the road solution that is not optimal for aircraft gross weight.

Research Questions

The key research questions that will be answered by this research include:

1. Can liquid hydrogen be a replacement fuel for Air Mobility Command aircraft?
2. What are the advantages and disadvantages of liquid hydrogen as a JP-8 replacement?
3. What are the costs associated with liquid hydrogen and its infrastructure?
4. How should the United States implement the transition to liquid hydrogen?
5. What is the best propulsion system for liquid hydrogen using available technology?

Hypotheses

The critical hypotheses that will be tested by this research include:

1. Liquid hydrogen is a feasible fuel for AMC aircraft.
2. Liquid hydrogen is a superior fuel to JP-8.
3. The costs of inaction outweigh the costs of making the transition to liquid hydrogen.
4. The transition should be phased from large aircraft (C-5) replacement toward small aircraft (C-130) with the exception of tankers, which will not be the focus of this research.
5. Hydrogen turbines turning generators powering high temperature superconducting motors would be the best propulsion system of available technologies.

Research Focus

The research focus is the transition of AMC from JP-8 fueled aircraft to liquid hydrogen fueled aircraft. The liquid hydrogen will be produced via renewable energy technologies. An in depth analysis into the transition costs will be contrasted against the costs of inaction.

Methodology

Current monthly oil consumption statistics by base will be converted to hydrogen requirements based on a gross weight conversion factor. These hydrogen requirements will be used to determine the storage, liquefaction and production costs associated with hydrogen infrastructure.

Limitations

Hydrogen aircraft are not in widespread use, so the in depth analysis required for individual geographical locations is beyond the scope of this research. The models used will apply generic models for production and liquefaction and scale those models up to meet the required demand. If the Air Force chooses a transition to hydrogen aircraft, the generic models of this research need to be updated with site specific plans. Although hydrogen is in widespread use and there exists a great deal of familiarity with it in space shuttle applications, it would be cutting edge in large commercial aircraft. Hydrogen commercial aircraft have been designed to exacting details in the 1970s, but prototype testing has never been accomplished.

Implications

Transitioning to hydrogen aircraft can lead to energy independence for Air Mobility Command. AMC's energy independence would contribute to the reduction of the United States' trade deficit. Hydrogen aircraft would have the potential to reduce carbon dioxide emissions, toxic jet fuel pollutants and noise pollution. The use of a cryogenic fuel has a vast assortment of advanced military uses due to the superconducting properties of certain materials at liquid hydrogen temperatures. Hydrogen as an aircraft fuel also provides options for operations at speeds far in excess of those that can be obtained with JP-8.

II. Literature Review

History of Hydrogen

Hydrogen has been used in powered flight since 1852, when Henry Giffard flew a hydrogen filled airship from the hippodrome in Paris (see Figure 10). Building upon Giffard's discovery, in 1872, Paul Haenlein designed a hydrogen filled airship powered by an internal combustion engine that used the hydrogen from within its own lifting cells. Yet, these airships were unable to provide round trip transportation. In 1884, the first airship capable of returning to its point of departure was constructed by Charles Renard and A. C. Krebs. These advances paved the way to the first commercial airship, the LZ-1, in 1900. Count Ferdinand Von Zeppelin built the LZ-1 as the first rigid airship. By 1911, Commercial air operations were under way in Germany with 5 airships. By 1916, these hydrogen filled airships made 1,600 flights carrying 37,250 people without incident (Brewer, 1991).

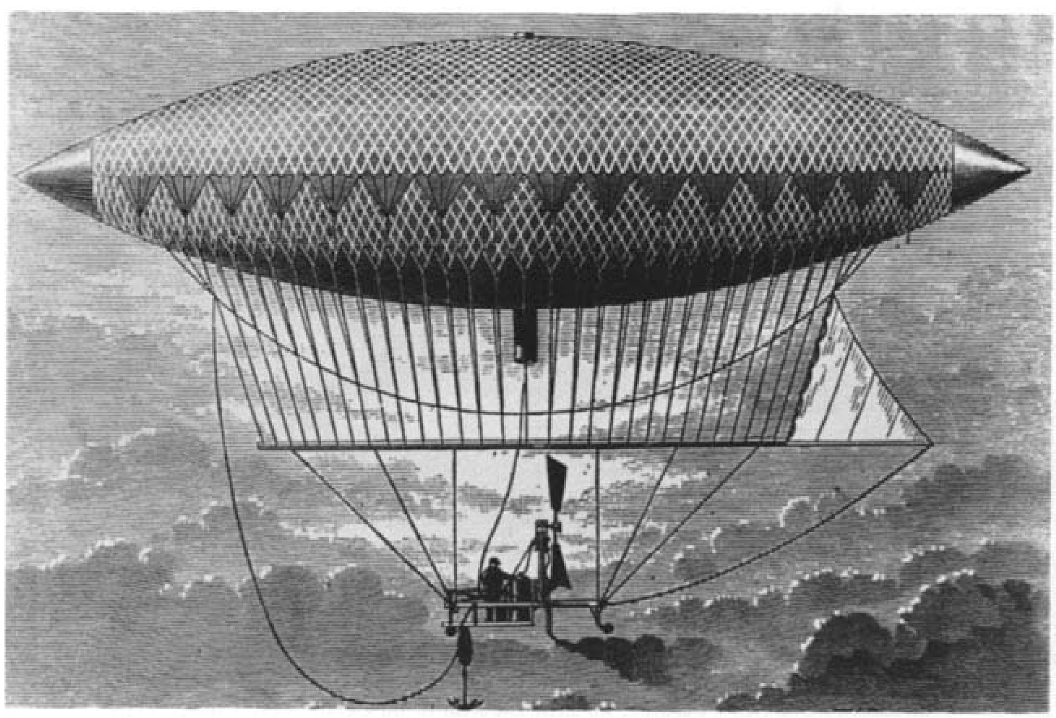

Figure 10
Giffard's Airship (Livescience, 2009)

The next major development in airships occurred in 1928 with the LZ-127 (see Figure 11). This hydrogen filled airship flew over 1 million miles carrying more than 13,000 passengers and 118 tons of cargo on 590 flights over 9 years. The Hindenburg was the second to last of the LZ line. The LZ-129, the Hindenburg, made history when it caught on fire and crashed in Lakehurst, NJ in May 1937. Of the 97 people on board, 35 lost their lives. Most of the fatalities were caused by ground impact after jumping from the airship. At that time, these were the first passenger fatalities in commercial airship history (Brewer, 1991). Even with the inclusion of this one tragedy, commercial hydrogen airships had an impressive safety record, despite their flimsy construction.

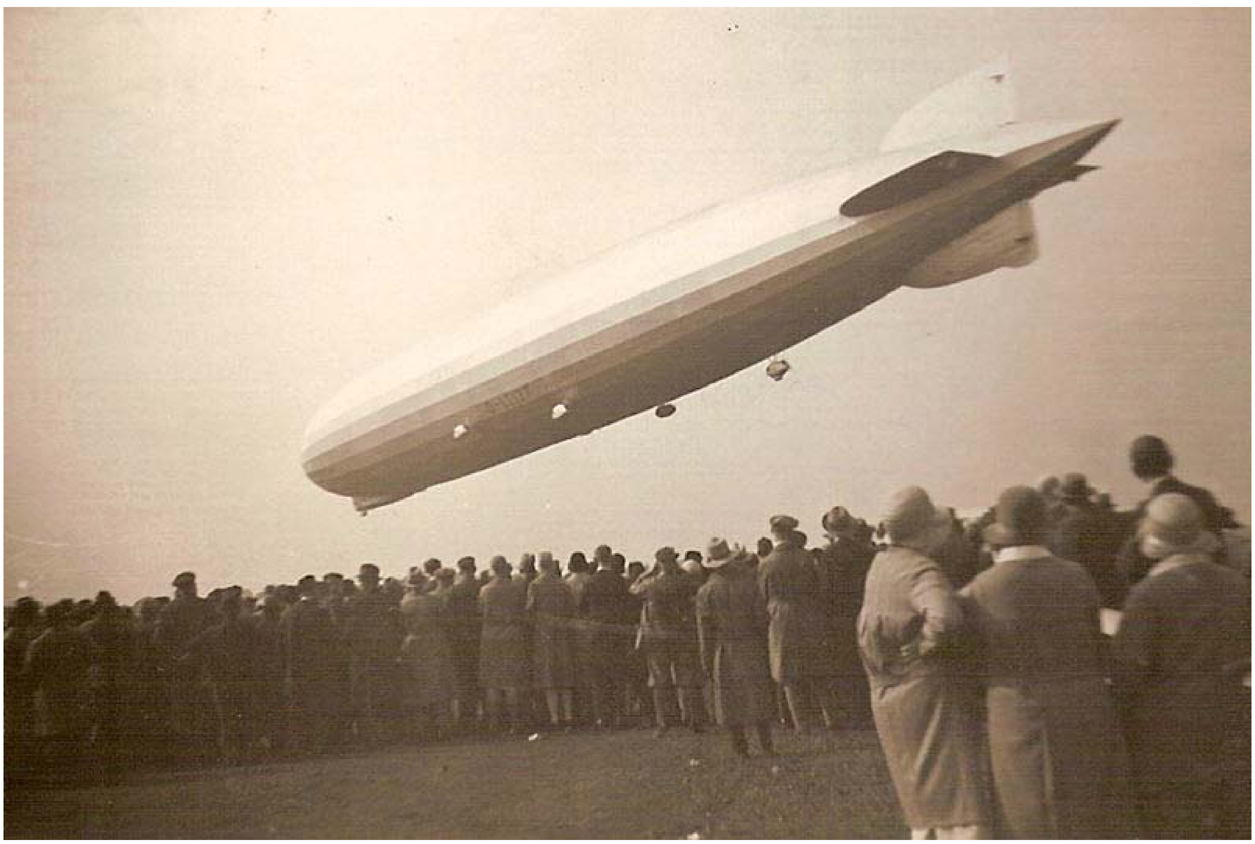

Figure 11
LZ-127 Graf Zeppelin (Wikipedia, 2009)

In 1954 to 1955, Lockheed designed the prototype, CL-400, as a hydrogen fueled aircraft capable of cruising at 2.5 Mach at 100,000 ft (see Figure 12). The aircraft was never built due to the lack of liquid hydrogen infrastructure around the world. Lack of hydrogen infrastructure is a recurring theme in the termination of hydrogen aircraft programs. Despite the program's cancellation, the program developed the technology necessary to prove the feasibility of a hydrogen fueled plane. The testing also showed that liquid hydrogen could be handled as easily and safely as hydrocarbon fuel (Brewer 1991).

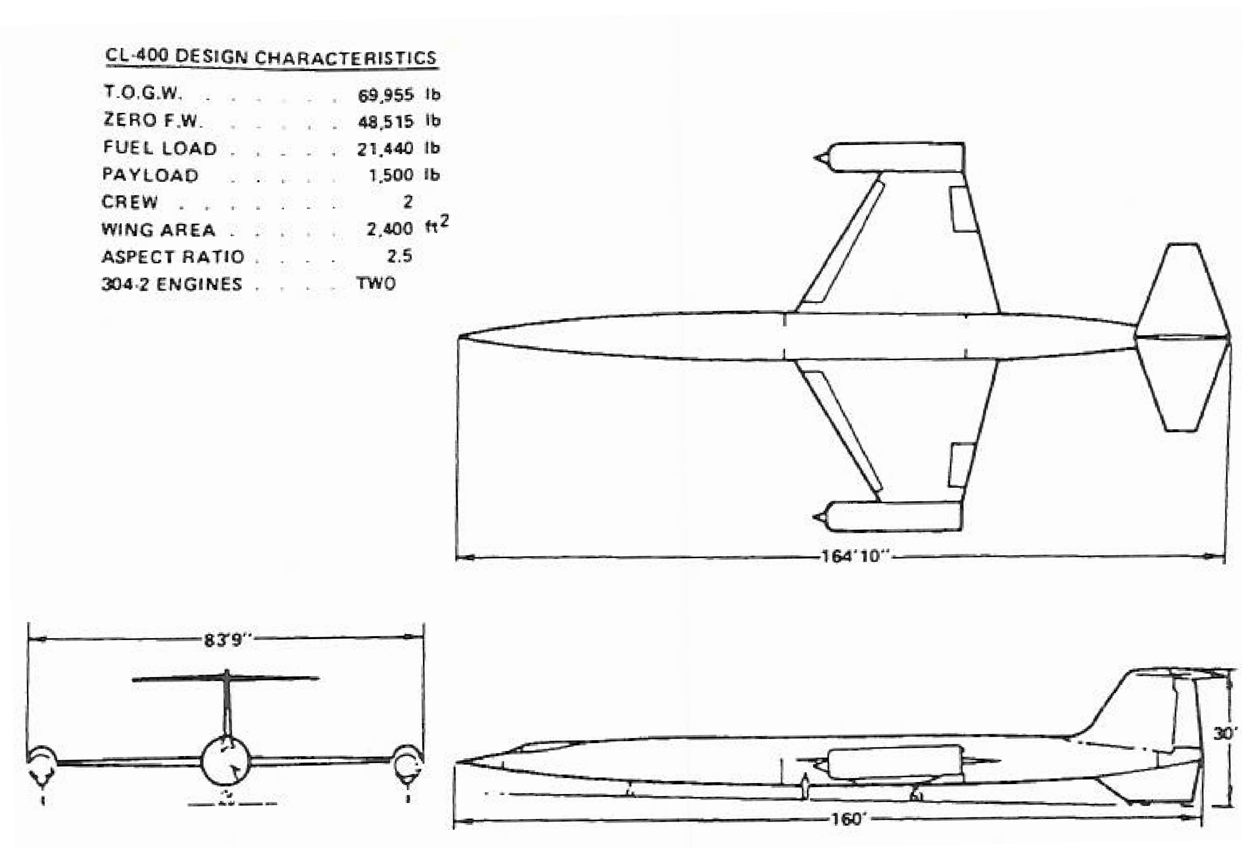

Figure 12
CL-400 2.5 Mach Hydrogen Aircraft (Brewer, 1991)

From 1956 to 1959, liquid hydrogen was tested as the fuel source on one of the two engines of a modified B-57 jet (Browne, 2008). During the tests, the performance of the engine was found to be smooth and reliable (see Figure 13). The aircraft flew to 50,000 ft and .75 Mach. The hydrocarbon fuel was stopped and the hydrogen fuel was routed to the same combustion chamber. Hydrogen was burned for 21 minutes and then the engine switched back to hydrocarbon operation. No operational safety problems with the hydrogen fuel system were encountered. The 1950's were an important period in validating the feasibility of hydrogen aircraft technology and made the United States a world leader in this area of research.

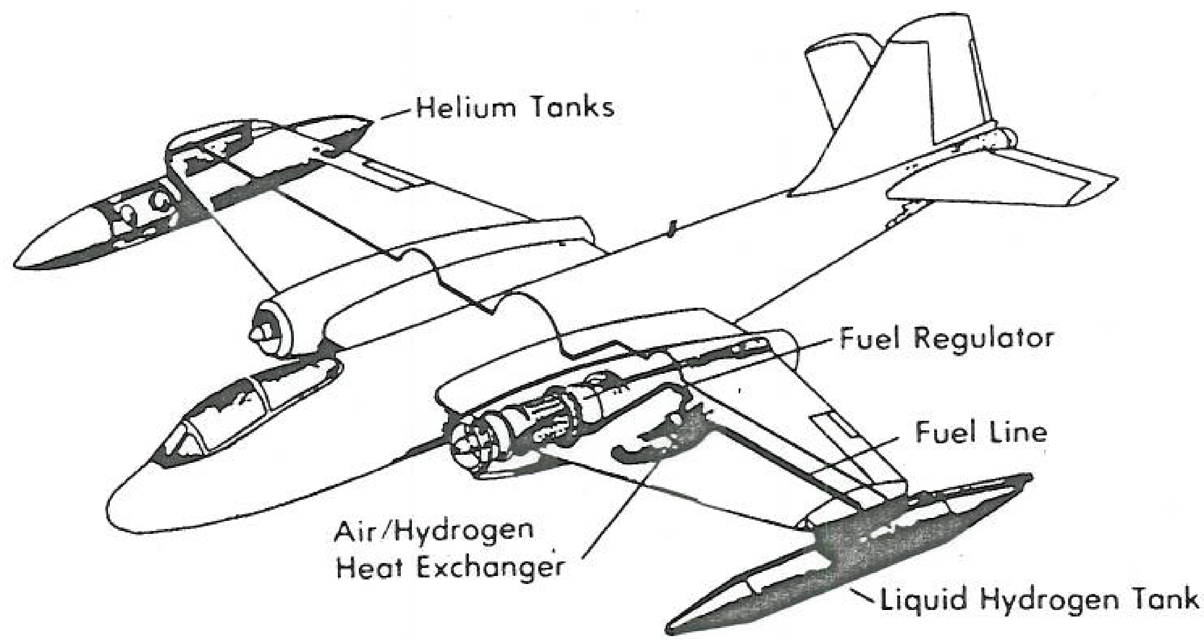

Figure 13
B-57 Hydrogen Aircraft Used in 1956 NACA Test (Brewer, 1991)

In 1963, the first launch of a liquid hydrogen and liquid oxygen rocket engine took place. Hydrogen replaced the lubricants as the heat sink for the rocket. The Saturn V rocket which launched the module for the United States lunar astronauts used over 200,000 lbs of liquid hydrogen. During the Apollo program there was never a failure of the hydrogen fueled rocket engines. In 1973, NASA began to study hydrogen aircraft in great detail. NASA studied both supersonic and subsonic aircraft. The studies were extremely detailed and covered every component part, including the airport infrastructure necessary to fuel the aircraft. The results of these studies suggested that liquid hydrogen was not only a feasible choice for air mobility, but that it was the preferred alternative to hydrocarbon fuel. Brewer, one of the authors of the NASA studies comparing synjet, liquid methane and liquid hydrogen aircraft states, "The LH2 design is superior in nearly every basis of comparison. Its gross weight, fuel weight and operating empty weight are all significantly less" (Brewer, 1991). Yet, the price of oil was so low at the conclusion of the study that the decision was made to continue with hydrocarbon fuels.

The aircraft designs used in these studies illustrate the need for a slightly larger and longer fuselage for hydrogen aircraft. Also note that the hydrogen tanks are located inside the fuselage. Most aircraft carry their fuel in their wings. The reason for the liquid hydrogen tanks being placed in the fuselage is because liquid hydrogen needs to be maintained at cryogenic temperatures. To minimize heat transfer, the tanks need to have a minimal surface area to volume ratio. The best geometric shape to achieve the best ratio is a sphere, and the next best option is a cylinder. Therefore hydrogen aircraft tend to have large cylindrical tanks in the fuselage. Figure 14 is a graphic representation of the liquid hydrogen .85 Mach passenger aircraft used in the study and Figure 15 is the design drawing for that aircraft. Also note in the design drawing that the tanks are located on both sides of the passengers due to weight and balance concerns.

Figure 14
.85 Mach Liquid Hydrogen Passenger Aircraft (Brewer, 1991)

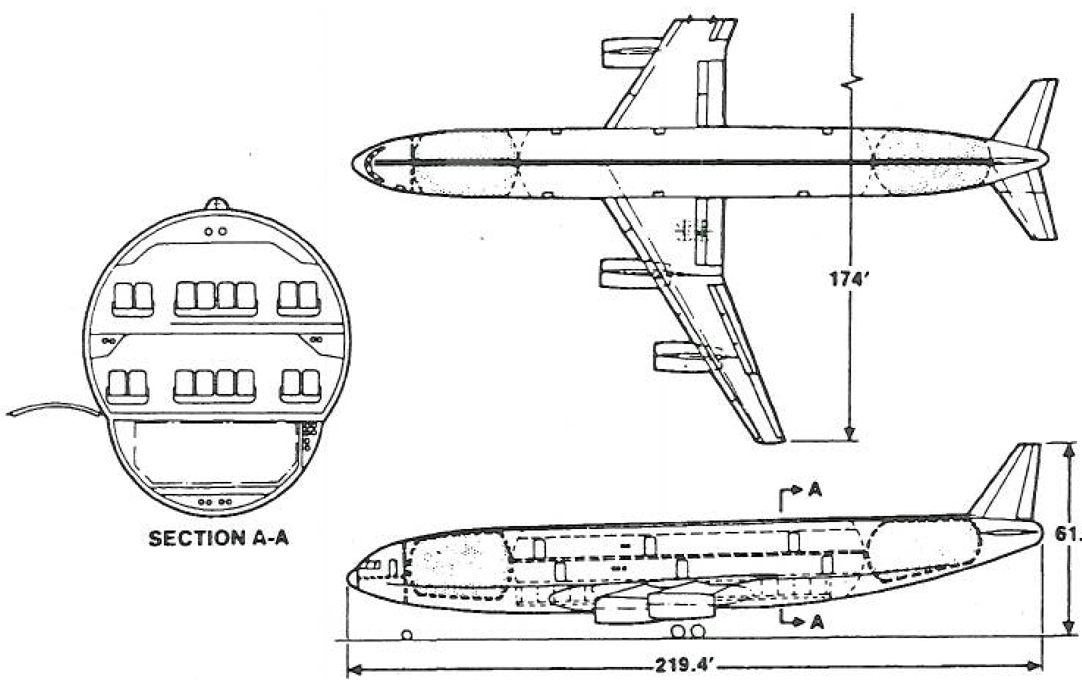

Figure 15
.85 Mach Liquid Hydrogen Passenger Aircraft (Brewer, 1991)

In addition to the passenger aircraft, the study also looked into the design of a cargo aircraft (see Figure 16). Due to the inherent difficulties of side loading an aircraft, the design shifts from tanks being located fore and aft to multi lobe tanks located above the cargo compartment.

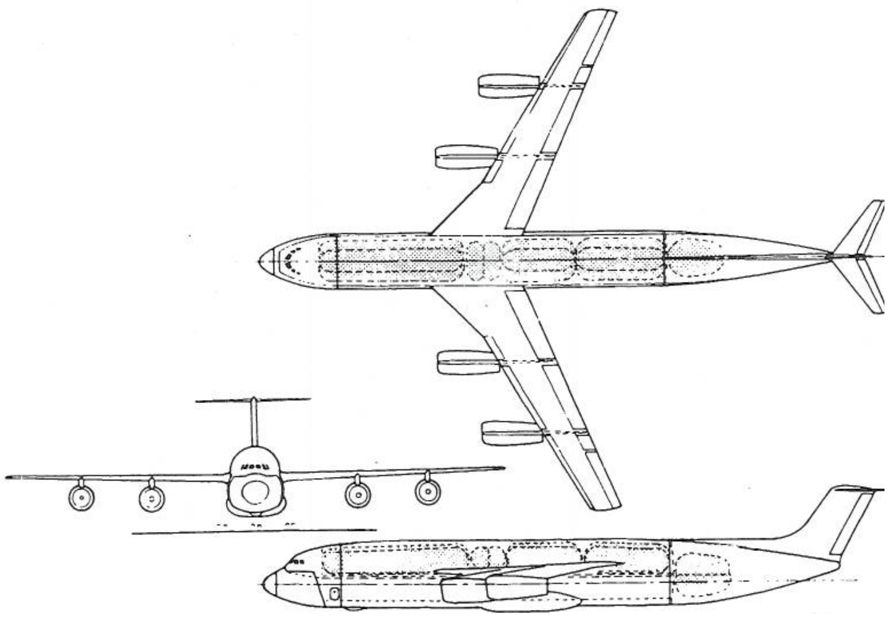

Figure 16
.85 Mach Liquid Hydrogen Cargo Aircraft (Brewer, 1991)

Speed is essential to successful military operations. Yet, as aircraft reach speeds far beyond the speed of sound they tend to have issues with the heating of their leading edges. To combat these high surface temperatures, a heat sink is often required. Hydrogen makes an excellent heat sink due to its high specific heat. The NASA studies included analysis on both a 230 passenger 2.7 Mach liquid hydrogen aircraft (see Figure 17) and a 6 Mach passenger aircraft (see Figure 18). It is important to note how the size of the aircraft increases with speed. The .85 Mach, 2.7 Mach and 6 Mach passenger aircraft are 220 feet, 328 feet and 390 feet respectively. Contrast these dimensions against a Boeing C-17 at 174 feet and a Boeing 747-400 at 211 feet.

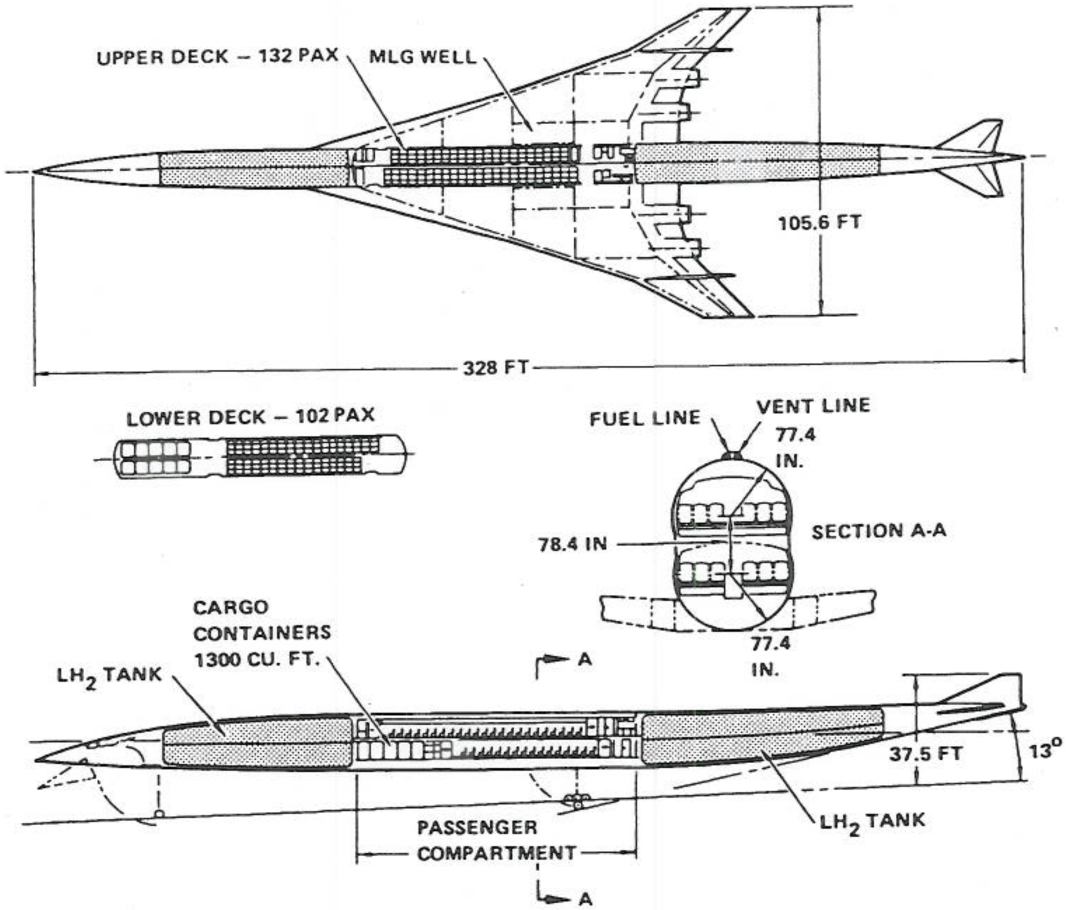

Figure 17
2.7 Mach Liquid Hydrogen Passenger Aircraft (Brewer, 1991)

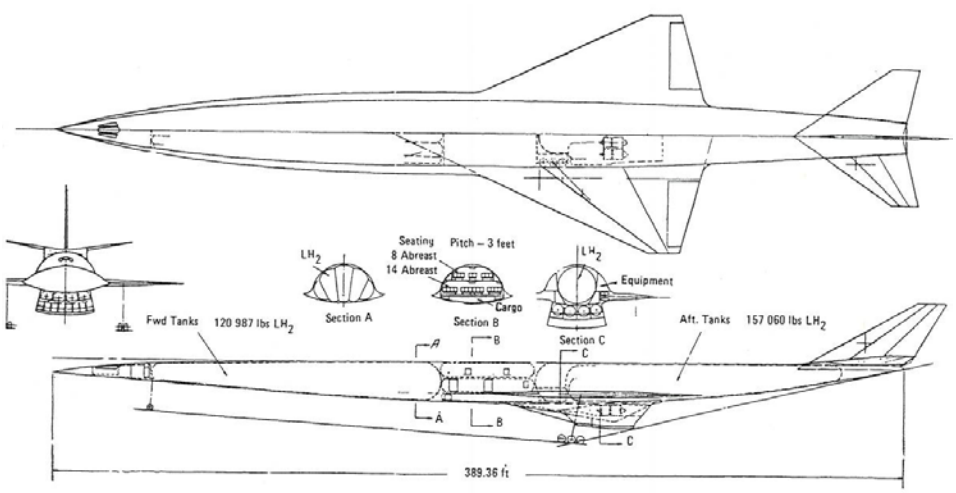

Figure 18
6 Mach Liquid Hydrogen Passenger Aircraft (Brewer, 1991)

The NASA studies covered a wide range of aircraft capabilities. Due to the exacting details of the 1970's studies, they remain one of the top sources of information available on hydrogen aircraft technology. The United States was not alone in the pursuit of alternative aircraft fuels. In 1988, a Tupolev TU-155 was modified to use liquid hydrogen in one of their engines and flew 21 minutes on the fuel (see Figure 19). The Russians were able to achieve the same technological hurdle that the United States achieved in the 1950's with a much larger aircraft.

Figure 19
1988 TU-155 Liquid Hydrogen Aircraft (Tupolev, 2009)

This achievement marked the beginning of what later became the Cryoplane project. The Cryoplane project supplemented the work that NASA had done in the 1970's to add validity to the technological capability of liquid hydrogen aircraft. The design of the TU-155 liquid hydrogen test aircraft included a small internal tank (see Figure 20). The NASA studies concluded that the tank should not be internal. The studies recommended a tank that was part of the aircraft structure to help reduce weight. It is also important to recognize that in the design of the NASA version, the tanks and fuselage were bigger and longer.

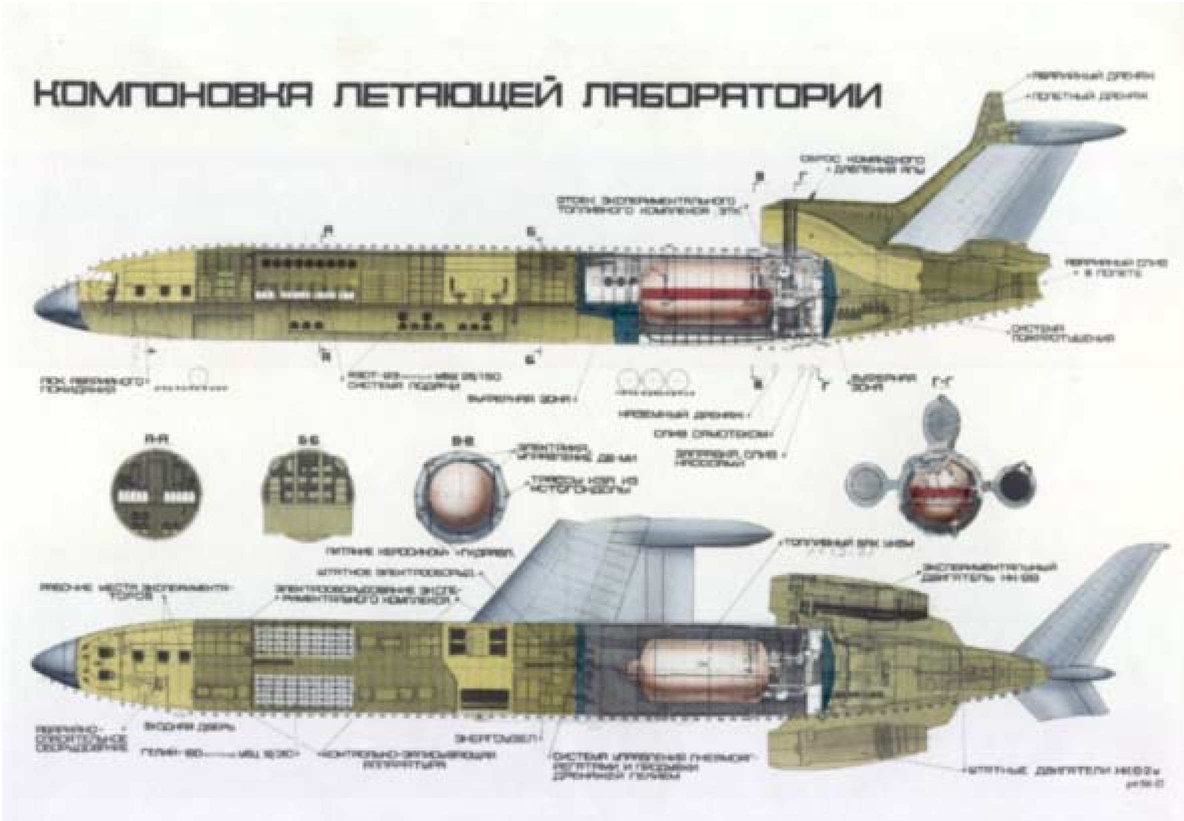

Figure 20
TU-155 Liquid Hydrogen Aircraft Design (Tupolev, 2009)

Not only were the Russians able to demonstrate the feasibility of liquid hydrogen aircraft technology, they were able to advance the knowledge of the support infrastructure required to fuel a liquid hydrogen aircraft. They built an advanced cryogenics complex to fuel the aircraft (see Figure 21). From this perspective, the Russians advanced beyond the United States' accomplishments of the 1950's. Their cryogenics refueling operation was of a greater scale than the United States. It could be argued that the space shuttle fueling operations more than compensate for the Russian liquid hydrogen support facility.

Figure 21

TU-155 Liquid Hydrogen Distribution Complex (Tupolev, 2009)

While the Cryoplane project was progressing, there were several advances in the United States that are of importance. In 1988, an aviation enthusiast in the United States flew the first powered flight in a small single engine aircraft using only hydrogen as fuel. Then in 1996, NASA selected Lockheed Martin Skunk Works to design a single stage to orbit vehicle. The X-33 was the prototype design for this concept (see Figure 22). The design was rocket based, but the cryogenic hydrogen storage used in the design and the reusable nature made the design directly applicable to hydrogen aircraft. After the aircraft was 85% complete, the program was cancelled in 2001. The primary reason for the cancellation was the weight of the composite liquid hydrogen tank exceeding requirements. The engineers had originally suggested an aluminum-lithium alloy liquid hydrogen tank similar to the space shuttle since the technology for a composite tank was not mature. Although the composite tank was lighter in the skins, it was heavier in the joints than the aluminum tank. The overall weight of the composite tank was heavier (NASAspaceflight, 2006).

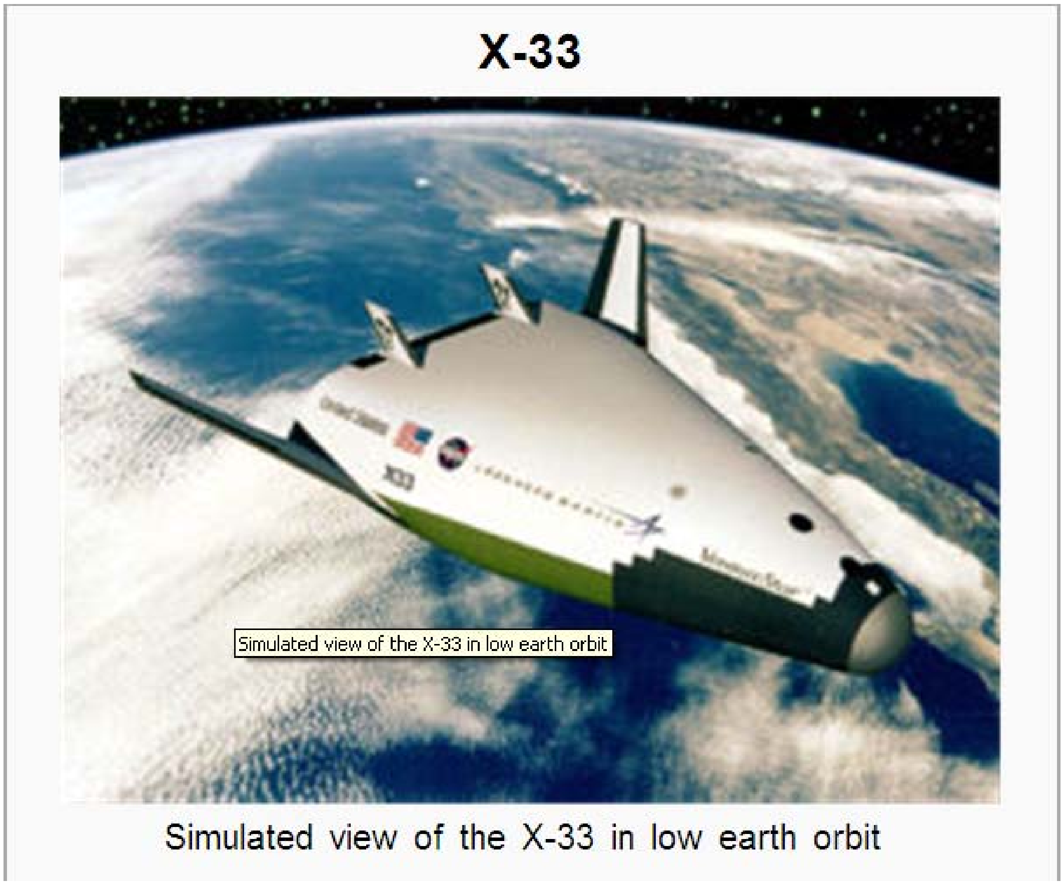

Figure 22
X-33 Reusable Space Vehicle

Work continues on cryogenic composite tanks for the Air Force in their Fully Reusable Access to Space Technology (FAST) program and the technology has advanced significantly since the X-33 (Mallick, 2007). In 2002, NASA performed a study to determine the effect on noise and aircraft emissions of above the wing mounted hydrogen fueled engines. The study concluded that aircraft emissions and noise could be greatly reduced (Guynn, 2002). The liquid hydrogen aircraft is the larger one below the conventional design (see Figure 23).

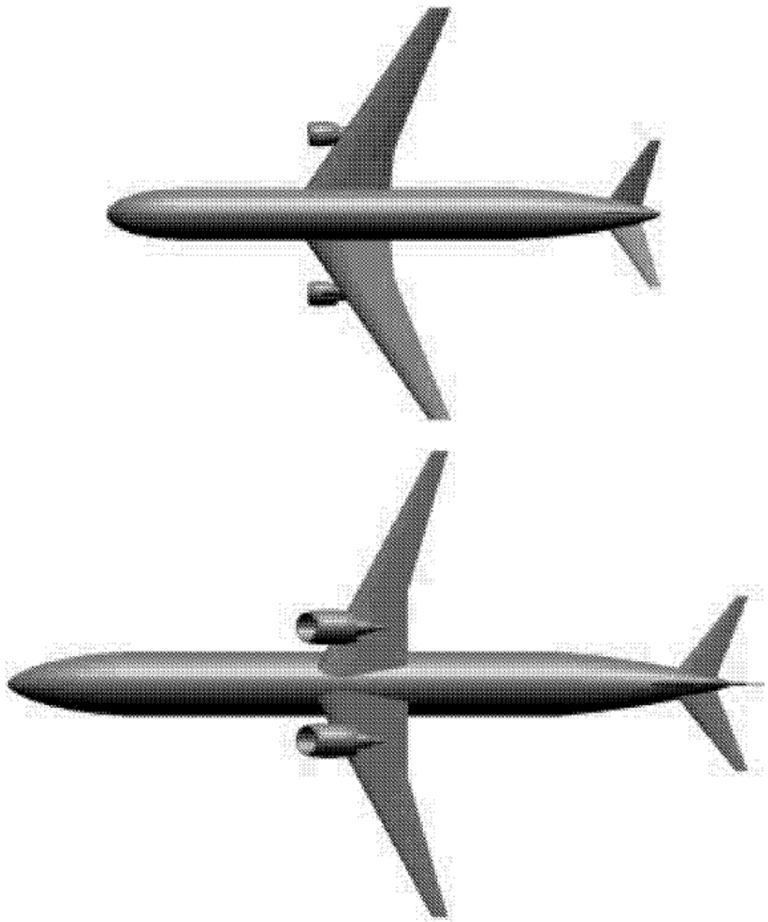

Figure 7. Size comparison of Concept A and conventional baseline.

Figure 23

Baseline Aircraft on Top vs Liquid Hydrogen Aircraft on Bottom (Guynn, 2002)

While hydrogen aircraft technology in the United States progressed at a slow pace, the Cryoplane project allowed a European-Russian alliance to catch up to the work of NASA in the 1970s. The Cryoplane project was a joint project between Daimler-Benz Aerospace Airbus and Tupolev to develop commercial aircraft using liquid hydrogen instead of jet fuel. The study was initiated due to the economics of rising fuel prices and jet fuel's impact on air pollution, greenhouse gas emissions and ozone depletion (Schmidtchen, 1998). The Hydrogen Aircraft and Airport Safety Report shows the economic impetus behind the program (see Figure 24).

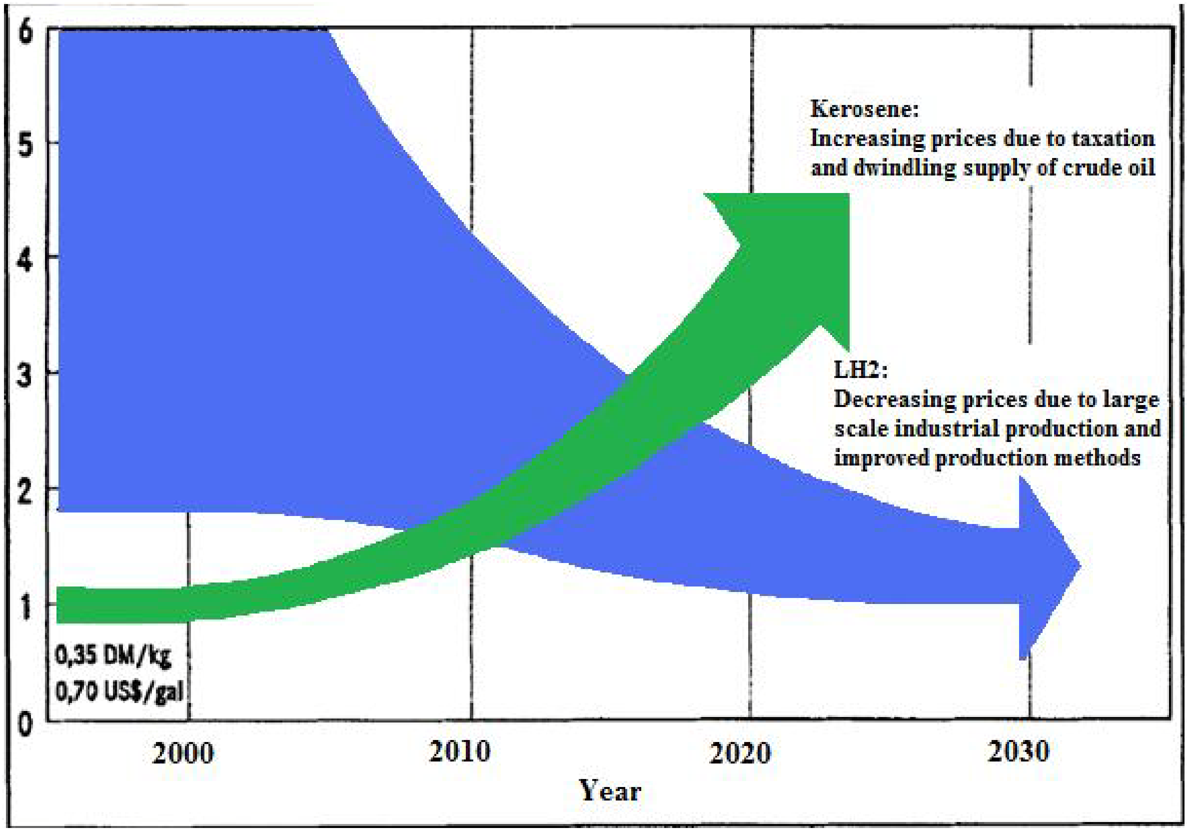

Figure 24

Cryoplane Project Hydrogen vs Jet Fuel Price Trends (Schmidtchen, 1998)

The Cryoplane project began in 1990. From 1990 to 1993, a feasibility study of a modified A310 to run on liquid hydrogen was conducted (see Figure 25). From 1992 to 1996, the Euro-Quebec Hydro-Hydrogen Pilot Project combustion chamber tests occurred. From 1994 to 1999, Tupolev, Airbus and Air Liquide collaborated on liquid hydrogen tank tests. From 1995 to 1998, Germany and Russia collaborated on a demonstrator aircraft based on a Dornier 328. From 2000 to 2002, a systems analysis of liquid hydrogen aircraft implementation was conducted. The results of the systems analysis illustrated the feasibility of hydrogen aircraft technology.

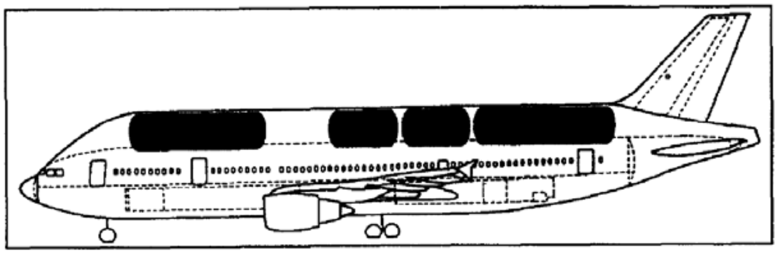

Fig. 7. Cryoplane tank arrangement, side view.

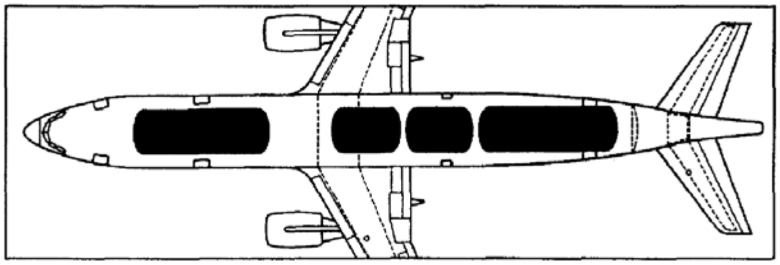

Fig. 8. Cryoplane tank arrangement, top view.

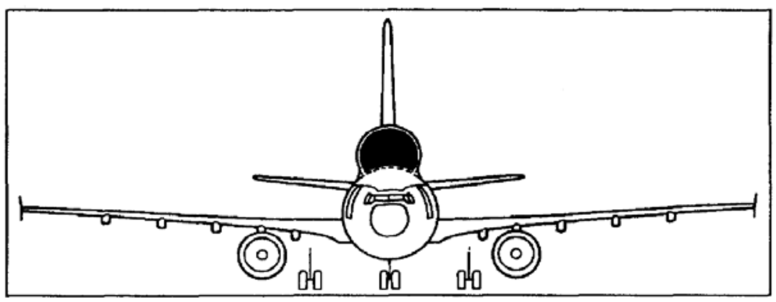

Fig. 9. Cryoplane tank arrangement, front view.

Figure 25

Modified Airbus A-310 to Liquid Hydrogen (Schmidtchen, 1998)

The modified A310 differed from the 1970s NASA designs in several important aspects. First, the tanks were not located fore and aft, but were instead located above the passengers. This design is not optimal for multiple reasons. First, the design adds drag due to a larger frontal cross section. In addition to adding drag, the design contributes a substantial weight over the 1970s NASA designs. The added weight is due to not using integral tanks with aircraft structure. Modifying an aircraft designed for jet fuel to run on liquid hydrogen fails to take advantage of liquid hydrogen's unique properties.

The Cryoplane study results in 2003 stated that "hydrogen could be a suitable alternative fuel for future aviation" (Airbus, 2003). The study suggested some hurdles need to be overcome, including missing materials, parts, components and engines for hydrogen aircraft. The study also detailed the problems associated with a lack of a liquid hydrogen infrastructure. The study concluded that further R&D has to be performed. The United States is not alone in the search for alternative fuels. The success of commercial aviation in the future could hinge on who makes the correct bet on the next alternative fuel. While the Cryoplane project was making impressive progress, the United States took hydrogen propulsion to the next level.

This achievement in hydrogen propulsion was made by NASA's X-43 program. On November 16, 2004, the NASA X-43A set a new speed record of 9.8 Mach (see Figure 26). The air breathing engine was hydrogen powered and based upon scramjet technology. The supersonic combustion ramjet engine was powered by roughly 1 kilogram of hydrogen to reach its top speed. The future variants of the X-43 were based on more conventional fuels. The military implications of this achievement include enhanced global strike and rapid logistics.

Figure 26
X-43 Scramjet (Dfrc, 2009)

Following the successful X-43 unmanned flight, the next major hydrogen flight achievement was by Aerovironment. The Aerovironment Global Observer aircraft took off on its maiden flight on May 26, 2005 (see Figure 27). Over a couple of test flights, the aircraft reliably flew for over an hour. The unmanned liquid hydrogen aircraft had the capability to climb to 65,000 ft and stay aloft for 24 hours on a full tank of liquid hydrogen (Barrett, 2005). The propulsion system is a fuel cell powering an electric motor. The flight also demonstrated the feasibility of mobile liquid hydrogen fueling operations. The Global Observer is still available today with the same altitude capability, but an increased endurance of 7 days. The current version continues to be powered by liquid hydrogen (AVINC, 2008).

Figure 27
Global Observer Aircraft (Avinc, 2009)

Boeing is also in development of a liquid hydrogen unmanned aircraft and had a successful engine test on October 24, 2007 (Boeing, 2007). In 2007, the Georgia Institute of Technology built a demonstrator aircraft to test the performance of a hydrogen fuel cell aircraft. The tests provided data for comparison of fuel cell aircraft performance to that of conventional aircraft (Bradley, 2007). In 2008, Boeing constructed the first hydrogen manned aircraft to use a fuel cell (see Figure 28). The plane was capable of flying for 45 minutes, but the tests were for only half that amount of time. This manned aircraft can be seen below.

Figure 28
Boeing Manned Fuel Cell Aircraft (Bbc, 2009)

The history of hydrogen aircraft is filled with a multitude of successful tests and optimistic projections. The primary hurdle to hydrogen aircraft advancement has been the economics of oil. The infrastructure for the delivery of oil and the aircraft platforms designed specifically for that fuel are in widespread use. A transition to hydrogen aircraft was hard to justify at low oil prices. Yet, if oil prices continue to rise and hydrogen prices continue to fall, the failure to transition to hydrogen will be hard to justify. Hydrogen aircraft research was conducted in the United States, Europe and Russia. The details of that research will be examined in detail in the following comparison between hydrogen and JP-8.

Hydrogen vs JP-8

Hydrogen is the most abundant element in the universe. On the planet Earth, nearly all of that hydrogen is tied up in other molecules. One method for obtaining hydrogen that does not lead to resource depletion is electrolysis. To obtain hydrogen from electrolysis requires two inputs, electricity and water. Any location that can provide electricity from wind, solar, hydro or geothermal and has water can produce hydrogen. Thus, at least one of the resources to make hydrogen is available in every congressional district of the United States. Oil on the other hand is not easily available, as can been seen by the amount of oil that is imported into the United States.

When hydrogen is combusted or enters a fuel cell, the primary byproduct is water. This contrasts to JP-8, which when combusted produces carbon dioxide, water and nitrous oxide. Carbon dioxide production causes concern due to the potential contribution toward global warming. Using water to make hydrogen, which is combusted back into water, is a completely sustainable cycle. Oil use on the other hand leads to depletion and rising costs. Thus, from a perspective of sustainability, hydrogen is truly a superior fuel. Sustainability is important to the stability and future prosperity of the United States for it enables more accurate forecasting of future energy costs. In addition to availability and sustainability, hydrogen will be contrasted with JP-8 with respect to chemical properties, environmental impact, economics, safety, aircraft design, military applications and political considerations.

Table 1
(Brewer, 1991)

Hydrogen vs JP-8		
Chemical Properties		
Item	**Hydrogen**	**JP-8**
Molecular Weight	2.016	168
Low Heat of Combustion (KJ/g)	120	42.8
Liquid Density (g/cm^3) H2 at normal boiling point/JP-8 at 283 K	0.071	0.811
Specific Heat (J/(g*K))	9.69	1.98
Boiling Point at 1 ATM (Degrees F)	-423	332-510
Freezing Point (Degrees F)	-434	-41

Chemical Properties

The heat of combustion of hydrogen is 2.8 times the energy per unit mass of JP-8. Despite the energy per mass superiority of hydrogen over JP-8, liquid JP-8 is 11.4 times the density of liquid hydrogen. This density advantage gives JP-8 four times the energy per unit volume compared to liquid hydrogen. Hydrogen has 4.9 times the heat carrying capacity of JP-8 when contrasting their specific heat. Hydrogen must be cooled below -423 degrees Fahrenheit to remain liquid, while JP-8 will remain liquid from -41 to between 332 and 510 degrees Fahrenheit. Below -41 degrees Fahrenheit, JP-8 can freeze solid. The properties of hydrogen and JP-8 will have clear impacts to the discussion of aircraft design. The cryogenic aspect of liquid hydrogen will also impact the safety section.

Table 2

Hydrogen vs JP-8		
Environmental		
Item	**Information**	**Advantage**
Fuel Spills	JP-8 would require cleanup and would negatively impact the environment due to its toxicity. Hydrogen would rapidly evaporate and dissipate and is not harmful to the environment (Dfdl, 2001).	Hydrogen
Global Warming	A combustion byproduct of JP-8 is carbon dioxide, a global warming gas, while hydrogen has zero carbon emissions from combustion (Ponater 2006).	
Nitrous Oxide	JP-8 aircraft have at least 3 times the NOx emissions of hydrogen aircraft (Ponater, 2006). In addition, there is an innovative hydrogen engine turbine with a theoretical 12% increase in efficiency and zero NOx emissions (Jin, 2000).	
Noise	A hydrogen combustion turbine is approximately 75% the noise level of a JP-8 turbine. In addition, the advanced concepts of High Temperature Superconducting (HTS) motor driven fans would also offer tremendous noise reductions (Guynn, 2008).	
Sustainable	Hydrogen is made from water and when burned or used in a fuel cell returns to water (Ciaravino, 2003).	
Toxicity	JP-8 is a liver toxin, kidney toxin, nerve toxin, blood toxin, lung aspiration hazard and a reproductive fetotoxin, while hydrogen is not toxic (Dfld, 2001).	

Environmental

Hydrogen is a non toxic element that can sustainably be used as a fuel source. JP-8 is a known carcinogen in animals and a suspected carcinogen in humans. It is a liver toxin, kidney toxin, nerve toxin, blood toxin, lung aspiration hazard and a reproductive fetotoxin (Dfld, 2001). Analysis of the health of individuals in close proximity to airfields provides insight into the toxic effects of jet fuel. The health of those individuals in close proximity of Boeing Field experienced "a 57% higher asthma rate, a 28% higher pneumonia/influenza rate, a 26% higher respiratory disease rate, an 83% higher pregnancy complication rate, a 50% higher infant mortality rate, mortality rates are 48% higher for all causes of death: 57% higher for heart disease, a 36% higher cancer death rate with pneumonia and influenza among the top five leading causes and the average life expectancy was 70.4 years (the same as in many developing nations) compared to Seattle's of 76.0 years" (JP8jetfuel, 2005). In the event of a JP-8 fuel spill, there is a potential for environmental damage and toxins entering the water table. Due to this potential, cleanup is necessitated requiring additional resources and expenditures. In the event of a hydrogen fuel spill, the hydrogen would rapidly evaporate and disperse in the atmosphere. A liquid hydrogen fuel spill is not a cause for concern environmentally.

A 2006 global climate impact assessment contrasted liquid hydrogen aircraft to kerosene powered aircraft. The study examined the global warming impact of a transition to liquid hydrogen aircraft. The study concluded that there would be a reduction in Radiative Forcing (RF) of 71% for a transition to hydrogen aircraft that begins with small and medium size aircraft in 2015 and large aircraft in 2025, with a complete transition by 2050. RF is the change in net irradiance at the Tropopause. Net irradiance is the difference between incoming and outgoing radiation. Lower RF means less energy is trapped in the form of heat and reduces the impact of global warming. Aircraft emissions that impact global warming include carbon dioxide, nitrous oxide (linked to ozone and methane), water and contrails. Liquid hydrogen aircraft emit no carbon dioxide and 25% of the nitrous oxide of kerosene aircraft. Increased nitrous oxide leads to increased ozone and decreased methane. Liquid hydrogen aircraft would therefore lead to lower ozone, but higher methane. The net result on RF by ozone and methane would still be a reduction for liquid hydrogen aircraft compared to kerosene aircraft. Since liquid hydrogen aircraft produce more water and water contributes to global warming, there is a small increase in

RF for liquid hydrogen aircraft compared to kerosene aircraft. The final component factored in is contrail production. Liquid hydrogen aircraft contrails have lower RF than kerosene aircraft. The conclusion is that a transition to hydrogen aircraft would be beneficial in the effort to reduce global warming (Ponater, 2006).

To contrast the results of the 2006 European study, a 2002 NASA sponsored study compared the emissions of a liquid hydrogen aircraft to that of a kerosene based aircraft. The study similarly concluded that carbon dioxide emissions would be eliminated for a liquid hydrogen aircraft. Yet, the NASA study discovered that a liquid hydrogen engine would result in a reduction of only 18% in nitrous oxide over landing takeoff cycle time. This contrasts the results of the European study, but the engine designs were different and the European study was completed 4 years after the NASA study. The study does suggest that advanced engine designs can reduce nitrous oxide emissions further. One such proposed design for liquid hydrogen combustion, offers no nitrous oxide emissions and a 12% increase in efficiency (Jin, 2000). The NASA study suggests that the impact of water vapor is far less significant than carbon dioxide due to water vapor only lasting in the atmosphere for a couple of weeks, while carbon dioxide can last in the atmosphere for over 100 years (Guynn, 2002).

A comparison of the impact of hydrogen vs JP-8 on global warming also needs to include the global warming costs of obtaining and distributing the fuels. Since hydrogen does not occur naturally, energy has to be utilized to separate it from the molecules in which it is bound. If the energy comes from fuel sources that release greenhouse gasses, then hydrogen contribution to global warming could be significant. If global warming reduction is a concern, then hydrogen needs to be produced by the use of renewable energy. The cheapest method for hydrogen production is currently steam methane reforming which releases carbon dioxide in the process.

The environmental impact needs to be fully evaluated against the economic realities of hydrogen production.

The NASA study not only compared aircraft emissions, but also compared the noise pollution caused by liquid hydrogen aircraft versus kerosene aircraft. The study showed that liquid hydrogen aircraft have a reduction of 53% in the areas exposed to noise levels of 55 dB or greater. The noise level deemed objectionable for the study is 55 dB. The noise levels for liquid hydrogen engines are approximately 75% of their kerosene equivalents. The study also illustrated that a transition to hydrogen aircraft would lead to airframe noise becoming the predominant source of noise (Guynn, 2002). Further noise reductions are possible with airframe modifications or the use of superconducting motors instead of hydrogen turbines. The use of superconducting motors will be explained in further detail in the aircraft design section of this paper. The noise reductions do not only have positive environmental implications, but also include military benefits.

Hydrogen is a superior aviation fuel compared to JP-8 environmentally. Transitioning to hydrogen would eliminate the environmental impact of fuel spills and their associated cost, would reduce the impact on global warming and would improve the health of those that live and work near airfields. In addition, it would reduce the medical costs of addressing JP-8's negative health impact and would reduce the noise levels around airfields. Hydrogen is a sustainable fuel and sources of hydrogen are widely available anywhere water can be found. With superconducting motors or advanced combustion cycles, hydrogen aircraft environmental performance can be enhanced even further. The full impact on the environment of a transition to hydrogen aircraft is tied to the energy used to produce and liquefy hydrogen. Renewable energy is the preferred source of energy to make hydrogen from an environmental perspective.

Table 3

Hydrogen vs JP-8		
Economic		
Item	**Information**	**Advantage**
Capital Costs	High capital costs exist for the implementation of hydrogen aircraft to include the purchase of renewable electricity generation, hydrogen production, hydrogen storage, hydrogen distribution and hydrogen liquefaction equipment, while JP-8 infrastructure is well established.	JP-8
Distributed Generation	Economies of scale can be achieved by distributing the generation of hydrogen among all congressional districts.	Hydrogen
Engine Life	Hydrogen engine life is approximately 30% greater than JP-8 engine life. (Brewer, 1991)	Hydrogen
Engine Maintenance	Hydrogen engine maintenance is approximately 30% less than JP-8 engine maintenance. (Brewer, 1991)	Hydrogen
Jobs	Many jobs will be created in the implementation of a switch to hydrogen as aircraft fuel, since the transition will require added local labor.	Hydrogen
Operating Costs	Renewable electricity generation, hydrogen production and liquefaction present added operating costs.	JP-8
Prices	The price of oil will likely rise due to supply limitations. The price of hydrogen will likely decline, due to technological innovations.	Hydrogen
Research and Development	Research and development costs of hydrogen aircraft, hydrogen liquefaction, distribution, storage, production and renewable electricity generation will be high, while JP-8 research and development is mature.	JP-8
Supply Constrained	Oil supply is limited. Since the use of hydrogen creates its source, the supply is unlimited.	Hydrogen
Trade Deficit	Oil accounts for over 60% of the trade deficit, while hydrogen can be produced in the United States, reducing our trade deficit. (Time-Blog, 2008)	Hydrogen

Economic

To compare the use of liquid hydrogen versus JP-8 economically, capital costs are critical. JP-8 currently has a worldwide infrastructure for its transport, storage and delivery. Hydrogen also has a worldwide infrastructure for transport, storage and delivery, but on a vastly smaller scale. From an aviation perspective, fuel transport to airfields, fuel storage at airfields and fuel delivery vehicles to aircraft are primarily kerosene based. To transition to synfuel would not require additional capital investment. Liquid hydrogen on the other hand would require a tremendous investment in the required infrastructure. The costs could include hydrogen production, liquefaction, transport, storage and delivery. Not only would infrastructure costs be an issue, but the research and development costs for that infrastructure would also have to be taken into consideration. In addition, new aircraft would need to be built to take advantage of hydrogen's unique properties with their associated research and development costs. From a capital cost perspective, JP-8 or a synthetic fuel alternative could be cheaper.

Although the entire infrastructure for kerosene would need to eventually be replaced by a liquid hydrogen infrastructure, the costs of that liquid hydrogen infrastructure would be reduced by the widespread use of hydrogen in industry. To compare the oil and hydrogen industries, realize that 1 gallon of oil is the energy equivalent of 1 kilogram of hydrogen. Annual United States oil production is 320 billion gallons while annual hydrogen production is 20 billion kilograms. Hydrogen's main industrial uses are the production of ammonia, the production of methanol and the refining of oil. Hydrogen consumption in oil refineries is 23 percent of total hydrogen demand (EERE, 2003). Reducing oil consumption could allow the hydrogen used in refining to be used directly as a fuel source. With the tremendous demand for hydrogen in the United States, the infrastructure for the production, transport, storage and delivery of hydrogen has achieved relative economies of scale. These economies of scale can be further enhanced by distributed energy production.

Distributed energy production for hydrogen has distinct economic benefits. Any location that has water and can produce electricity can make hydrogen. Some regions where water is scarce can produce electricity and transport that electricity to regions with abundant water resources. The ability to produce hydrogen onsite reduces transportation costs, provides for local jobs and provides for economies of scale through mass production of system components. Transportation costs are reduced since the fuel can be produced closer to its point of intended use. Local jobs are created through the shift of energy production from foreign to local producers. Economies of scale can be created by building common components for the distributed production sites. In addition to these economic benefits, the ancillary benefits of improved reliability through system redundancy and increased survivability through asset dispersal are achieved.

A concern with achieving these economic benefits is increased operating costs. Hydrogen production, liquefaction and distribution will require additional operations and maintenance costs. In addition to production, liquefaction and distribution, the operations and maintenance cost for liquid hydrogen aircraft need to be considered. The operating costs for liquid hydrogen aircraft differ from the NASA and Cryoplane studies. The NASA studies suggest a 5 to 8 percent reduction in aircraft operating and maintenance costs, while the Cryoplane studies suggest a 4 to 5 percent increase. The reasons for NASA's reduced operating costs include improved engine life and reduced engine maintenance. According to Brewer, hydrogen engines have an estimated 30% greater engine life and 30% reduced maintenance than JP-8 engines (Brewer, 1991). This increased engine life and reduced maintenance are due to both the high specific heat of hydrogen and the purity of hydrogen fuel. The high specific heat cools hot metal engine parts reducing metal fatigue. Hydrogen fuel does not contain impurities that can either erode or corrode the engine. In addition, hydrogen diffuses more rapidly leading to smoother combustion.

The cost of hydrogen infrastructure has been a significant deterrent to the use of hydrogen as a fuel. Yet, the cost of not using hydrogen in the face of rising oil prices can be even more damaging. With inexpensive oil being supply constrained and the United States' trade deficit being tied to the price of oil, the United States' economy can be negatively impacted by rising oil prices. The current price of liquid hydrogen is $3.00 per kilogram or Gallon of Gas Equivalent (GGE) (Air Products, 2008). This price is based on a process called steam methane reforming, which is linked to the price of natural gas. There are several methods for hydrogen production based on renewable technology that are sustainable such as electrolysis. Yet, these methods increase cost. The current price of JP-8 is $3.04 per gallon (DESC, 2008). The decision to transition to hydrogen over continued use of JP-8 is tightly linked to the prices of these various fuels. Capital expenditures are made for aircraft that are expected to last 50 years (Schmidtchen, 1998). Making future aircraft purchase decisions requires a vision of the economics of fuel that far into the future. The most critical aircraft acquisition question is which fuel will be the least expensive 20 years into the future?

Table 4

Hydrogen vs JP-8		
Safety		
Item	**Information**	**Advantage**
Detonation	Gun shot tests into liquid hydrogen tanks failed to result in detonation. Heavy impact tests of liquid hydrogen tanks failed to result in detonation. Detonation of a perfect mixture of hydrogen and air only takes place with a strong detonator, but it is improbable that a perfect mixture of hydrogen and air will occur at the time of a strong detonation. JP-8 has a lower detonability limit in air as a percentage of volume than hydrogen. (Brewer, 1991)	Hydrogen
Emissivity	Hydrogen has a lower emissivity than JP-8 making the thermal radiation during a fire less. If a large hydrogen spill occurs outside an aircraft, remain inside for the heat will not be likely to enter the fuselage due to the low emissivity. (Brewer, 1991)	Hydrogen
Frost Bite	Contact with minute amounts of liquid hydrogen can lead to severe frost bite, while JP-8 poses no frostbite hazard. (Praxair, 2007)	JP-8
Fuel Spills	Hydrogen evaporates much more rapidly than JP-8 and if ignited burns quicker than JP-8. A 12,600 kg hydrogen fuel spill will dissipate in 32 seconds, while a similar volume of JP-8 would take closer to 13 minutes. (Brewer, 1990)	Hydrogen
Ignition Temperature	Hydrogen has a higher autoignition temperature than JP-8, but a lower temperature in an air mixture. A lit cigarette will not ignite in pure hydrogen although it could light a hydrogen-air mixture. A lit cigarette could ignite JP-8. (Brewer, 1991)	JP-8
Invisible Flame	Hydrogen can be a burn hazard due to invisible flame, while JP-8 has a visible flame. (Praxair, 2007)	JP-8
Suffocation	The high diffusion rate of hydrogen can rapidly replace the oxygen in an unventilated room leading to possible suffocation, while JP-8 poses a lesser suffocation hazard. (Praxair, 2007)	JP-8
Toxicity	JP-8 is a liver toxin, kidney toxin, nerve toxin, blood toxin, lung aspiration hazard and a reproductive fetotoxin, while hydrogen is not toxic. (Dfdl, 2001).	Hydrogen

Safety

Both JP-8 and liquid hydrogen have serious safety concerns. JP-4, although not identical to JP-8, was the closest fuel used in many of the safety tests. It is often used as a substitute for JP-8 in comparison and this is a limitation of the use of the older studies. The safety issues of concern with both JP-8 and liquid hydrogen include detonation and ignition. The JP-8 unique safety concern is toxicity while the liquid hydrogen unique safety concerns include frost bite, invisible flame and suffocation. These concerns have been analyzed through a series of safety studies. The major studies on the safety of hydrogen aircraft had similar conclusions. The NASA studies of the 1970s found that liquid hydrogen was safer than methane, Jet A or JP-4 from an aircraft crash perspective (Brewer, 1991). The Cryoplane safety report of the 1990s stated, "The result is that the Cryoplane and its infrastructure are feasible from the point of view of safety. The risks are not greater than those associated with any other great industrial plant, some of them even smaller" (Schmidtchen, 1998). Both studies considered the use of liquid hydrogen as an aviation fuel as feasible, but both cautioned that liquid hydrogen safety should be taken seriously.

Of the common safety concerns, detonation is a greater cause of concern for JP-8 and ignition is of equal concern for both JP-8 and hydrogen. JP-8 has a detonability limit in air of approximately 2%, which is far less than hydrogen's 20-60% (Brewer, 1991). If an ignition source is present, JP-8 will detonate long before hydrogen. Tests by Lockheed's "Skunk Works" from 1956-1957 determined that liquid hydrogen would not detonate even when solid oxygen was immersed in the liquid hydrogen unless a strong explosive charge was used as the initiator. In 61 experiments where liquid hydrogen in a thermos bottle was subjected to heavy impacts, ignition never occurred as a result of the impact alone. When the hydrogen was purposely ignited by a hot squib after impact, deflagration occurred instead of detonation (Brewer, 1991).

Following the 1956-1957 detonation tests, Arthur D. Little, Inc performed spill tests for the United States Air Force. The tests covered spills ranging from 5 liters to 5000 gallons. No spills resulted in detonation. In the tests where an ignition source was provided, the pressure effects were negligible unless the gasses were purposely confined. To achieve detonation required the presence of a perfect mixture of air and hydrogen and a strong detonator. The study commented that it was highly improbable that the perfect mixture of hydrogen and air would occur to result in detonation. The Little study demonstrated that hydrogen will not ignite from impact. The study fired bullets at liquid hydrogen containers and dropped them from various heights. The bullets being fired into liquid hydrogen containers and the container impact tests both failed to cause ignition. The only way to detonate liquid hydrogen is to confine it on three sides and use a strong detonator (Brewer, 1991).

Without ignition, a hydrogen spill will rapidly dissipate in the air and pose little threat. From a mathematical model used to model gas spills of natural gas in 1973, two spills were modeled both with and without ignition. For liquid hydrogen, the 12,600 kilogram spill took 32 seconds to vaporize without burning. This contrasts with JP-4, where a similar volume spill vaporizes in 13 minutes (Brewer, 1991). A liquid hydrogen spill after vaporization requires no clean up. Yet, a JP-8 spill will take much longer to vaporize causing a longer ignition hazard. In addition, due to JP-8's toxicity, it will require environmental clean-up (Schmidtchen, 1998).

Ignition of a spill is problematic to both liquid hydrogen and JP-8. Hydrogen has a higher autoignition temperature than JP-8, making it safer. A lit cigarette will not ignite pure hydrogen, but will ignite pure JP-8. Yet, when hydrogen combines with air it is much more vulnerable to ignition due to its minimum ignition energy in air, which is an order of magnitude less than JP-8. If hydrogen is ignited, since it is lighter than air, the fire tends to be vertical. Jet fuel in contrast will tend to form a fire carpet on the ground. This contrast can be best seen by a 2001 University of Miami study of hydrogen safety (Swain, 2001). A University of Miami side by side automobile test of tank ignition of a liquid hydrogen tank and a gasoline tank resulted in the destruction of the gas automobile and little damage to the liquid hydrogen car (see Figure 29).

Photo 1 - Time: 0 min, 0 sec -Hydrogen powered vehicle on the left. Gasoline powered vehicle on the right.

Photo 2 - Time 0 min, 3 seconds - Ignition of both fuels occur.

Photo 3 - Time: 1 min, 0 sec – Hydrogen flow is subsiding, view of gasoline vehicle begins to enlarge

Photo 4 - Time: 1 min, 30 sec - Hydrogen flow almost finished. Gasoline fire engulfs vehicle.

Figure 29
Liquid Hydrogen Automobile Tank vs Gasoline Tank Ignition (Swain, 2001)

The Arthur D. Little tests showed that liquid hydrogen will evaporate after ignition in 1/20th to 1/50th the time of a gasoline spill. From the Arthur Little spill tests, 26 gallons of liquid hydrogen burned in 27 seconds, while 26 gallons of JP-4 burned in 7 minutes (Brewer, 1990). The hydrogen fireball will increase in size with the delayed ignition after the spill occurs. The short duration of a liquid hydrogen fire will pose little threat to metal structures, while the prolonged burn of JP-8 can cause metal structures to fail. In addition, hydrogen's low emissivity, which is 1/10th of hydrocarbon fuels, means that areas exposed to the hydrogen flame will receive far less damage than those exposed to JP-8 flames. The ensuing fireball from both a liquid hydrogen fire and a JP-8 fire will ignite combustible materials and kill anyone consumed. An additional safety concern is that burned JP-8 has toxic combustion products while hydrogen combusts to form water.

Hydrogen poses unique hazards. Hydrogen vaporizes rapidly and diffuses rapidly. Although this has some safety benefits outdoors as can be seen by the spill tests, it provides additional safety concerns in enclosed spaces. Without proper ventilation, a hydrogen leak can pose a suffocation hazard (Praxair, 2007). Hydrogen is invisible and odorless making it hard to detect without sensors. Hydrogen MEMS sensors the size of a quarter are available to aid in resolving this issue. They can detect hydrogen levels of 25 parts per million and have no warm up time required. Their small size allows them to be mass produced at low cost (DOE, 2007). These sensors, although able to detect the presence of hydrogen, do not solve the difficulty associated with recognizing a hydrogen flame. A pure hydrogen flame is invisible posing a burn hazard (Praxair, 2007). Liquid hydrogen needs to be stored at -423 degrees Fahrenheit. If this cryogenic fluid touches air it will immediately freeze the air. If the cryogen spills onto an individual, severe frostbite will ensue which could easily be life threatening (Praxair, 2007). JP-8 is liquid at room temperature and poses no frost bite hazard.

From an aircraft perspective, safety considerations must include maintenance, refueling, operations and the effect of an aircraft crash. Maintenance of cryogenic tank equipment involves greater complications and increased safety measures. Refueling also requires measures to ensure the lines connected are purged of air before filling. The primary safety concerns of hydrogen operationally are the threat of a leak and the threat of tank pressurization problems. A hydrogen leak can pose a frost bite hazard if the cryogenic fluid reaches passengers. Hydrogen tank, passenger and barrier placement can be adjusted to improve this safety concern. In addition to frost bite hazard, there is a suffocation or ignition hazard. The solution to both of these problems involves venting the area surrounding the tank to prevent hydrogen gas accumulation in the cabin and passenger compartments. Tank pressurization problems can be solved with redundant pressure relief systems.

The Arthur D. Little, Lockheed, NASA and Cryoplane safety studies came to similar conclusions on the crash fire rescue threat of liquid hydrogen aircraft. The studies concluded that in a crash, the liquid hydrogen aircraft tanks would be less likely to rupture. This reduces the probability of a spill reducing the threat of ignition and fire. The primary reason for this is that liquid hydrogen tanks would be located in the fuselage while jet fuel is often located in the wings. The reason for this difference is the need to minimize surface area for cryogenic tanks. The tanks being located in the fuselage also have a significant amount of structure in front of and below the tanks to add further protection. Wing tanks for jet fuel have very little structural protection. Pressurization of liquid hydrogen tanks, although increasing weight, adds additional structural protection and eliminates air from the interior of the tank. Jet fuel tanks are unpressurized and mixed with air providing for a vastly more combustible mixture. Passenger compartments are rated at 18 psi while liquid hydrogen tanks are rated at 30 psi. In the event of a crash, the passenger compartment would probably break apart from the aircraft before the liquid hydrogen tank. Aircraft crash statistics show that during survivable crashes, the fuselage receives far less damage than the wings (Brewer, 1991).

If the tank is damaged and a fuel spill occurs, the liquid hydrogen would evaporate and dissipate more rapidly than jet fuel. The time and area of fuel exposure is much smaller for liquid hydrogen than JP-8. This reduced exposure also adds to increased safety. Finally, both reports suggest that in the event of fuel ignition that the liquid hydrogen burn would be so quick that it is unlikely to heat the fuselage to the point of collapse. Jet fuel, on the other hand, is more likely to cause structural collapse of the aircraft. In addition, the heat affected area would be much smaller. The primary reason for this difference is that the emissivity of hydrogen is only half that of jet fuel (Brewer, 1991). Ten to twenty percent of accident victims die in a fire after they have survived a crash (Schmidtchen, 1998). These victims would be much more likely to survive a liquid hydrogen crash.

Table 5

Hydrogen vs JP-8		
Aircraft Design		
Item	**Information**	**Advantage**
Heat of Combustion	JP-8 is 42.8 MJ/Kg vs liquid hydrogen at 120 MJ/Kg Due to hydrogen's high heat of combustion, a hydrogen turbine would only require 36% of the fuel weight of JP-8 for the same performance. (Hypertextbook, 2003)	Hydrogen
Specific Heat	High specific heat cools the engine leading to higher turbine inlet temperature, higher overall pressure ratio and reduced specific fuel consumption (Brewer, 1991)	Hydrogen
Density	JP-8 is .775 Kg/L vs liquid hydrogen .07 Kg/L Due to JP-8's high density, a hydrogen turbine would require 4 times the fuel volume for a similar performance which also adds to tank weight (Eere, 2008).	JP-8
Cryogenics Limitations	Fuel tanks must have large volume to surface area ratios for liquid hydrogen to reduce thermal transfer. (Brewer, 1991)	JP-8
	Liquid hydrogen fuel tanks require insulation adding to tank weights. (Brewer, 1991)	JP-8
	Liquid hydrogen fuel tanks will require special fill and vent procedures. (Brewer, 1991)	JP-8
	Liquid hydrogen fuel tanks require constant pressure to minimize boil off. (Brewer, 1991)	JP-8
Cryogenics Advantages	High temperature superconductors (HTS) provide potential for HTS motors to power motor driven fans for aircraft propulsion. (Masson, 2007)	Hydrogen
	Superconducting electric generators have an efficiency over 99% and their size is half that of conventional generators, reducing aircraft weight & fuel consumption. (S-cond, 2008)	Hydrogen
	HTS wire carries 150 times the current of conventional wire. Potential aircraft weight savings. (Amsc, 2008)	Hydrogen
	HTS gear, flap and flight control actuation. Potential to reduce weight & complexity. (Masson, 2007)	Hydrogen
	Boundary layer control through cryogenic cooling can result in a 20-28% reduction in fuel required for a .85 Mach, 12,000 km flight. (Cunnington, 1980)	Hydrogen
Embrittlement	Hydrogen can damage the structural integrity of certain materials.	JP-8

Aircraft Design

The aircraft design of a hydrogen powered aircraft should differ significantly from a kerosene based design. The primary factor that causes the designs to vary is that a hydrogen aircraft would have to store its fuel at cryogenic temperatures. This leads to several unique problems for a liquid hydrogen design. The first issue is thermal transfer. To keep liquid hydrogen at cryogenic temperatures, thermal transfer to the cryogen needs to be kept at a minimum. The tank that maintains the liquid cryogen will need insulation, need to be able to maintain constant pressure to minimize boil-off and need special fill and vent procedures. The requirements for insulation and structural strength to handle higher pressure differentials will lead to heavier tanks structures than JP-8 (Brewer, 1991).

The next issue for the liquid hydrogen design deals with energy. The heat of combustion for liquid hydrogen is 120 MJ/Kg while JP-8's heat of combustion is 42.8 MJ/Kg. This is a distinct advantage for hydrogen. A liquid hydrogen aircraft would only require 36 percent of the fuel weight of a JP-8 aircraft for the same energy expenditure (Hypertextbook, 2003). This advantage helps reduce liquid hydrogen's biggest disadvantage, energy per unit volume. The energy per unit volume for liquid hydrogen is 8.4 MJ/L while JP-8 is 33.17 MJ/L. JP-8 has 4 times the energy per unit volume than liquid hydrogen (Eere, 2008). This difference causes the liquid hydrogen tank to be a large cylinder. JP-8 fueled aircraft hold their fuel in their wings, but a liquid hydrogen aircraft would benefit from the tank being placed in the fuselage.

Part of the weight advantage of liquid hydrogen over JP-8 is lost in the added weight of the liquid hydrogen tank. The weight of the tank is based on surface area, while the weight of the fuel is based on volume. As tank size increases the ratio of fuel weight to tank weight increases. This leads to the conclusion that the tank weight is less significant to the total tank plus fuel weight as the tank size grows. Larger aircraft would therefore benefit more from the weight advantage of liquid hydrogen than smaller aircraft. Both the Lockheed studies of the 1970s and the Cryoplane studies of the 1990s agreed that for a given aircraft capability, the gross weight at takeoff would be less for the liquid hydrogen aircraft. The Lockheed studies showed that a Jet A fueled aircraft carrying 400 passengers a distance of 5500 nautical miles weighed 34% more at takeoff than a liquid hydrogen fueled aircraft with the same load and distance flown (Brewer, 1991). The Cryoplane studies showed that at 400 passengers travelling 5500 nautical miles, the liquid hydrogen aircraft weighed 14.8 percent less at takeoff per pax*nm than the jet fuel aircraft (Airbus, 2003).

Due to the low takeoff weight of liquid hydrogen compared to JP-8, the lift to drag ratio for a liquid hydrogen aircraft tends to be less than that of a JP-8 aircraft (Brewer, 1991). This would lead to smaller wings for a liquid hydrogen aircraft (see Figure 30). The Lockheed study 400 pax-5500 nautical mile jet fuel design with 24% larger wing surface area took 28% more runway for takeoff than the liquid hydrogen aircraft design, but needed 10% less landing distance than the liquid hydrogen design (Brewer, 1991). Lighter takeoff weight resulted in shorter takeoff distance, but the smaller wings led to higher approach speeds and longer landing distances.

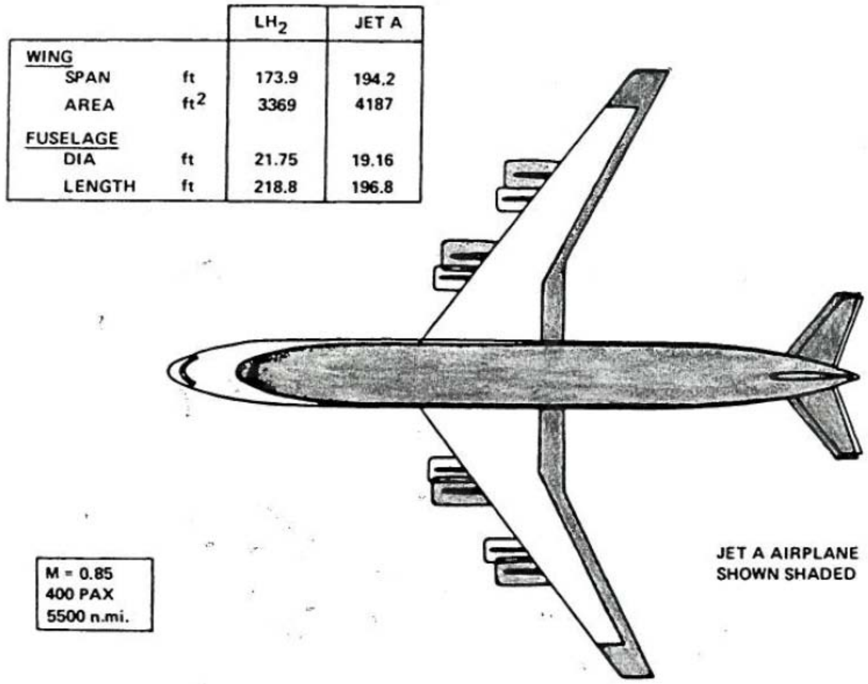

Figure 30
Liquid Hydrogen Comparison to Conventional Aircraft (Brewer, 1991)

The final concern in aircraft design that does not favor liquid hydrogen is hydrogen embrittlement. Hydrogen embrittlement occurs in certain materials leading to decreased structural strength of those materials. The entire C-130H fleet was recently grounded due to suspected hydrogen embrittlement of barrel nuts which secure parts of the outboard engines. It is necessary that material selection be chosen with the deleterious effects of hydrogen embrittlement taken into account. Despite these negatives, there are several aspects of liquid hydrogen that make it attractive from an aircraft design perspective. The specific heat of liquid hydrogen is much higher than JP-8. This enables higher turbine inlet temperatures, higher overall pressure ratio and reduced specific fuel consumption (Brewer, 1991).

Cryogenic liquid hydrogen fuel has advantages for use in both superconductors and boundary layer control. By routing the cryogen to cool the surface of the wings, boundary layer control can be enhanced. One study suggests a 20-28% reduction in fuel for a .85 Mach aircraft over a 12,000 kilometer flight (Cunnington, 1980). Further experimentation would be required to test this hypothesis and the question of icing on the wings due to boundary layer control through cooling needs to be addressed. Of the superconductor applications that could affect aircraft design, High Temperature Superconducting (HTS) motors appear to have the greatest potential for improvement in aircraft performance. A NASA funded study demonstrated HTS engine performance on par with current conventional aircraft turbines in the laboratory (Masson, 2007). The study said that the potential for an order of magnitude improvement over the first design is possible. Such an advance could leapfrog current aircraft engine technology and spark a rapid transformation to cryogenic aircraft. Figure 31 below illustrates current turbofan power with the blue line and the red circle shows the order of magnitude improvement potential of the cryo sync motor design (Masson, 2007). Improvement on the chart is to the right and down.

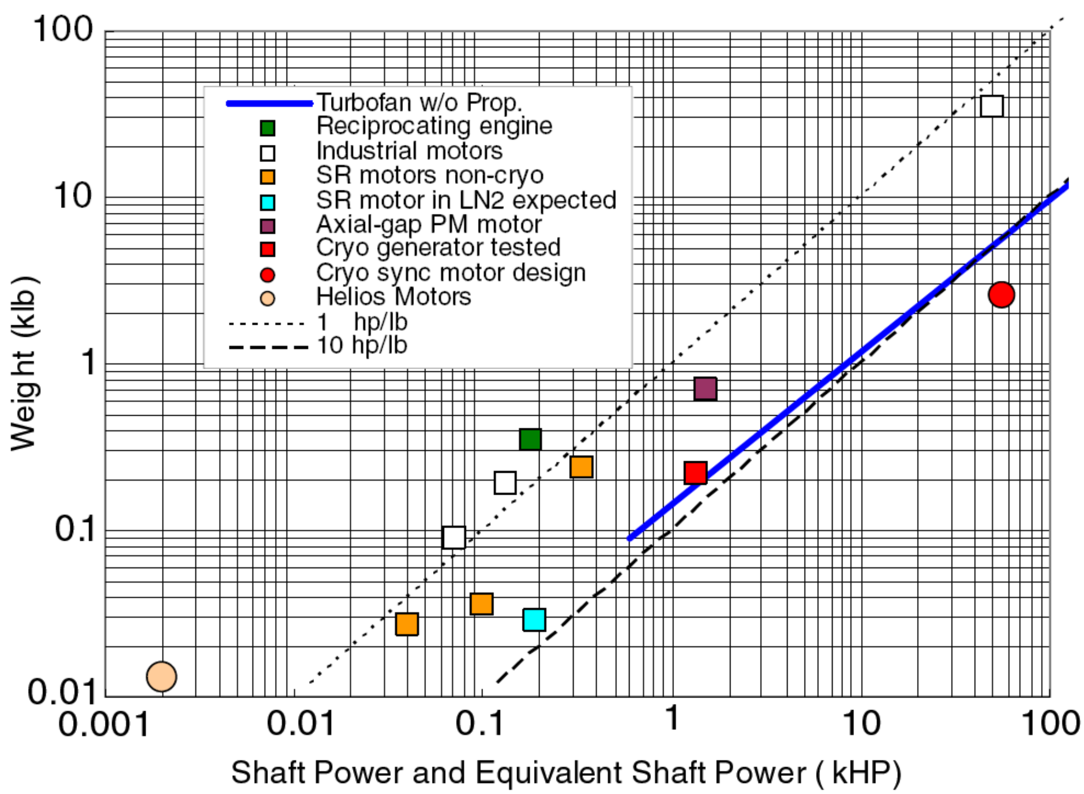

Figure 31
Weight vs Shaft Power (Masson, 2007)

The superconductor motor would be powered electrically from a generator attached to a hydrogen turbine. The cryogen to enable superconductivity would come from the liquid hydrogen. Another possible source of the electricity is a Solid Oxide Fuel Cell (SOFC). The use of an SOFC would require a long warm-up time, so a hybrid solution has been devised where a hydrogen turbine would power the generator until the SOFC reaches operating temperature and then the SOFC would take over using the hydrogen. The proposal for a hydrogen turbine-SOFC hybrid is attractive due to the improved efficiency of the SOFC, but comes with issues related to SOFC/total system weight. A view of the HTS motor concept envisioned by the NASA study can be seen in Figure 32.

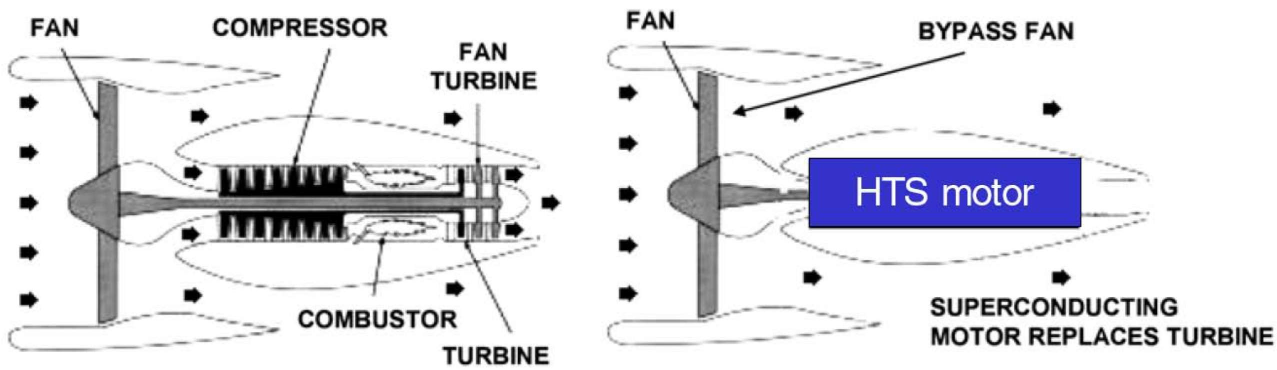

Figure 32
Convential Turbofan vs HTS Motor Concept (Masson, 2007)

Not only can the motor take advantage of superconductivity, but the generators, wiring and actuators can also utilize superconductivity. Superconducting generators are over 99% efficient and their size is half that of current generators (Superconductors, 2008). This means the generators can be made significantly smaller reducing aircraft weight and improving fuel consumption. Superconducting wires can carry up to 150 times the current of normal wires (AMSC, 2008). This can reduce the weight of the wiring. Finally, gear, flap and flight control actuation can use HTS linear motors. HTS linear motors would also provide substantial weight savings. Tests of HTS linear motors in Germany have been successful (Masson, 2007). The cryogenic aspect of hydrogen aircraft design is a difficult challenge, but is not insurmountable with current technology and the benefits may be found to outweigh the negatives.

Table 6

Hydrogen vs JP-8		
Military		
Item	**Information**	**Advantage**
Cryogenics	HTS Filters can improve signal to noise ratio for radios and data links. (Superconductors, 2008)	Hydrogen
	Superconducting Magnetic Energy Storage Systems can be utilized for on demand power availability. (Superconductors, 2008)	
	Superconducting transformers and fault limiters offer increased capacity and response time. (Supercon, 2008)	
	Superconducting microchips are capable of next generation processing speeds. (Supercon, 2008)	
	Superconducting Quantum Interference Devices can be used to detect mines and submarines. (Supercon, 2008)	
	Superconducting motors provide reduced weight for a given power. (Superconductors, 2008)	
	Superconducting magnetic fields can deliver an ElectroMagnetic Pulse (EMP) to disable an enemy's electronic equipment. (Superconductors, 2008)	
	Superconducting X-ray and light detectors offer superior sensitivity due to their capacity to detect low amounts of energy, which provides potential for improved intelligence, surveillance and reconnaissance. (Superconductors, 2008)	
	Superconductor Augmented Rail Gun launch velocities are increased 50% and efficiency is more than doubled. (Homan, 1986)	
	Radars can become more powerful by an order of magnitude. (Jackson, 1991)	
	Magnetic levitation can be used for advanced applications such as short field takeoff/landing and cargo movement. (Superconductors, 2008)	

Military Continued		
Distributed Generation	Huge logistical efficiencies can be obtained if fuel can be generated at any location as opposed to setting up the logistics chain to deliver the fuel. JP-8 requires a long logistics chain requiring a vast number of missions for fuel distribution. Hydrogen can be generated anywhere you can obtain water and create electricity.	Hydrogen
IR Signature	An HTS motor driven fan would have no heat signature for IR missiles to lock on to. In addition, cryogenic fluid can be placed in key locations to hide large heat sources.	
Noise Signature	A hydrogen combustion turbine is approximately 75% the noise level of a JP-8 turbine. In addition, the advanced concepts of High Temperature Superconducting (HTS) motor driven fans would also offer tremendous noise reductions. (Guynn, 2002)	
Radar	HTS filters can be used in ECM applications to detect radar signals that would otherwise go undetected. (Ryan, 1997)	
Scramjet	Hydrogen is the only fuel capable of holding combustion above 7 Mach. (Thespacereview, 2008)	
Supersonic	Liquid hydrogen with its high specific heat can cool the high temperatures on leading edges reaching high velocities.	

Military

The use of a cryogenic fuel source opens up a wide array of military applications. The cryogen enables superconducting applications. Superconductors can be used in antenna filters to improve the signal to noise ratio. This would enable superior data link performance against an adversary. With information superiority becoming more decisive in future combat, this capability enhancement could prove important. In addition to improved information exchange and increased electrical generating efficiency, superconductors have energy storage and electronic component advantages. There are superconducting magnetic energy storage devices that could increase power output for takeoff or enable large energy bursts for a solid state laser or a rail gun. From a short field takeoff perspective, this could provide added capability. The weight of these energy storage devices is currently problematic for aerospace applications. Electronic components such as fault limiters and transformers can have increased power capacity and improved response times. This allows for smaller components or added capability.

Processing power will be critical for advanced military aerospace applications. Superconducting microchips can achieve an order of magnitude improvement over current designs. In addition to improved processing power, intelligence gathering capabilities will be enhanced by superconducting applications. Superconducting Quantum Interference Devices (SQUIDs) have the capability to detect mines and submarines. Superconducting X-ray and light detectors have demonstrated amazing sensitivity. The enhanced resolution could enable improved analysis. Another asset to intelligence gathering is advanced superconducting radar applications. Superconducting radars offer an order of magnitude improvement over current radars (Ryan, 1997). Throughout the electromagnetic spectrum, superconductors enable information collection superiority. The combination of improved processing with more advanced data gathering could enable advanced onboard intelligence analysis.

At the heart of the advanced military applications, is the concept of superconducting motors. With infrared missiles being of primary concern to military aircraft, superconducting motors could eliminate the heat plume from the back of the aircraft engine. In addition, superconducting motors have a vastly reduced noise signature. A silent motor with no heat signature could reduce the enemy capability to target and destroy a superconducting motor aircraft. The cryogenic fuel can also be used to hide any other heat sources that an infrared missile might lock on to. The SOFC concept discussed before could be used to enable silent motor operation. Without the SOFC concept, noise reduction of 75% of JP-8 turbine levels is possible with a hydrogen turbine (Guynn, 2002).

In addition to capability enhancing superconducting applications, there are offensive weapon superconducting applications. Electro-Magnetic Pulse (EMP) weaponry is possible with superconductors. An EMP pulse could disable an enemy's electronic equipment. The use of such a weapon would require EMP hardening or removal of all coalition equipment within the effective radius of the blast. An alternative to the EMP is the use of superconductors in rail gun applications. The Superconducting Augmented Rail Gun (SARG) can increase launch velocities by 50% and double the efficiency of non superconducting rail guns (Homan, 1986).

Magnetic levitation technology might also be used in the distant future to enable extremely short field takeoff and landing capabilities. Currently, the use of superconductors to accelerate and decelerate an aircraft has not been thoroughly analyzed or proven feasible. Yet, one day this might become an extremely attractive solution. When the Air Force focuses on switching to scramjet technology in the distant future, liquid hydrogen will become a leading fuel candidate. Hydrogen is the only fuel capable of sustaining combustion above 7 Mach. Scramjet designs beyond this speed will require the use of hydrogen unless other technological advances enable the use of alternative fuels.

Perhaps the one advantage of hydrogen that could enable a transformation of the military is distributed generation. Hydrogen can be made anywhere there is access to fresh water and electricity. JP-8 can have an extremely long logistics chain to get the fuel to the war-fighter. If the fuel could be created near its point of final use, then the logistics chain could be extremely reduced. This would also reduce the need to protect the resource in transit. Portable electrolyzers are currently in existence, but portable hydrogen liquefaction is not. Distributed generation of liquid hydrogen would require serious advances in liquefaction technology. If achieved, distributed generation could alter military concepts of energy logistics.

Table 7

Hydrogen vs JP-8		
Political		
Item	**Information**	**Advantage**
Congress	Since hydrogen is made from water and electricity, hydrogen can be produced in every congressional district where those resources are present.	Hydrogen
Energy Corporations	Large contracts will be required for hydrogen production, storage and distribution.	
Jobs	Jobs will be created in every congressional district that produces hydrogen.	
Public Perception	Public perception of hydrogen suffers from fear of change to an unknown and unjustified safety concerns related to the Hindenburg disaster.	JP-8

Politics

For hydrogen to gain acceptance as an alternative to JP-8, the interests of the legislative, the public and industry will need to be aligned. The executive will need to lead the transition to hydrogen and the executive will need to place the transition as a top priority. To align the interests of Congress, each Congressional district should be part of a national distributed energy production plan. For water rich congressional districts, each district should have resources devoted to the production of hydrogen. For those regions that are rich in solar, wind or geothermal resources, they should build out renewable energy infrastructure and an updated grid to provide the electricity to water rich regions for hydrogen production. A national energy plan should be created that provides federal money for the creation of distributed energy production in every congressional district. Such a plan has the potential to improve local energy infrastructure, add local jobs and inject federal money to local projects. As a federal plan, it could ensure common standards to achieve further economies of scale. Such a plan would serve as a path forward to reduce the reliance on foreign oil.

The interests of the oil and natural gas industry will need to be taken into consideration as well for the successful implementation of a hydrogen transition. The oil and natural gas industry as previously discussed produce a large proportion of hydrogen used in the oil refining process. Their expertise with hydrogen production and distribution will need to be utilized and long term contracts for the hydrogen transition will need to be established with industry. The public perception of hydrogen energy as a possible alternative to jet fuel suffers from both a lack of knowledge and from the Hindenburg accident. For the transition to be successful, public perception must be influenced through a hydrogen information distribution campaign. If the transition has the support of the people, congress and industry, then the transition will likely proceed far more smoothly.

Hydrogen Production

There are many methods of hydrogen production. The methods will be separated into near term and long term. In the near term, steam methane reforming, renewable liquid reforming and electrolysis hold the most promise. In the long term, biomass gasification, coal with sequestration, wind electrolysis, solar electrolysis, nuclear electrolysis, hydroelectric electrolysis, geothermal electrolysis, solar high temperature thermo-chemical water splitting, nuclear high temperature thermo-chemical water splitting, photo-electrochemical and biological production are possible avenues to pursue. See Table 8 below for hydrogen production costs.

Table 8
Hydrogen Production Costs 2008 Dollars (Dillich, 1998)

Hydrogen Production Technology	Cost ($ /GGE)
Steam Methane Reforming	$3.00
Renewable Liquid Reforming	$4.50
Electrolysis	$5.00
Nuclear	$5.00
Coal	$5.25
Biomass	$5.75
Wind Electrolysis	$9.00

The cheapest method, steam methane reforming, is also the most widely used. It converts methane into hydrogen with high temperature steam and a nickel catalyst. The byproducts include carbon monoxide. Although the method is the cheapest, it is tied to the price of natural gas and produces carbon emissions. Renewable liquid reforming is biologically derived. Although potentially attractive from a carbon and cost perspective, this resource will compete with land use for agricultural production. Electrolysis offers several benefits. If the electricity is produced by renewable energy, then the carbon footprint is negligible and the economics of resource constraint become less of a factor. Electrolysis enables distributed generation, which provides for logistical efficiencies.

The long term solutions of wind electrolysis, solar electrolysis, hydroelectric electrolysis, geothermal electrolysis, solar high temperature thermo-chemical water splitting, photo-electrochemical and biological production possess lower carbon footprints and face lower resource constraints. Biological production might compete with agricultural land, which could become an issue. Nuclear electrolysis and high temperature nuclear thermo-chemical water splitting face issues with nuclear proliferation and the disposal of toxic nuclear waste. In addition, nuclear material is also resource constrained. Coal with sequestration suffers from cost issues concerning sequestration. Biomass gasification competes against agricultural production. If the biomass comes from agriculturally marginal lands, then the solution becomes more attractive. Figure 33 shows the renewable energy resources available to produce hydrogen.

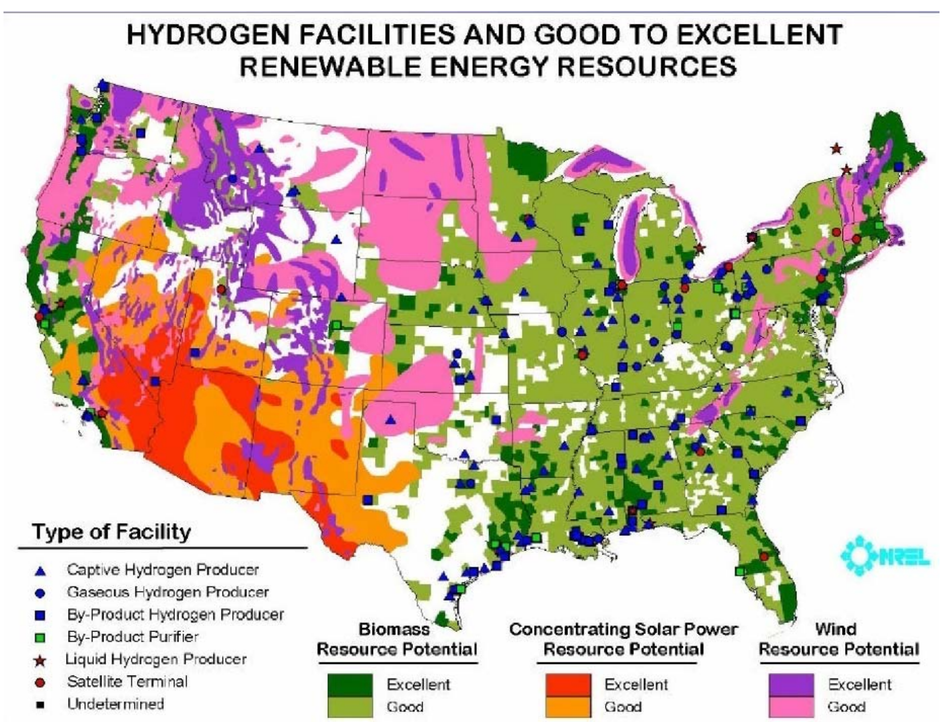

Figure 33
Hydrogen Facilities and Renewable Energy Resources (Arec, 2003)

Hydrogen production technologies are rapidly advancing and it is difficult to determine which technology will be the most economically viable in the future. Using a combination of different technologies to maximize the nation's resource strengths might prove to be the best solution. To refine the focus of this research, production methods that were resource constrained and production methods that had no cost projections were avoided. With a focus on renewable energy powering electrolyzers to produce hydrogen, the important capital costs involve renewable infrastructure, electrical grid upgrades and electrolyzer costs. Operations and maintenance costs will also be important factors. Following production, the next major consideration is storage and distribution.

Hydrogen Storage and Distribution

After the hydrogen is produced, it must either be stored on site or delivered to a storage facility until it is ready for use. The options for storing hydrogen include underground, pipeline, compressed gas or liquid storage. The cheapest method of storage is underground storage. This method should be used where available. Pipeline storage is also efficient where built, since a small increase in pipeline pressure due to the distances involved stores a large amount of hydrogen. Compressed gas tanks are expensive and take up large area for the energy of hydrogen that they contain. Liquid hydrogen tanks are very expensive compared to jet fuel tanks due to their cryogenic need for insulation. Table 9 shows the capital costs associated with hydrogen storage.

Table 9
Hydrogen Storage Costs 1995 Dollars (Amos, 1998)

	Base Cost	Range
JP-8 tank	$1.50/gallon	
2,900 psia Compressed Hydrogen Gas Tank	$1,323/kg	$625/kg to $2,080/kg
Liquid Hydrogen Tank	$441/kg	$18/kg to $520/kg
Metal Hydride Tank	$2,200/kg	$820/kg to $16,000/kg
Underground	$8.80/kg	$2.50/kg to $28.60/kg

Hydrogen storage at an airfield will depend on liquefaction capability. Ideally, each airbase should have a hydrogen liquefaction capability. They should have liquid hydrogen storage capacity sufficient to level demand for the liquefaction plant. The reason for each base having its own liquefaction capability has to do with hydrogen boil-off. Liquid hydrogen turns into a gas as thermal energy creeps into the liquid hydrogen tank. The hydrogen gas will then build pressure in the liquid hydrogen tank. That pressure must be relieved and either vented to the air and lost or routed back to the liquefaction plant. If the liquefaction plant is located at the airbase, then this vented hydrogen will not be lost.

Hydrogen can be produced through electrolysis on base, purified and liquefied at a plant on base and stored as a liquid in a tank until delivery either by vacuum jacketed (VJ) pipeline to the aircraft or truck to the aircraft. If not produced or liquefied on base, there are multiple methods of delivery for liquid hydrogen from a central production and liquefaction facility. These include pipeline, gaseous hydrogen truck, liquid hydrogen truck, liquid hydrogen rail car and barge (see Figure 34). Liquid hydrogen trucks are double walled and have a boil-off of approximately .3% per day. They can carry almost 3,600 kilograms of hydrogen. A gaseous hydrogen tube trailer in contrast can carry only 360 kilograms (Airproducts, 2008). Rail cars carry roughly 9,000 kilograms of hydrogen and barges about 20,000 kilograms (Amos, 1998).

Figure 34
Hydrogen Gas Tube Trailer (Left) Liquid Hydrogen Trailer (Right)
(Airproducts, 2008)

From a storage and distribution perspective, to transition to hydrogen aircraft, a great infrastructure investment in storage tanks, pipelines and trucks would be required. Yet, there have been several significant advances recently that will help reduce the cost of hydrogen storage and distribution. An important major advance in hydrogen storage occurred during the transition from metal storage tanks such as aluminum and steel to Carbon Fiber Reinforced Plastics (CFRP). The Institute of Space and Astronautical Science (ISAS) designed a liquid hydrogen composite tank to help reduce the weight of its stainless steel alternative for a reusable space launch vehicle. The composite tank consisted of an aluminum shell interior with a carbon fiber reinforced plastic outer shell with insulation and water proof tape cover (see Figure 35). The tank ended up weighing 36.5 kilograms compared to 82 kilograms for the stainless steel alternative (Higuchi, 2005). The tank proved a practical solution after multiple flight tests.

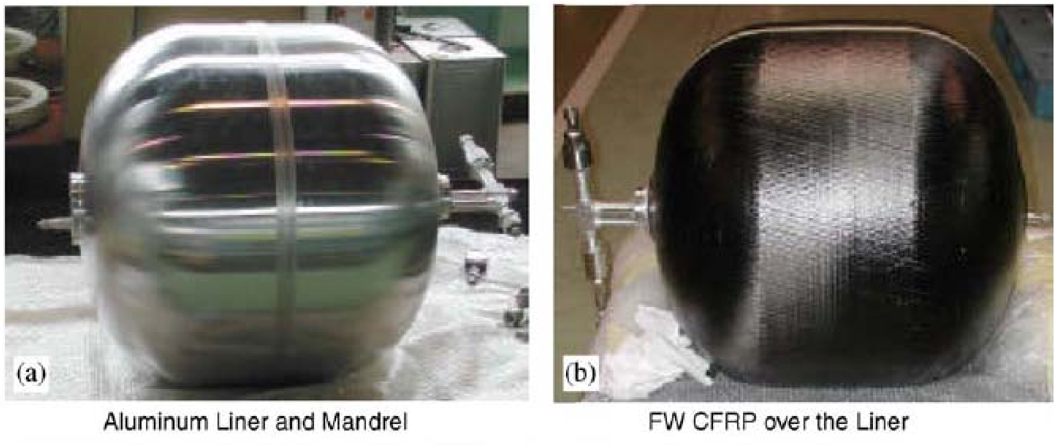

Figure 35
Aluminum Liner (Left) CFRP Shell (Right) (Higuchi, 2005)

The main problems experienced by composite cryogenic storage tanks include micro-cracking, thermal cycling and hydrogen diffusion. To resolve these problems as in the ISAS example, an aluminum inner layer has been used. Yet, that layer adds significant weight and the thermal cycling between the aluminum and CFRP layers is a concern. A recent discovery which has the potential of removing the aluminum inner shell is Claist. The National Institute of Advanced Industrial Science and Technology has developed a clay-plastic composite material with an excellent hydrogen gas barrier property. The material has higher durability and more than 100 times higher hydrogen gas barrier performance than CFRP (Aist, 2008). By embedding the Claist in CFRP, the need for the aluminum layer could potentially be removed. This could result in an additional 20% reduction in weight (Black, 2005).

Wilson Composites, XCOR Aerospace and HyPerComp have several material alternatives which also offer the potential for liner-less composite tanks (Black, 2005). The weight savings from liner-less composite tanks have not been factored into the analysis of hydrogen aircraft, but their successful implementation would definitely shift the balance of the equation in favor of hydrogen. Another important innovation in hydrogen storage has been in the use of insulated pressure vessels. The technology helps with one of the major hurdles of hydrogen storage, boil-off. The concept is to use a pressure vessel to store the hydrogen gas from boil-off under increased pressure. The insulated pressure vessel is more compact than an ambient temperature pressure vessel and has lower evaporative losses (Aceves, 2006).

The insulated pressure tank was placed in a Toyota Prius (see Figure 36). The tank when filled with 10 kilograms of liquid hydrogen enabled a 650 mile driving range. Under city conditions a 500 mile driving range should be expected (Aceves, 2006). The important aspect of the insulated pressure vessel is that even if the vehicle sits so long that boil-off removes most of the liquid hydrogen enough pressurized gaseous hydrogen will remain for a significant driving range. For short trips, the tank can be fueled with lower cost gaseous hydrogen, but for long trips, the higher cost liquid hydrogen could be used. The tanks used have an aluminum liner, so weight savings could be obtained from a liner-less design.

Figure 36
Hydrogen Insulated Pressure Tank in Toyota Prius (Aceves, 2006)

Hydrogen storage vessels are advancing rapidly. These storage advances have strong implications to the use of hydrogen in aviation. As tank weights continue to decrease through advances in composites and hydrogen barriers, hydrogen aircraft will become more capable than their jet fuel counterparts. Not only are tanks becoming lighter, but technology advances, such as insulated pressure vessels, are evolving which help reduce the negative impact from boil-off. These advances are critical to speed the transition to installing the required hydrogen infrastructure.

Hydrogen Liquefaction

Hydrogen liquefaction currently requires large plants. It is performed in bulk to help reduce costs. The vision of distributed generation of hydrogen depends on advances in liquefaction technology to help reduce costs and size. Current liquefaction technology adds 30 cents per kilogram to the cost of liquid hydrogen (Air Products, 2008). Gas Equipment Engineering Corporation (GEECO) estimates for the added cost of liquefaction range from $1.19/kg to $2.00/kg. Larger scale plants could help reduce this cost, but it is advantageous to have a liquefaction plant at every base. The efficiency of hydrogen liquefaction is currently 20 to 30%, but there is a theoretical plant model designed by Valenti and Macchi that could achieve efficiencies close to 50% (Valenti, 2008). Energy consumption for liquefaction currently ranges from 12.5 kWh/kg to 15 kWh/kg (Drnevich, 2008). GEECO has a pilot plant in development that when scaled to 50,000 kilograms a day of liquid hydrogen will operate at 44% Carnot efficiency, will utilize 7.4 kWh/kg of energy and will have a capital cost of $39 million (Shimko, 2008). This represents impressive improvements in efficiency and critical reductions in energy and capital costs.

There are exciting refrigeration technologies that have the potential to drastically lower liquefaction costs and enable small scale liquefaction. These include magnetic and acoustic refrigeration. Preliminary analysis suggests a 300,000 kg/day plant using magnetic refrigeration could achieve an efficiency of 52-62% (Iwasaki, 2003). The need for valves and compressors will be eliminated helping to reduce cost and size. Magnetic refrigeration used to be limited to a 20 degree temperature differential, but thanks to new metallic glass materials that range has been extended to 100 degrees (Dume, 2008). Acoustic refrigeration technologies such as Qdrive can cool to -223 degrees Celsius at 80 to 90% efficiency (Qdrive, 2008).

The Path Forward

To make the transition from JP-8 aircraft to hydrogen aircraft, a prototype hydrogen aircraft will have to be built and tested. Since a hydrogen aircraft is ideal as a strategic lift asset, the initial concept should include hydrogen infrastructure at two strategic hubs. For example, Dover AFB and Ramstein AFB can build hydrogen infrastructure. Both are near liquid hydrogen industrial sites that could easily ship liquid hydrogen as needed should infrastructure issues arise. As with any new technology, there will likely be initial technological hurdles. It is better to fix these problems with the prototype and the two strategic hubs than to address these concerns during a full scale acquisition program implementation.

The reason to start with large aircraft is that there are greater efficiency gains that can be obtained starting with large aircraft. In addition, using large aircraft operating between strategic hubs reduces the problems of capacity utilization associated with a lack of global hydrogen infrastructure. Once proof of concept has been established, a large scale acquisition program should be established to replace aging strategic airlift assets. Civilian commercial and international partners should be brought on board to help spur investment in hydrogen infrastructure at airfields across the globe.

Before transitioning smaller aircraft to hydrogen, a distributed generation system should be developed. Shipping liquid hydrogen to small airports around the globe is an expensive proposition. It would be far cheaper to design a small scale combination electrolysis/liquefaction machine. Such a machine can generate liquid hydrogen on site and reduce the logistic footprint. With this machine available, a major acquisition program for the transition of small cargo aircraft can begin. The rate of transition would be dependent on the urgency of the energy or climate problems that are being faced. If the transition is made out of fear without adequate prototype testing, far more critical resources could be wasted. To avoid a needless rush due to delayed decision making, prototype testing should begin quickly. If a successful hydrogen aircraft prototype is available, the transition has the capability to accelerate at the speed required. Without a successful prototype, the implementation of a hydrogen transition would be far more difficult.

III. Research Methodology

The research methodology used is a cost analysis. The research is broken down into several sections. These include AMC JP-8 usage to hydrogen usage conversion, storage costs, liquefaction costs, electrolysis costs and electricity costs. The conversion section provides the hydrogen requirements upon which storage, liquefaction and electrolysis are based. Liquefaction and electrolysis provide the electricity required to determine electricity costs. Various levels of technology development impact each section. Storage utilizes current technology. Liquefaction utilizes both current and near term technology. Electrolysis utilizes current, near term and long term technology. Electricity generation examines wind using current technology and solar using current and near term technology. These various options lead to a wide array of combinations.

The excel spreadsheet model in Appendix A is the primary tool used for the analysis. The spreadsheet starts with solar radiance and wind capacity factors for 12 AMC base locations. The spreadsheet then continues with common inputs for the price of hydrogen, JP-8 and an interest rate for future value (FV) calculations. Then there are 12 base specific pages that pull hydrogen usage statistics derived from Table 12. Table 12 is developed in the first section of research methodology. Each base page calculates storage, liquefaction, electrolysis and electricity generation data. The results are combined in table form for comparison in the subsequent sections. Capital, operations and maintenance costs are taken into consideration and all dollars are inflation adjusted to 2008.

AMC JP-8 Usage to Hydrogen Usage Conversion

To examine the costs of a transition to hydrogen aircraft, current fuel usage statistics for bases in Air Mobility Command were used as a starting point. Fuel use data for Andrews, Charleston, Dover, Fairchild, Grand Forks, MacDill, McChord, McConnell, McGuire, Pope, Scott and Travis were compiled. The data covered fuel usage for the first 3 quarters of 2008. That figure was divided by 9 to arrive at the average monthly fuel consumption per base. The average monthly fuel consumption was then divided by 30 to arrive at the daily fuel consumption per base. From these fuel usage statistics, a conversion to hydrogen was calculated. To perform this conversion, conversion factors derived from Brewer's *Hydrogen Aircraft Technology* were utilized. These conversion factors were based off the 1970s Lockheed studies.

To arrive at the conversion factors, I separated aircraft into four separate categories based on Operating Weight Empty (OWE). For each class of aircraft, Brewer provides a hydrogen conversion factor. He arrives at these conversion factors by designing two aircraft for a particular mission, a hydrogen and jet fuel version. Then he compares their fuel requirements to achieve this mission. As you can see by Table 10 as you move down the scale from light to heavy, the conversion factor tends to favor hydrogen more. There was little information for very small aircraft, so the conversion factor for anything smaller than a C-130 does not have a design twin in the Brewer study.

Table 10
Jet Fuel to Hydrogen Conversion Factor

Operating Weight Empty Low (1000's lbs)	Operating Weight Empty High (1000's lbs)	Conversion Factor	Source
0	85	0.373	Brewer
86	160	0.342	Brewer
161	270	0.323	Brewer
271	Top of Scale	0.288	Brewer

After the conversion factor was calculated, the next step was to determine what conversion factor to use at each base. This was complicated by the factor that each base did not have one type of aircraft. Since it would be difficult to apportion conversion factors by aircraft type usage statistics, a simple average was calculated. For example, Travis has C-5s, KC-10s and C-17s. I took the conversion factors for these three aircraft types, summed them up and divided by three. A future improvement would be to use a weighted average using the actual percentages of aircraft at each base. How conversion factors were allocated to different aircraft was based on OWE. The exact distribution of those conversion factors can be seen below.

Table 11

Hydrogen Conversion Factor Allocation by Aircraft Type

<table>
<tr><th>Aircraft</th><th>Empty Weight (lbs)</th><th>Range (nm)</th><th>Pax</th><th>Cargo (Pallets)</th><th colspan="2">Bases</th><th>LH2 Conv Ratio</th></tr>
<tr><td>C-5</td><td>380000</td><td>6320</td><td>81</td><td>36</td><td>Travis</td><td>Dover</td><td>0.288</td></tr>
<tr><td>KC-10</td><td>241000</td><td>4400</td><td></td><td>27</td><td>Travis</td><td>McGuire</td><td>0.323</td></tr>
<tr><td rowspan="2">C-17</td><td rowspan="2">282500</td><td rowspan="2">5000</td><td rowspan="2">102</td><td rowspan="2">18</td><td>Travis</td><td>McChord</td><td rowspan="2">0.288</td></tr>
<tr><td>Charleston</td><td>McGuire</td></tr>
<tr><td rowspan="2">KC-135</td><td rowspan="2">98500</td><td rowspan="2">1500</td><td rowspan="2">37</td><td rowspan="2"></td><td>MacDill</td><td>McConnell</td><td rowspan="2">0.342</td></tr>
<tr><td>Fairchild</td><td>GrandForks</td></tr>
<tr><td>C-130</td><td>83000</td><td>1000</td><td>92</td><td>6</td><td>Pope</td><td></td><td>0.373</td></tr>
<tr><td>C-130J</td><td>75500</td><td>1700</td><td>128</td><td>8</td><td>NA</td><td></td><td>0.373</td></tr>
<tr><td>C-20</td><td>38000</td><td>3700</td><td>12</td><td></td><td>Andrews</td><td></td><td>0.373</td></tr>
<tr><td>C-21</td><td>10000</td><td>2300</td><td>8</td><td></td><td>Scott</td><td></td><td>0.373</td></tr>
<tr><td>C-32</td><td>200000</td><td>5500</td><td>45</td><td></td><td>Andrews</td><td></td><td>0.323</td></tr>
<tr><td>C-37</td><td>46000</td><td>6300</td><td>12</td><td></td><td>Macdill</td><td></td><td>0.373</td></tr>
<tr><td>C-40</td><td>126000</td><td>5000</td><td>32</td><td></td><td>Scott</td><td></td><td>0.342</td></tr>
</table>

Fuel consumption statistics for the bases were given in gallons, but were converted to kilograms using a conversion factor of 3.180 kilograms/gallon. This conversion factor was determined using a density of .84 kilograms/liter multiplied by 3.785 liters/gallon. Kilograms were used for hydrogen since a kilogram of hydrogen represents a gallon of gas equivalent

(GGE) in terms of energy. With fuel use in kilograms per day for each base, the average conversion factor was used to obtain the equivalent hydrogen use in kilograms per day. Obtaining fuel use for hydrogen in kilograms per day for each base enabled a thorough examination of the costs required to obtain, liquefy and store that amount of hydrogen under various scenarios. The hydrogen usage statistics can be seen in the table below.

Table 12
Liquid Hydrogen Fuel Usage per Base in Kilograms/Day

	JP-8 (000's)						Hydrogen (000's)	
	Gallons			Kilograms				Kilograms
	Q1-3 08 Fuel Usage	Monthly Average	Daily Average	Q1-3 08 Fuel Usage	Monthly Average	Daily Average	LH2 Conv Ratio	Daily Average
Andrews	11,583	1,287	42.9	36,831	4,092	136	0.348	47.5
Charleston	103,263	11,474	383	328,349	36,483	1,216	0.288	350
Dover	40,256	4,473	149	128,003	14,223	474	0.288	137
Fairchild	41,303	4,589	153	131,333	14,593	486	0.343	167
Grand Forks	41,887	4,654	155	133,189	14,799	493	0.343	169
MacDill	21,963	2,440	81.3	69,838	7,760	259	0.373	96.5
McChord	115,556	12,840	428	367,440	40,827	1,361	0.288	392
McConnell	40,603	4,511	150	129,109	14,345	478	0.343	164
MCGuire	114,493	12,721	424	364,059	40,451	1,348	0.288	389
Pope	8,996	999	33.3	28,604	3,178	106	0.373	39.5
Scott	2,305	256	8.54	7,329	814	27.1	0.358	9.71
Travis	132,480	14,720	491	421,253	46,806	1,560	0.300	468
Total	674,688	74,965	2,499	2,145,337	238,371	7,946		2,428

Storage Costs

The daily average hydrogen usage in kilograms of liquid hydrogen became the starting input for a spreadsheet on each base. The first calculation from the daily average was the storage calculation. To arrive at a storage capacity to meet the daily average usage, several assumptions were made. First, each base has its own liquefaction facility. This reduces the need for distribution of liquid hydrogen. Second, each base will have gaseous hydrogen delivered just in time to the liquefaction facility so that there is no need for gaseous hydrogen storage. This can easily be achievable through onsite gaseous hydrogen production or pipeline delivery where the pipeline is the storage mechanism for gaseous hydrogen. Finally, due to boil-off losses, no more than 7 days usage of liquid hydrogen storage will be required. Although greater storage capacity of JP-8 is often desired, JP-8 is not produced onsite. To arrive at the storage requirement, the average daily usage is multiplied by 7 and then multiplied by $24.83/kg to arrive at the storage cost. The $24.83 figure was inflation adjusted from the 1995 $18/kg figure for a storage system of 300,000 kilograms (Amos, 1998). Inflation adjustments were calculated to the 2008 year using an internet based inflation calculator (Coinnews, 2009). The average storage requirement of all the bases was slightly over 200,000 kilograms. The assumption is made that the storage system contract could take advantage of the large number of storage systems that would be ordered to minimize costs. Table 13 below shows the costs for the various bases. The total cost for all liquid hydrogen storage tanks is slightly over $420 million.

Table 13

Liquid Hydrogen Storage Tank Costs Per Base

	Daily Average (kilograms)	Storage Capital Costs
Andrews	47,452	$8,248,000
Charleston	350,463	$60,914,000
Dover	136,624	$23,747,000
Fairchild	166,582	$28,954,000
Grand Forks	168,936	$29,363,000
MacDill	96,514	$16,775,000
McChord	392,187	$68,166,000
McConnell	163,760	$28,463,000
MCGuire	388,579	$67,539,000
Pope	39,530	$6,871,000
Scott	9,712	$1,688,000
Travis	467,513	$81,258,000
Total	2,427,852	$421,985,000

Liquefaction Costs

After the determination of storage costs, the capital costs and operations and maintenance costs of liquefaction had to be determined. Two estimates were used to encompass costs of previous liquefaction plants (see Table 14) and near future pilot programs (see Table 15). The Amos estimate represents current liquefaction capital and O&M costs, while the GEECO estimate represents a near future option which is currently under prototype testing. To determine the capital costs, the GEECO estimate of $39.1 million for 15.9 million kilograms of hydrogen liquefaction annually (43,562 kilograms a day) was utilized and the Amos estimate of $38.8 million for 36,000 kilograms a day liquefaction was utilized (Shimko, 2008 and Amos, 1998). The Amos method was adjusted for inflation to $53.5 million, since Amos was in 1995 dollars. The estimates resulted in capital cost ratios of $897.58/kg for GEECO and $1,486.75/kg for Amos. These ratios were multiplied by daily usage to arrive at liquefaction plant costs.

After the capital costs were determined, inflation adjusted Operations and Maintenance (O&M) costs were calculated. The estimate was calculated at $1.66/kg for Amos (Amos, 1998). To determine the GEECO estimate of O&M, $12.2 million annual O&M was divided by 15.9 kilograms produced annually to arrive at $.77/kg (Shimko, 2008). These numbers were multiplied by daily usage and then by 365 to get annual O&M costs. Finally, the electricity consumption figures were included (see Table 16). Electricity costs were included in O&M. Electricity costs represent approximately 60% of total O&M costs for liquefaction. Electricity consumption for current liquefaction was 15 kWh/kg, but is half that for the GEECO plant at 7.4 kWh/kg. The total current liquefaction capital cost is $3.6 billion for all bases and the total current liquefaction O&M cost is $1.47 billion per year for all bases. Using the GEECO prototype in the near future, the total liquefaction capital cost drops to $2.2 billion for all bases and the total liquefaction O&M cost is reduced to $.68 billion per year for all bases. There are more futuristic liquefaction options that can result in far greater cost reductions, but they are not included in this model due to the uncertainty of their economic feasibility.

Table 14
Current Hydrogen Liquefaction Plant Capital and O&M Costs Per Base

	Daily Average (kilograms)	Current Capital Cost	Current O&M Costs per Year
Andrews	47,452	$70,549,000	$28,751,000
Charleston	350,463	$521,051,000	$212,346,000
Dover	136,624	$203,126,000	$82,780,000
Fairchild	166,582	$247,666,000	$100,932,000
Grand Forks	168,396	$250,363,000	$102,031,000
MacDill	96,514	$143,492,000	$58,478,000
McChord	392,178	$583,071,000	$237,621,000
McConnell	163,760	$243,470,000	$99,222,000
MCGuire	388,579	$577,720,000	$235,440,000
Pope	39,530	$58,771,000	$23,951,000
Scott	9,712	$14,439,000	$5,885,000
Travis	467,513	$695,075,000	$283,266,000
Total	2,427,303	$3,608,793,000	$1,470,703,000

Table 15
Near Future Hydrogen Liquefaction Plant Capital and O&M Costs Per Base

	Daily Average (kilograms)	Near Future Capital Costs	Near Future O&M Costs per Year
Andrews	47,452	$42,592,000	$13,336,000
Charleston	350,463	$314,569,000	$98,498,000
Dover	136,624	$122,631,000	$38,398,000
Fairchild	166,582	$149,521,000	$46,818,000
Grand Forks	168,396	$151,149,000	$47,328,000
MacDill	96,514	$86,629,000	$27,125,000
McChord	392,178	$352,011,000	$110,222,000
McConnell	163,760	$146,988,000	$46,025,000
MCGuire	388,579	$348,781,000	$109,210,000
Pope	39,530	$35,481,000	$11,110,000
Scott	9,712	$8,717,000	$2,730,000
Travis	467,513	$419,630,000	$131,395,000
Total	2,427,303	$2,178,699,000	$682,194,000

Table 16
Current and Near Future Hydrogen Liquefaction Electricity Use Per Base

	Daily Average (kilograms)	Current Daily Electricity for Liquefaction (kWh/day)	Near Future Daily Electricity for Liquefaction (kWh/day)
Andrews	47,452	711,780.00	351,144.80
Charleston	350,463	5,256,945.00	2,593,426.20
Dover	136,624	2,049,360.00	1,011,017.60
Fairchild	166,582	2,498,730.00	1,232,706.80
Grand Forks	168,396	2,525,940.00	1,246,130.40
MacDill	96,514	1,447,710.00	714,203.60
McChord	392,178	5,882,670.00	2,902,117.20
McConnell	163,760	2,456,400.00	1,211,824.00
MCGuire	388,579	5,828,685.00	2,875,484.60
Pope	39,530	592,950.00	292,522.00
Scott	9,712	145,680.00	71,868.80
Travis	467,513	7,012,695.00	3,459,596.20
Total	2,427,303	36,409,545	17,962,042

Electrolysis Costs

To obtain the gaseous hydrogen that was input into the liquefier, the costs of electrolysis of water was examined. The cheapest method of steam methane reforming is attractive, but is dependent on the price of natural gas. The model was created to analyze the costs of creating a sustainable energy source for AMC not dependent on commodity prices. The model analyzed three different electrolyzers, one current and two prototypes. The current electrolyzer was a $1.5 million Hydrogenics hydrogen generator capable of producing 66 Nm^3/hr in 2006 dollars. The two prototypes were from Proton Energy and GE. Steve Szymanski of Proton Energy provided the details of the Proton concept and Richard Bourgeois of GE Research provided the details of the GE concept. From the kg of hydrogen from the liquefaction plant, the volume of gaseous hydrogen was determined using a density of .0887 kg/m^3 at 0 degrees Celsius and .1 MPa (NIST, 2008). The volume of gaseous hydrogen for each base can be seen in Table 17. The total hydrogen volume for all AMC bases is 27.37 million meters cubed.

Table 17
Gaseous Hydrogen Output from Electrolyzer Per Base

	Daily Average (kilograms)	Daily Average (Normal Meters^3)
Andrews	47,452	534,971.82
Charleston	350,463	3,951,104.85
Dover	136,624	1,540,293.12
Fairchild	166,582	1,878,038.33
Grand Forks	168,396	1,898,489.29
MacDill	96,514	1,088,094.70
McChord	392,178	4,421,397.97
McConnell	163,760	1,846,223.22
MCGuire	388,579	4,380,823.00
Pope	39,530	445,659.53
Scott	9,712	109,492.67
Travis	467,513	5,270,721.53
Total	2,427,303	27,365,310.03

From the volume of gaseous hydrogen, the inputs of water and electricity were determined for each electrolyzer. To determine the water input, the conversion factor of .7 gallons of water per 100 standard cubic feet of normal hydrogen gas was used (HYSTAT, 2008). All three electrolyzers were assumed to utilize the same water input. The result was in gallons, which was difficult to visualize, so the number of Olympic sized pools that could hold that volume of water per day was calculated. The conversion factor of 660,253 gallons per Olympic size pool was used. Then the average rainfall for each state was used to match bases with their average rainfall to determine the amount of area required to capture the necessary water requirement (Betweenwaters, 1988). The local base rainfall might significantly differ with the state average so this analysis is merely an estimate. McChord, Fairchild and Travis were updated with local information due to the state average differing so significantly from local conditions. The water needs for AMC are significant, totaling over ten Olympic sized pools a day. Reservoirs might need to be built to prevent overtaxing local water supplies (see Table 18).

Table 18
Daily Water Needs for Electrolyzer Per Base

	Daily Average Hydrogen Gas (Meters^3)	Daily Average Water (Gallons)	Daily Average Water (Olympic Pools)	Average Rainfall (inches per year)	Area to Meet Water Requirement (Square Miles)
Andrews	534,971.82	132,246.64	0.20	41.84	0.08
Charleston	3,951,104.85	976,724.97	1.48	51.59	0.48
Dover	1,540,293.12	380,765.08	0.58	41.38	0.23
Fairchild	1,878,038.33	464,256.71	0.70	33.94	0.35
Grand Forks	1,898,489.29	469,312.25	0.71	15.36	0.77
MacDill	1,088,094.70	268,980.27	0.41	49.91	0.14
McChord	4,421,397.97	1,092,982.84	1.66	39.00	0.71
McConnell	1,846,223.22	456,391.92	0.69	28.61	0.40
MCGuire	4,380,823.00	1,082,952.59	1.64	41.93	0.65
Pope	445,659.53	110,168.37	0.17	42.46	0.07
Scott	109,492.67	27,066.92	0.04	33.34	0.02
Travis	5,270,721.53	1,302,938.18	1.97	24.55	1.34
Total	27,365,310.03	6,764,786.74	10.25	443.91	5.23

The other input besides water required for the electrolyzers is electricity. To determine the electricity requirement a conversion factor was used. The Hydrogenics electrolyzer had a conversion factor of 4.8 kWh per normal meter cubed (HYSTAT, 2008). The Proton electrolyzer prototype had a conversion factor of 60 kWh per kilogram (Szymanski, 2008). The GE electrolyzer prototype had a conversion factor of 50 kWh per kilogram (Bourgeois, 2008). The GE electrolyzer was the most efficient at hydrogen production, but required over 120 million kWh per day for all AMC bases (see Table 19).

Table 19
Daily Electricity Needs for Electrolyzer Per Base

	Daily Average (kilograms)	Daily Average (Normal Meters^3)	Daily Hydrogenics Electricity (kWh)	Daily Proton Electricity (kWh)	Daily GE Electricity (kWh)
Andrews	47,452	534,971.82	2,567,865	2,847,120	2,372,600
Charleston	350,463	3,951,104.85	18,965,303	21,027,780	17,523,150
Dover	136,624	1,540,293.12	7,393,407	8,197,440	6,831,200
Fairchild	166,582	1,878,038.33	9,014,584	9,994,920	8,329,100
Grand Forks	168,396	1,898,489.29	9,112,749	10,103,760	8,419,800
MacDill	96,514	1,088,094.70	5,222,855	5,790,840	4,825,700
McChord	392,178	4,421,397.97	21,222,710	23,530,680	19,608,900
McConnell	163,760	1,846,223.22	8,861,871	9,825,600	8,188,000
MCGuire	388,579	4,380,823.00	21,027,950	23,314,740	19,428,950
Pope	39,530	445,659.53	2,139,166	2,371,800	1,976,500
Scott	9,712	109,492.67	525,565	582,720	485,600
Travis	467,513	5,270,721.53	25,299,463	28,050,780	23,375,650
Total	2,427,303	27,365,310.03	131,353,488	145,638,180	121,365,150

To calculate the capital costs of hydrogen production, the number of electrolyzers required to meet the production target had to be calculated. The Hydrogenics electrolyzer costs \$1.5 million and could process 1,584 Nm^3 of hydrogen per day (Highbeam, 2006). The Proton electrolyzer costs \$1.5 million and could process 500 kilograms of hydrogen per day. The GE electrolyzer costs \$150,000 and could process 480 kilograms of hydrogen per day. To determine the number of electrolyzers required, the daily average requirement was divided by the processing capability of the electrolyzer per day and rounded up. The number of electrolyzers required was multiplied by the electrolyzer cost to obtain a system cost. O&M costs were built on estimates by Szymanski and Bourgeois. The Hydrogenics O&M was estimated at \$25,000 per electrolyzer per year which was derived from the Proton and GE O&M estimates. The cost analysis for the three electrolyzers can be seen in the following tables.

Table 20

Hydrogenics Electrolyzer Capital and O&M Costs Per Base (Current Technology)

	Daily Average (Normal Meters^3)	# of Hydrogenics Electrolyzers	Hydrogenics Initial System Cost	Hydrogenics O&M Annual Cost
Andrews	534,971.82	338	$507,000,000.00	$8,450,000.00
Charleston	3,951,104.85	2,495	$3,742,500,000.00	$62,375,000.00
Dover	1,540,293.12	973	$1,459,500,000.00	$24,325,000.00
Fairchild	1,878,038.33	1,186	$1,779,000,000.00	$29,650,000.00
Grand Forks	1,898,489.29	1,199	$1,798,500,000.00	$29,975,000.00
MacDill	1,088,094.70	687	$1,030,500,000.00	$17,175,000.00
McChord	4,421,397.97	2,792	$4,188,000,000.00	$69,800,000.00
McConnell	1,846,223.22	1,166	$1,749,000,000.00	$29,150,000.00
MCGuire	4,380,823.00	2,766	$4,149,000,000.00	$69,150,000.00
Pope	445,659.53	282	$423,000,000.00	$7,050,000.00
Scott	109,492.67	70	$105,000,000.00	$1,750,000.00
Travis	5,270,721.53	3,328	$4,992,000,000.00	$83,200,000.00
Total	27,365,310.03	17,282	$25,923,000,000.00	$432,050,000.00

Table 21

Proton Electrolyzer Capital and O&M Costs Per Base (Near Future Technology)

	Daily Average (kilograms)	# of Proton Electrolyzers	Proton Initial System Cost	Proton O&M Annual Cost
Andrews	47,452	95	$142,500,000.00	$2,351,250.00
Charleston	350,463	701	$1,051,500,000.00	$17,349,750.00
Dover	136,624	274	$411,000,000.00	$6,781,500.00
Fairchild	166,582	334	$501,000,000.00	$8,266,500.00
Grand Forks	168,396	337	$505,500,000.00	$8,340,750.00
MacDill	96,514	194	$291,000,000.00	$4,801,500.00
McChord	392,178	785	$1,177,500,000.00	$19,428,750.00
McConnell	163,760	328	$492,000,000.00	$8,118,000.00
MCGuire	388,579	778	$1,167,000,000.00	$19,255,500.00
Pope	39,530	80	$120,000,000.00	$1,980,000.00
Scott	9,712	20	$30,000,000.00	$495,000.00
Travis	467,513	936	$1,404,000,000.00	$23,166,000.00
Total	2,427,303	4,862	$7,293,000,000.00	$120,334,500.00

Table 22
GE Electrolyzer Capital and O&M Costs Per Base (Future Technology)

	Daily Average (kilograms)	# of GE Electrolyzers	GE Electrolyzer Initial System Cost	GE Electrolyzer O&M Annual Cost
Andrews	47,452	99	$14,850,000.00	$2,475,000.00
Charleston	350,463	731	$109,650,000.00	$18,275,000.00
Dover	136,624	285	$42,750,000.00	$7,125,000.00
Fairchild	166,582	348	$52,200,000.00	$8,700,000.00
Grand Forks	168,396	351	$52,650,000.00	$8,775,000.00
MacDill	96,514	202	$30,300,000.00	$5,050,000.00
McChord	392,178	818	$122,700,000.00	$20,450,000.00
McConnell	163,760	342	$51,300,000.00	$8,550,000.00
MCGuire	388,579	810	$121,500,000.00	$20,250,000.00
Pope	39,530	83	$12,450,000.00	$2,075,000.00
Scott	9,712	21	$3,150,000.00	$525,000.00
Travis	467,513	974	$146,100,000.00	$24,350,000.00
Total	2,427,303	5,064	$759,600,000.00	$126,600,000.00

Electricity Costs

With the costs of the electrolyzers determined, the final element to model a sustainable AMC is the production of the electricity for both the electrolyzers and the liquefaction. Some of the available methods for sustainable electricity production include wind, solar, geothermal and hydroelectric. The model concentrated on thin film solar and wind for electricity production, but also contrasted them to electricity from the grid. Solar and wind are widely available and were chosen for their successes in renewable energy generation. To obtain the costs for thin film solar and wind, the best case and worst case electricity requirements were chosen from the combinations of electrolyzers and liquefaction plants. The costs of electricity from the grid used a conversion factor of 7 cents per kWh (Energetics, 2008).

The costs of the thin film solar system were determined by first calculating the area of solar cells necessary to produce the given electrical need. The NREL location specific solar energy available to produce electricity can be seen in Figure 37 (NREL, 2008). The values chosen from this map to be included in the model can be seen in Table 23. Two types of solar cells were used in the model, Nanosolar thin film solar cells and an industry average solar cell. The efficiency of the Nanosolar cell is 14.5% (Nanosolar, 2006). The efficiency of the industry average is 10% (Sciencedaily, 2007). The NREL location specific solar energy was multiplied by the efficiency to determine the actual kWh that could be produced per m^2. The electrical requirement in kWh was then divided by the production capability to determine the area of solar cells required.

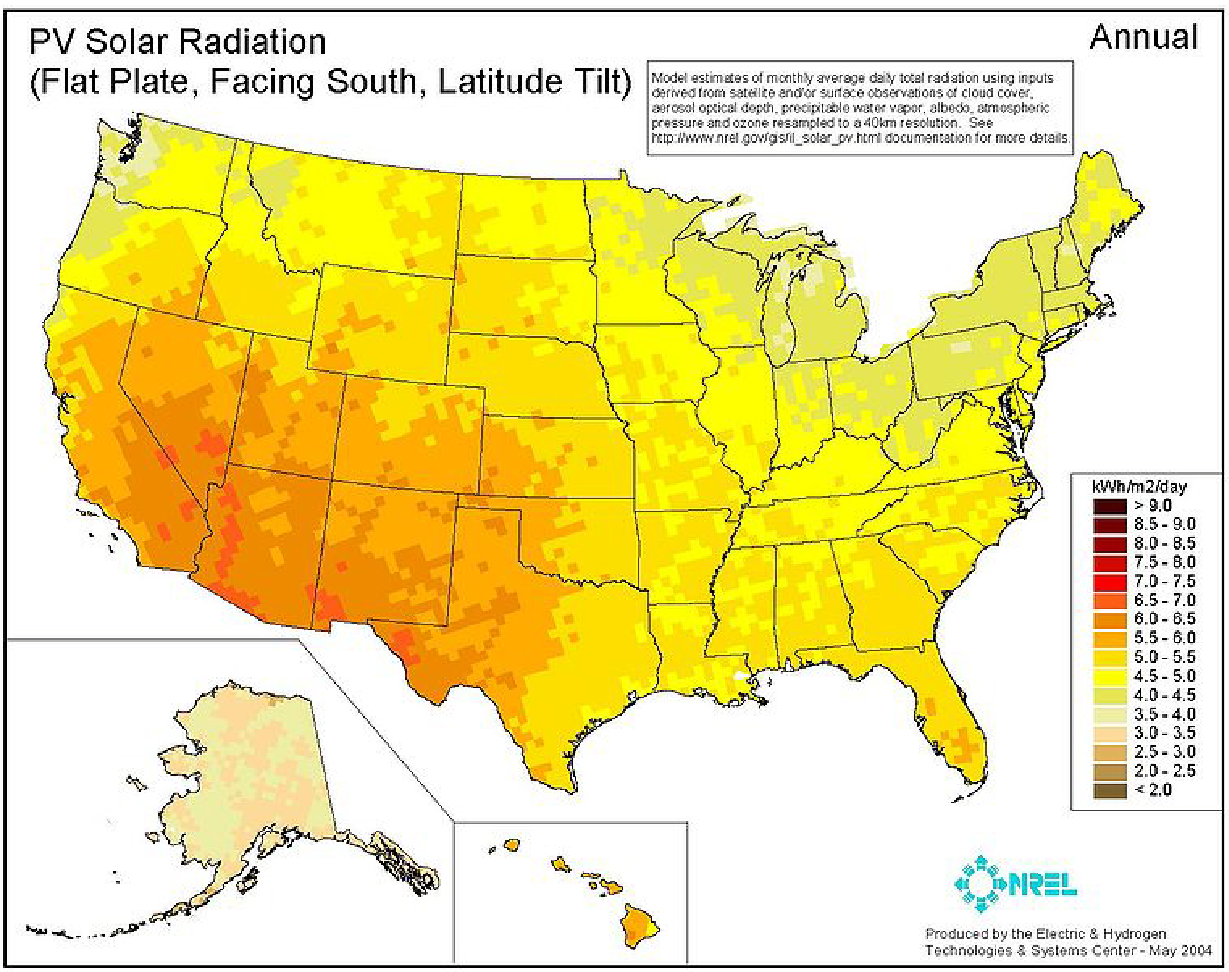

Figure 37
Annual Solar Radiation

Table 23
Solar Radiation by Base

	PV Solar Radiation (kWh/m^2 Per Day)
Andrews	5.0
Charleston	5.5
Dover	5.0
Fairchild	5.0
Grand Forks	5.0
MacDill	5.5
McChord	4.0
McConnell	6.0
MCGuire	5.0
Pope	5.0
Scott	5.0
Travis	6.0

After the area of solar cells was determined, the cost for the installation of the photovoltaic system was calculated. Dividing the NREL location specific solar energy by the industry standard average solar radiance of 1,000 W/m^2 gives the average hours of solar exposure per day (Americansolareconomy, 2009). To obtain the quantity of kW of solar cells needed to provide the required electricity, the model divided the electrical requirement in kWh/day by the average hours of solar exposure per day. The resulting kW is then multiplied by the installed photovoltaic system cost per kW. For current technology solar cells, $6.80 per Watt was used (Wiser, 2009). For the near future Nanosolar cells, $2.00 per Watt was used (Nytimes, 2007). For solar photovoltaic O&M costs, 5% of capital expenditures was used (Canada, 2004).

To model the costs of wind generation, only historical data was utilized. The model took into account capacity factors by region which can be seen in Table 24. A wind capacity factor is the actual amount of power produced over time divided by the power that would have been produced if the wind turbine operated at maximum output all of the time. The model used the capacity factors to obtain the Wattage required under the minimum and maximum electrical usage scenarios. From that wattage, initial capital and O&M costs were calculated. Initial capital costs were calculated from the average installed costs of wind projects in 2007 at $1,710 per kW (Wiser, 2008). For the O&M costs, a figure of $9 per MWh was used (Wiser, 2008). To obtain annual O&M costs, $.009 per kWh was multiplied by required kWh per day and then by 365 days per year.

Table 24
Wind Capacity by Base

	Wind Capacity Factors
Andrews	29.40%
Charleston	29.40%
Dover	29.40%
Fairchild	31.30%
Grand Forks	40.80%
MacDill	29.40%
McChord	31.30%
McConnell	40.80%
MCGuire	29.40%
Pope	29.40%
Scott	31.00%
Travis	36.90%

The capital costs of renewable energy systems are high, but the systems themselves have a long service life. For example wind turbines have a design lifetime of 20 years (Renewable, 2005). Nanosolar warranties its solar products for 25 years (Nanosolar, 2009). To compare the use of using JP-8 to the switch to renewable electricity generated hydrogen, the capital costs have been allocated over a 20 year lifetime. The model assumes the liquefaction plant and electrolyzer design lifetimes will exceed 20 years. To adjust for the time value of money a capital expenditure future value bonus is calculated and included at 2 percent per year.

IV. Results and Analysis

The model illustrated that the major cost factor preventing the shift to hydrogen as a renewable fuel source was the cost of electrolyzers. To transition to the use of electrolyzers to provide the total hydrogen fuel requirement for AMC would cost almost $26 billion with current electrolyzer technology. With the Proton electrolyzer that is in near term development the cost could be reduced to a little over $7 billion. The cheapest possibility which requires more significant technological development to achieve commercialization is the GE electrolyzer at a cost of $760 million. The next cost factor beyond the electrolyzer is the liquefaction plant. With current technology, the capital outlay for the liquefaction plant is a little over $3.6 billion. With the advanced GEECO pilot plant in successful operation, the liquefaction plant cost should decline to just under $2.2 billion.

For both the storage and renewable electricity generation, the cheapest method is one that is currently in use. Storage costs are only a minor part of total capital costs at just over $420 million even if the most advanced technology electrolyzer and liquefaction plant combination are used. For renewable electricity generation, wind power is currently the least expensive alternative. For every base, wind is the electrical generation source of choice (see Table 25). Even Nanosolar's breakthrough thin film solar technology that drops installed costs from $6.80 to $2 per Watt cannot compare to wind's current average installed cost of $1.71 per Watt. In addition, wind appears to have lower O&M costs. Using the advanced GEECO liquefaction plant and GE electrolyzer, the total capital cost of the required wind systems would be just over $30.6 billion. The cost of the advanced Nanosolar option is almost twice that at over $54.6 billion. Solar O&M is almost five times wind O&M at over $2.7 billion. Solar O&M has the potential to decline as economies of scale come into effect.

Table 25
Wind vs Solar Capital and O&M Costs by Base

	Current Prices		Near Future (Nanosolar)	
Base	Wind Initial Capital	Wind O&M	Solar Initial Capital	Solar O&M
Andrews	$660,091,000	$8,948,000	$1,089,498,000	$54,475,000
Charleston	$4,875,191,000	$66,083,000	$7,315,119,000	$365,756,000
Dover	$1,900,537,000	$25,762,000	$3,136,887,000	$156,844,000
Fairchild	$2,176,609,000	$31,411,000	$3,824,723,000	$191,236,000
Grand Forks	$1,693,397,000	$31,854,000	$3,878,771,000	$193,939,000
MacDill	$1,342,579,000	$18,199,000	$2,014,510,000	$100,726,000
McChord	$5,124,431,000	$73,950,000	$11,255,767,000	$562,788,000
McConnell	$1,641,513,000	$30,878,000	$3,133,275,000	$156,664,000
MCGuire	$5,405,411,000	$73,270,000	$8,921,774,000	$446,089,000
Pope	$549,891,000	$7,454,000	$907,609,000	$45,380,000
Scott	$128,128,000	$1,831,000	$222,988,000	$11,149,000
Travis	$5,181,602,000	$88,154,000	$8,945,082,000	$447,254,000
Total	$30,679,381,000	$457,793,000	$54,646,001,000	$2,732,300,000

The total cost breakdown of developing the required infrastructure to renewably produce fuel for AMC is broken down into three categories. These include minimum cost with technologies that are in the prototype stage, likely cost that can be started quickly and cost for currently available technologies. The total capital cost to produce enough hydrogen to meet AMC's fuel needs is just over $34 billion. That cost is the equivalent of buying over 12 years of JP-8 at the price of $3.04 for AMC. This capital expenditure covers storage, liquefaction, electrolyzers and electrical generation via wind. This cost was contrasted against the cost of commercial hydrogen and the cost of commercial JP-8. To make the comparison the capital costs were allocated over a 20 year period. The future value of the capital expenditure was calculated to provide a bonus to the price of oil for a more accurate comparison.

Table 26
Total Renewable Energy System Capital Costs

Category	Min Cost	Category	Near Term Cost	Category	Current Cost
Storage (Current)	$421,985,000	Storage (Current)	$421,985,000	Storage (Current)	$421,985,000
Liquefaction (GEECO)	$2,179,191,000	Liquefaction (GEECO)	$2,179,191,000	Liquefaction (Current)	$3,609,609,000
Electrolyzer (GE)	$759,750,000	Electrolyzer (Proton)	$7,294,500,000	Electrolyzer (Current)	$25,929,000,000
Electrical Generator (Wind-Current)	$30,679,381,000	Electrical Generator (Wind-Current)	$30,679,381,000	Electrical Generator (Wind-Current)	$30,679,381,000
Total	$34,040,307,000	Total	$40,575,057,000	Total	$60,639,975,000

The minimum cost column will be used to contrast the price per day for AMC with the current commercial price of JP-8. The analysis will take into account the future value implications of the capital expenditures with a 2% interest rate. The result will be a price of JP-8 at which it would be less expensive to convert to hydrogen aircraft with and without the future value calculation. The analysis does not take into account the cost of developing a hydrogen aircraft since that will be part of recapitalizing AMC aircraft. The price of JP-8 at which it becomes cheaper to switch to hydrogen from the perspective of AMC is $4.14 a gallon. With the price over $4.14 a gallon, the Air Force would be paying more for JP-8 over a 20 year period than they would pay for the capital infrastructure and O&M required to make the equivalent level of hydrogen. It is important to note that this analysis examines only AMC bases. A transition to hydrogen will affect bases in other geographic Combatant Commands. An area for future study would be to include all strategic mobility bases in the price breakeven analysis.

Table 27
Renewable Energy Hydrogen vs JP-8 Cost

Base	Renewable Energy Hydrogen Daily Cost	JP-8 Daily Cost	JP-8 Price to Match Renewable Energy Cost	JP-8 Price to Match Renewable Energy Cost with FV Bonus
Andrews	$166,124.78	$130,416.00	$3.87	$5.00
Charleston	$1,226,920.66	$1,162,660.16	$3.21	$4.14
Dover	$478,303.51	$453,248.80	$3.21	$4.14
Fairchild	$563,958.65	$465,040.96	$3.69	$4.73
Grand Forks	$501,439.45	$471,613.44	$3.23	$4.06
MacDill	$337,943.09	$247,291.84	$4.15	$5.36
McChord	$1,327,622.02	$1,301,077.44	$3.10	$3.98
McConnell	$486,145.82	$457,164.32	$3.23	$4.06
MCGuire	$1,360,314.53	$1,289,108.96	$3.21	$4.14
Pope	$138,437.64	$101,283.68	$4.16	$5.36
Scott	$33,111.24	$25,952.48	$3.88	$4.98
Travis	$1,455,520.41	$1,491,627.68	$2.97	$3.76
Total	$8,075,841.80	$7,596,485.76	$3.23	$4.14

If the GEECO plant, the GE electrolyzer and the Proton electrolyzer fail to work as predicted, then the price of JP-8 to match renewable energy cost could climb as high as $5.89 without the bonus and $7.50 with the bonus. Due to airframes lasting over 50 years and the long design lifetimes of renewable energy systems, policy makers need to forecast the price of oil over the next twenty years and compare the average forecast price of oil with the transition cost. If the average forecast price of JP-8 over the next 20 years exceeds $7.50, then the choice to transition to hydrogen aircraft and infrastructure makes sense economically.

V. Discussion

Initially, the question was asked whether liquid hydrogen can be a replacement fuel for AMC and it was hypothesized that it would be feasible. The research suggests that hydrogen can be used as a replacement fuel for AMC and that the original hypothesis is true. The second question addressed the advantages and disadvantages of JP-8 compared to hydrogen and it was hypothesized that hydrogen would be a superior fuel. The literature review covered the advantages and disadvantages of hydrogen and JP-8 and showed the original hypothesis to be false. Although hydrogen was superior in many areas, JP-8 had distinct advantages in its storage temperature, energy per unit volume and existing infrastructure. The superiority of one fuel over the other then becomes dependent upon what categories they are being measured against and the weights given to those categories.

The third question of the costs associated with liquid hydrogen and its infrastructure was examined in detail through the results and analysis section. The costs ranged from $34 to $60 billion for a complete transition to hydrogen for AMC. The location in this range depends on the success of technological advances with $60 billion for current technology. It was hypothesized that the cost of inaction would outweigh the costs of making the transition from JP-8 to hydrogen. The analysis suggested that the truth of the hypothesis was dependent on the future price of oil. If the average price is greater than $7.50 a gallon over the next 20 years than the hypothesis is true. If the average price over the next 20 years is less than $4.14 a gallon then the hypothesis is false. Anywhere in between depends on the state of hydrogen technology.

The fourth question asks how to transition from JP-8 to hydrogen and it is hypothesized that the transition should begin with a large aircraft replacement and finish with smaller aircraft. The suggested solution going forward is to build a hydrogen aircraft prototype and the required infrastructure for a large cargo aircraft. When proof of concept has been established, the transition can expand to increase the hydrogen fleet to include smaller aircraft and increase hydrogen production infrastructure. There is a lack of data to properly validate the proper path going forward and is an area for further research.

The final question looked into the optimal propulsion method for liquid hydrogen. It was hypothesized that hydrogen turbines turning generators powering high temperature superconducting motors would be the best. The hypothesis was validated by the research. If the use of high temperature superconductors advances as expected, then HTS powered motors could provide an order of magnitude improvement over their turbofan equivalents in terms of thrust per weight ratio. HTS motor powered aircraft would provide benefits in terms of reduced thermal signature, reduced noise levels, reduced weight, enhanced electronics, enhanced radar and enhanced communications equipment.

The technology is currently available for Air Mobility Command to switch from JP-8 powered aircraft to hydrogen powered aircraft. Producing the hydrogen for these aircraft through renewable energy technologies such as wind turbines and electrolyzers enables AMC to produce its own fuel without reliance on industry or foreign oil producers. In addition to energy independence, AMC switching to hydrogen aircraft could reduce the trade deficit, reduce the price of oil, reduce global warming, reduce air pollution, increase the number of United States' jobs, improve the image of the United States abroad and reduce the risk of oil conflicts.

The costs of action include advances in bio-fuels that could synthesize a JP-8 equivalent at far lower cost, large discoveries of new oil reserves, failures during proof of concept testing and failures during large scale implementation. The costs of inaction include massive economic losses from rapidly rising oil prices, reduced airlift capability from reduced flights due to high oil prices, falling behind other countries technologically, increased global warming, increased air pollution and increased global instability. Hydrogen can be used in a sustainable cycle, while the use of coal or natural gas will eventually result in resource depletion. Coal and natural gas also have their carbon dioxide emissions problems. If bio-fuels are to surpass the use of hydrogen as a fuel source, then they must not compete with land capable of food production.

The Air Force has researched synfuel as a partial JP-8 replacement. Synfuel has excellent potential to help reduce JP-8 consumption, but other options should be explored more aggressively. The Air Force should invest more resources in hydrogen aircraft technology. If successful, the benefits to the United States economically, technologically, politically and militarily could be tremendous. If oil is expected to exceed $7.50 on average over the next 20 years, then the decision to transition makes economic sense even without taking the trade deficit or job creation into consideration. If NASA achieves the HTS motor improvements they expect, then the decision to transition makes technological sense even without taking into account the other ancillary benefits of superconductors. If politicians are concerned with job creation, the trade deficit, global warming, air pollution and global instability, then the decision to transition makes political sense. If the capacity to generate liquid hydrogen can be quickly transported to anywhere there is water and wind/sunlight then the transition to hydrogen makes sense logistically. Finally, if superconductors enable an asymmetric military advantage over potential adversary actions then the transition makes sense militarily. The choice to make the transition to hydrogen or a superior alternative should be made long before JP-8 hits $7.50 a gallon.

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14. ABSTRACT

The purpose of this research is to compare the costs associated with the transition to hydrogen aircraft for Air Mobility Command (AMC) to the costs of continuing using JP-8. Using current technology, air mobility aircraft can be designed to use liquid hydrogen instead of JP-8. This transformation will be capital intensive. A model was built that converted current AMC JP-8 usage to liquid hydrogen usage and calculated the costs of the infrastructure for that transition. The model focused on hydrogen production through renewable energy. The model covered the costs and requirements for electricity generation, hydrogen production, hydrogen liquefaction and liquid hydrogen storage. The analysis of hydrogen as a fuel for AMC aircraft covered the history of hydrogen aircraft, previous hydrogen aircraft studies, a comparison of hydrogen to JP-8 and liquid hydrogen to thrust conversion. The three areas of focus for liquid hydrogen to thrust conversion include hydrogen turbojets, hydrogen turbines powering High Temperature Superconducting (HTS) motors and fuel cell powered HTS motors. The results of the

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