ILF

A Study of the Implications of Liquid Fuel (ILF) for Rotary Aircraft in Future Warfare

Final Report

Sponsored by:

Sikorsky
A United Technologies Company

ILF Team:

Tariq Islam
Jessica Kaizar
Hong Tran

George Mason University

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EXECUTIVE SUMMARY

The Implications of Liquid Fuel (ILF) project is the study of the consequences of liquid fuel in future warfare. The project began with the survey of energy usage throughout history. Based on assessment of past and current war tactics, several fuel consumption metrics were developed. Evaluation of current war tactics also led to the identification of ranges of Army, Navy, Marine Corps and Air Force operational scenarios for modeling purposes. Several different types of technologies were evaluated and characterized for model incorporation to reduce fuel consumption. Examined technologies included alternate energies and helicopter design. Alternate energies provide the capability of becoming less dependent on fossil fuels. Helicopter design technologies aim to improve efficiency associated with different helicopter's components. Estimation of future fuel cost was also accomplished. Analyses were conducted to gain insight to the fuel consumption characteristics of the model. Finally, recommendations were provided to indicate impact of fuel efficiencies an on rotary aircraft.

1 PROBLEM DESCRIPTION

1.1 Background

The industrial world, as it stands today, is dependent upon liquid fuel. From civilian vehicles to aircraft, from rocket propulsion systems to military vehicles, all forms of transportation are supported by liquid fuel. As such, fuel efficiency has become a hallmark in engineering and production of all different types and forms of vehicles that use fuel today.

The most notable reason for the new focus on fuel efficient vehicles and engines is due to the fact that the price of fuel has begun to rise. Consumers are now taking the fuel efficiency of their vehicles into far more consideration than ever before. Fuel, as a commodity, is now being seen within a more critical scope in terms of usage and availability. Just as everyday consumers are giving focus to fuel efficiency in their vehicles, so is the United States military.

Today, the U.S. military or the Department of Defense (DOD) in general, consumes more oil and petroleum than the 300 million consumers that reside within the U.S. The U.S. military is actually the largest consumer of liquid fuels in the world, with fuel use in 2004 being the equivalent consumption level of the entire country of Greece. Within the construct of Operation Iraqi Freedom (OIF) and in the years pursuant, as of 2005, the US military was consuming 1.7 million gallons of fuel per day, which averages to about 9 gallons of fuel per deployed soldier each day. These metrics are in stark contrast to past wars, where, by comparison, three weeks of fuel usage in the recent Iraq War equates to the total fuel usage of all Allied forces in World War I. (Sohbet)

The U.S. military must seek out more fuel efficient and/or alternate energy-based systems for its operations and update its tactics in future war campaigns, or risk substantial increases in cost to the American people. One such vehicle that the U.S. military, must reconsider is the helicopter, as well as other vehicles that utilize rotary engines. Helicopters are the least fuel efficient vehicles used today in the campaign scenario. However, the advantage provided by rotary aircraft make them an essential part of military operations.

1.2 Problem Statement

The need of the U.S. military and the DOD to have helicopters in various warfare scenarios stems from the fact that they provide a tactical advantage and options that are often used, from cargo lifting to urban warfare support.

This project will serve to provide a background study on past wars in terms of their fuel usage, and compare them to the metrics of modern day warfare. What is needed, and what will be answered here subsequently, is that given various future warfare scenarios, how will helicopters be leveraged and used in those scenarios? The study will also address a major concern for operators of any type of vehicles, systems, or machinery - that of energy usage efficiency. In each of the warfare scenarios, fuel efficiency will be analyzed from two perspectives, design and tactical. The main objective is to provide some feasibility consideration to assist in the decision-making related to helicopter production for the next 10 to 20 years. In addition, alternate energy sources, where useful, must be leveraged in conjunction with liquid fuel use to alleviate the cost of using liquid fuel exclusively. The efficiencies in these various scenarios will inevitably affect the procurement and resulting revenue associated with the production and sale of helicopters in the coming decades.

1.3 Stakeholders

The following stakeholders are directly involved in the project outlined in this document:

1. Sikorsky - David Kingsbury
2. ILF Team- Tariq Islam, Jessica Kaizar, Hong Tran,
3. Dr. Laskey (Faculty Advisor) and SEOR Faculty

2 PRELIMINARY REQUIREMENTS

2.1 Task Organization

This project consists of technical and management tasks. The technical tasks will be assigned to team members according to their expertise. The management supporting tasks will be shared by all members. The project team members plan to collaborate closely to integrate individual efforts in delivering quality results within the project time-frame.

2.2 Data Collection

The ILF team will perform preliminary research to obtain data related to fuel consumption in past and current wars. Factors affecting the fuel consumption such as war scenario, environment, equipment used, types and sources of fuel will be collected and analyzed to define fuel-consumption metrics and baselines for the project. The following tasks reflect the desires of the customer and the need for data collection required to initiate the project.

- Conduct analyses of fuel consumption of past wars
- Propose metrics associated with past-war fuel consumption
- Identify the fuel-consumption baselines based on the analyses of Desert Storm and OIF

3 TECHNICAL APPROACH

3.1 Background Research

The ILF team began the analyses of the implication of liquid fuels in future warfare with an emphasis on rotary aircraft by surveying the use of energy in warfare throughout history. The purpose of this activity is to project future fuel usage in warfare and to choose or derive metrics to quantify the varying aspects of fuel consumption. The analyses indicated there was not much public information available concerning fuel consumption of past wars. Two studies were found documenting fuel consumption of previous war results.

3.1.1 Background Research Results

The first study was completed by the U.S. Army who had access to DOD fuel consumption of past wars. The second study was performed by Deloitte LLP. The Army documented the historical fuel consumption rates and projected rates for future wars in Figure 1. The Army stated the following about the chart: " This figure was generated by the Research, Development, and Engineering Command (RDECOM) P&E technology Integrated Product Team (IPT) now Technology Focus Team, and presented by the Commanding General, Army Materiel Command at last year's P&E symposium (Aug 07). It provides Soldier daily fuel consumption estimates for various major US military operations from the Civil War to Operation Iraqi Freedom (OIF). It should be noted this was based on various sources and usages, but the bottom-line is that Army fuel consumption usage has increased significantly over time primarily due to power demand increases for both moving and non-moving operation to provide the necessary capability for those operations. With the increased power demands of the network-centric future battle field, P&E issues will take on greater importance in future system acquisition. The Army will need these methods to address the analytical challenges of future power growth while satisfying Soldier requirements." (Roche 2008)

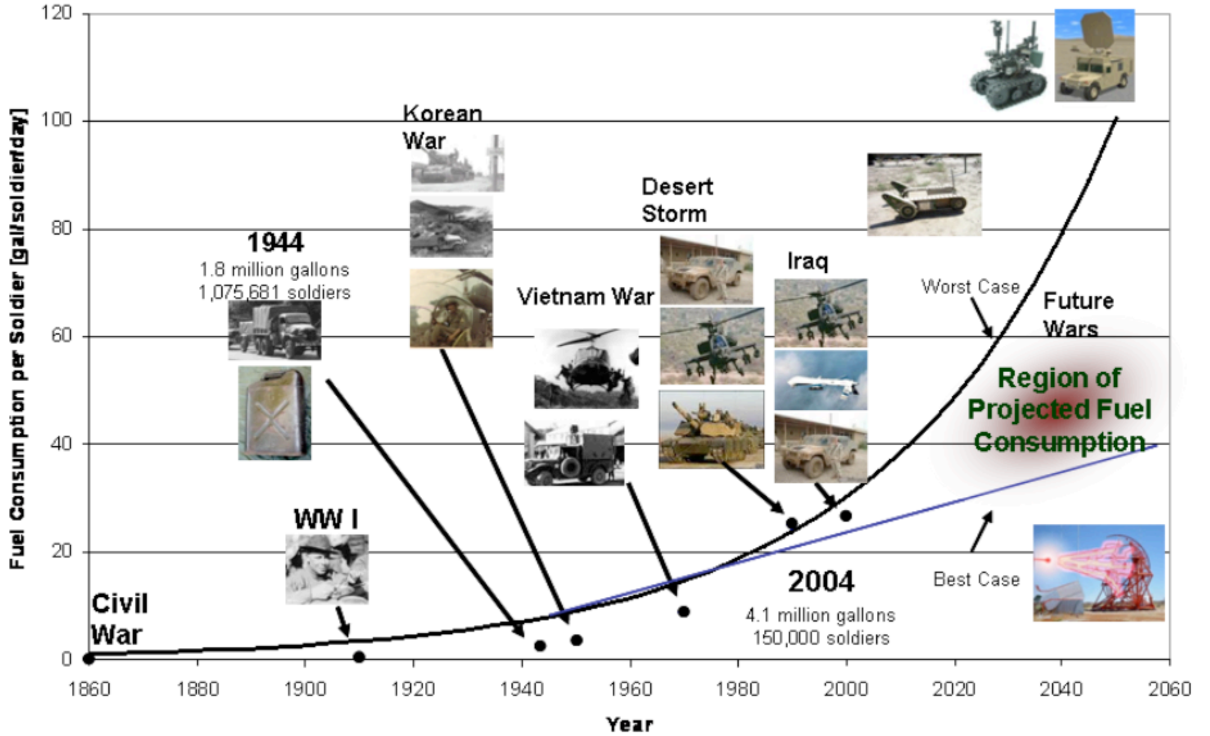


Figure 1: History and Projection of Fuel Consumption by the US Army

The Deloitte study concluded "that there has been a steady increase in the dependence on fossil fuels since World War II. It is estimated that as of 2007, the average gallons of consumption in OIF/OEF per U.S. soldier per day was 22 gallons. Using a least squares regression forecasting meth odology, it is predicted that there will be a 15.6% increase in gallons consumed per U.S. soldier per day by 2017, for a 1.5% compounded annual growth rate (CAGR) increase."

3.1.2 Past and Present Metrics

Metrics are meant to capture the performance and effectiveness of the scenarios with respect to fuel consumption. They are indications of how fuel is expended and highlight benefits of increased fuel efficiency. The metrics or Measures of Performance (MoP) are identified below. Each of these metrics will be converted into fuel consumed and cost in the model to determine the effectiveness of fuel efficiencies of saving the consumer money.

Total Fuel Expended is the overarching metric. This metric is calculated in pounds (lbs) of fuel expended over the course of the individual scenarios or campaign.

Cost of Fuel Expended converts the total fuel consumption to cost in fiscal year 2010 dollars (FY$10). This metric indicates how much is may cost to complete a mission.

Lift Capacity is an essential capability of the helicopter. The more pounds the helicopter lifts, the more fuel it consumes. This was modeled by decreasing the cruising speed to simulate greater fuel consumption.

Time on Station (TOS) is the time helicopter devoted to perform the mission.
This MOP is impacted by refueling effort (increase mission time by removing the need to refuel eliminating delays) and weight (lighter aircraft may move faster and does not consume much fuel).

Total Mission Time is the time it takes the helicopter to complete a mission. The speed of travel and the necessity to refuel mid-mission impact the total mission time.

Additionally, lesser metrics were gathered to assist in analysis as applicable:

- Mid-Mission Refueling Time
- Average Fuel Consumed per Hour
- Average Fuel Consumed per Nautical Mile
- Average Mission Cost per Hour
- Average Mission Cost per Nautical Mile
- Personnel (PAX) Transported

3.2 Scenarios

The ILF team identified representative scenarios to encompass the range of mission areas and tactical situations (TACSIT) for rotary aircraft in the Army, Navy, Marine Corps and the Air Force. The mix of force, missions, helicopters, and metrics is depicted in Figure 2 below.

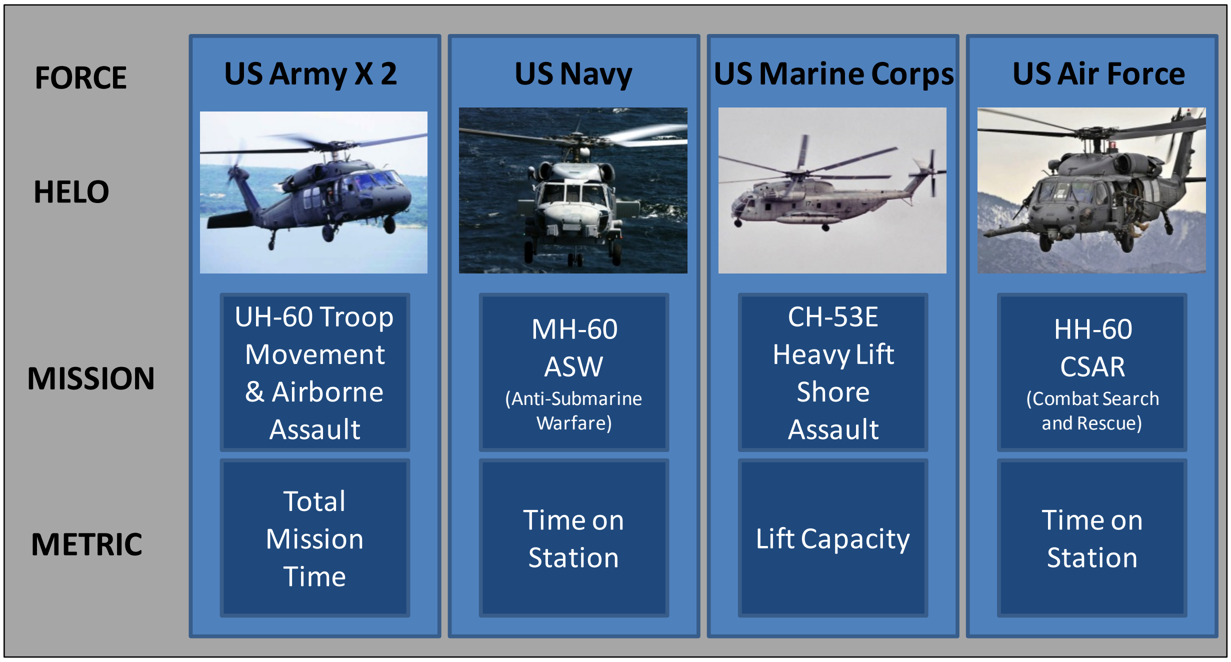


Figure 2: Representative Range of Scenarios for Modeling Rotary Aircraft Fuel Consumption

The U.S. Army scenarios consist of a single troop movement and an air assault. The troop movement consists of 15 UH-60A/L helicopters used to transport a battalion. The battalion must be transported 370 nautical miles (nm). With a maximum flight time of 2.3 hours, the helicopter will have to refuel mid-mission on both legs out and back. The air assault consists of an air assault battalion. On the assault side 15 UH-60A/L helicopters deliver troops to the front line for assault and support. In addition to assault craft, 8 medical evacuations are performed during the assault as well as 5 administrative lifts. The assault occurs 215nm from base and the helicopters will have to stop at least once to refuel during the mission.

In both Army scenarios the tactical implication is to minimize time to complete the mission. The projected force mix for Army aircraft over the next 20 years for Blackhawks incorporates the MH-60M coming online and replacing legacy models. The MH-60M has only a slightly higher fuel consumption rate of 1152 lbs/hr versus legacy models with 1081 lbs/hr.

The U.S. Navy scenario consists of a single day of anti-submarine warfare (ASW) operations. A squadron of MH-60R is embarked upon a U.S. Navy aircraft carrier (CVN) as part of the carrier air wing. It consists of 11 MH-60R, five of those remain on the CVN, while six go in pairs on three cruiser destroyer escorts (CRUDES). The littoral combat ship (LCS) has a single MH-60R embarked as an independent deployer.

A number of assumptions were made to characterize flight operations and fuel burn for the MH-60R. All flight time is considered to be on station time. MH-60R on CVN fly six hours per day, on CRUDES the pair totals nine flight hours per day per platform and the independent deployer on the LCS flies six hours per day. The ASW missions require a mix of hovering, slow prosecution and cruising. A Sikorsky provided a standard fuel expenditure rate for ASW mission, of 1194 lbs. per hour was used. MH-60R are recently acquired aircraft for the U.S. Navy and there is no significant model changes projected over the next 20 years.

The U.S. Marine Corps scenario is a heavy lift occurring over a 15 hour period. There are two squadrons of CH-53E embarked from two large deck amphibious assault ships, LHA/LHA(R), embarked with 16 aircraft each. The majority of the mission is heavy lift for vehicles such as the High Mobility Multipurpose Wheeled Vehicle (HMMWV) or Humvee. The lift occurs in three waves. Each wave consists of 20 vehicle lifts and four CH-53E assisting with refueling. It is assumed that two remain as back-up and six are in maintenance. Based upon an analysis of flight schedules for multiple sea to shore projection scenarios 65% of vehicle lifts were single HMMWV and 35% of vehicle lifts were tandem HMMWV. Each HMMWV weighs on average 13,000lbs. Lift leg increased burn rates are primarily driven by the decrease in cruising speed, increasing total mission time and the total fuel consumption. Over the next 20 years the Marine Corps will phase in the CH-53K to replace the CH-53E for heavy lift. The CH-53K has a significantly higher burn rate of 4780 lbs/hr compared to the CH-53E at 4008 lbs/hr.

The U.S. Air Force scenario is a Combat Search and Rescue (CSAR) mission. It is a pair of HH-60 helicopters performing an extended search and rescue of 800nm. The HH-60 is outfitted with additional fuel tanks to support the extended range search. No significant changes to the current CSAR aircraft are project over the next 20 years.

In addition to the primary scenarios listed the team looked at a 24 hours intelligence, surveillance, and reconnaissance (ISR) mission. This was added to include mission that will continue to migrate into unmanned technologies over the next 20 years.

3.3 Technologies for Inspection: Alternate Energy Sources/Rotorcraft Design

The alternative technology research for the ILF project covers the examination of different alternative energies and alternative helicopter designs to improve fuel consumption. The alternative energy sources examined include biofuel, electric, fuel cell and solar power. These energy sources do not originate from fossil fuel, which petroleum, coal and natural gas are derived from. Examined alternative helicopter designs consist of hybrid diesel-electric propulsion system, optimum speed rotor with tilt rotor technology, airframe/engine material and rotor blade design.

3.3.1 Alternate Energy Sources

3.3.1.1 Algal Biofuel

The alternate technology research indicates algal biofuel is a viable candidate to replace military jet fuel in the near future. Freshwater algae which grow in freshwater river or pond are the choice of feedstock. Algae grow rapidly by doubling two to three times a day. Algae can also be grown in clear containers, or bioreactors to stimulate the growth. The ingredients needed to grow algae are sunlight, nontoxic wastewater and an abundance of carbon dioxide. Carbon dioxide (CO2) emission from local power plants could be reduced by recycling the CO2 in the algal pond. The algae are then harvested to extract for oil and the oil is converted to fuel. Algae are an attractive choice because it is not a food crop. Also, the fuel created from algae works with current fuel infrastructure. No modification to fuel pipelines, refineries or to the propulsion system of gas, trucks, aircraft or helicopter is expected. Continental Airlines successful flight with 50% biofuel blend indicated current aircraft technology can accommodate this alternative fuel. Continental test flight data showed the algal molecular structure is the same as gas, diesel or jet fuel but with 4% increase in energy density (Howell 2009). In addition, algae biofuel is preferred because they could be grown in theatre such as Afghanistan where fuel transportation to this destination area is costly and deadly due to Afghanistan's insufficient fuel transport infrastructure (at least for the purposes of a full-scale military campaign) and frequent roadside bombings/attacks (Edwards 2010). In 2009, the not-for-profit Center for Naval Analyses concluded that the U.S. military's dependence on foreign oil impacts national security because U.S. oil purchases support countries associated with terrorism and therefore "the U.S. was indirectly financing both sides of the terrorist conflict" (Lombardi, 2010). The Center recommended DOD to actively pursue alternative energies and electric vehicles. Different venues are aggressively pursuing algae biofuel research. One such example is Sapphire Energy Inc. which is working to produce gasoline from algae. Among Sapphire's major investors are Microsoft co-founder Bill Gates and the Rockefeller family's venture capital firm. Meanwhile, Exxon Mobil teams with Synthetic Genomics Inc. to change genetic structure of certain algae to ease the algal oil extraction (Foroohar 2010). The U.S. Navy has been purchasing algal shipboard and jet fuel from Solazyme with the objective to achieve 50% usage of alternative resources by 2020. U.S. Navy also conducted testing of the experimental RCB-X riverine command boat using 50% blend of algal biofuel and petroleum (McCluney 2010). Higher education is also actively pursuing algae as a sustainable resource for jet fuel. The U.S. military funded a $2.346 million grant to New Mexico State University to research "better ways to grow algae and refine its oil while working with the University of Central Florida to determine the effects of algae-based fuel on jet engines." (Bannister 2010). The Department of Energy, through its National Renewable Energy Laboratory (NREL), also commits to algae investigation. "NREL is working with the U.S. Air Force Office of Scientific Research (AFOSR) to perform a proteomics analysis of an oil-accumulating green algal strain. This basic research will answer fundamental algal biology questions regarding oil production that could lead to the development of cost-effective, algal-based jet fuel." (NREL 2010) Defense Advanced Research Projects Agency (DARPA), a DOD research arm recently released its algae analyses' progress status. DARPA studies on converting algal oil to military jet JP-8 fuel began in December 2008. JP-8 is the focus because it is the military's preferred war-time jet fuel. The program objective is to have JP-8 production cost under $3 per gallon at a production capacity of 50 million gallons per year. The program accomplishment so far included "Implement algal growth and productivity improvement methods; Demonstrate scalability of algae growth and processing system; Understand the potential market value of the co-products on the final cost of jet fuel." DARPA also revealed that samples of algal oil passed the key first-level specifications (Mantz 2011). At the 2010 ILA air show in Berlin, a twin engine Diamond DA42 NG light aircraft flew with one engine using 100% algae-based biofuel and the other using conventional jet kerosene. Flight test data indicated that "Due to the higher energy content of the algae biofuel… showed that fuel consumption of the biofuel is 1.5 litres per hour lower, equivalent to fuel savings of 5-10 percent." (Greenair 2010)

3.3.1.2 Solar Power

Another source of energy that will not exploit fossil fuel is solar power. Solar power coupled with high-performance batteries and composite airframe could enable a helicopter to operate as an unmanned rotorcraft. Although no solar powered helicopter currently exist, several sun-powered manned and unmanned aircraft have flown the sky. One example of a manned solar powered aircraft is the Sunseeker

II. It is a one-seater and has solar cells integrated into the wing structure. There are 48 lithium polymer batter cells in the wing to power the 5kW electric motor during takeoff and climb. Once in cruise, the pilot could drain the batteries, switch to solar, or glide. Sunseeker II dry weight is 264 pounds with maximum speed of less than 100 mph and cruising speed of 40 mph. This aircraft only flies during sunlight. Sunseeker III with a two man-seat is in work. The electric motor for this manned aircraft is expected to be 20kW (Ridden 2010). An example of the unmanned solar powered aircraft is the Zephyr Unmanned Air Vehicle (UAV). With solar arrays bonded to the composite wing, Zephyr UAV "flies on solar power generated by amorphous silicon arrays covering the aircraft wings, no thicker than sheets of paper. It is powered day and night by rechargeable lithium-sulphur batteries that are recharged during the day using solar power. The aircraft uses United Solar Ovonic solar arrays, a full flight-set of Sion Power batteries, as well as a novel solar-charger and bespoke autopilot developed by QinetiQ" During a test in Arizona, the Zephyr UAV stayed aloft for 14 days and 21 minutes on solar and charged batteries. (QinetiQ 2007). "Despite those successful applications, many observers believe that fuel cells and solar panels will primarily be used secondary power-generating systems on aircraft, such as auxiliary power units for large commercial airlines, rather than primary power units." (Weber 2010)

3.3.1.3 Electrical Power

Electrical power from lithium ion batteries is a technology that has been in the commercial industry for many years and has made its way into military research and applications just recently. As the cost of fuel steadily rises, so does the need for a fuel source that has the potential to fully supplement liquid fuel during vehicle operation.

The most significant advancement in the application of electrical power has been in Sikorsky's Firefly helicopter. A basic S-300C frame was used, mounted with a lithium ion energy storage system designed by Gaia. The obvious advantage to using a purely electrical rotary system is that there are fewer moving parts, therefore less weight.

"Through the electrical conversion, propulsion efficiency of the aircraft has been increased roughly 300 percent from baseline. Electric propulsion also inherently simplifies the complexity of the propulsion system by reducing the quantity of moving parts, increasing reliability while reducing direct operating costs." -- Mark Miller, Vice President of Sikorsky Research and Engineering

However, this advantage is nullified by the fact that the power output of lithium ion batteries is currently not sufficient enough to power an operational military helicopter as the sole source of energy for the rotary blades for the duration required during a mission.

In the coming future, a newer battery design known as the lithium air battery is a much more viable option for powering, at least in a supplemental role, a fully operational military rotary aircraft at full capacity.

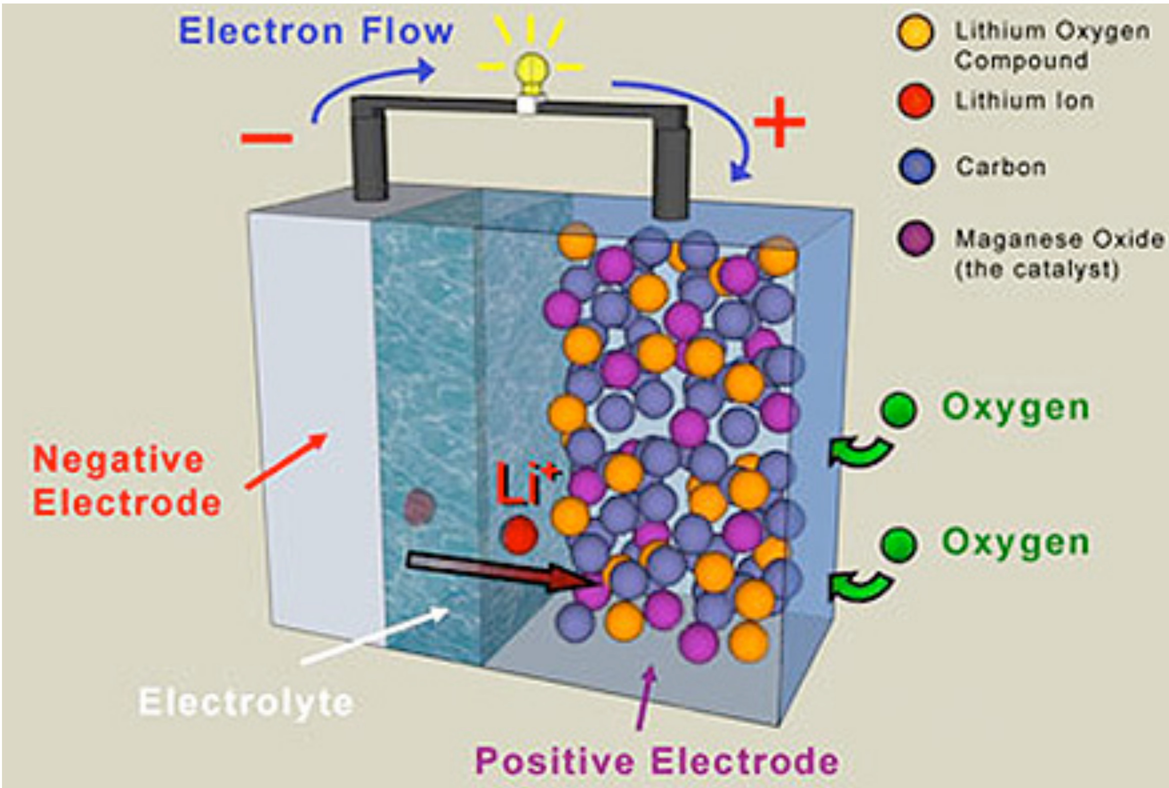


Figure 3: Lithium Air Battery

The expected timeline for the lithium air battery to be available for operational use is at least 15 years away; however, the benefits associated with it are very much worth the wait and the investment. Currently, lithium ion batteries are seeing a 300% increase in propulsion efficiency from baseline. With lithium air batteries that percentage shoots up to 2700% in propulsion efficiency. This would provide a three hour flight time for a 2150 pound helicopter as an example. This is due to the fact that lithium air batteries are much more lightweight since they have no anode, and have nine to ten times the energy density of current lithium ion batteries.

3.3.1.3.1 Removing the Conventional Rotary Driveshaft Components

Unfortunately, since operational military helicopters are far greater in weight (approximately 10x heavier than the Sikorsky Firefly prototype), the lithium air batter would be best suited in a supplemental role on board. The biggest advantage here is the removal of the tail rotor driveshaft and all associated components. Current calculations place fuel efficiency at a savings of .5% for every 700 pounds saved (this is the average weight for military-grade helicopter tail rotor driveshafts). This is a conservative estimate considering the fact that the on-board liquid fuel would then be dedicated solely for the propulsion of the main rotor turbine engines. Furthermore, by removing the driveshaft for the tail rotor and enabling an electronic motor with a computer that would calculate the exact rotor speed needed to counter the torque effects of the main rotor, a tactical advantage is given to the pilot: The pilot can then specify a speed for the tail rotor (or the computer may calculate this) for extremely quick movements of the helicopter itself without having to change the main rotor speeds. The tail rotor would be completely independent of the main rotor, making the overall helicopter extremely agile in any environment.

Extensive research is now being done and has been underway for a number of years now for lithium air batteries by companies such as General Motors. A concept developed at MIT, it is certainly the next generation in electrical battery technology.

3.3.1.4 Hydrogen Fuel Cells

Hydrogen fuel cells (Polymer Electrolyte Membrane, or PEM) are the most immature of technologies being researched. While they have a relatively high power to weight ratio, military helicopters would require too much on-board storage to make hydrogen fuel cells a practical solution. The idea for applying hydrogen fuel cells is similar to that of the lithium air battery as described above (powering the tail rotor and facilitating the removal of the tail rotor driveshaft), however the energy density of the hydrogen fuel cell is so low that too many stacks of them would be needed to make a helicopter operationally sound. At the moment, hydrogen fuel cells are barely making headway in the automotive industry, and it will be decades before they are applicable in military missions where energy is an extremely large constraint, along with space and weight.

3.3.2 Alternate Rotorcraft Technology

The Duncan Hunter National Defense Authorization Act for FY 2009 has provisions for Secretary of Defense to select a federally funded research and development center (FFRDC) to examine the alternative fuel usage in military aircraft and vehicles. The RAND National Defense Research Institute was asked to perform the alternative fuel study. (RAND 2011). One of their conclusion included "it makes more sense for the military to direct its efforts toward using energy more efficiently. Providing war fighters with more energy-efficient equipment such as aircraft or combat vehicles improves operational effectiveness, saves money and reduces greenhouse gas emissions." (Free Republic 2011). RAND recommendation makes good sense as no matter what types of fuels are used, military equipment must be designed to be fuel efficient--this is a core value. For that reason, the technologies identified below are different methods to reduce the fuel consumption for helicopter.

3.3.2.1 EADS Hybrid Diesel-Electric Propulsion System

The study of alternative technology covers areas of inefficient helicopter design areas which contribute to substantial fuel consumption. A helicopter engine is typically a turbine engine, which is powerful, but is very inefficient with regards to fuel consumption. An alternative type engine was recently introduced by EADS which is a parent company of Airbus. At the 2010 Berlin air show, EADS announced and described its new proposed hybrid diesel-electric propulsion system. This propulsion system will be incorporated in the company's new helicopter which is scheduled to fly in 2020. EADS propulsion system consists of two (or more) EcoMotors Open Piston Open Cylinder (OPOC) turbocharged two-stroke diesel engines with electric motor-generators, a pair of high-performance batteries and a power electronics unit. The two-stroke design is preferred over the four-stroke because of improvement in power to weight and volume ratios. "The OPOC engine's power output shafts are fitted with advanced, weight-optimized generators delivering electrical current to a power electronics unit, which manages the distribution of the electricity to the electrical motors driving the main rotor and the tail rotor as well as the other user systems on the helicopter." (EADS 2010). Fuel efficiency of EADS new helicopter is enabled by: 1) high performance batteries stored sufficient energy for takeoff and landing; 2) four sources of energy; 3) electrical motor driving of main and tail rotors eliminates transmission gear boxes weight and allows for flexible and power-optimized rotor speed settings, 4) tilting of main rotor and the electric motor allows fuselage to be in its optimum alignment with the airstream and thus minimizes aerodynamic drag and 5) multiple OPOC engines operate at their most fuel efficient operating condition (EADS 2010). EADS also mentioned that this hybrid propulsion system can be integrated into other combustion propulsion systems. With the new hybrid propulsion system, EADS expected "the hybrid concept would be suitable for small or large airframes" and "for a 600-plus-kilometer range [320nm], we think a hybrid helicopter would consume 660 pounds of fuel, versus 1230 pounds with today's technology." (Dubois 2011). This information provides a calculation of 50% fuel consumption saving. In an advertisement, EADS Corporate Technical Office states the engine alone can achieve 30% of fuel saving,"The OPOC TM (Opposed Piston, Opposed Cylinder) diesel engines, designed and built by EcoMotors International in the USA, offer a fuel economy improvement of up to 30 percent compared to today's helicopter turbine engines." (EADS).

3.3.2.1 Optimum Speed Rotor with Tilt Rotor Technology

Another characteristic worth examining for fuel inefficiency is helicopter rotor speed. As Boeing stated "the conventional rotor systems, which tend to have a fixed rotor RPM that is set for a worst-case flight condition (e.g., takeoff at maximum weight) and is suboptimal under all other flight conditions. A helicopter can run more efficiently if it can operate across a wide range of RPMs as the A160T does. By varying the RPM of its rotors to account for differences in weight, altitude and cruise speed, peak efficiency of its rotor system can be achieved throughout various flight regimes." (Boeing 2011) To correct the single rotor speed, Boeing incorporated the optimum speed rotor technology in the A160T Hummingbird rotorcraft unmanned air system. "During flight, an operator can vary the RPM of the A160T's rotors (speed them up or slow them down) to improve overall efficiency at different flight conditions" (Boeing 2011). Boeing purchased Frontier Aircraft which originally owned the A160T design. The optimum speed rotor technology is enabled due to the usage of composite on majority of the airframe (metal is only found in the nose frame where the intelligence, surveillance and reconnaissance payload is installed and in few bulkhead areas). Boeing stated "It wasn't until recent years that we've had the technology from a composites perspective and also from a computational perspective that we've been able to design structures that can accommodate varying the rotor speeds without hitting resonant frequencies that would break up the airframe," and "one of the reasons conventional helicopters' rotor speeds are fixed is because varying it drives resonant frequencies into the airframe, essentially rattling it apart" (Putrich 2010) . "The aircraft's unique blades are also a factor in its speed and range. The stiffness and cross-section of the A160's rotor blades vary along their length. The low-loading hingeless design allows for changing RPMs to optimise efficiency at different speeds and altitudes." Changing the rotor speed improves fuel consumption. After 18.7 hours of flying, the A160 with 300 pounds of payload landed with an hour and half worth of fuel (Putrich 2010). This information provides a calculation of 7.4% (1.5/((18.7+1.5)=20.2) in fuel consumption saving . The A160T Hummingbird fuel capacity is 375 gallons (Guffy). "The A160 has demonstrated unrefuelled flight of nearly 20h, and is perhaps capable of 30h flight." (Trimble 2009) Tilting the rotor to allow helicopter-aircraft mode conversion also works well with optimum speed rotor technology in reducing fuel consumption. This design has been applied by Abe Karem on the 120-seat TR53 Aero Train. This commercial aircraft is aimed to optimize passenger transport between airports. (Trimble 2009) The AeroTrain will be in production by 2018 (Belfiore 2008)

3.3.2.2 Materials to Reduce Airframe & Engine Weight

"To reduce the amount of fuel burnt you can reduce both aircraft weight and its parasitic drag (drag due to the non-lift component, i.e. the fuselage). For a large turbojet aircraft, a weight reduction of 1,000 kg cuts fuel use by about 1.1-1.5 per cent. To improve engine efficiency, the engine has to run at a higher turbine inlet temperature, with a 50°C increase relating to a 1 to 1.33 per cent increase in engine efficiency, allowing less fuel to be burnt for the same thrust output." (King, Inderwildi, Carey). There exist three aspects of materials to reduce the airframe and engine weight and to improve the engine efficiency (by increase the turbine inlet temperature). They are new composite materials, improved existing materials and current and in-development material structures. The new materials are ceramic matrix composite, metal matrix composite, nanocomposite and shape memory metals. These materials have the potential to be used in future aviation. Using ceramic matrix composite in the hot section of the engine such turbine disks, combustor linear, turbine aerofoils, transition duct convergent flags and acoustic liners could increase the turbine inlet temperature by 300o C which translates to 6-8% fuel efficiency increase. The metal matrix composite could reduce the airframe/engine weight when use in helicopter rotor blade, turbine fan blade and floor support. Nanocomposite has potential, but expects to be costly and subjects to production issues. Shape memory metal could be used as variable jet intake. The materials that have been improved in through the processing/production advances are aluminum alloy, super-alloy, titanium, steel and ceramic. Aluminum alloy has been improved to reinforce specific strength and corrosion resistance. Super-alloys improvements include the increases in micro-structural stability and high temperature creep strength. Titanium improvement is in the production process with the purpose of lowering the cost. The improvements in steel are gain in strength and toughness. An example is AerMet family of alloys which has higher yield strength and improved ductility. Steel alloys are used in transmission gears and parts because of their structural efficiency. Ceramic with high thermal and mechanical properties could be used in shaft bearing, engine seals and thermal barrier coating on turbine blades allowing the engine to operate in high temperature. (King, Inderwildi, Carey) Lattice, foam and laminate are different kinds of material structures that could be used in aviation. The authors believe that foam structure with higher performance and lower cost could replace honeycomb structure. Lattice structure weighs less yet exhibits good strength. Usage of low-density super-alloy foam in noise abatement application increases engine efficiency by reducing fuel consumption. "The laminate structure prevents catastrophic failure and exhibits improved impact characteristics" (King, Inderwildi, Carey). The U.S. Army's Advanced Composite Airframe Program (ACAP) manufacturing technology advances was applied in the V-22 to reduce cost of using composites. The aft fuselage skin was fabricated in one piece rather one assembly of ten skin panels. And the U.S. funded Design and Manufacture of Low Cost Composites-Bonded Wing (DMLCC-BW) provided the bonded assembly technology to eliminate mechanical fastening and allow integration of structural attachments to composite components. To reduce its weight, V-22 had composite in 50% of its airframe weight. The DMLCC-BW also ensured the low cost and defect-free bonded assembly of the Bell/Augusta BA609 wing structure (Deo, Starnes, Holzwarth 2001). For incorporation in the model, a 0.07% of fuel consumption reduction is used. This number is based on the 100lbs saving in weight given by Sikorsky and based on the assumption of 1.5% fuel reduction for every 2200 lbs decrease in weight.

3.3.2.3 Helicopter Rotor Blade Design

DARPA worked with NASA, U. S. Army and Boeing to design the SMART shape changing helicopter rotor blades which were “made with piezoelectric materials that flex when subjected to electrical fields” as “helicopter rotors rely on passive designs, such as the blade shape, to optimize the efficiency of the system.” (Greig 2009). The first full scale rotor blades were subjected to wind tunnel testing and “the system significantly reduced vibrations, saved energy, and allowed rotor movement to be more precisely controlled.“ (Sauser 2009). To further continue the research on the helicopter rotor blades, DARPA has awarded the Mission Adaptive Rotor (MAR) contracts to three teams. “The goal of MAR is a rotor that can change its configuration before a mission and in flight, between mission segments and with every revolution” and “the blades on an adaptive rotor could change their length, sweep, chord, camber, tip shape, twist, stiffness, rotational speed or other attributes.” (Warwick 2010). MAR performance objectives include the increase in 30% payload and 40% range, and a reduction of 50% rotor acoustic-detection range and 90% vibration. DARPA plans to fly helicopter with adaptive rotor by 2018.

3.4 Cost Estimation

A cost estimation was conducted to project the cost of fuel in the 2021 and 2031 timeframe. The historical price of aviation fuel since 1978 was used to determine the trend in aviation fuel. Using the data available from the Energy Information Administration and Bureau (EIA) and the Consumer Price Index for Urban Consumers (CPI-U) the price of fuel was converted into 2010 dollars as shown in Figure 4 below.

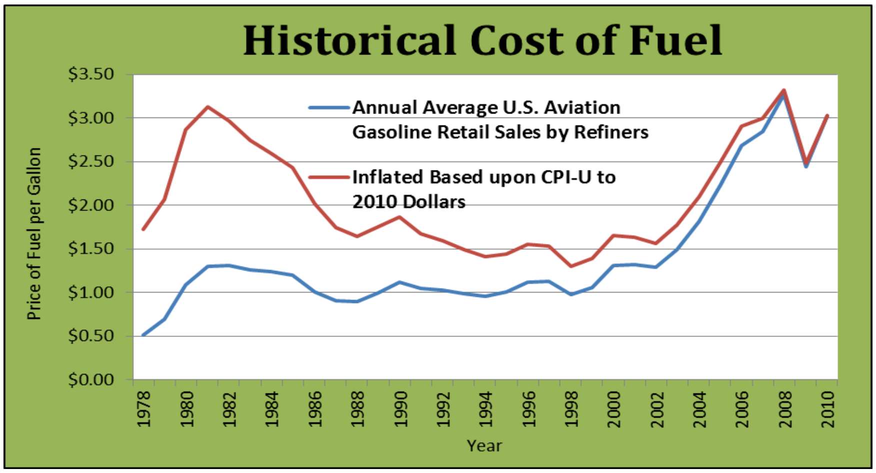


Figure 4: Historical Cost of Aviation Fuel

Fitting the trend curve very little correlation was found to cost over time, as shown below in Figure 5.

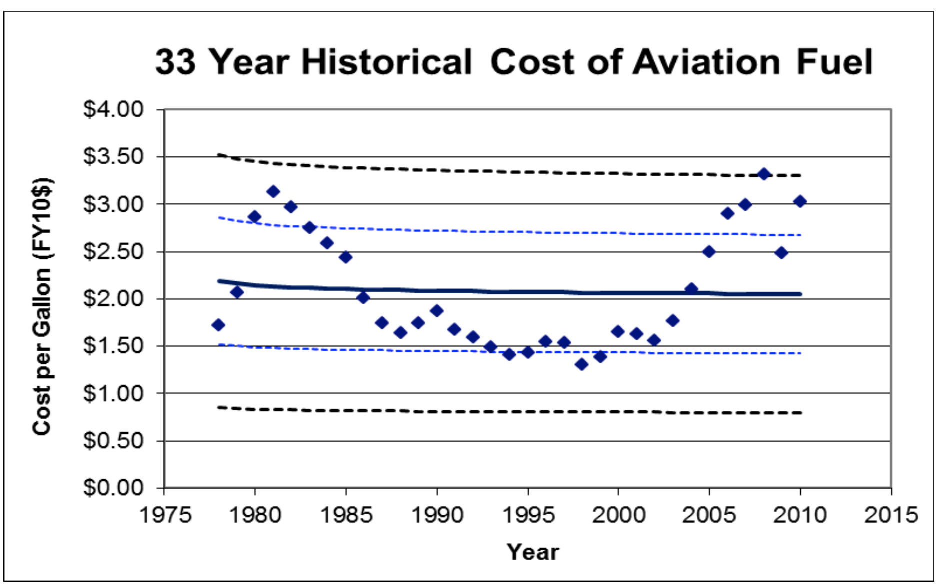


Figure 5: Trendline with 1σ and 2σ

The price of aviation fuel was then compared to that of standard gasoline and the spot price of barrels of fuel in the U.S. to determine correlation. As can be seen below in Figure 6 a high level of correlation was found. This indicated that the prices were not influenced by an aviation specific event and that the historical price of fuel is not a good predictor of future prices of fuel.

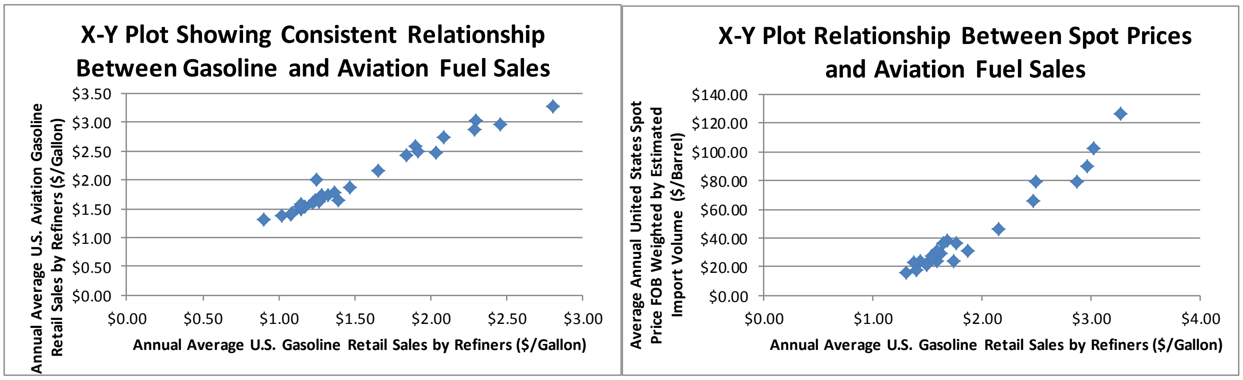


Figure 6: The price of aviation fuel correlated to the price of gasoline and spot prices

Fuel costs prior to 1991 are greatly increased after applying inflation. To create a point of comparison, only the data for the past 20 years was used to create a projected estimation for the future price of fuel. A general error regression model was used to fit the curve with multiplicative error and zero bias constraints.

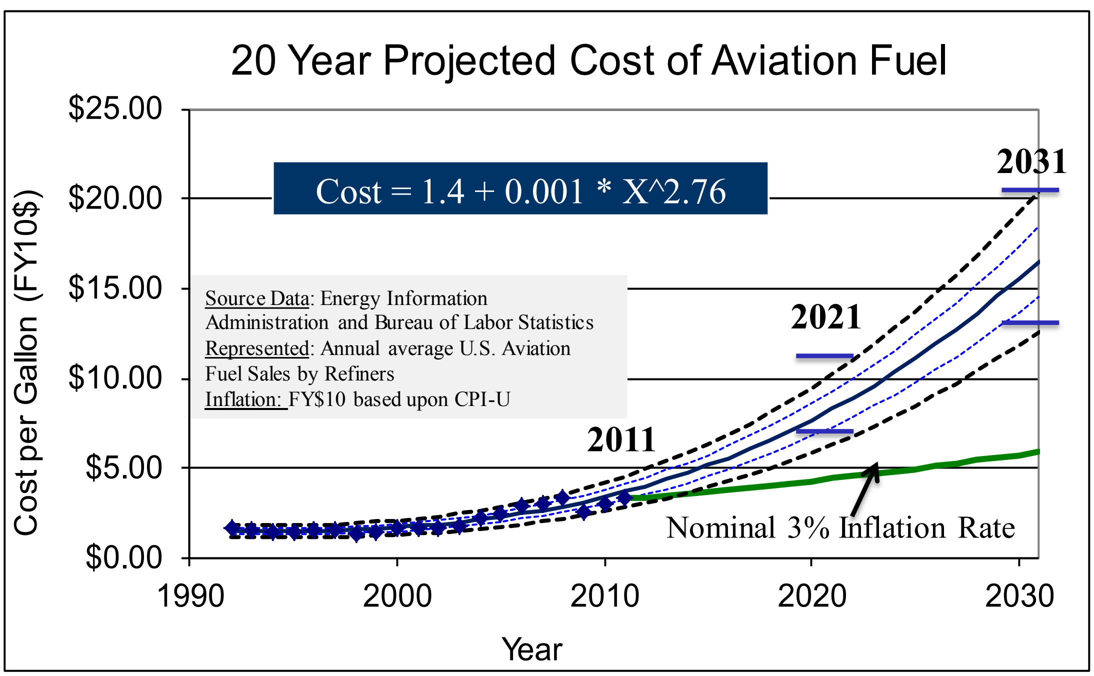


Figure 7: Projected cost of fuel based upon 20 years of historical data

The trend found was exponential. That noted, even with the predict price of fuel rising exponentially and significantly outpacing a nominal 3% inflation rate the predictions given are a conservative estimate since limited resources and rising consumption are not taken into account.

3.5 Modeling

The ILF team developed a mathematical model of fuel consumption for each war scenario. The model is Excel based in order to easily manipulate variables for analysis. The model collects key metrics measuring performance such as fuel consumption per mile, per hour, and per lift pound, time on station, time to complete mission and cost ($/mile, $/lb lift,$/flight hour). Performance variables include but are not limited to helicopter range, speed, and the cost of fuel. Appropriate graphs and trending charts are generated for the purposes of analyses.

In addition to the individual scenarios a campaign tab was created to allow the user to view multiple days worth of combined scenarios.

The model allows the alternate energy sources and the alternate helicopter designs to be applied to determine the effect on the individual scenarios or the campaign. The technologies are modeled as a percentage of fuel efficiency gained. This was calculated by converting fuel efficiency (e.g. gallons per minute) into units of energy (per fuel gallon), or joules, and applying that metric to the model to obtain the efficiency gain in terms of fuel reduction provided by the alternate energy source.

4 RESULTS

4.1 Baseline Results

Using the modeled scenarios baseline fuel consumption was calculated and is depicted in Figure 9 below.

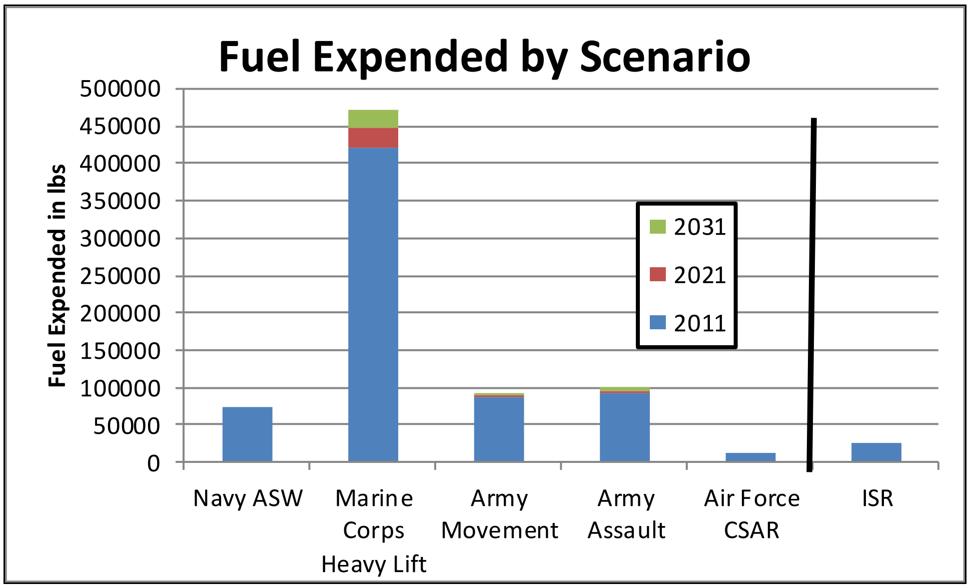


Figure 8: Fuel Expended by Scenario

The Marine Corps Heavy Lift scenario far out expends all of the other scenarios. The rotary aircraft used for heavy lift, the CH-53E, has three engines and subsequently a very high rate of fuel consumption. As expected the CSAR and ISR missions have the lowest rates of expenditures due to how few aircraft are needed for those individual missions.

The expenditures based upon future program of record were different that the ILF team would have expected after conducting the background research. Background research indicated a trend of exponentially increasing fuel consumption by the military but, the rotary aircraft in the scenarios examined did not follow this trend. Very few new rotary aircraft are in the acquisition process for the program of record through 2031. The new Blackhawk and CH-53K that are scheduled for procurement to replace legacy aircraft have increased fuel consumption rates but not enough to heavily influence the fuel consumption over the entire scenario.

While the scenario level comparison of expenditures are intuitive to expectations based upon aircraft type and number required per mission that does not encompass all scenario aspects. The campaign level results provide frequency as an input to create a comparison over the course of a campaign. For example a single Army Assault expends more fuel than a day of ASW operations by a Navy CSG, but based upon campaign type and mission frequency in a long campaign daily operations may begin to out expend the main assault. This is show in Figure 10 below.

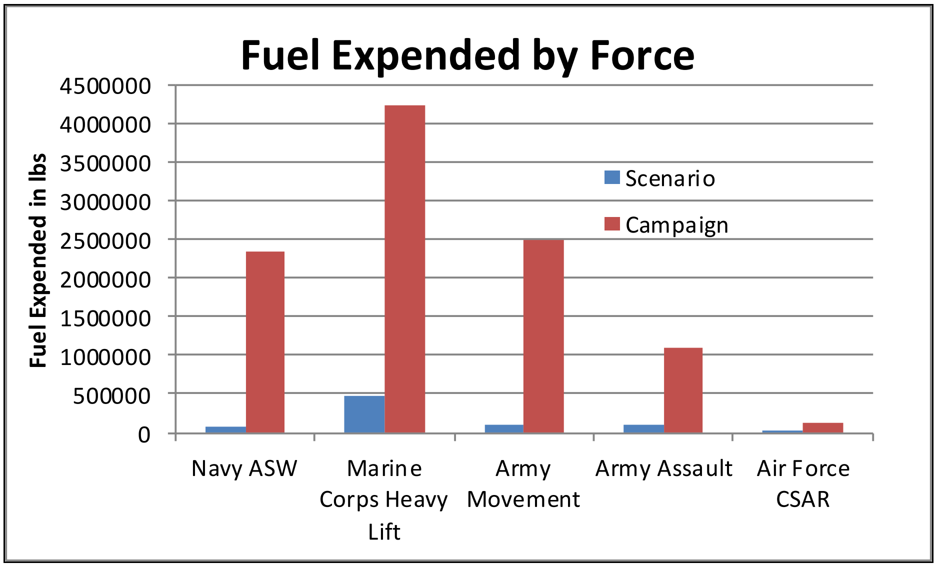


Figure 9: Individual Scenario Expenditures compared to Force Expenditures of the Campaign

Campaign expenditures increasing over time are depicted below in Figure 11.

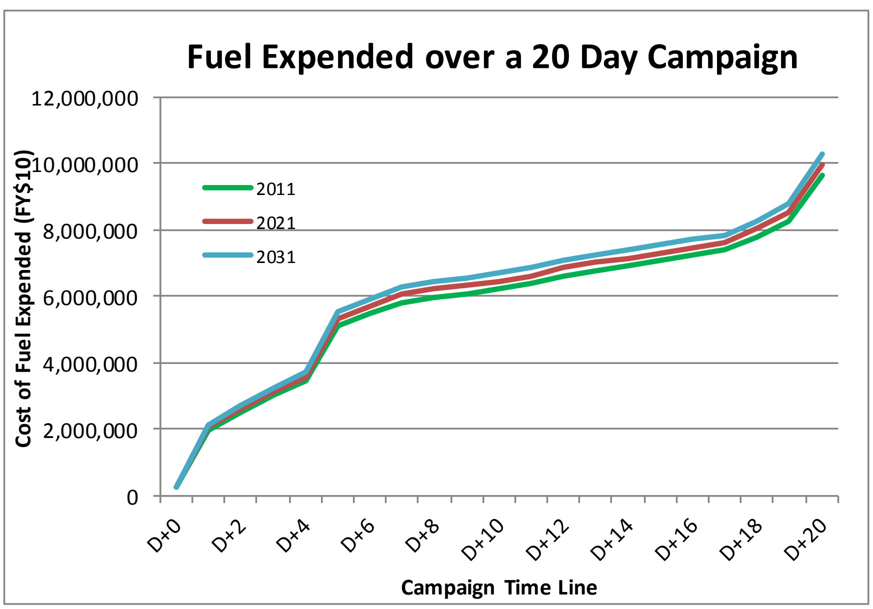


Figure 10: Project Mission Expenditures over Campaign

4.2 Cost Sensitivities and Results

The cost of fuel consumption was calculated for each scenario and computed over the course of the campaign. The section below outlines these results and the sensitivities that were considered.

As seen in Figure 11 above, there is minimal increase in project fuel expenditures based upon rotary aircraft acquisitions in these mission areas through 2031. The factor that will most influence the cost of these missions in future warfare is the expected increase in fuel prices. Below is a comparison of the cost of each mission based upon the current price of fuel and how mission cost is expected to increase over time. The bars represent the 2σ potential cost based upon the cost estimation done projecting fuel prices from historical data over the past 20 years.

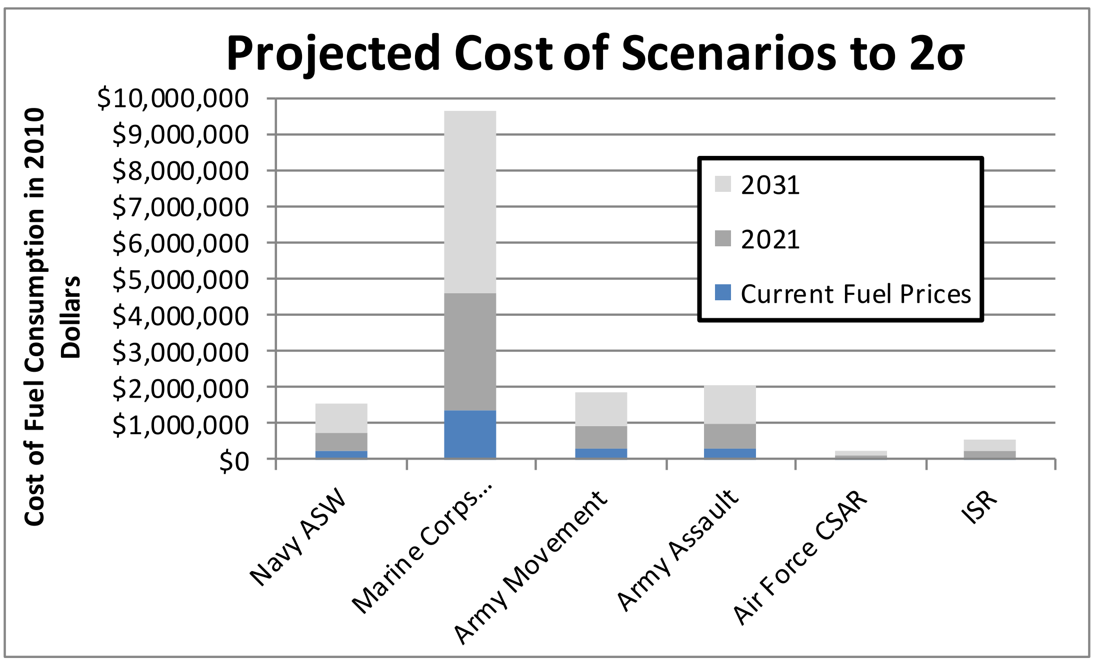


Figure 11: The Potential Cost of Scenarios

The potential campaign impacts with 1σ and 2σ error bars are shown in Figure 13 below.

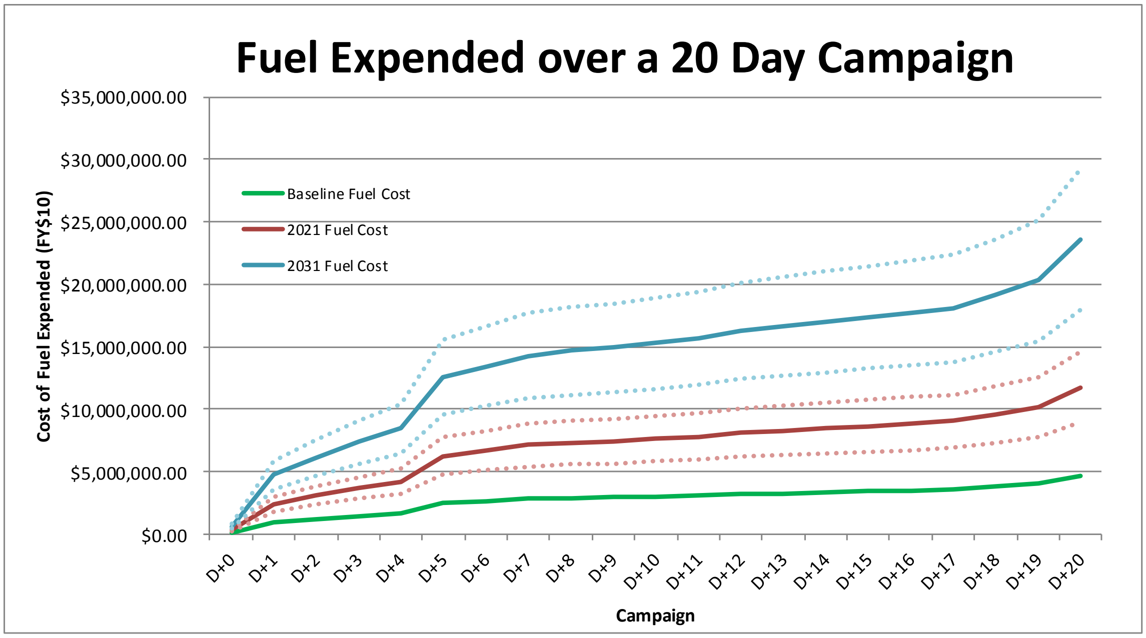


Figure 12: Future Fuel Prices Applied to Campaign Expenditures

As shown above future fuel prices will be the largest driver in the cost of rotary aircraft mission in future warfare scenarios. And, this cost estimation does not take into account the economic and geopolitical influences to the cost of fuel. Demand for fuel worldwide is increasing and resources are limited. At best the projected fuel cost is a conservative estimate. The EIA projects gasoline fuel prices will average $1 more per gallon in 2011 than in 2010 but only an additional $0.10 increase in 2012. The future price of fuel is extremely volatile and the military has begun to take this into account by incorporating fuel efficiency and design into the procurement and acquisition process. Next the potential energy efficiencies based upon alternate fuels and designs are evaluated as a means of mitigating these future costs.

4.3 Technology Sensitivities and Results

The ILF team will deliver to Sikorsky the executable model. This model allows Sikorsky to extrapolate the relationships between the various input parameters, such as weight and fuel efficiency, into each of the future scenarios. It should be noted that due to the nature of researching future implications, this modeling is an estimated perspective. In addition to the baseline model wherein the scenarios may be updated, the various researched technologies may also be applied so that an estimate in fuel cost savings may be viewed.

The following chart provides information for each of the technologies in terms of fuel efficiency percentages as they stand today from research being done:

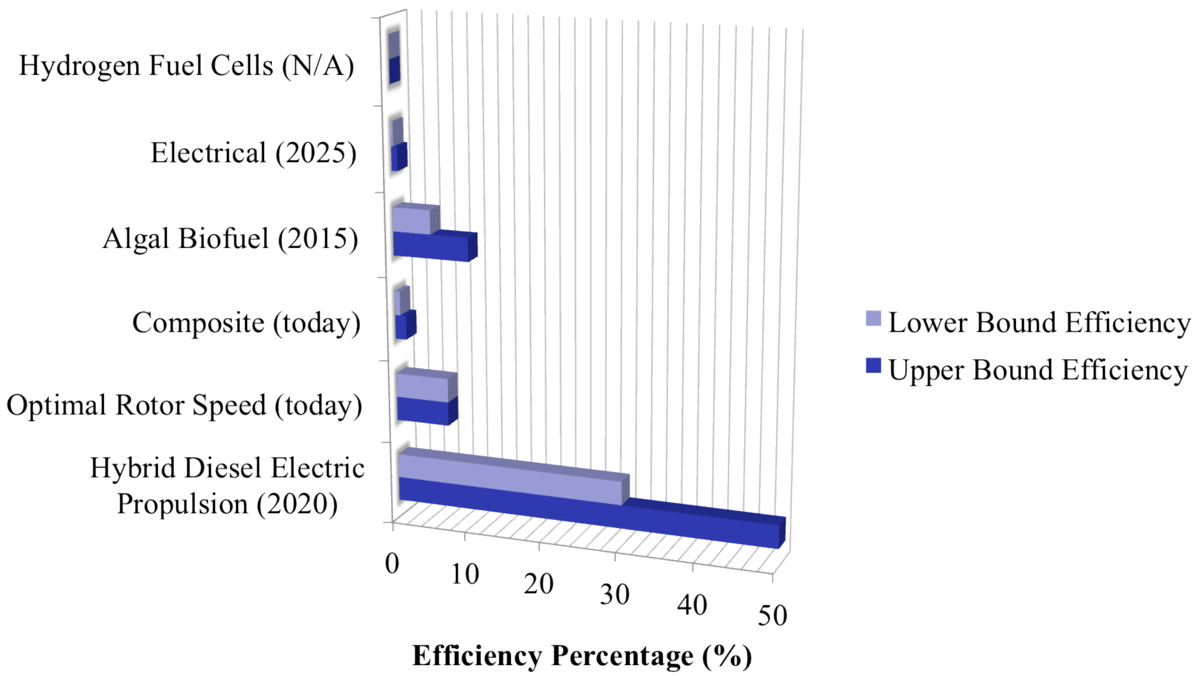


Figure 13: Alternate Technology Energy Efficiency Percentages

The above chart shows that the Hybrid Diesel Electric Propulsion system provides the most efficiency gains, however it will not be available for use until at least 2020. It should be noted that the Electrical efficiency rating reflects the removal of the tail rotor driveshaft components. Unfortunately, the efficiency of hydrogen fuel cells as applied to helicopters is to be determined, as there is extremely little research being done in this energy source due to the low energy density of hydrogen fuel cells.

The following graph is a display of how the technology efficiencies shown in Figure 13 affect the various baseline scenarios outlined in our executable model.

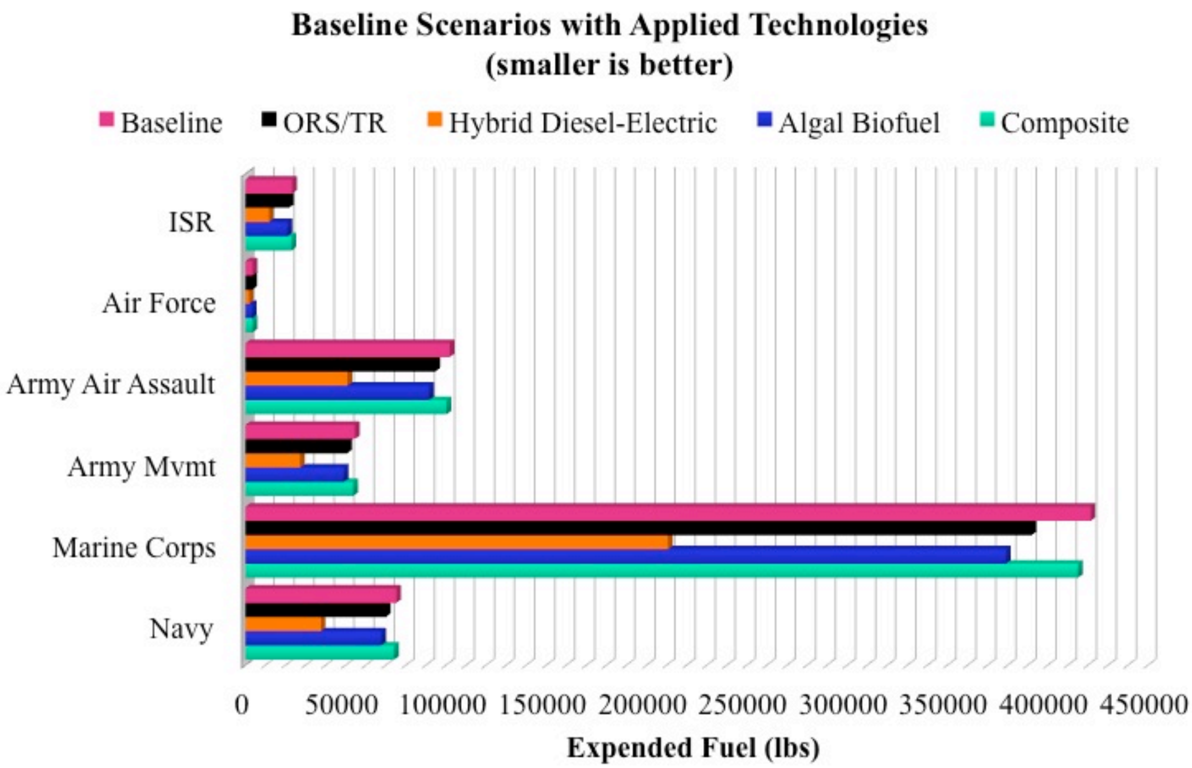


Figure 14: Alternate Technologies Applied to Baseline Scenarios

The above chart is significant for the reason that the x-axis represents the expended fuel in pounds for the given scenario. The savings in pounds of fuel is self-evident, and is worth noting, particularly for the Marine Corps. Scenario.

In order to conduct a proper sensitivity analysis for the technology efficiency percentages, we applied the lower bound efficiency percentages from Figure 13 against the baseline executable model scenarios. The following is a depiction of the sensitivity results.

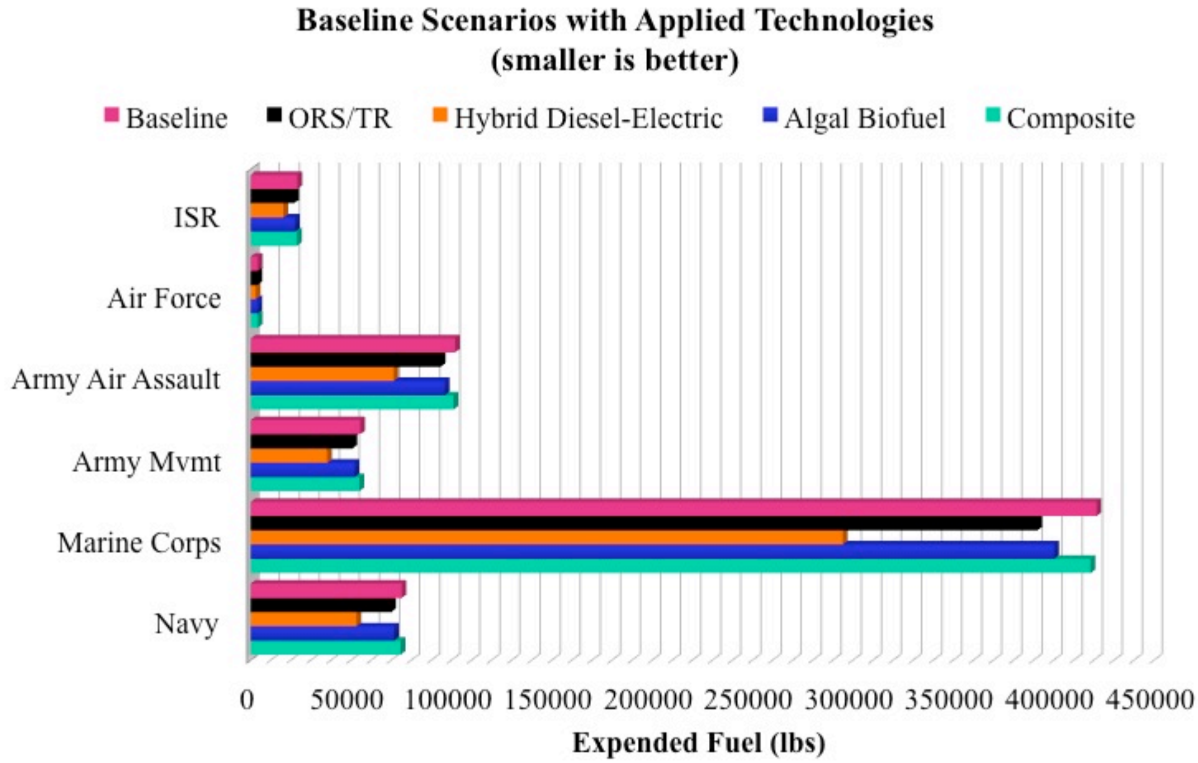


Figure 15: Alaternate Technologies Applied to Baseline Scenarios (lower sensitivity bounds)

While the lower bounds do yield lesser results, as shown above in Figure 15, the results are still significant enough to be considered as viable technology solutions.

Lastly, the application of electrical motors in this research deals primarily with the removal of the tail rotor driveshaft and associated components, as outlined in Section 3 of this document. Using the metric of 1.5% fuel expended per 2200 pounds, we found by dividing by a factor of three that .5% in energy consumption could be saved per approximately 700 pounds. The following chart is a display of the energy efficiency percentages for each applicable scenario when the electrical motor design option is applied in conjunction with select applicable alternate technology combinations.

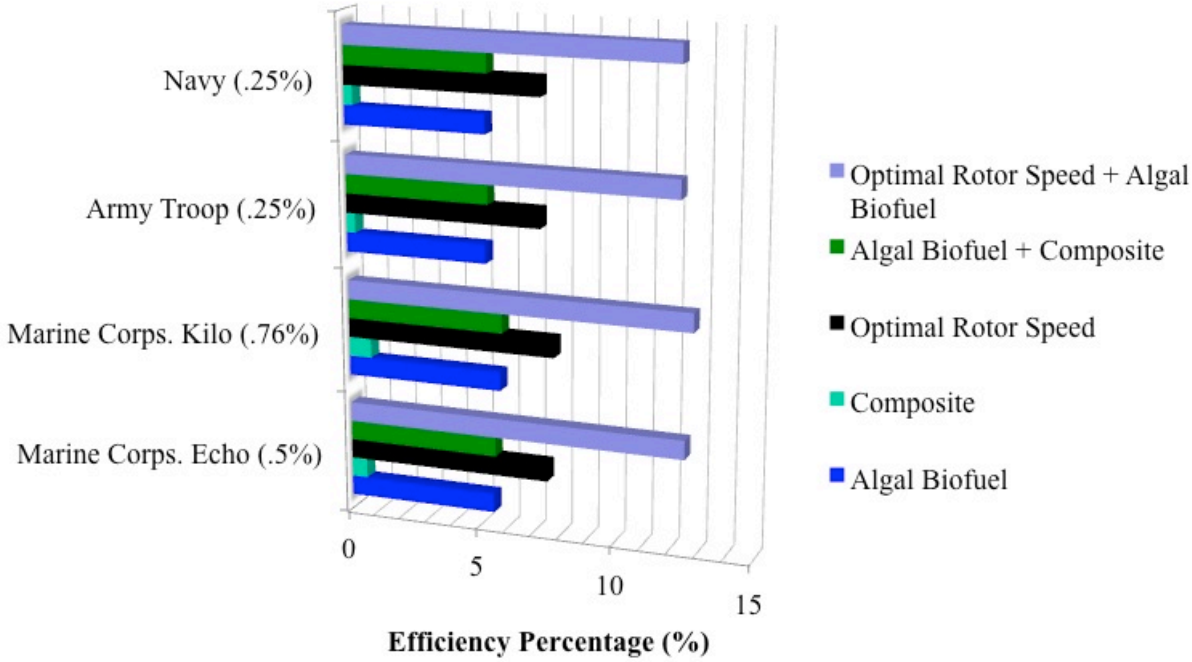


Figure 16: Applied Electrical Motor Design w/ Removed Tail Rotor Driveshaft Weight

Assuming that a given rotary vehicle is used repeatedly throughout a single or multiple mission scenarios, the percentages shown above will add up to a significant number depending upon which technology combination is used. The efficiencies displayed in Figure 16 are a result of weight information provided by Sikorsky, to the exclusion of the other rotary vehicles, for which the tail rotor driveshaft weight data could not be procured.

4.4 Insights and Recommendations

Based on the results of the technology research and the fuel consumption model, the ILF team generates the following recommendations. While some recommendations are specific to the Services' operational scenarios, some apply to all DOD war fighting equipment.

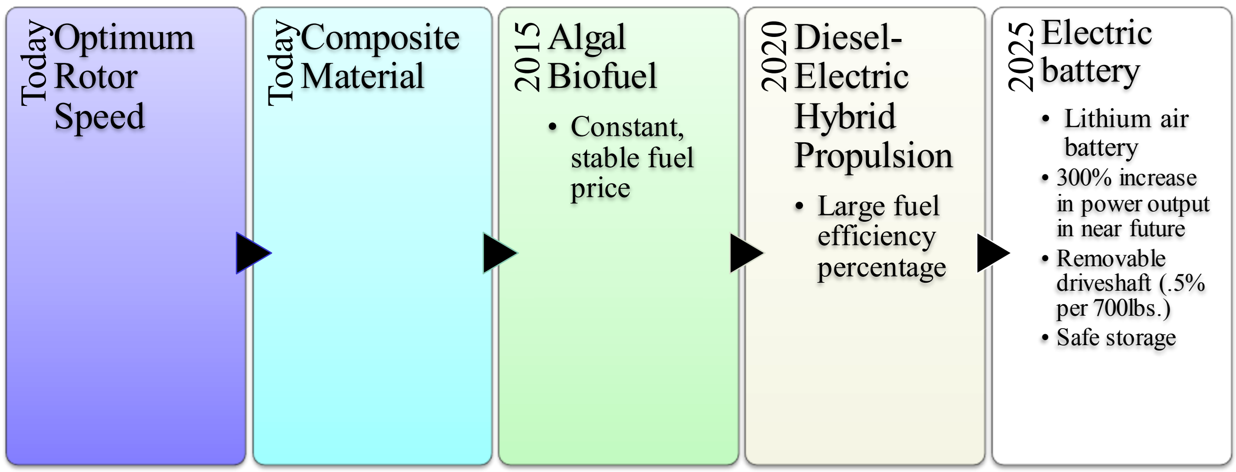


Figure 17: Technology Recommendations

Present:

1) Fuel efficiency requirement must be identified in the Tri Services' acquisition performance specifications.

Marine Corp Heavy Lift & Army Air Assault:

1) Use composite in airframe and engine to reduce overall helicopter weight as composite manufacturing and repair technology are in mature stage. The optimum rotor speed technology could also be employed to gain the extra fuel.

Future (2020):

1) Incorporate the hybrid diesel-electric propulsion system in different helicopter configurations to save fuel.

2) Invest further into Lithium air batteries for the electrical design option, such that the tail rotor is powered by these batteries and have its speed calculated by an on board computer.
3) Consider engines that are capable of taking advantage of the efficiencies and cost savings of algal biofuel in conjunction with either optimum rotor speed and/or the electric battery design.
4) Further research is very much required in each of these technologies before any significant investment can be made. This research is ongoing however as shown in Figure 17, the military-grade production of these technologies and alternate fuel sources is at least a decade away.

Future (2030):

1) Consider Lithium air batteries very heavily. The maturity of this technology depends upon the investment being given towards its research, and that investment currently is very significant.
2) Consider the application of as many technologies as possible. No single technology will provide the optimum solution alone, but rather a more complex hybrid of the technologies and alternate energy sources will provide the best procurement option for the DoD, particularly within the context of their future Analysis of Alternatives with regard to "green" procurement initiatives.
3) Dependence upon liquid fuel will only increase, seemingly exponentially, therefore an investment into these technologies, and any other emerging technologies that could still be researched as part of future work beyond the scope of this paper, would be prudent.

Army Troop Movement:

1) The TR53 AeroTrain, a fuel-efficient 120-seat could be used transport soldiers.
2) There may be impacts to military operations in the next 20 years due to the rising cost of fuel.

Appendices

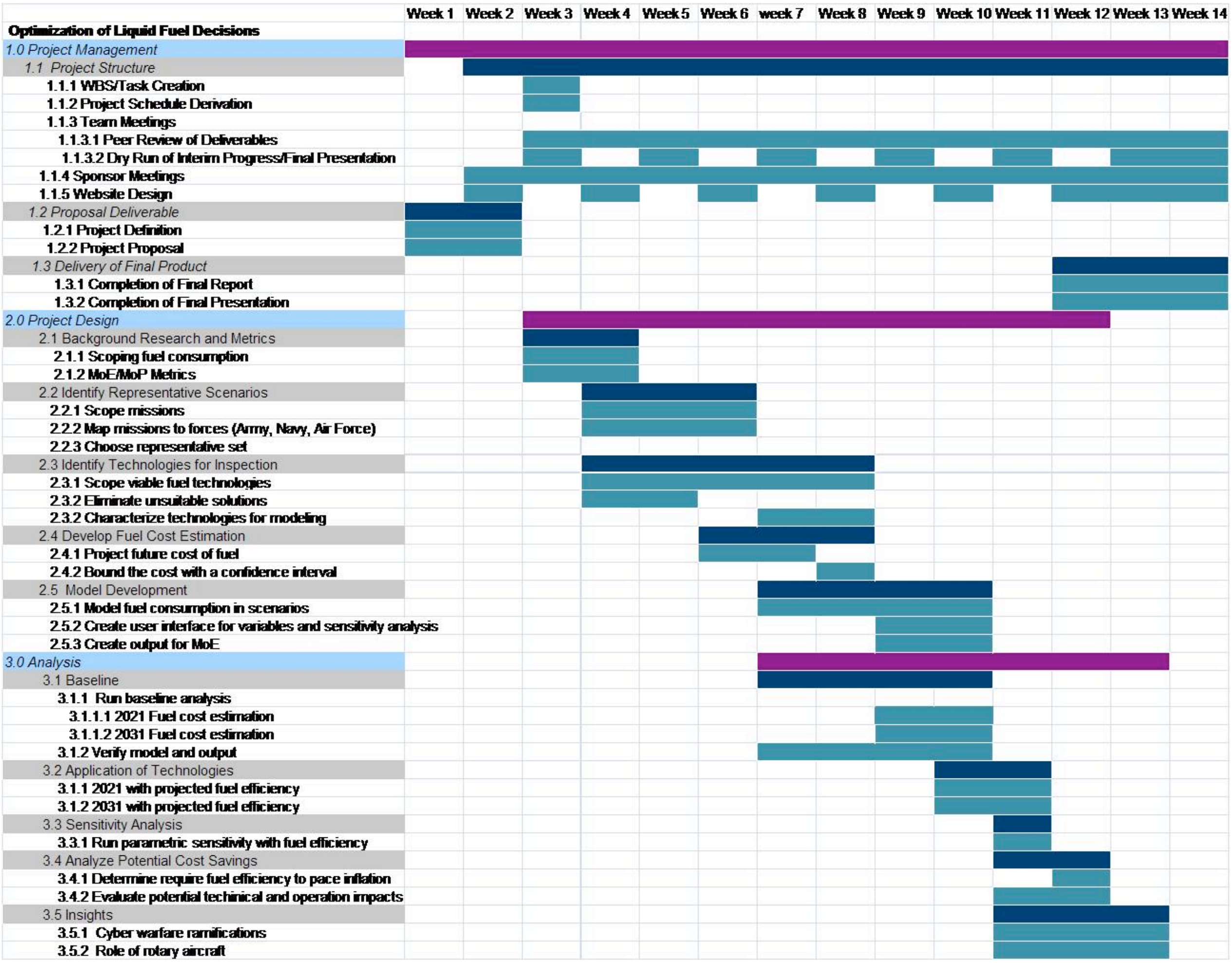
Appendix A PROJECT PLAN

A.1 Work Breakdown Structure

The Work Breakdown Structure (WBS) is organized around the management and technical tasks. The Project Management WBS 1.0 collects effort related to the definition of the project structure, finalizing project proposal and the generation and completion of the final project deliverables. The remaining WBSs cover the technical effort relating to the implementation of the project design tasks, WBS 2.0 (performing background research and defining metrics, identifying scenarios and technologies, developing fuel cost estimation and developing model) and execution of various analyses, WBS 3.0 (baseline analyses to establish future fuel cost, model verification and validation, application of technologies, sensitive analysis, potential cost saving analysis and model modification to reflect cyber warfare and examination of rotor aircraft role against future warfare)

A.2 Project Schedule

The project tasks are scheduled throughout the 14-week semester and are based on an input of 10-hour per person per week. The scheduled tasks also represent the budgeted cost of work scheduled (BCWS) and are shown in the below figure. The project schedule reflects one-week buffer to cover the unexpected unknowns. The project team also builds another schedule to record the actual hours worked (ACWP) and earned value (credit taken) hours (BCWP). The team will take credit for the hours worked only if the results/milestones are achieved. This earned value method is known as the 0-100 technique.



Below is an enlarged view of the various tasks and their organization from the above schedule diagram:

1.0 Project Management
1.1 Project Structure
1.1.1 WBS/Task Creation
1.1.2 Project Schedule Derivation
1.1.3 Team Meetings
1.1.3.1 Peer Review of Deliverables
1.1.3.2 Dry Run of Interim Progress/Final Presentation

1.1.4 Sponsor Meetings
1.1.5 Website Design
1.2 Proposal Deliverable
1.2.1 Project Definition
1.2.2 Project Proposal
1.3 Delivery of Final Product
1.3.1 Completion of Final Report
1.3.2 Completion of Final Presentation
2.0 Project Design
2.1 Background Research and Metrics
2.1.1 Scoping fuel consumption
2.1.2 MoE/MoP Metrics
2.2 Identify Representative Scenarios
2.2.1 Scope missions
2.2.2 Map missions to forces (Army, Navy, Air Force)
2.2.3 Choose representative set
2.3 Identify Technologies for Inspection
2.3.1 Scope viable fuel technologies
2.3.2 Eliminate unsuitable solutions
2.3.2 Characterize technologies for modeling
2.4 Develop Fuel Cost Estimation
2.4.1 Project future cost of fuel
2.4.2 Bound the cost with a confidence interval
2.5 Model Development
2.5.1 Model fuel consumption in scenarios

2.5.2 Create user interface for variables and sensitivity analysis
2.5.3 Create output for MoE
3.0 Analysis
3.1 Baseline
3.1.1 Run baseline analysis
3.1.1.1 2021 Fuel cost estimation
3.1.1.2 2031 Fuel cost estimation
3.1.2 Verify model and output
3.2 Application of Technologies
3.1.1 2021 with projected fuel efficiency
3.1.2 2031 with projected fuel efficiency
3.3 Sensitivity Analysis
3.3.1 Run parametric sensitivity with fuel efficiency
3.4 Analyze Potential Cost Savings
3.4.1 Determine require fuel efficiency to pace inflation
3.4.2 Evaluate potential techinical and operation impacts
3.5 Insights
3.5.1 Cyber warfare ramifications
3.5.2 Role of rotary aircraft

A.4 Project Deliverables

The following deliverables are required of the ILF team. The last two deliverables are also requirements from the customers. All deliverables have been incorporated in the project schedule.

1. Project Proposal
2. Two Interim Briefings
3. A Spreadsheet File Documenting Modeling and Analyses Effort
4. Briefing that communicates work done and results
5. Written report that details analysis and rationale used

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Appendix C Technical Approach

1. Survey energy usage in warfare throughout history and develop energy consumption metrics
2. Identify a range of representative scenarios
   - Primary missions
   - Army, Navy, Marine Corps, Air Force
3. Identify technologies for inspection and characterization
4. Conduct cost estimation of fuel prices in 2021 and 2031
5. Model Scenarios
6. Analyze Scenarios
   - Vary fuel price
   - Apply technologies
   - Conduct excursions for potential changes in future warfare
7. Provide insight and recommendation for the impact of fuel efficiencies and rotary aircraft