



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE REPORT

MOBILE FUEL GENERATION IN CONTESTED ENVIRONMENTS

by

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September 2023

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This project was funded in part by the NPS Naval Research Program.

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 2023	3. REPORT TYPE AND DATES COVERED Systems Engineering Capstone Report		
4. TITLE AND SUBTITLE MOBILE FUEL GENERATION IN CONTESTED ENVIRONMENTS			5. FUNDING NUMBERS NPS-23-N273-A	
6. AUTHOR(S) Albert Apaloo, Jake C. Brown, Aaron E. DuPree, Andrew A. Herold, and Ryan A. Ussing				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. This project was funded in part by the NPS Naval Research Program.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) The United States Navy and Marine Corps have a need to operate in contested maritime spaces while minimizing supply chain vulnerabilities and maintaining access to fuel abroad during prolonged operations. This capstone project analyzed the Navy's ability to generate alternative fuels in contested environments, while maintaining operational readiness and assessed the amount of power that would need to be supplied to maintain that capability. The mobile fuel generation system (MFGS) focused on solutions that can be delivered between now and 2045. This study considered an MFGS supporting an MQ-8C Fire Scout conducting intelligence, surveillance, and reconnaissance (ISR). Operations were defined in two scenarios that dealt with two specific instances of ISR mission requirements in contested waters. Five primary fuel alternatives were considered: JP-5, liquid hydrogen (LH2), methane, synthetic jet fuel, and LH2 with fuel cell. The LH2 with fuel cell alternative had the best performance in terms of operational availability, flight hours per day, and power requirement for the MFGS. This project recommends further research be dedicated to the development of LH2 fuel cells as an alternative fuel/technology solution for the Navy.				
14. SUBJECT TERMS mobile fuel generation system, MFGS, intelligence, surveillance, and reconnaissance, ISR, liquid hydrogen, LH2			15. NUMBER OF PAGES 99	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
September 2023**

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ABSTRACT

The United States Navy and Marine Corps have a need to operate in contested maritime spaces while minimizing supply chain vulnerabilities and maintaining access to fuel abroad during prolonged operations. This capstone project analyzed the Navy's ability to generate alternative fuels in contested environments, while maintaining operational readiness and assessed the amount of power that would need to be supplied to maintain that capability. The mobile fuel generation system (MFGS) focused on solutions that can be delivered between now and 2045. This study considered an MFGS supporting an MQ-8C Fire Scout conducting intelligence, surveillance, and reconnaissance (ISR). Operations were defined in two scenarios that dealt with two specific instances of ISR mission requirements in contested waters. Five primary fuel alternatives were considered: JP-5, liquid hydrogen (LH2), methane, synthetic jet fuel, and LH2 with fuel cell. The LH2 with fuel cell alternative had the best performance in terms of operational availability, flight hours per day, and power requirement for the MFGS. This project recommends further research be dedicated to the development of LH2 fuel cells as an alternative fuel/technology solution for the Navy.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of Variance
Ao	Operational Availability
BLOS	Beyond Line of Sight
CDC	Center for Disease Control and Prevention
CONOPS	Concept of Operations
DAF	Department of the Air Force
DOD	Department of Defense
DODAF	Department of Defense Architecture Framework
DOE	Design of Experiment
DON	Department of the Navy
HSD	Honestly Significant Difference
INDOPACOM	Indo-Pacific Command
ISR	Intelligence, Surveillance and Reconnaissance
LCS	Littoral Combat Ship
MFGS	Mobile Fuel Generation System
NATO	North Atlantic Treaty Organization
NDAA	National Defense Authorization Act
OV-1	Operational View-1
SE	Systems Engineering
SLOC	Sea Lines of Communication
SysML	Systems Modeling Language
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicles
USCG	United States Coast Guard
USMC	United States Marine Corps
USN	United States Navy
WIC	Warfare Innovation Continuum

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EXECUTIVE SUMMARY

The United States Navy and Marine Corps seek to operate distributed across multiple domains with additional emphasis placed on great power competition and sustained operations within contested maritime spaces. The U.S. Navy can no longer rely on its traditional methods of power projection due to supply chain vulnerabilities and the need to maintain access to fuel and energy sources abroad during prolonged operations. This capstone project analyzed the Navy and Marine Corps' ability to generate alternative fuel in contested environments, while maintaining operational tempo and readiness (Department of the Navy [DON] 2022).

The value of this research lies in its potential to increase the U.S. Navy (USN) and Marine Corps (USMC) expeditionary force's operational range with cleaner energy sources. The Department of Defense (DOD) and the individual warfighter will directly benefit from the impacts of sustainable fuel sources produced in contested environments, untethered by logistically burdensome fuel and supply routes (DON 2022). This allows these units to maintain tempo on the battlefield, press the advantages of requiring a lighter logistical footprint, and exploit the adversary's supply and logistical vulnerabilities.

This research was conducted in five phases and focused on the development of a Mobile Fuel Generation System (MFGS) with alternative fuel solutions that could be delivered by 2045 utilizing the following systems engineering approach by phase (Todorovich 2022):

1. Problem Framing and Requirements Analysis
2. Research and Analysis
3. Preliminary Analysis of Alternatives
4. Alternative Selection and System Modeling
5. Future Concept Integration and Employment

The research started with an annotated bibliography that included DOD service documents as the project's primary initial sources. These service documents helped define

the problem and scope of the solution space for the 2045 timeframe. Primary sources included the Tri-Service Maritime Strategy (Department of Defense 2020), the Department of the Navy (DON 2022) and Air Force's Climate Action Plan 2030 (Department of the Air Force [DAF] 2022), and the CNO's NAVPLAN 2045 (Burgess 2023).

Future USN and USMC operations in contested maritime environments require increased unmanned aerial system (UAS) operations and sustainable fuel sources (DON 2022). To address this, a modular and mobile fuel generation capability is needed, capable of accommodating multiple sorties per day while maintaining a low signature and a high degree of mobility. The MFGS must support expeditionary operations and forces, be deliverable by 2045, and comply with USN safety requirements. This research included two vignettes to model and compare alternative fuel sources for the MQ-8C Fire Scout with specific requirements analysis focused on three fuel types: liquid hydrogen (LH2), synthetic jet fuel (dodecane), liquid methane, and addresses one fuel technology, LH2 hydrogen fuel cells.

The system model was developed utilizing the discrete-event modeling tool ExtendSim to evaluate the MFGS fuel production capability during MQ-8C ISR operations from a Littoral Combat Ship (LCS). The simulation depicted system operational characteristics in terms of mission variables. The input variables for the model were divided into three groups: mission-related variables, LCS capability and MQ-8C characteristics. The mission-related variables included: fuel type, flight duration, hot refueling, and number of missions available. The LCS capability variables were the number of flight decks and MQ-8Cs available. This model's main aim was to evaluate how well each fuel alternative performed when compared to JP-5.

This model analyzed four fuel technology alternatives: synthetic jet fuel (dodecane), liquid methane, liquid hydrogen, and a liquid hydrogen fuel cell electric motor. There were three key measures used to evaluate the overall performance of the system: operational availability (Ao), power requirements for the MFGS, and average number of flight hours per day.

The model was composed of four functional areas: mission assignment and launch, mission execution, aircraft recovery, and aircraft repair and refueling. The model addressed all significant operational functions of the MQ-8C while aboard a USN LCS.

A design of experiment (DOE) approach was used, resulting in 60 design configurations for phase one and 54 configurations for phase two. Each configuration was replicated 30 times. This resulted in 1,800 simulation runs for phase one and 1,620 runs for phase two.

The simulation analysis compared the potential alternative fuel sources to the baseline fuel, JP-5. The data was analyzed with a statistics software program to determine the effects of the inputs on operational characteristics. The Analysis of Variance (ANOVA) and partition tree analysis was then used to evaluate both vignettes, the alternative fuels, and their effects on the system's operational performance in the model. From the project's modeling data, the team concluded that fuel type was the primary contributor to variations of operational characteristics in both vignettes and was also the driving influence affecting power requirements in the MFGS.

In terms of fuel alternatives, synthetic jet fuel maintained the largest power requirement and did not provide any significant advantages over other fuels, while LH2 maintained the lowest Ao and number of flight hours with no significant reduction in power requirements. Liquid methane performed well operationally, but the power requirements to generate and store it with the MFGS were significantly larger when compared to the LH2 fuel cell. The LH2 fuel cell required the least amount of power while maintaining mission capabilities and the greatest potential to reduce overall carbon emissions. For those reasons, LH2 with fuel cell technology is this team's recommendation for future research and development.

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ACKNOWLEDGMENTS

We would like to express our heartfelt gratitude to Dr. Paul Beery and Dr. Eugene Paulo for their guidance, knowledge, and expertise during our capstone project. Your support and encouragement helped us stay focused throughout the project, and your insightful feedback significantly shaped the project's outcome.

We would also like to thank the thesis staff for their unwavering dedication to ensuring that everything we needed was available on time, be it resources or mentorship. Their valuable input helped create a well-rounded project that pushed us to new heights.

To our spouses, significant others, and support system, your unwavering support and patience cannot be underestimated. Thank you for continuously believing in and supporting us through this process. We could not have succeeded in this project without you.

We would like to thank our friends, colleagues, and coworkers for their helpful advice, honest feedback, and always encouraging us to push boundaries. We really could not have done this without everyone.

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I. INTRODUCTION

A. BACKGROUND

The United States Navy (USN) and the United States Marine Corps (USMC) currently utilize traditional petroleum for a significant amount of their energy requirements during operations. There are two fundamental issues with this dependence on petroleum: (1) the vulnerability of the traditional supply chain; and (2) the environmental impact of petroleum-based fuel usage. With these issues comes an opportunity to take advantage of current developments in synthetic fuel developments.

The Assistant Secretary of Defense for Energy, Installations, and Environment has been tasked by the 2022 National Defense Authorization Act (NDAA) to conduct “an assessment of any technologies, including electric, hydrogen, or other sustainable fuel technologies, that may reduce operational energy demand in the near-term or long-term” and to conduct “an assessment of how combatant commanders can better plan for challenges presented by near-peer adversaries in a contested logistic environment” (2022, 1652). As part of the assessment this research sought to address fuel and sustainment challenges posed by contested maritime spaces. The focus of this study was to develop a potential near-term solution (2045) for optimizing Navy and Marine Corps goals of enhancing operational capabilities while reducing carbon emissions regarding mobile fuel generation alternatives. This research included the development of a concept of operations (CONOPS) designed to model a system capable of producing fuel in a contested environment that optimized maritime operations while reducing overall carbon emissions.

With both NAVPLAN 2022 and the Tri-Service Maritime Strategy emphasizing the future fleet will rely on alternative designs that strengthen naval power through the utilization and integration of unmanned systems, this study focuses on unmanned intelligence, surveillance, and reconnaissance (ISR) platforms as an example of a critical capability that can be maintained using this type of fuel system (Department of the Navy [DON] 2022).

The developed CONOPS highlights the operational relevance of the mobile fuel generation system (MFGS) as it relates to maritime ISR operations. Recent efforts focused on seawater to fuel, hydrogen generation, drop in fuel systems, and scavenging of nuclear power have been proposed as potential solutions but much of the effort has focused on technical demonstration, rather than operational impact. This project investigated the utility, viability, and critical capabilities for fuel generation in the Indo-Pacific Command (INDOPACOM) theater. Accordingly, this research evaluated aspects of alternative fuel sources and mobile fuel generation techniques for an in-theater fuel generation system.

B. PROBLEM STATEMENT AND RESEARCH QUESTIONS

The USN and USMC seek to operate more distributed across multiple domains with more emphasis placed on great power competition and sustained operations within contested maritime spaces. The USN can no longer rely on its traditional methods of power projection due to supply chain vulnerabilities and the need to maintain access to fuel and energy sources abroad during prolonged operations. This capstone project will analyze the DOD's ability to generate alternative fuel and energy sources in contested environments, with varying methods of supply and delivery to forward operating units.

The objectives of this research: to develop a mobile fuel alternative system capable of sustaining USN and USMC operations in contested environments, yielded the following research questions:

- What capabilities and CONOPS could mobile fuel generation enable in the 2045 timeframe?
- What are the limits/challenges (in terms of fuel generation, fuel storage, and ship integration) with fielding and sustaining mobile fuel generation technologies?
- What is the potential for mobile fuel generation to sustain combat capabilities and reduce logistics demand in contested environments? What capabilities are best suited to support using alternatively fueled unmanned

systems and how do changes to unmanned system tasking impact the viability of alternative fuels?

C. TAILORED SYSTEM ENGINEERING PROCESS

The systems engineering approach implemented by the team followed a modified version of Winston Royce's Waterfall Model. The original waterfall model was comprised of seven phases; however, the team revised the model into a five-phase model that better suited the project's needs. This project's progression followed a model comprised of the following five phases (Todorovich 2022):

1. **Problem Framing and Requirements Analysis.** The team began with the characterization of the problem and analysis of the requirements for mobile fuel generation in contested environments.
2. **Research and Analysis.** Second, in lieu of a physical design phase, the team conducted research and presented potential alternatives to the current state of fuel supply reliability in the DOD today.
3. **Preliminary Analysis of Alternatives.** Third, analysis of alternatives was conducted to identify the primary performing fuel generation method, as it relates to operational reach and logistical sustainability.
4. **Alternative Selection and System Modeling.** Fourth, an analysis of the selected alternative was conducted through a series of models and simulations aimed at identifying a variety of alternative operational performance characteristics that have the largest impact on system effectiveness.
5. **Future Concept Integration and Employment.** Finally, the team explored current and future applications of fuel generation alternatives and discussed the scale and sustainability of the method, as well as its implications for commanders in the fleet.

D. LITERATURE REVIEW

1. Introduction to Literature Review

The team conducted a literature review of service documents and sources. The project's annotated bibliography served as a working document designed to catalog and centralize the project's primary research documents originally outlined by the project stakeholders. The following list of references afforded the team the ability to share similar research topics of interest, key information, and brainstorming concepts for the project all in a centralized collaborative location. These documents served as the initial base for the team's research.

2. Warfare Innovation Continuum Hybrid Force 2045

The warfare innovation continuum (WIC) used classroom projects, theses, and research to advance naval concepts, assess technologies, and develop tactics. The 2021 WIC addressed a design challenge: "How might emerging technologies, new operational concepts, and alternative fleet designs contribute to a more effective naval force across the spectrum from competition to conflict? How do the alternative fleet designs enhance the effectiveness and resilience of joint, combined and coalition forces across all domains?" (Burgess 2022).

This challenge, based on the Chief of Naval Operations' *Navigation Plan for Force Design 2045*, sought to understand how alternative designs and innovative integration of emerging technologies may complement the U.S. fleet and make them a more lethal and efficient naval force in the year 2045 (Burgess 2022).

Force Design 2045, as found in *Chief of Naval Operations Navigation Plan 2022*, envisions a hybrid fleet of "more than 350 manned ships, 150 large, unmanned surface and subsurface platforms, and approximately 3,000 aircraft" (DON 2022, 10), noting that those numbers may be updated as the security threat changes.

Some of the key takeaways identified at the conclusion of this workshop included the addition of human in the loop machine learning or using human decision making in wargaming multiple tactical situations to form a database for supervised machine learning,

leveraging the undersea environment across the spectrum of competition and warfare by creating seafloor mapping and infrastructure capabilities (Burgess 2022).

The workshop touched on implementing, autonomy in sustainment, repair, and replacement through unmanned system platforms with additive manufacturing capability and the creation of an integrated fleet of forward high-risk offensive unmanned systems for sea control and carrier strike group operations (Burgess 2022).

As it relates to generating fuel alternatives for the fleet in contested environments, the autonomy in the sustainment point will be a driving factor in our ability to extend the operational reach and sustainment time of the fleet. Unmanned systems that can conduct autonomous refueling, repairs, maintenance, part replacement, and sustainment will provide operational advantages for fleet commanders and allow them to maintain tempo during combat actions. As it relates to generating fuel alternatives for the fleet in contested environments, the autonomy in the sustainment point will be a driving factor in our ability to extend the operational reach and sustainment time of the fleet.

3. Executive Order 14057 Catalyzing Clean Energy Industries and Jobs through Federal Sustainability

This Executive Order addressed the executive branch's goals regarding clean energy. This order placed some significant constraints on the Department of Defense regarding clean energy. One of the key aspects of this order is the president's directive to have the federal government transition to clean energy and sustainable technologies by 2050 (The White House 2021).

4. USAF, Climate Action Plan

The *United States Air Force Climate Action Plan* addresses how the Air Force intends to maintain mission capability while addressing the risks of climate change and developing climate mitigation measures (Department of the Air Force [DAF] 2022). The *Climate Action Plan* identified three climate priorities: “(1) Maintain air and space dominance in the face of climate risks; (2) Make climate-informed decisions; and (3) Reduce energy and pursue alternative energy sources” (DAF 2022, p. 5). The plan was

derived from Executive Order 14057 which outlines the President’s intent regarding the government’s responsibility regarding climate change.

The *Climate Action Plan* developed several objectives, the top three relevant to this project are: 1) Modernize Infrastructure and Facilities, 2) Incorporate Climate Considerations into Department Requirements, Acquisition, and Supply Chain Processes, and 3) Adopt Alternative Energy Sources (DAF 2022, 10–15). These three objectives are directly related to this project’s research. The MFGS would require modernized infrastructure to be outfitted aboard USN vessels and climate considerations would impact the reduced carbon emissions requirement for the system. The MFGS would reduce DOD reliance on traditional supply chains which become vulnerable in a contested environment. Also, the MFGS’ pursuit of alternative energy sources directly aligns with the project stakeholder’s desire to enhance capabilities by extending the operational range of critical platforms.

One of the goals that the Air Force has is to develop a reduced carbon emission fuel solution (DAF 2022). The objective of the project is to validate operational, infrastructure, and logistical requirements to produce said fuel.

5. The Department of the Navy Climate Action 2030

The Department of the Navy (DON)’s *Climate Action 2030* article asserted that climate change is an essential threat that will impact military operations and readiness (Department of the Navy [DON] 2022); this includes infrastructure, the warfighter, and their families. Climate change issues such as flooding and rising sea levels will continue to worsen; however, the U.S. Navy is positioned and equipped to adapt to these challenges. Building climate resilience and reduced climate threat are two performance goals that need to be addressed to be better positioned to adapt to these new phenomena. Building climate resilience ensures that U.S. forces continue to operate effectively and achieve mission success amidst declining climate conditions. This is done by addressing climate threats and reducing the overall carbon footprint and greenhouse gas output.

Concerning this capstone project, the research on mobile fuel generation in contested environments will need to explore frequent weather events that stress the warfighter system, platform, and installation.

The DON's commitment to acquiring 100 percent zero emissions and 100 percent carbon pollution-free electricity means future systems must be dependent on sequestering energy from the atmosphere, sea, or earth (DON 2022). The DON is continually addressing pathways to achieving net zero in 2030; thus, the capability and infrastructure will already be in place.

These energy resilience efforts ensure that proposed systems, such as MFGS in a contested environment are secure from physical threats. Additionally, an energy resilience approach seeks to deploy cyber-secure microgrids that will leverage carbon pollution-free power generation and long-duration battery storage, a vital component of a mobile system.

A similar effort currently underway boasts related technology that would be needed to ensure the warfighter is supported in their mission. The Navy's climate action intent for the future relies heavily on power generation and optimizing fuel use amongst several tactical vehicles. *Climate Action Plan 2030* asserts that tactical reduction in forces footprint will result in improved resilience and survivability (DON 2022).

E. CAPSTONE REPORT ORGANIZATION

This report is organized into five chapters. Chapter I presented background and motivation and reviewed relevant literature. Chapter II presents an analysis of the operational scenario relevant to the MFGS and describes the MFGS from multiple perspectives using systems architecture artifacts. Chapter III presents a discrete-event simulation model of the MFGS in an operational scenario. Chapter IV presents simulation analysis. Chapter V presents conclusions and identifies opportunities for future work.

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II. ANALYSIS

This chapter focuses on the stakeholder analysis, operational needs, requirements, and functional analysis conducted by the team regarding operating the MFGS in contested environments. The needs analysis is based on stakeholder requirements taken from USN and USMC service documents and introduces the operational concept in which the MFGS will be employed. The requirements analysis focused on the technical aspects of integrating the MFGS with fleet UAV operations, specifically the MQ-8C Fire Scout. Finally, the functional analysis described the MFGS environmental relationships, hierarchy, and basic architecture with operational and system-level diagrams.

A. STAKEHOLDER ANALYSIS

The primary stakeholders affected by this research can be divided into two main categories: operational and industrial stakeholders. The operational stakeholders are fleet commanders, warfighters, and system operators directly impacted by the operational performance of the MFGS and the alternative fuel sources being developed (See Table 1). These stakeholders are deployed forward and invested in the performance of this system in contested environments and potentially during combat operations. The industrial stakeholders include the defense companies, the DOD contractors, engineers, and project managers assigned to the design, development, evaluation, and compliance of the system with DOD standards and safety parameters.

The stakeholder needs presented in Table 1 identify the primary stakeholders, their role in the development of the system, their specific needs, and the impact of those needs on the project's problem and overall solution space.

Table 1. Primary Stakeholder Needs

Stakeholder	Impact	Needs	Role
Pentagon	High	N.1.1 Reduce carbon footprint for Navy operations N.1.2 Improved fuel supply chain security	Funding and Policy Makers
Combatant Commanders	High	N.2 Increased situational awareness in contested maritime environments	Operations
UAV operators	High	N.3 Safe refueling options for MQ-8C	Operations
Fuel Generation Crew	Medium	N.4 Simple and safe fuel production	System Support
Ship's Crew	Medium	N.5 Safe Fuel Option for shipboard operations	Operations
Northrup Grumman	Medium	N.6 Improved MQ-8C performance	MQ-8C supplier
General public	Low	N.7 Reduced environmental impact from Navy operations	Corporative Compliance

B. NEEDS ANALYSIS

Future USN and USMC operations in contested maritime environments will require an increase in unmanned aerial system (UAS) operations and placement and access to sustainable fuel sources to maintain the fleet's ISR coverage. Those fuel sources will require alternative methods of production and delivery to forward units and vessels operating in contested waterways. In order to provide fleet commanders with sustained energy alternatives for ISR platforms that maximize operational capabilities while minimizing risk to ships, supply chains, and sea lines of communication (SLOC) a mobile fuel generation capability is needed. The following system needs analysis was derived from the project's problem statement, background, and inputs from project sponsors, and operational and industrial stakeholders. The MFGS needs to be modular and capable of accommodating multiple sorties per day across the range of UAS maritime operations while maintaining mobility and low signature. It must be able to support USN and USMC expeditionary operations and forces in contested environments and must be deliverable by 2045. It needs to be compliant with U.S. Navy safety, handling, and storage requirements

for fuel systems while embarked aboard U.S. vessels. It must be able to produce fuel on its own from sources like electricity, seawater, and carbon dioxide.

The MFGS must have minimal training and maintenance requirements to make it an effective addition to the fleet commander's sea-based capabilities. The MFGS needs to be compatible with the U.S. Navy's amphibious assault ships to include an LCS.

From the needs analysis, Figure 1 illustrates the external system interfaces with inputs to the MFGS above and outputs below. As seen in the diagram, the MFGS is independent of the ship, and its energy source, and does not include an air capture system. It is designed to be completely modular between amphibious assault ship classes and compatible with all on-board Navy system regulations.

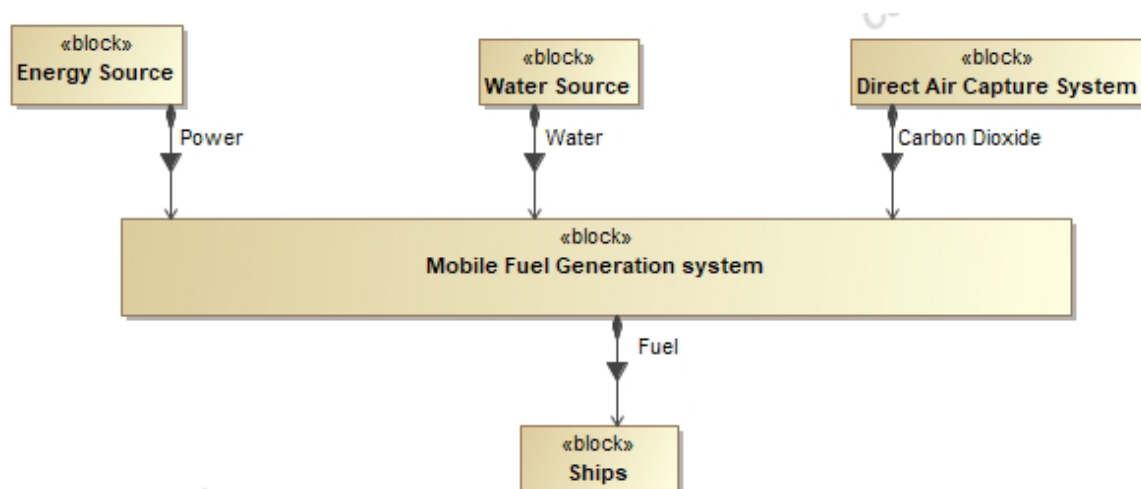


Figure 1. MFGS External System Interface Description

1. The Contested Environment

The South China Sea is a vital trade route shared by the Philippines, Malaysia, Taiwan, Singapore, Brunei, Vietnam, and Indonesia. China's sweeping claims of sovereignty, territorial infringements, and malign maritime activities in the South China Sea (SCS) have destabilized the economic and geopolitical balance of the region. China's 9-Dashed Line and Taiwan reunification policies directly conflict with U.S. and partner interests in the region. China currently lays sovereignty claims to all maritime territory within the 9-Dashed Line, encompassing the Spratley and Parcel Islands, the Straits of

Taiwan, and approximately 90 percent of the three million square kilometers that make up the SCS as depicted in Figures 2 and 3.

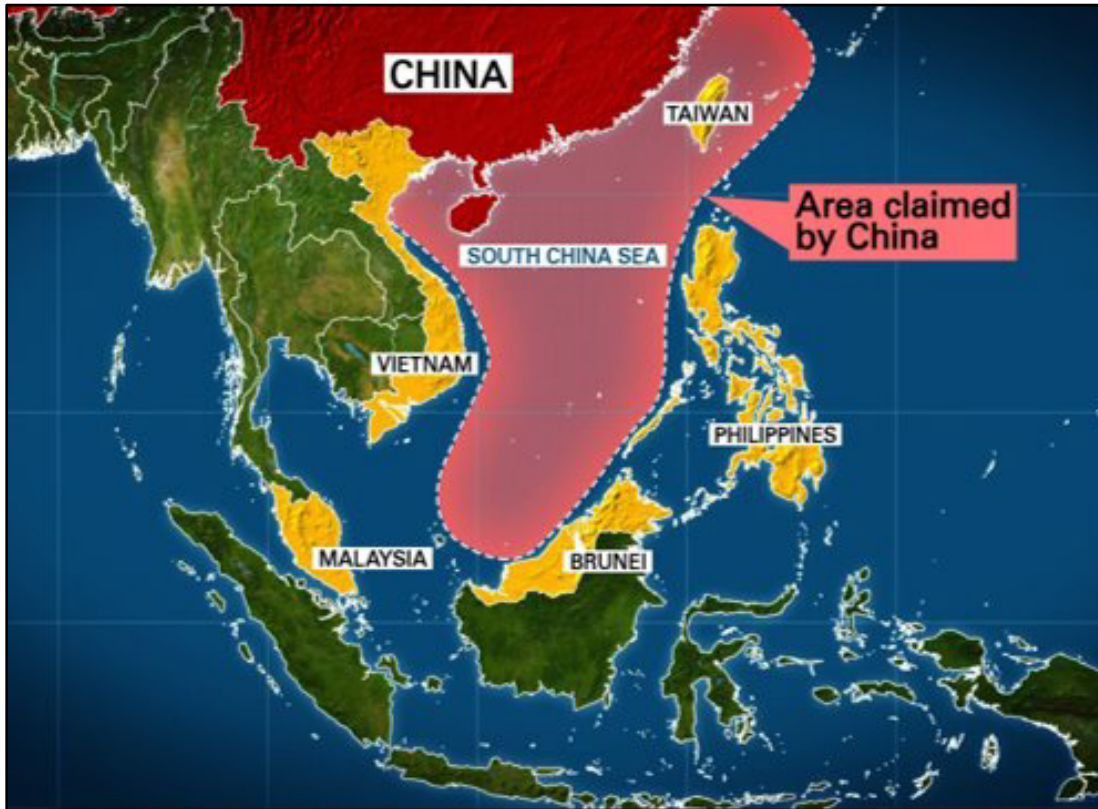


Figure 2. Area Claimed by China. Source: Menon (2020).

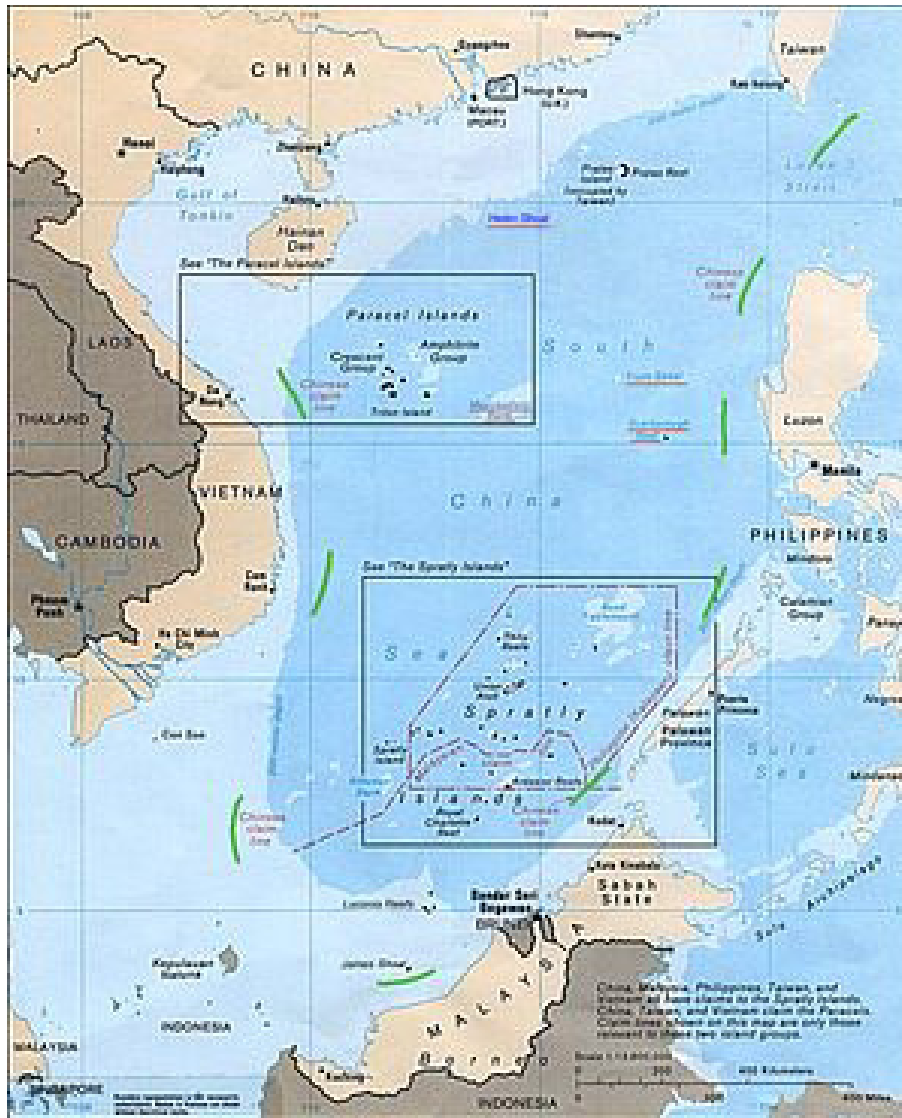


Figure 3. The 9-Dashed Line. Source: The Diplomat (2016).

The 9-Dashed Line border has created tensions in the region with U.S. partners and allies. Because of the Mutual Defense Treaty that the U.S. shares with the Philippines, the U.S. is obligated to support its partner.

2. The Operational Concept

Operational View-1 (OV-1) is a High-Level Operational Graphic (Figure 4). It “provides a graphical depiction of what the architecture is about, and an idea of the players and operations involved” (DOD Chief Information Officer 2023). The OV-1 as shown in

Figure 4 depicts maritime UAS operations in contested bays, straits, and open ocean, supported by the MFGS in one of two operational scenarios, or vignettes modeled in the research. In the figure, the alternative fuel is generated on board via the MFGS and transferred to adjacent ships and systems, for UAV ISR operations. In this study, the MQ-8C was the primary platform modeled with the MFGS alternative fuel solution.



Figure 4. MFGS OV-1

The UAV CONOPS for this research included two vignettes designed to model and highlight the differences in the operational capabilities between the team's selected alternative fuel sources. The goal of these vignettes was to provide a modeling structure from which the team could best identify the highest performing fuel alternative.

1. Vignette one – Figure 5 shows the first operational concept. A UAV provides ISR coverage of an open bay area located in contested waters. The UAV must provide 24-hour coverage over 6 months. The figure illustrates a scenario in which the friendly vessel deploys a UAV to

provide ISR coverage of an area of interest in contested waters without risking the ship.



Figure 5. Operational Concept Vignette 1

2. Vignette two – Figure 6 shows the second operation concept. A UAV must provide consistent maximum coverage in the open ocean for 24 hours a day over the course of 6 months. The figure depicts a UAV deployed forward of the friendly ship formation to provide ISR coverage and early warning for friendly ships along their routes.

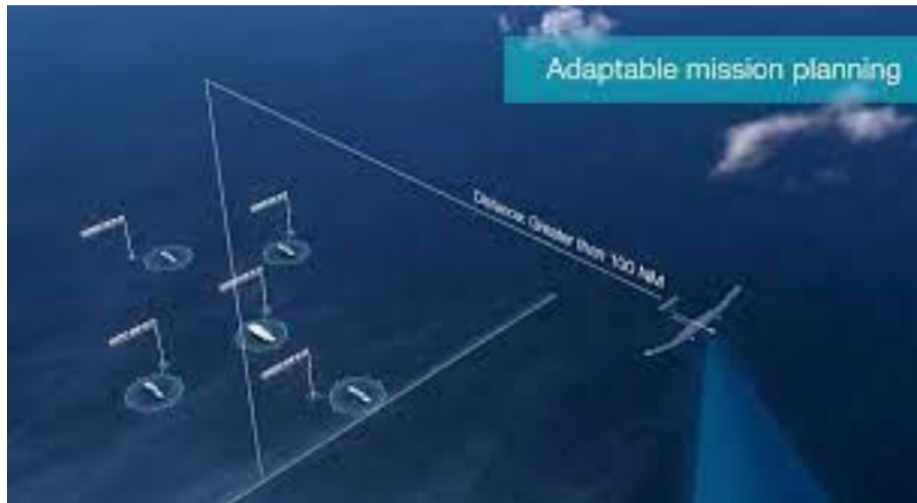


Figure 6. Operational Concept Vignette 2

The needs of the MFGS are further refined in an analysis of system requirements for operations in contested environments while aboard U.S. Navy vessels.

C. REQUIREMENTS ANALYSIS

The ability to use unmanned systems such as the MQ-8C on long-range missions is dependent on refueling capabilities. This is especially true for maritime missions, where the refueling facility needs to be mobile and capable of generating fuel on board. Because of the requirement of operating in a contested environment, a mobile fuel generation facility needs to be capable of producing and dispensing fuel for the MQ-8C on board an amphibious vessel.

1. Background

Mobile fuel generation facilities are self-contained units capable of producing and dispensing fuel. These units would be used in remote locations where access to conventional fuel sources is limited or non-existent such as in disaster relief scenarios, battlefields, and maritime environments. These facilities are designed to produce fuel from available resources such as solar, wind, or water.

The MQ-8C is an unmanned autonomous helicopter used for reconnaissance and surveillance. It can fly for durations up to 12 hours with a service ceiling of 16 thousand

feet and a top speed of 135 knots (Naval Drones 2023). The MQ-8C has an advanced avionics and sensor suite and is operated from a ground control station, which can be located anywhere within a range of 150 nautical miles (Keller 2017). However, the MQ-8C's design restricts its fuel capacity, the addition of a supplementary or alternative fuel supply will enhance its operational range and provide an operational advantage for the Navy (Burgess 2023). The team researched three fuel types and one technology: Liquid hydrogen, synthetic jet fuel (dodecane), liquid methane, and liquid hydrogen fuel cell with an electric motor. Figure 7 depicts the published specifications of the MQ-8C.

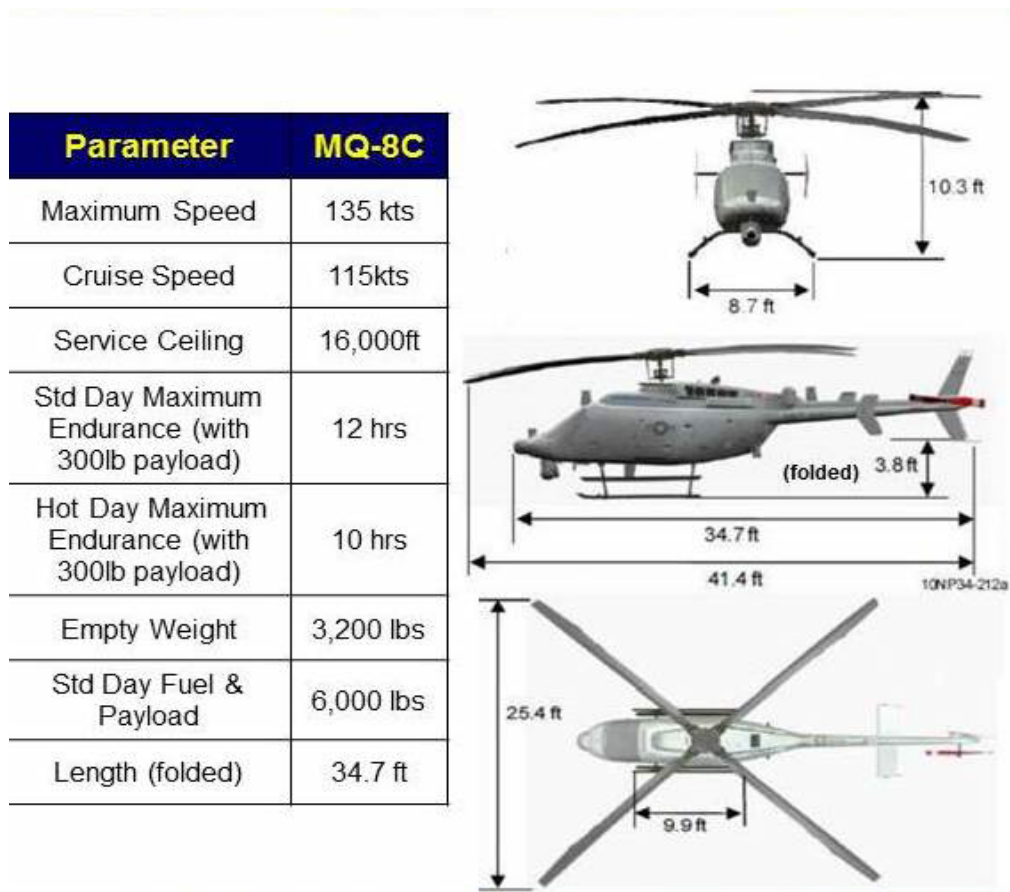


Figure 7. MQ-8C Specification and Dimensions. Source: Naval Drones (2023).

“A littoral combat ship (LCS) is a fast, agile, mission-focused platform designed to operate in near-shore environments, winning against 21st-century coastal threats. The LCS

can support forward presence, maritime security, sea control, and deterrence” (DON 2022). It can launch and recover autonomous vehicles, landing craft and transport troops and equipment, and provide the joint force with access to the littorals and other contested maritime spaces. The LCS can operate independently or in high-threat environments as part of a networked battle force that includes larger, multi-mission surface combatants (DON 2022).

2. MFGS Requirements

The following is a detailed requirements analysis for an MFGS to fulfill the refueling needs of the MQ-8C onboard an LCS. The MFGS must be capable of producing JP-8/JP-5 fuel or fuel capable of being used by an MQ-8C or similar aircraft. JP-8 is the primary fuel used by the MQ-8C and other similar unmanned systems JP-5 is the Navy’s standard aviation jet fuel. It is a high flashpoint kerosine that meets and complies with the requirements of U.S. Navy vessels and is primarily used as jet fuel for aircraft embarked aboard U.S. carriers and amphibious ships (NATO 1997). The MQ-8C can also run on JP-5 although JP-8 is preferred. “The primary difference between the two military fuels is that the flash point temperature for JP-5 is higher (60°C) as compared to JP-8 (38°C)” (CDC 2017, 150).

JP-8 is also the preferred fuel for military applications due to its high flashpoint, high energy content, and stable storage characteristics. The mobile fuel generation facility’s fuel production capacity must be able to produce enough fuel to meet the requirements from vignettes one and two.

The mobile fuel generation facility must have appropriate safety and protection mechanisms to ensure the safety of personnel, equipment, and the environment. It must be designed with safety systems to prevent fires or explosion hazards. Additionally, the facility must adhere to the safety regulations and standards of the Navy. Additionally, the facility must be designed with maintenance and repair in mind to ensure it is always in operational condition. Further, the design must also simplify access to the mobile fuel generation facility’s critical systems and subsystems.

The mobile fuel generation facility should be designed to be highly mobile and adaptable to the environmental and technical constraints of the LCS. The design must be modular and flexible to accommodate the ship's unique design and operating configurations. The facility must be compact and able to fit within the small space provided on a landing docking ship.

The facility must also have a sizeable production capacity that can meet the refueling requirements of the MQ-8C. The facility must, therefore, be able to generate and store sufficient fuel to sustain extended flight operations, and the fuel generation technology must be highly efficient and able to produce fuel in sufficient quantity to support mission requirements.

3. Liquid Hydrogen

Liquid hydrogen is an efficient fuel source with almost three times the energy content of conventional marine fuels (Hebden 2020). Therefore, a mobile fuel generation facility that can produce liquid hydrogen onboard a ship will facilitate the replenishment of the MQ-8C's hydrogen fuel tank, allowing for more extended and continuous flight operations.

a. Liquid Hydrogen Environmental Concerns

While liquid hydrogen is a more environmentally friendly fuel source than traditional fossil fuels, some hydrogen production process still creates carbon emissions. One of the key aspects of environmentally friendly produced hydrogen is the use of green electricity in an electrolysis process to produce the hydrogen.

b. Liquid Hydrogen Safety Concerns

Liquid hydrogen is an efficient fuel for combustion and can easily catch fire or explode if exposed to an ignition source. Additionally, the production, storage, and transport of liquid hydrogen requires high pressure and can pose risks to personnel and equipment. Thus, to ensure the safety of personnel and equipment, all operators must undergo training on handling and maintaining liquid hydrogen and its equipment to avoid accidents and injuries.

4. Synthetic Jet Fuel (Dodecane)

The MQ-8C requires jet fuel with the minimum specifications of JP-8/JP-5. As such the synthetic jet fuel produced by the mobile fuel generation facility should produce fuel that meets or exceeds the specifications of JP-8/JP-5. The synthetic fuel generated from renewable and non-petroleum sources will require similar characteristics as JP-8/JP-5 to be considered a viable replacement.

a. Synthetic Fuel Safety Issues

Synthetic jet fuel production and combustion may cause the release of greenhouse gases and other air pollutants such as nitrogen oxides. Like liquid methane, discharges from the fuel production or loading process may contaminate the waterways on which the landing docking ship operates. Accidents or spills of synthetic jet fuel may create safety hazards for sailors and pollute the environment. Synthetic jet fuel is highly flammable and poses a fire risk during production, storage, and use. The production and use of synthetic jet fuel generates several types of waste, including toxic substances and hazardous waste, and releases exhaust emissions that contain particulate matter, greenhouse gases, and other harmful substances. Strict safety protocols must be implemented to avoid accidents, spills, and other safety hazards during synthetic jet fuel production, storage, and use. As such, an environmental impact statement must be conducted before the mobile fuel generation facility is placed onboard the vessel.

b. Equipment Requirements

Synthetic jet fuel generation facilities should be designed to be inherently safe with built-in safety features ensuring operational safety for the personnel onboard the LCS. The facility should comply with all environmental and occupational requirements and regulations, including emissions regulations. It should incorporate the latest technology to improve fuel quality, increase efficiency, improve reliability, and reduce emissions. It should be designed with a human-machine interface that simplifies its operation and enhances performance.

5. Liquid Methane

The facility must produce enough liquid methane fuel to sustain the MQ-8C and other similar aircraft. The mobile fuel generation facility's fuel production capacity must be able to produce enough fuel to meet the requirements from vignettes one and two. The system should be designed to minimize energy consumption and maximize the conversion of raw materials into fuel. The facility should be designed to integrate with existing equipment on the landing docking ship. This will minimize the need for additional equipment and reduce the system's overall weight. The system should be built to withstand the harsh marine environment, including salt and moisture exposure. The materials used in the construction of the system should be corrosion-resistant and durable.

The facility should be designed to comply with all relevant regulations and standards for producing and storing liquid methane fuel. The facility should be designed with redundancy to minimize downtime in case of component failure or maintenance requirements. Dual equipment backup can also help ensure that the production of liquid methane fuel is not interrupted.

a. Liquid Methane Safety Concerns

Traditional jet fuels like JP-8 and JP-5 contain toxic substances that emit harmful pollutants into the atmosphere that pose environmental and human health concerns. Among the cleaner alternative fuels are synthetic jet fuels (SJFs), which are renewable, bio-derived, and have a low carbon footprint. Despite being a cleaner alternative, the gasification process of liquid methane onboard a landing docking ship to refuel an MQ-8C poses several environmental concerns.

- During fuel production, the gasification of feedstock and cleaning of the syngas produces significant carbon monoxide emissions.
- Liquid methane is a greenhouse gas that contributes to global warming. When used as fuel, it emits nitrogen oxide, which can cause respiratory problems and acid rain.

- Methane is a natural gas that can dissolve in water and contaminate it. In the case of a spill or leak, liquid methane can cause harm to aquatic wildlife and their surrounding habitat.
- Liquid methane is highly flammable and can pose a significant risk of fire or explosion if not handled correctly. It is crucial to ensure proper storage, handling, and transportation of liquid methane.
- Exposure to methane gas can cause health effects such as eye, nose, and throat irritation or headaches, and in extreme cases, can lead to suffocation.
- The transportation of liquid methane via ship presents the risk of spills and leaks, which could harm marine wildlife and ecosystems.
- The mobile fuel generation facility and associated ship activities can generate significant noise that may impact wildlife and humans.

To mitigate these concerns, effective safety protocols, training, and strict regulations should be implemented to ensure that the refueling process is conducted safely, minimizing risks to the environment and human health. Additionally, monitoring of air and water quality during and after refueling should be conducted to assess any potential negative impacts.

D. FUNCTIONAL ANALYSIS

“Functional analysis is a fundamental tool of the design process to explore new concepts and define their architectures” (Viola et al. 2012). The process described is a top-down approach that connects the broader requirements gathered in the Stakeholder Needs Analysis, as outlined in Table 1, with the more intricate requirements necessary for the development phase, depicted in Figure 8. This process, known as Functional Analysis, yields a well-defined functional architecture. This architecture includes system requirements linked to each system function in a way that can be easily traced and understood (Viola et al. 2012).

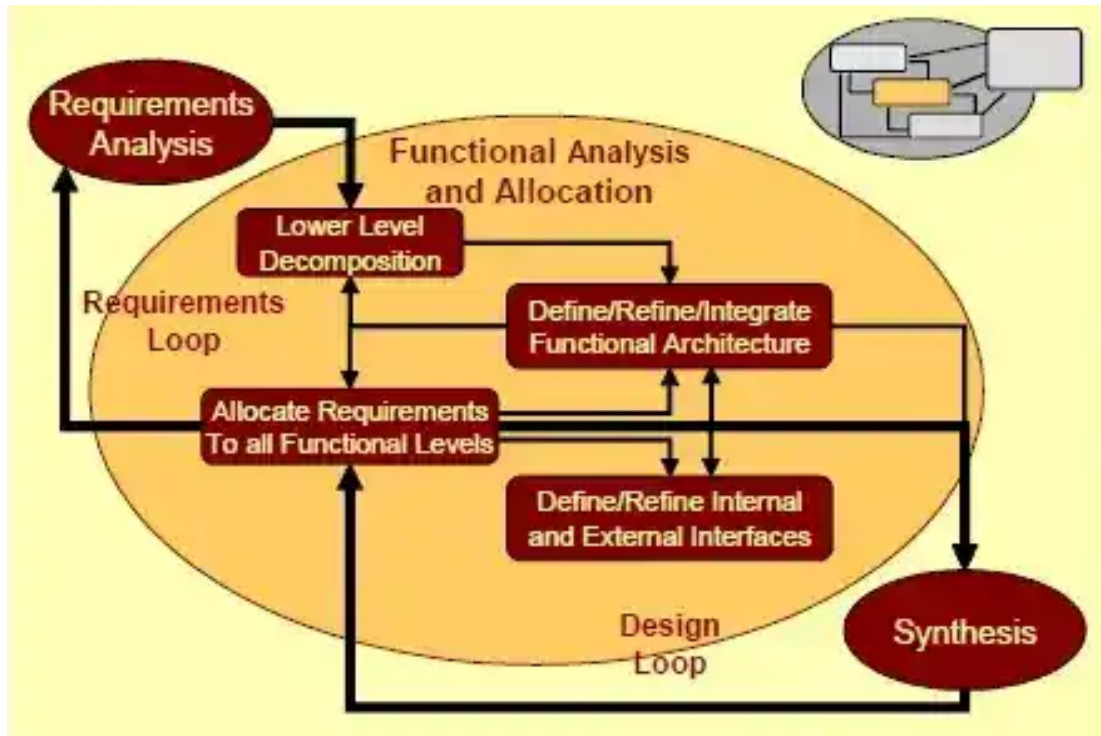


Figure 8. Functional Analysis and Allocation Conceptual Diagram. Source: Department of the Air Force (2005)

A functional hierarchy diagram “shows all functions evolved in your system in a hierarchical manner” (Kaur 2016). The functional hierarchy for this project is shown in Figure 9. The top-level function of the Mobile Fuel Generation System was to “produce fuel in a contested environment.” Five subfunctions were then decomposed from the top-level function. Table 2 describes the functions and sub-functions of the system. Table 3 provides traceability from the system functions back to the stakeholder needs.

Table 2. Functional Description

	Function
F.1	Provide Fuel for Combat Operations
F.1.1	Provide Safe Fuel Production
F.1.2	Provide Fuel for Continuous Operations
F.1.2.1	Provide Fuel for Normal Refueling
F.1.2.2	Provide Fuel for Hot Refueling
F.1.3	Provide Fuel Appropriate for MQ-8C
F.1.4	Provide Fuel from Locally Procured Materials and Energy
F.1.5	Operate with Zero Carbon Emissions

Table 3. System Functions to Stakeholder Needs Traceability Matrix

	N.1.1	N.1.2	N.2	N.3	N.4	N.5	N.6	N.7
F.1		O			O			
F.1.1		O	O	O	O	O		
F.1.2			O					
F.1.2.1			O	O			O	
F.1.2.2			O	O			O	
F.1.3		O	O				O	
F.1.4		O						
F.1.5	O							O

Figure 10 shows the SysML activity diagram for the top-level functions. The diagram shows the flow of system operations and event occurrences needed to perform mobile fuel generation at sea. The blocks within the diagram identify the actions. The block connections represent the action flows and identify the inputs and outputs of the corresponding action.

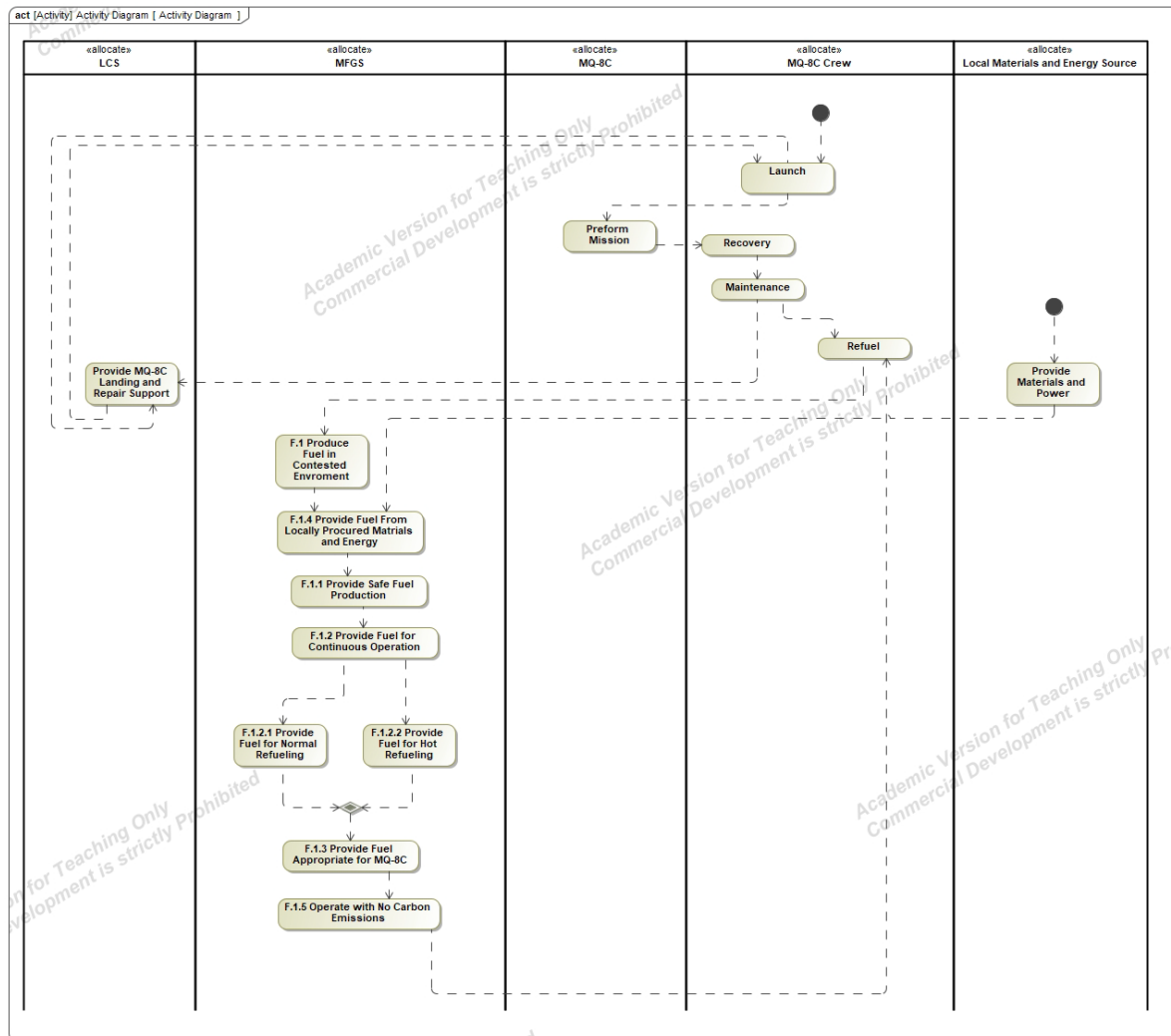


Figure 10. SysML Activity Diagram for Top-Level Functions

III. MODEL DESIGN

The following chapter outlined the development of the ExtendSim model used to evaluate the mobile fuel production capability coupled with the ISR platform MQ-8C operating from an LCS. The model addressed the fuel production rate, fuel type, and MQ-8C performance characteristics. The simulation provided an in-depth understanding of the interactions of power requirements, fuel alternatives, and flight hours.

A. MODEL OUTLINE

The ExtendSim model had four major functional areas:

1. Mission Assignment and Launch
2. Mission Execution
3. Recovery
4. Repair and Refuel

In the mission assignment and launch functions, two independent items are created within the model: MQ-8Cs and missions. The MQ-8Cs are defined by individual attributes such as fuel type, launch pad usage, and launch delay. Missions are independent from the systems to allow for assessment of the percentage of missions that can successfully be accomplished by different design configurations. The mission execution function executed the mission and released the mission to a new MQ-8C with sufficient time for the aircraft to take flight before the incoming aircraft lands. The recovery functional area assessed the aircraft and determined the quantity of fuel needed for refueling, and if the aircraft needs to be repaired. The repair and refueling functions prepare the aircraft for mission reassignment. Figure 11 details the high-level view of the flow of the simulation.

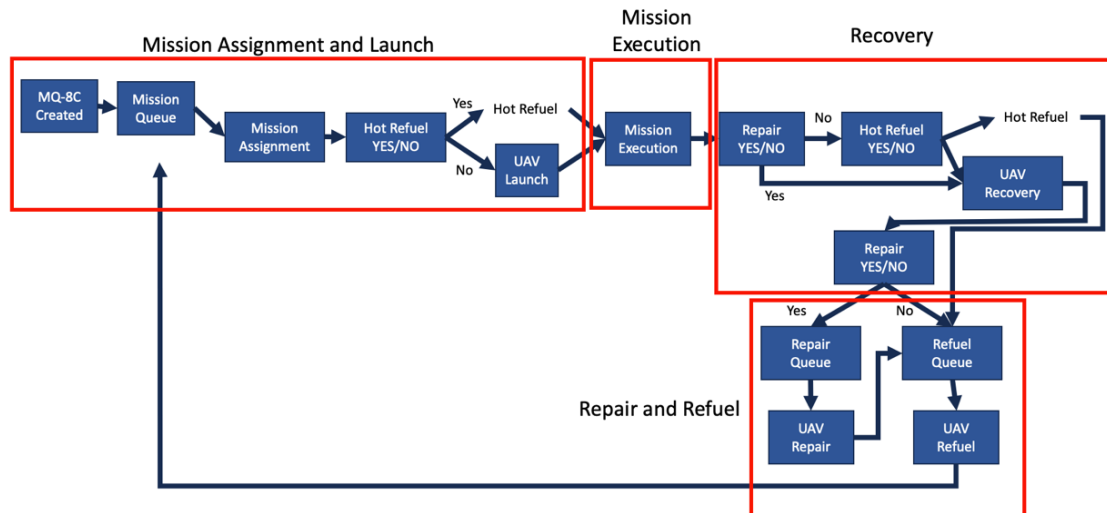


Figure 11. Simulation Diagram

B. DESIGN VARIABLES

This section outlines the model input variables and provides context on how these variables were incorporated into the ExtendSim Model. There were three types of variables: mission, MQ-8C support capabilities, and MQ-8C characteristics. When these designed variables were developed, they were traced back to the functional activities of the system (see Table 5).

1. Mission Variables

Four mission-related variables were evaluated in the model: fuel type, flight duration, hot refueling, and the number of missions. These variables were used to address the vignettes of interest. The team identified these variables as the ones most likely to impact the CONOPS involving the vignettes of interest (see Table 4).

2. Capability Variables

The project also investigated the impact of changes in the LCS capabilities. The two changes assessed, from a capability perspective, were the number of landing decks, and the number and MQ-8C available.

Table 4. Design Variables

DV	Variable	Description
DV.1.1	Fuel Type Production	1: JP-5 2: Synthetic Jet Fuel 3: Liquid Hydrogen 4: Methane 5: Liquid Hydrogen W/Fuel Cell
DV.1.2	Number of Missions	1-4, Number of missions available for the MQ-8Cs to perform
DV.1.3	Hot Refueling	Is the aircraft being refueled while the engines are running? yes, or no?
DV.1.4	Flight Duration	The Duration of MQ-8C flight is based on 70 percent fuel load burned, 90 percent fuel burned, or a distribution between the two: minimum, max, or distribution
DV.2.1	Number of Landing Pads	The number of landing pads available on the supporting ship. 1 or 2
DV.2.2	Number of MQ-8Cs	The Number of MQ-8Cs that can be supported from a single ship.

Table 5. Design Variables to System Functions Traceability Matrix

	F.1	F.1.1	F.1.2	F.1.2.1	F.1.2.2	F.1.3	F.1.4	F.1.5
DV.1.1	O	O	O				O	O
DV.1.2			O			O		
DV.1.3			O	O	O			
DV.1.4		O	O					
DV.2.1								
DV.2.2	O					O		

3. MQ-8C Performance Characteristics

The MQ-8C is a UAV based on the Bell 407 helicopter. The aircraft has been one of the key intelligence, surveillance, and reconnaissance (ISR) platforms for the Navy and will play a critical role in future Navy operations. The following section will review the design and operational characteristics of the MQ-8C, with particular emphasis on the characteristics that impact fuel consumption and platform endurance.

The MQ-8C has a fuel capacity of 1225 kg when using JP-5 but is limited to 1000 kg of fuel during shipboard operations due to the gross weight restrictions of the aircraft. Because the project assessed fuels that are significantly less dense than traditional JP-5 fuel it is important to note the volumetric usable fuel capacity of the MQ-8C, which is 1487L.

The MQ-8C can conduct hot refueling operations. Hot refueling is when the aircraft returns from a mission and is refueled and relaunched without shutting down the engine. Hot refueling reduces the downtime of the aircraft and will impact overall operational availability (Ao).

The maintenance and repair cycle will also impact the aircraft's Ao. The mean time between maintenance (MTBM) is defined by the number of flight hours between required preventative maintenance. The mean time to repair (MTTR) is the time it takes to perform preventive maintenance. Data regarding the MQ-8C is in Table 1.

Table 6. MQ-8C Characteristics

Characteristic	MQ-8C
Mean Time Between Maintenance (h)	25
Mean Time to Repair (h) (normal)	1.6 sd 0.2
Launch Time (h) (normal)	0.5 sd 0.08 ¹
Recovery Time (h) (normal)	0.5 sd 0.08 ¹
Refuel Time (h) (normal)	0.5 sd 0.1 ¹
1 (Na 2023)	

a. Fuel Burn Rate

According to Northrup Grumman, the fuel burn rate (FBR) of the MQ-8C is 104 kg per hour of JP-5. To calculate the FBR for each fuel alternative, the ratio of the fuel energy density of JP-5 and the alternative fuel was multiplied by the FBR for JP-5 (see the following equation and Table 3).

$$JP5\ FBR\left(\frac{kg}{h}\right) \times \frac{JP5\ ED\left(\frac{kwh}{kg}\right)}{Alternative\ Fuel\ ED\left(\frac{kwh}{kg}\right)} = Alternative\ FBR\left(\frac{kg}{h}\right)$$

Note 1 ED= Energy Density

Note 2 FBR=Fuel Burn Rate

The exception to this method is the liquid hydrogen (LH2) fuel cell. The method for the LH2 fuel cell needed to account for the efficiency difference between the Rolls-Royce 250-C47E turbine engine and the hydrogen fuel cell and electric motor. The efficiency of most helicopter turbine engines ranges between 15 and 25 percent (Russell et al. 2015). Hydrogen fuel cells have an efficiency of about 50 percent, and it is likely that they will exceed 60 percent soon. For the purposes of the simulation, 60 percent was used as the efficiency of the hydrogen fuel cell and 20 percent was used as the efficiency of the turbine engine. To calculate the fuel burn rate for the fuel cell, the ratio of the turbine efficiency and fuel cell efficiency was multiplied by the fuel burn rate of the LH2 turbine.

$$\frac{\text{Turbine Efficiency (20\%)}}{\text{Fuel Cell Efficiency (60\%)}} \times \text{LH2 Turbine FBR} \left(\frac{\text{kg}}{\text{h}} \right) = \text{LH2 Fuel Cell FBR} \left(\frac{\text{kg}}{\text{h}} \right)$$

b. Fuel Load and Mission Length

The mission length was driven by the fuel load capability of the MQ-8C. The fuel load capacity is 1487 L and has a maximum fuel mass of 1000 kg for shipboard operations. For this project's purpose, it was assumed that the fuel volume of the aircraft was fixed and could not be increased. Because of the low density of the fuel alternatives LH2, LH2 with fuel cell, and methane, the fuel load was limited by the tank volume of the MQ-8C. The mission minimum and maximum lengths were established by assuming the aircraft would land once it had burned 70 to 90 percent of the maximum fuel load respectively. Data from Table 8 was used to calculate fuel burn rates and the maximum fuel load. The mission length minimum and maximum, fuel burn rate, and fuel load mass can be found in Table 7. All of this information was provided by Northrup Grumman.

Table 7. MQ-8C Fuel Performance Data

MQ-8C	Fuel Load (kg)	Fuel Burn Rate (kg/h)	Mission length Minimum (h)	Mission length Maximum (h)
JP-5	1000	104.5	6	8.5
Synthetic Jet Fuel	1000	100.5	6.32	8.95
Liquid Methane	979	84.9	7.33	10.38
LH2	232	37.3	1.79	2.54
LH2 Fuel Cell	232	12.4	5.93	7.62

Table 8. Fuel Alternatives Specifications

Specification	JP-5	Synthetic Jet Fuel	LH2	Methane
Fuel Density (kg/gallon)	2.98	2.98 ¹	0.27 ²	2.49 ³
Energy Density (kwh/kg)	12.5	13.0 ¹	35.0 ²	15.4 ³
Conversion Efficiency (kwh/kg)	N/A	44.1 ¹	51.1 ²	27.0 ³
¹ (Male 2021) ² (Guo et al. 2022) ³ (Stempien 2015)				

C. MEASURES

There were three outputs from the ExtendSim model that were to evaluate the impact of the input variables. These measures were: operational availability (Ao), flight hours per day, and the power requirements for the mobile fuel production system. These measures allowed for the evaluation and development of the concept of operations for a mobile fuel production capability.

The power requirement for the mobile fuel production system was one of the measures that provided insight into how well the system would fulfill the Stakeholder's needs. This measure was meant to show how much power would be required by an MFGS

to maintain the capabilities outlined in both vignettes. To calculate the power requirement for the MFGS the simulation calculated the total fuel usage and then used the conversion efficiency for each fuel alternative to determine the power input requirements.

The flight hours per day measure was calculated by taking the total flight hours during the simulation divided by the duration of the simulations in days. This measure was used to evaluate the impact of the addition of MQ-8Cs and additional landing pads.

Ao was calculated by taking the total flight time and the time waiting for mission assignment and dividing that by the total system hours. The total system hours include flight time, the time waiting for a mission assignment, maintenance, launch, recovery, refuel and all associated wait times.

D. LIMITATIONS AND ASSUMPTIONS

The goal of any model is to describe the real world. The more detailed and accurate the data used to build the model the more accurate the depiction of the real world. To overcome the limitations in the data, assumptions about the limitations were made. The assumptions for this project were based on academic research, personal expertise of the team members, and logical reasoning.

1. Limitations

The following is a list of limitations identified when the model was developed.

1. There was no data available on the impact of fuel type on the maintenance cycle of the aircraft.
2. Data on the correlations of fuel type versus fuel efficiency was extremely limited.
3. Very little data on flight operations and mission frequency is releasable to the public.

2. Assumptions

The following is a list of assumptions used in model design and development.

1. The model was based on two MQ-8Cs stationed on an LCS.
2. The simulation duration was 6 months.
3. The model only addressed the power requirement of the MFGS, and not manpower or other needs of the system.
4. The fuel type did not impact the maintenance cycle of the aircraft.
5. The fuel efficiency of the turbine engine was unaffected by fuel type.
6. Refuel time is not impacted by fuel type.

IV. MODEL ANALYSIS

This section outlines the analysis approach, design of experiment (DOE), and the model results. The analysis approach outlines the goal of the model, input variables, and the model response. The DOE outlines the input variables with the goal of evaluating the model's sensitivity and the performance of each alternative fuel. The model results section will present all the output data regarding the two vignettes.

A. ANALYSIS APPROACH

The analysis approach focused on the impact of the MFGS on naval operations. Five fuel types were analyzed with the goal of determining which fuel provides the best performance with the lowest power input requirements for the MFGS. JP-5 was used as a base line to evaluate all the fuel alternatives or technology alternatives. Synthetic jet fuel, liquid methane, and LH2 were evaluated along with the LH2 fuel cell which was LH2 fuel type coupled with an electrolytic fuel cell and electric motor technology. The data set was analyzed with JMP Pro 17, with the goal of understanding the model responses regarding the input variables.

As a secondary goal, the team investigated possible configuration changes to ship design. The two major changes the team looked at were the number of landing decks and the addition of one or two additional MQ-8Cs.

B. DESIGN OF EXPERIMENT

The design of experiment (DOE) was conducted in two phases. The first DOE was used to evaluate the two operational vignettes, the different fuel types, whether hot refueling was being conducted, and whether the flight duration was a minimum flight time, maximum flight time or flight time that was distribution between the minimum and maximum. Input data can be found in Table 9. A full factorial design was completed and resulted in 60 different combinations with 30 replicates of each for 1,800 runs.

Phase two was designed to determine the impact of ship configuration changes. This second DOE evaluated the operational impacts of supporting varying numbers of MQ-

8Cs, landing/launch pads, fuel types and additional missions. To reduce the number of runs the team reduced the number of fuel types to JP-5, methane, LH2 fuel cell. Input data can be found in Table 10. A full factorial design was completed and resulted in 54 combinations with 30 replicates of each for 1,620 runs.

Table 9. Input Variables DOE Phase One

Factor	Value	Description
Fuel Type	1, 2, 3, 4, 5	1: JP-5 2: Synthetic Jet Fuel 3: Liquid Hydrogen 4: Methane 5: Liquid Hydrogen W/Fuel Cell
Number of Missions	1, 2	number of missions for the MQ-8Cs to perform
Hot Refueling	0, 1	no or yes
Flight Duration	0, 1, 2	minimum, distribution, or maximum flight length

Table 10. Input Variables DOE Phase Two

Factor	Value	Description
Fuel Type	1, 4, 5	1: JP-5 4: Methane 5: Liquid Hydrogen W/Fuel Cell
Number of Missions	2, 3, 4	number of missions for the MQ-8Cs to perform
Number of Landing Pads	1, 2	
Number of MQ-8Cs	2, 3, 4	

C. MODEL RESULTS

This section outlines the results from the model with the corresponding analysis. JMP Pro 17 was the team's primary analysis tool. This data analysis tool enables users to evaluate large data sets and understand the value of the data and the statistical significance of that data. The team first analyzed variance analysis (ANOVA) with a Tukey honestly significant difference (HSD) test for each measure. Once the ANOVA and Tukey HSD test

was completed, a partition tree analysis was conducted to evaluate the input variables that had a substantial impact to the model. The intent of this analysis was to identify the fuel type or technology that would result in the best performance of the system so that decision makers will be able to make informed decisions on the development of future fuel technologies.

1. Phase One Analysis

This subsection analyzed the performance of the MQ-8C and MFGS with respect to vignettes one and two.

a. Vignette One Analysis

This section covers the analysis of vignette one. The ANOVAs and Tukey HSD tests can be found in Appendix C. The ANOVA and Tukey HSD tests indicated that there are statistically significant differences that can be seen in operational availability and flight hours per day caused by changed to fuel type, hot refueling, and flight duration. The impact of hot refueling and flight duration is not statistically significant for power requirement. The analysis also indicates that the impact of fuel type is more pronounced than the impact of either hot refueling or flight duration. To conduct a combined analysis of the impact of each potential variable, partition tree analysis highlights the variables that have the largest impact on each output metric is conducted.

(1) Operational Availability vs. Fuel Type

Ao provides a measure of how often a system is available to perform an assigned mission. The data for the partition tree and Ao as related to fuel type can be found in Figure 12. This analysis showed an R-Squared value of 0.602 (denoted as 1 in Figure 12). This indicated that there was substantial difference between fuel type 3 and fuel types 1, 2, 4, and 5. The overall average Ao was 0.86 (denoted as 2 in Figure 12) with fuel type 3 having an average Ao of 0.72 (denoted as 3 in Figure 12) and fuel types 1, 2, 4, and 5 having an average Ao of 0.89 (denoted as 4 in Figure 12). This suggests fuel type 3 is a poor candidate for employment in terms of increasing operational availability.

and 4 had a combined average power requirement of 2107 kW (denoted as 4 in Figure 13). This suggests that to minimize the power requirement, fuel type 5 is the preferred solution and fuel type 2 is the most burdensome.

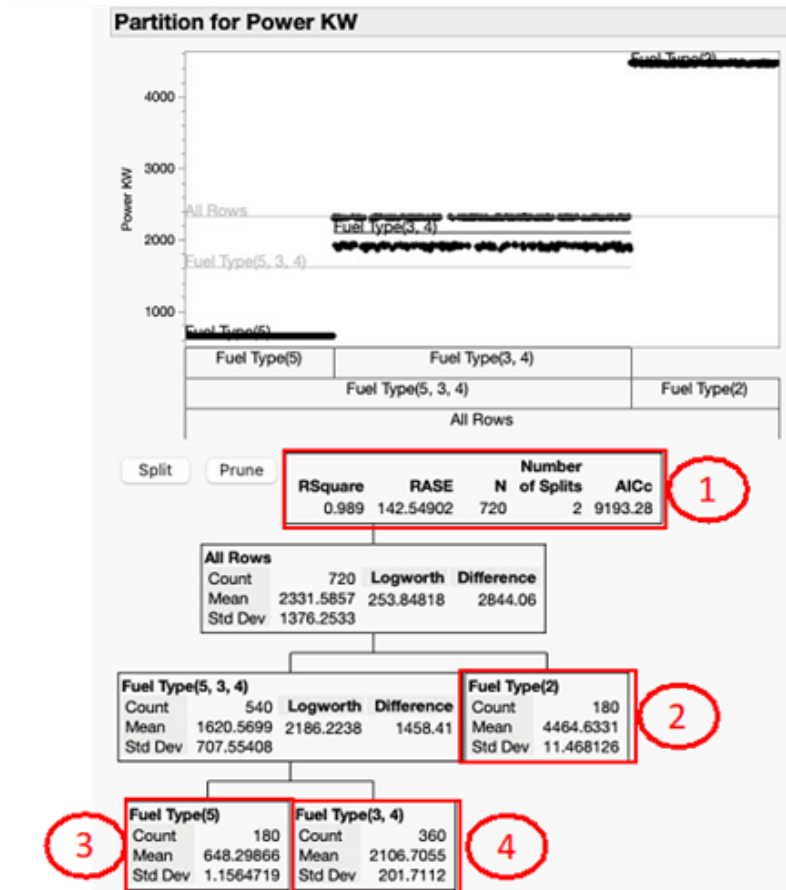


Figure 13. Partition Tree for MFGS Power Requirement vs. Fuel Type for Vignette One

(3) Flight Hours per Day vs. Fuel Type

Flight hours per day was a measure of how many flight hours would be conducted per day and was an effective way to evaluate the input variables. The partition analysis shows an R-squared value of 0.593 (denoted as 1 in Figure 14), when partitioning out fuel type 3 from the other fuels. Fuel type 3 had an average of 23.8 flight hours per day (denoted as 2 in Figure 14). The combined average for the other fuel alternatives was 24.2 flight

hours per day (denoted as 3 in Figure 14). This is consistent with previous analysis, which showed that fuel type 3 realizes lower operational availability than all other fuel types.

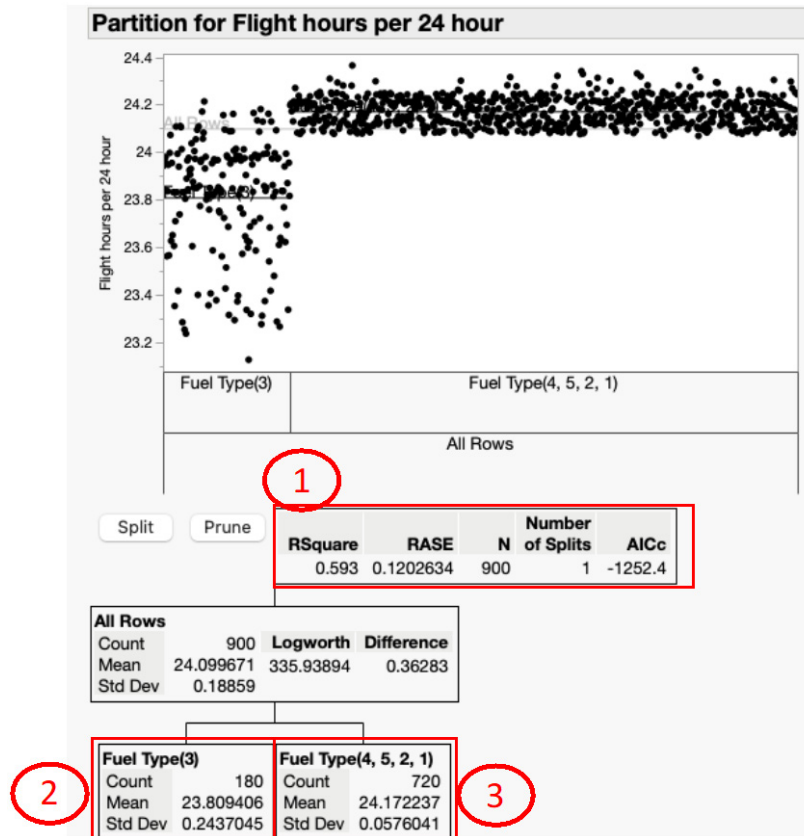


Figure 14. Flight Hours per Day vs. Fuel Type for Vignette One

b. Vignette Two Analysis

This section covers the analysis of vignette two. The ANOVAs and Tukey HSD tests can be found in Appendix C. As with vignette 1, the ANOVA and Tukey HSD tests show statistically significant differences in operational availability and flight hours per day from changes to fuel type, hot refueling, and flight duration. When assessing power requirements hot refueling and flight duration is not statistically significant. As with vignette 1, partition tree analysis is used to assess the relative impact of each potential variable.

(1) Operational Availability vs. Fuel Type

The data for the partition tree and Ao, as related to fuel type, can be found in Figure 15. This analysis showed an R-Squared value of 0.600 (denoted as 1 in Figure 15). This indicated a substantial difference between fuel type 3 and fuel types 1, 2, 4, and 5. The overall average Ao was 0.79 (denoted as 2 in Figure 15) with fuel type 3 having an average Ao of 0.65 (denoted as 3 in Figure 15) and fuel types 1, 2, 4, and 5 having an average Ao of 0.82 (denoted as 4 in Figure 15). This suggests fuel type 3 is a poor candidate for employment in terms of increasing operational availability. This is consistent with the findings from vignette 1.

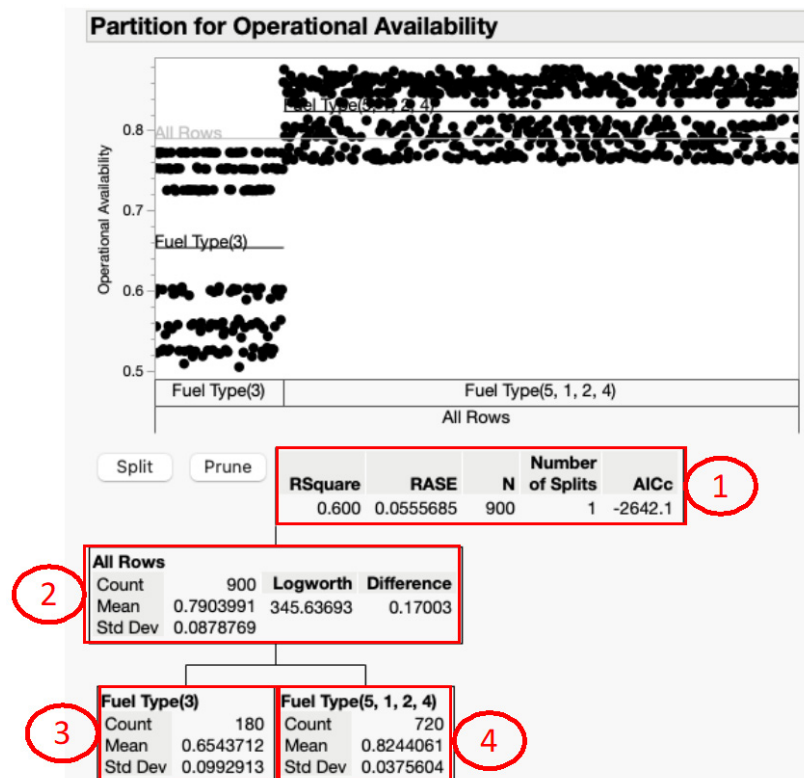


Figure 15. Decision Tree for Ao vs. Fuel Type for Vignette Two

(2) MFGS Power Requirement vs. Fuel Type

The data for power requirement as related to fuel type can be found in Figure 16. It should be noted that fuel type 1 was omitted from this analysis because it is not applicable

to the MFGS and was used as a comparison for the Ao and flight hours per day. The team conducted a partition tree analysis that resulted in an R-Squared value of 0.946 (denoted as 1 in Figure 16). This analysis showed that fuel type was the driving factor for the MFGS power requirement regarding vignette two.

This analysis showed that fuel type 2 would require the most power (power requirement of 7,300 kW; denoted as 2 in Figure 16), fuel type 5 had the lowest power requirement (power requirement of 1,050 kW; denoted as 3 in Figure 16), and fuel types 3 and 4 had a combined average power requirement of 3,177 kW (denoted as 4 in Figure 16). This suggests that, to minimize the power requirement, fuel type 5 is the preferred solution and fuel type 2 is the most burdensome. This is consistent with the findings from vignette 1.

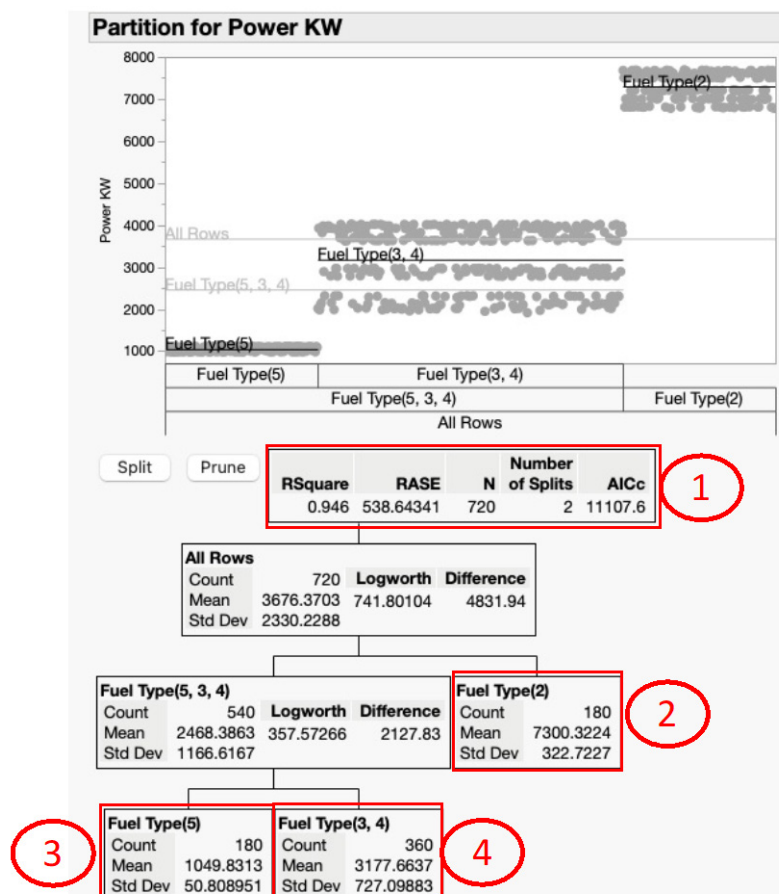


Figure 16. Partition Tree for MFGS Power Requirement vs. Fuel Type for Vignette Two

(3) Flight Hours per Day vs. Fuel Type

The partition analyses show an R-squared value of 0.600 (denoted as 1 in Figure 17), when partitioning out fuel type 3 from the other fuels. Fuel type 3 had an average of 31.4 flight hours per day (denoted as 2 in Figure 17). The combined average for the other fuel alternatives was 39.6 flight hours per day (denoted as 3 in Figure 17). This is consistent with previous analysis, which showed that fuel type 3 realizes lower operational availability than all other fuel types and is consistent with the findings from vignette 1.

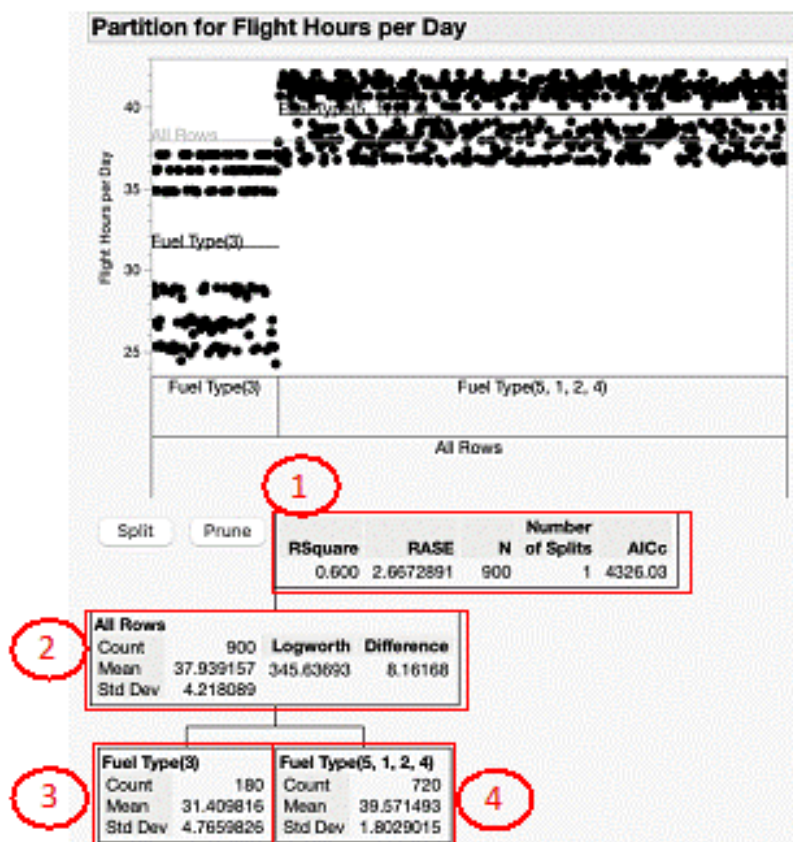


Figure 17. Flight Hours per Day vs. Fuel Type for Vignette Two

c. Phase one summary

Fuel type was the driving factor for all the measures for both vignette one and two. For the power requirement fuel type 2 performed the poorest with fuel type 5 performing

the best. For both Ao and flight hours per day fuel type 3 performed the poorest and there was no substantial difference between the rest of the fuel types.

2. Phase Two Analysis

Phase two analysis focused on changes to the capabilities that support MQ-8C operations to include the addition of more MQ-8Cs and landing decks. For this analysis fuel types 2 and 3 were eliminated based on their poor performance in the phase one analysis. The purpose of eliminating these fuels was to reduce the number of required simulations runs.

a. Ao Analysis

The data for the partition tree and Ao as related to fuel type can be found in Figure 18. This analysis showed an R-Squared value of 0.132 (denoted as 1 in Figure 18). This R-Squared value is much lower than the previously observed values and indicates that fuel type has less of a relative impact on the operational availability when other operational considerations are introduced. The overall average Ao was 0.776 (denoted as 2 in Figure 18) with fuel type 1 having an average Ao of 0.74 (denoted as 3 in Figure 18), fuel type 5 having an average Ao of 0.79 (denoted as 4 in Figure 18), and fuel type 4 having an average Ao of 0.80 (denoted as 5 in Figure 18). This suggests that both fuel types 4 and 5 have a better Ao than fuel type 1 (JP-5).

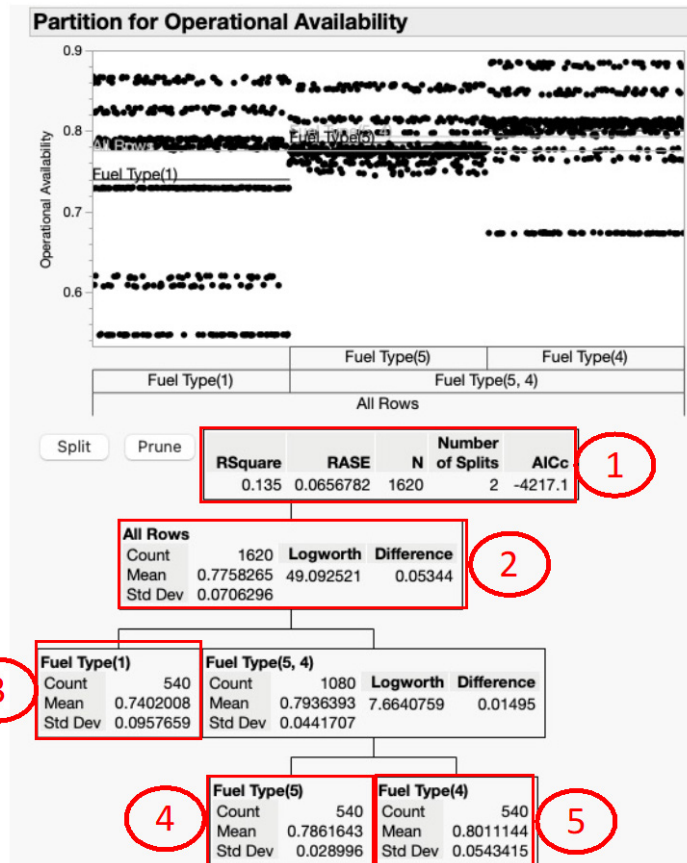


Figure 18. Ao vs. Fuel Type Phase Two

The next factor that impacted Ao was the number of missions being requested. The data for the partition tree analysis for Ao as related to the number of missions can be found in Figure 19. This analysis showed an R-Squared value of 0.293 (denoted as 1 in Figure 19). This indicated that there was only a slight difference between two, three, and four mission requests. However, this analysis was consistent with expectations. The expectation would be that the greater the operational tempo the lower the Ao due to an increase in maintenance, refueling, launch, and recovery cycles. This analysis showed that with additional mission requests the overall availability dropped. The overall average Ao was 0.76. The number of mission requests varied from 2, 3, and 4 and Ao of 0.83, 0.76, and 0.74 respectively (denoted as 2, 3, and 4 in Figure 19).

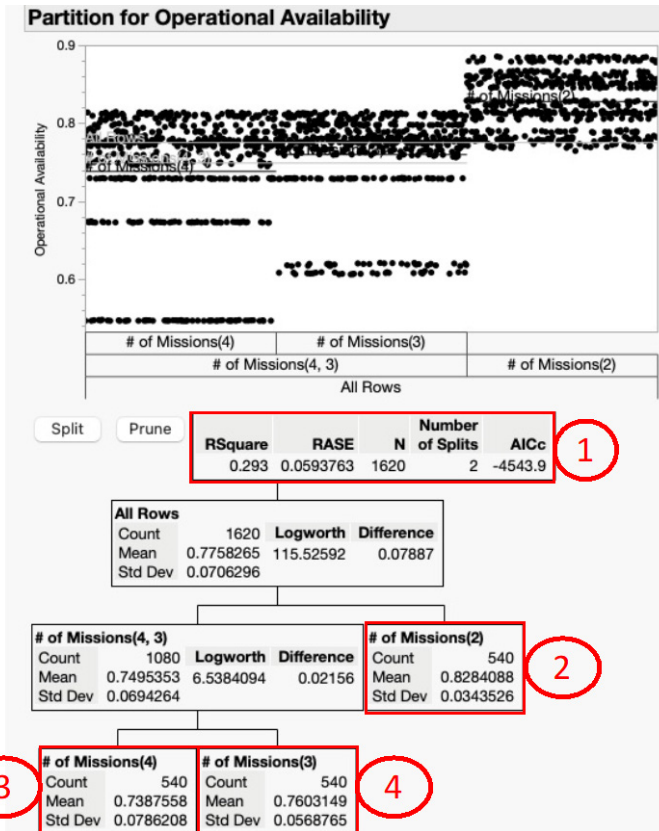


Figure 19. Ao vs. Number of Missions Phase Two

b. Power Requirement Analysis

The data for power requirement as related to fuel type can be found in Figure 20. It should be noted that fuel type 1 was omitted from this analysis because it is not applicable to the MFGS and was used as a comparison for the Ao and flight hours per day. The team conducted a partition tree analysis that resulted in an R-Squared value of 0.852 (denoted as 1 in Figure 20). This analysis showed that fuel type was the driving factor for the MFGS power requirement regarding phase two analysis.

This analysis showed that fuel type 4 would require the most power (power requirement of 4,848 kW; denoted as 3 in Figure 20), and fuel type 5 had the lowest power requirement (power requirement of 1,369 kW; denoted as 3 in Figure 20). Recall that fuel types 2 and 3 were removed from this portion of the analysis due to previously identified

shortcomings, so this analysis presents a one-to-one comparison of the differences between fuel types 4 and 5.

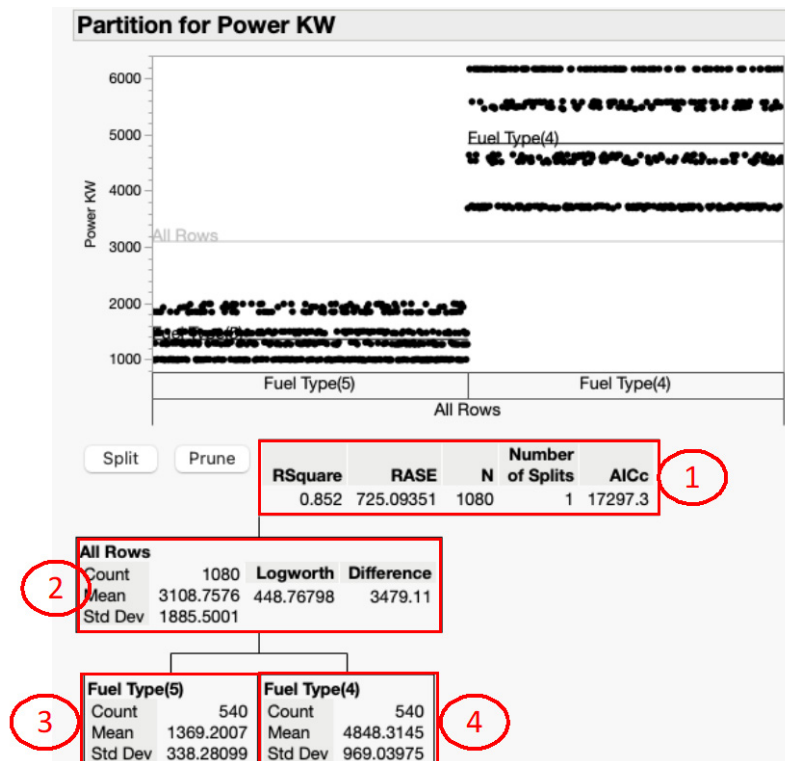


Figure 20. Power Requirement vs. Fuel Type Phase Two

c. *Flight Hours per Day Analysis*

The partition analyses of flight hours per day vs. the number of MQ-8C has an R-squared value of 0.675 (denoted as 1 in Figure 21). By increasing the number of MQ-8C, the average number of flight hours per day increased substantially (as denoted as 2, 3, and 4 in Figure 21). The largest increase in flight hours occurred when going from two to three MQ-8Cs (additional 14.7 flight hours per day) and a slight increase when going from three to four MQ-8Cs (additional 5.3 flight hours per day).

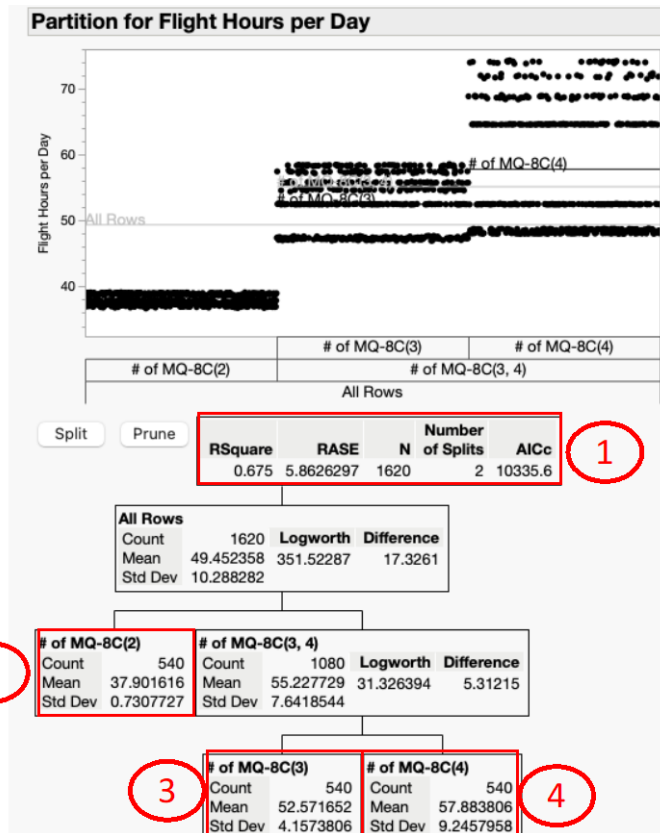


Figure 21. Flight Hours per Day vs. Number of MQ-8C Phase Two

The partition analysis of flight hours per day vs. the number of missions has an R-squared value of 0.115 (denoted as 1 in Figure 22). By increasing the number of missions there was a slight increase in the average number of flight hours per day (denoted as 2, 3, and 4 in Figure 22) with the largest change in flight hours when comparing two missions against three missions and only a slight increase in flight hours when comparing three and four missions. The low R-Square value means that the number of missions per day is only loosely correlated with this metric.

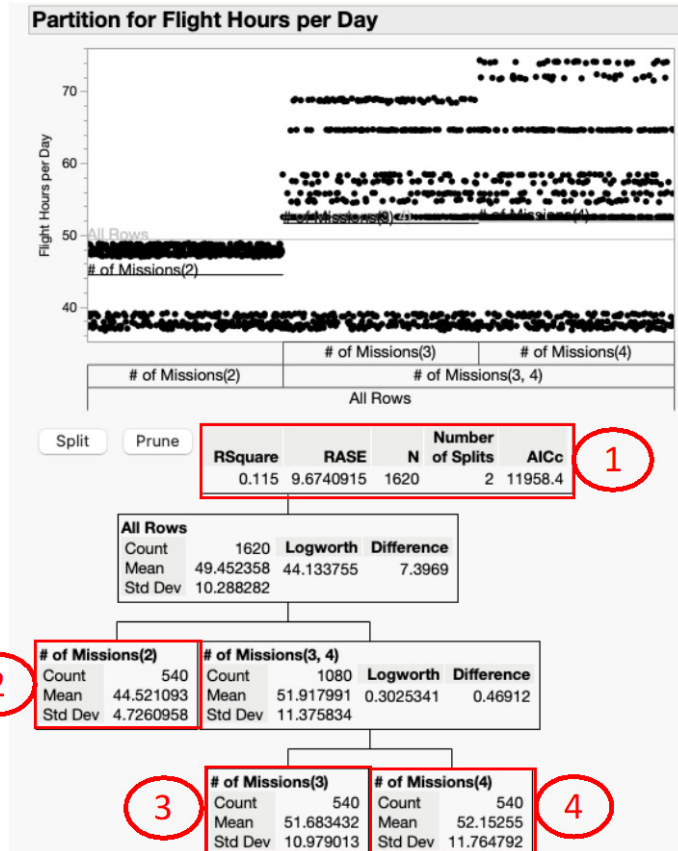


Figure 22. Flight Hours per Day vs. Number of Missions Phase Two

d. Phase Two Analysis Summary

The number of missions had the largest influence on Ao with a reduction in Ao as the number of missions increased. This is an expected result because of the increased number of flight hours associated with additional missions, there is more time associated with refueling and repair.

Fuel type was the driving factor for the power requirement for phase two. For phase two, the focus was a comparison of the two best performing fuel types from phase 1, fuel type 4 and fuel type 5. For the power requirement fuel type 4 performed the poorest with fuel type 5 performing the best. Fuel type 4 required almost three times more power than fuel type 5 to maintain the same capability.

The number of landing pads had no impact on any of the output metrics but the number of MQ-8Cs had the largest influence on flight hours per day. The largest increase

in flight hours occurred when going from two to three MQ-8Cs (additional 14.7 flight hours per day) and only a slight increase when going from three to four MQ-8Cs (additional 5.3 flight hours per day).

V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

This project built and evaluated different fuel and technology alternatives using a discrete-event simulation tailored to assess the capabilities and CONOPS that mobile fuel generation can enable in the 2045 timeframe. The project identified limits to operation and technology that impact the viability of fuel generation, fuel storage, and ship integration. Simulation analysis was conducted in two phases to identify the technologies most promising to support ISR operations in the 2045 timeframe. The following subsections summarize the recommendations developed from each analysis phase and identify opportunities for future research.

1. Phase One

The first phase of analysis considered five alternative fuel types. Each fuel type is assessed in terms of its impact on operational availability, power requirement, and the number of flight hours completed each day. The first phase also examined the sensitivity of fuel type recommendations to operational considerations such as hot refueling and flight duration.

Fuel type was the driving factor for all the measures for both vignettes one and two. Synthetic jet fuel had the largest power requirement and did not provide any significant operational advantages over the other fuels in terms of power requirements and average flight length. LH2 had the lowest Ao and flight hours with no substantial advantage for the power requirement. LH2 with fuel cell however, maintained the lowest power requirement with no substantial disadvantage and is the fuel technology that the team recommends for future research and development.

2. Phase Two

The second phase of this analysis compared the two primary performing fuel alternatives from phase one: LH2 fuel cell and the Navy's current standard fuel for the MQ-8C, JP-5. Each fuel type was assessed in terms of impact on operational availability,

power requirements, and number of flight hours completed per day. This phase also considered additional operational factors that may impact mission performance by varying the number of missions requested, landing pads available, and the number of MQ-8Cs available to fly.

Fuel type was the driving factor for the power requirement with LH2 with fuel cell having the lowest requirement. The simulation indicated that liquid methane would require almost three times more power to maintain the same capability. The model also indicated that by adding additional MQ-8Cs there would be a significant increase in the number of flight hours available per day.

In conclusion it is this team's assessment that LH2 when combined with a fuel cell provides fleet commanders with the most operationally balanced fuel alternative. The LH2 fuel cell alternative performed well operationally when compared with other alternatives, while reducing the overall power requirements for the system. This fuel source accomplishes the fleet commander's MQ-8C operational requirements under moderate fuel consumption parameters while reducing overall carbon emissions.

B. FUTURE RESEARCH

The following section outlines recommendations for future research. The following recommendations will lead to a greater understanding of Navy operations and have the potential to reduce or provide a greater understanding of carbon emissions relating to Navy operations.

1. MQ-8C LH2 Fuel Cell

Liquid hydrogen fuel cell development is an area of ongoing research and interest in the pursuit of clean, sustainable energy solutions. This technology presents a promising future for electricity, heat, and power production with water as the only environmentally friendly byproduct. These fuel cells combine hydrogen, stored in a liquid state at sub-zero temperatures, with oxygen from the air to produce electricity and water vapor. They have the potential to power a variety of vehicles, engines, and electronic devices.

In the case of the MQ-8C Fire Scout, a liquid hydrogen fuel cell would power the electrical motor, applying power to the rotors, producing extended lift, flight, and additional time on station for missions. The operational applications of LH2 fuel cells in the MQ-8C and other UAS platforms in the DOD offers more benefits to operational availability for unmanned systems conducting ISR operations when compared to other alternative fuel types that increase the on-station time, operational availability, and number of ISR missions available to the USN and USMC during maritime operations. Furthermore, the LH2 fuel cell water byproduct will directly impact the joint force's goals of reducing carbon emissions.

Further research is needed to determine the viability of implementing LH2 fuel cells across multiple UAS platforms and potentially manned aircraft.

2. LH2 Shipboard Operations and Handling

When it comes to operating and handling LH2 fuel cells for fuel generation on board naval warships, there are several technology gaps that need to be considered. In the year 2045, LH2 fuel cells are expected to have undergone significant advancements and may have several future considerations. While the team cannot predict the exact future scenario, based on current trends and potential developments, LH2 fuel cells are likely to achieve higher levels of efficiency, allowing for more efficient conversion of hydrogen into electricity. Thus, a technology gap need would be to develop a robust liquid hydrogen storage system installed on an LCS capable of storing fuel generation at extremely low temperatures.

It is important to note that specific considerations may vary depending on the type of ship and its operational requirements. Collaboration with industry, research institutions, and relevant government agencies is essential for successfully integrating LH2 fuel cell technology onto U.S. Navy ships. The process may also require compliance with naval regulations, safety standards, and environmental requirements.

Future efforts should be dedicated to conducting further research on the use of salt water as a source to generate liquid hydrogen. The use of salt water in liquid hydrogen production is an area of ongoing research and development. Also, salt in seawater can cause

issues such as corrosion of electrodes and decreased efficiency of the electrolysis process (Hebden, 2023). Thus, in-depth research is required to develop a technology that minimizes corrosion to the mobile fuel generation system.

Future research could also leverage current research and explore techniques such as using corrosion-resistant materials and optimizing electrolysis conditions to improve efficiency and durability and investigating methods to separate and capture toxic materials for potential reuse or safe disposal (Hebden, 2023).

3. Synthetic Jet Fuel Efficiency Improvements

Improving the process used to produce synthetic jet fuel would make it a far more competitive option. With the current low efficiency of the process, there is significant room to improve. Further research in the process could improve the efficiency of the process. One area of research could include the development of a more efficient catalyst for use in the Fischer-Tropsch conversion process. Other potential research could include lowering the energy required for the process to proceed or recapturing some of the energy used in the process to be reused.

4. Modeling with MTBF Data

Modeling of the Fire Scout with more information about the maintenance needs of the system would be useful. With accurate information regarding the mean time between failure and mean time to repair for both the conventional engine as well as the alternative fueled engines, more accurate simulations could be run. This would give a more accurate picture of the advantages and disadvantages of using each fuel system.

It may also be advantageous to model the Fire Scout system in greater detail to improve the data on fuel usage for given fuels. Specifically looking at the weight of each fuel system and how said weight affects the performance of the Fire Scout system in flight may affect the results.

C. CONCLUSIONS

This project investigated the need and requirement for reducing carbon emissions and fuel supply chain security by researching Navy, DOD, and federal government policies, and regulations. This resulted in the perceived need to reduce carbon emissions and the need for fuel supply chain security. The team identified five potential fuels that could be produced by an MFGS and used to maintain an ISR capability. The ISR capability the team chose to focus on was the MQ-8C Fire Scout. The team developed two vignettes. Vignette one was focused on 24/7 ISR coverage in a fixed area such as an inland bay area. Vignette two was focused on maximum ISR in the open ocean. The simulation developed focused on MQ-8C characteristics and the fuel type alternatives. LH2 with fuel cell was identified as the option requiring the lowest input power to the MFGS. It is important to note that even with the LH2 fuel cell alternative for vignette two the power requirement is just over one megawatt. To provide context, using the average power requirement for homes at Altamont Pass in Alameda County, CA, this would be enough to power 817 homes (East Bay Community Energy 2021). From phase two analysis, the simulation indicated there would be an advantage to increasing the number of MQ-8Cs supported by a single support ship. The recommendation from the team is for the U.S. Navy to do a full analysis of the use of fuel cells using liquid hydrogen, with a focus on future technology development.

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APPENDIX A. EXTENDSIM

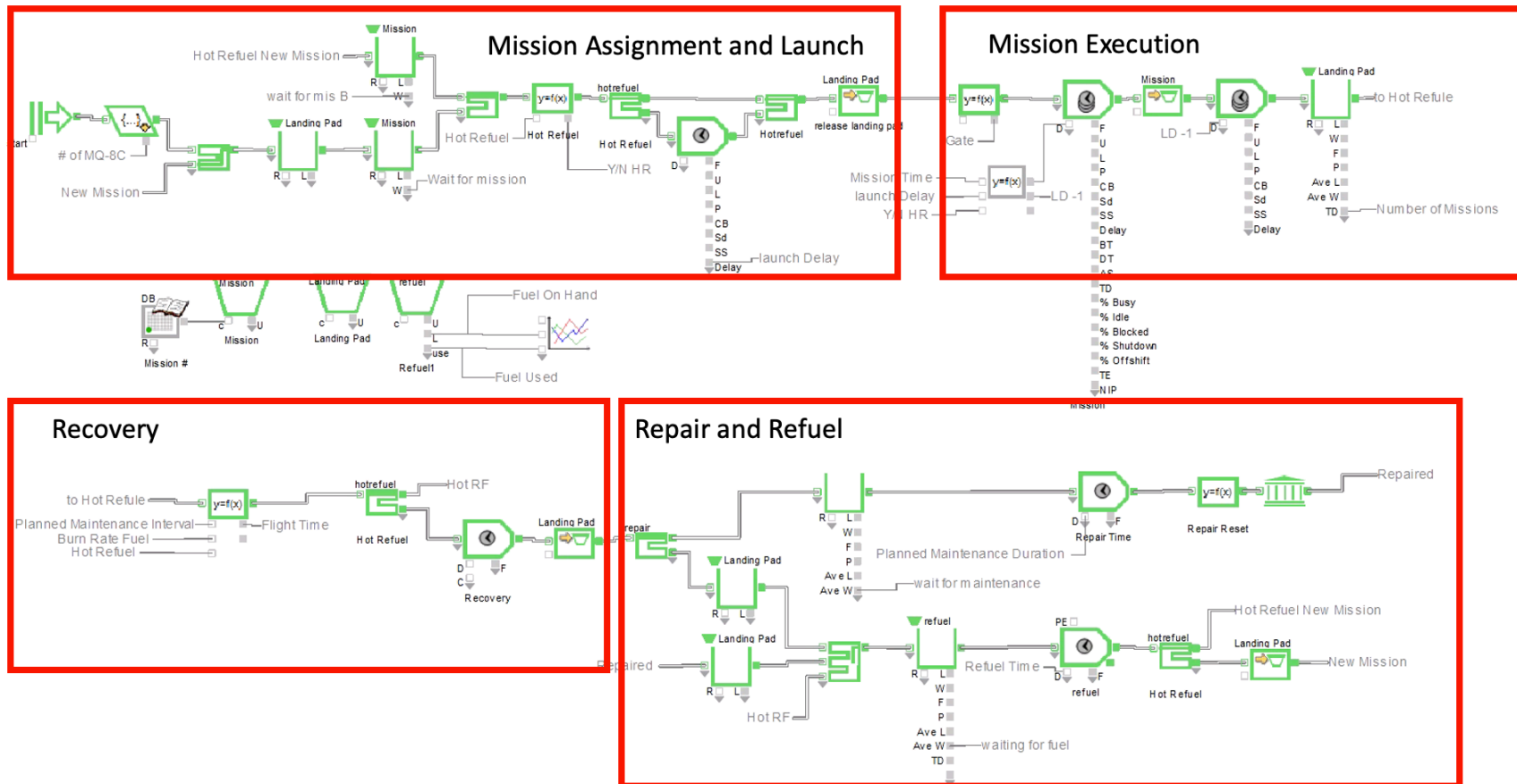


Figure 23. ExtendSim Outline

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APPENDIX B: DOE

Table 11. DOE Phase One

Run	Fuel Type	Hot Refuel	Flight Duration	# of Missions
1	1	0	0	1
2	2	0	0	1
3	3	0	0	1
4	4	0	0	1
5	5	0	0	1
6	1	1	0	1
7	2	1	0	1
8	3	1	0	1
9	4	1	0	1
10	5	1	0	1
11	1	0	1	1
12	2	0	1	1
13	3	0	1	1
14	4	0	1	1
15	5	0	1	1
16	1	1	1	1
17	2	1	1	1
18	3	1	1	1
19	4	1	1	1
20	5	1	1	1
21	1	0	2	1
22	2	0	2	1
23	3	0	2	1
24	4	0	2	1
25	5	0	2	1
26	1	1	2	1
27	2	1	2	1
28	3	1	2	1
29	4	1	2	1
30	5	1	2	1
31	1	0	0	2
32	2	0	0	2

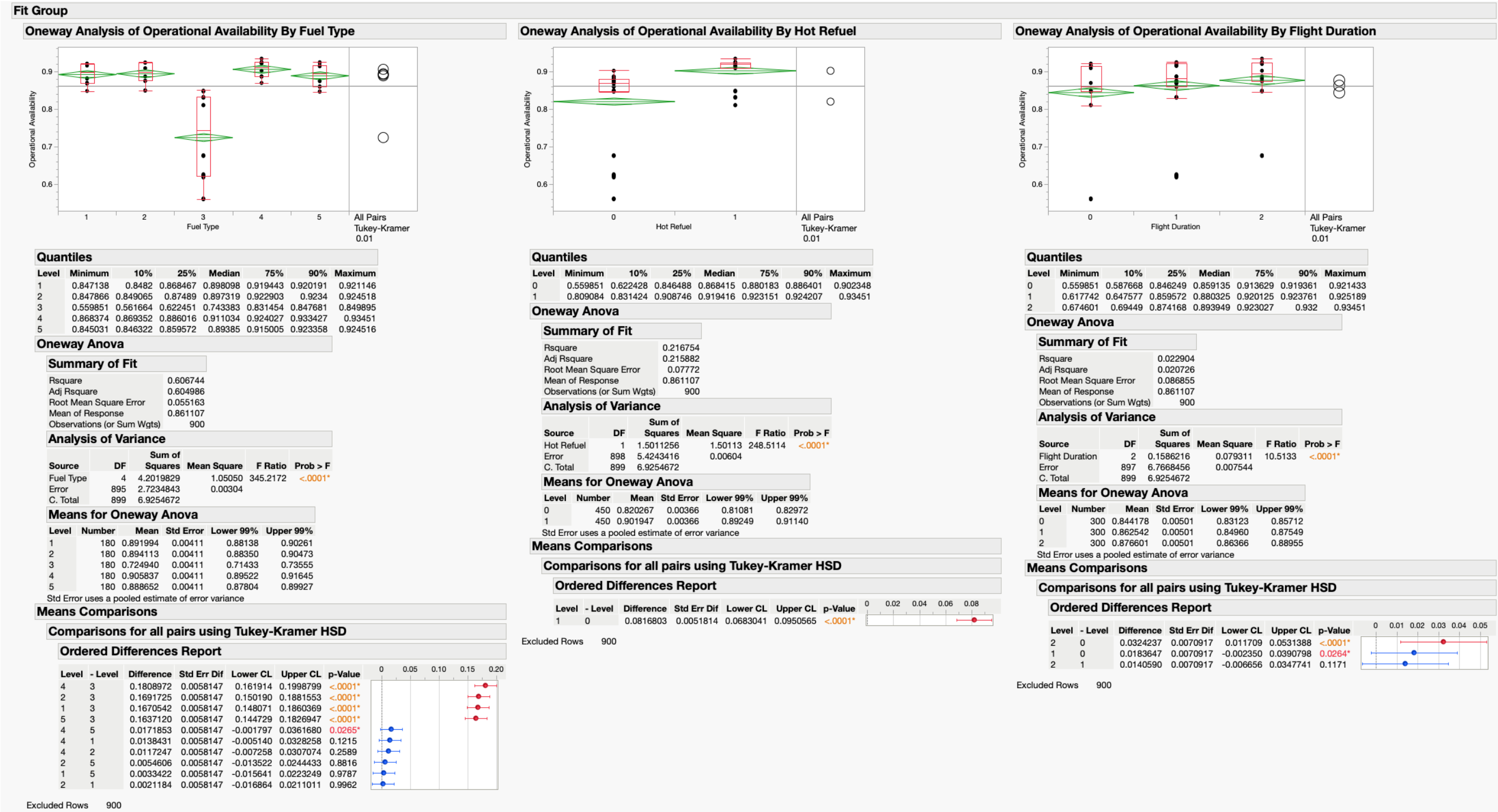
Run	Fuel Type	Hot Refuel	Flight Duration	# of Missions
33	3	0	0	2
34	4	0	0	2
35	5	0	0	2
36	1	1	0	2
37	2	1	0	2
38	3	1	0	2
39	4	1	0	2
40	5	1	0	2
41	1	0	1	2
42	2	0	1	2
43	3	0	1	2
44	4	0	1	2
45	5	0	1	2
46	1	1	1	2
47	2	1	1	2
48	3	1	1	2
49	4	1	1	2
50	5	1	1	2
51	1	0	2	2
52	2	0	2	2
53	3	0	2	2
54	4	0	2	2
55	5	0	2	2
56	1	1	2	2
57	2	1	2	2
58	3	1	2	2
59	4	1	2	2
60	5	1	2	2

Table 12. DOE Phase Two

Run	Fuel Type	# of Missions	# of MQ-8C	Hot Refueling
1	1	2	2	0
2	4	2	2	0
3	5	2	2	0
4	1	3	2	0
5	4	3	2	0
6	5	3	2	0
7	1	4	2	0
8	4	4	2	0
9	5	4	2	0
10	1	2	3	0
11	4	2	3	0
12	5	2	3	0
13	1	3	3	0
14	4	3	3	0
15	5	3	3	0
16	1	4	3	0
17	4	4	3	0
18	5	4	3	0
19	1	2	4	0
20	4	2	4	0
21	5	2	4	0
22	1	3	4	0
23	4	3	4	0
24	5	3	4	0
25	1	4	4	0
26	4	4	4	0
27	5	4	4	0
28	1	2	2	1
29	4	2	2	1
30	5	2	2	1
31	1	3	2	1
32	4	3	2	1
33	5	3	2	1
34	1	4	2	1
35	4	4	2	1

Run	Fuel Type	# of Missions	# of MQ-8C	Hot Refueling
36	5	4	2	1
37	1	2	3	1
38	4	2	3	1
39	5	2	3	1
40	1	3	3	1
41	4	3	3	1
42	5	3	3	1
43	1	4	3	1
44	4	4	3	1
45	5	4	3	1
46	1	2	4	1
47	4	2	4	1
48	5	2	4	1
49	1	3	4	1
50	4	3	4	1
51	5	3	4	1
52	1	4	4	1
53	4	4	4	1
54	5	4	4	1

APPENDIX C: EXTENDSIM ANOVA AND TUKEY HSD TEST ANALYSIS



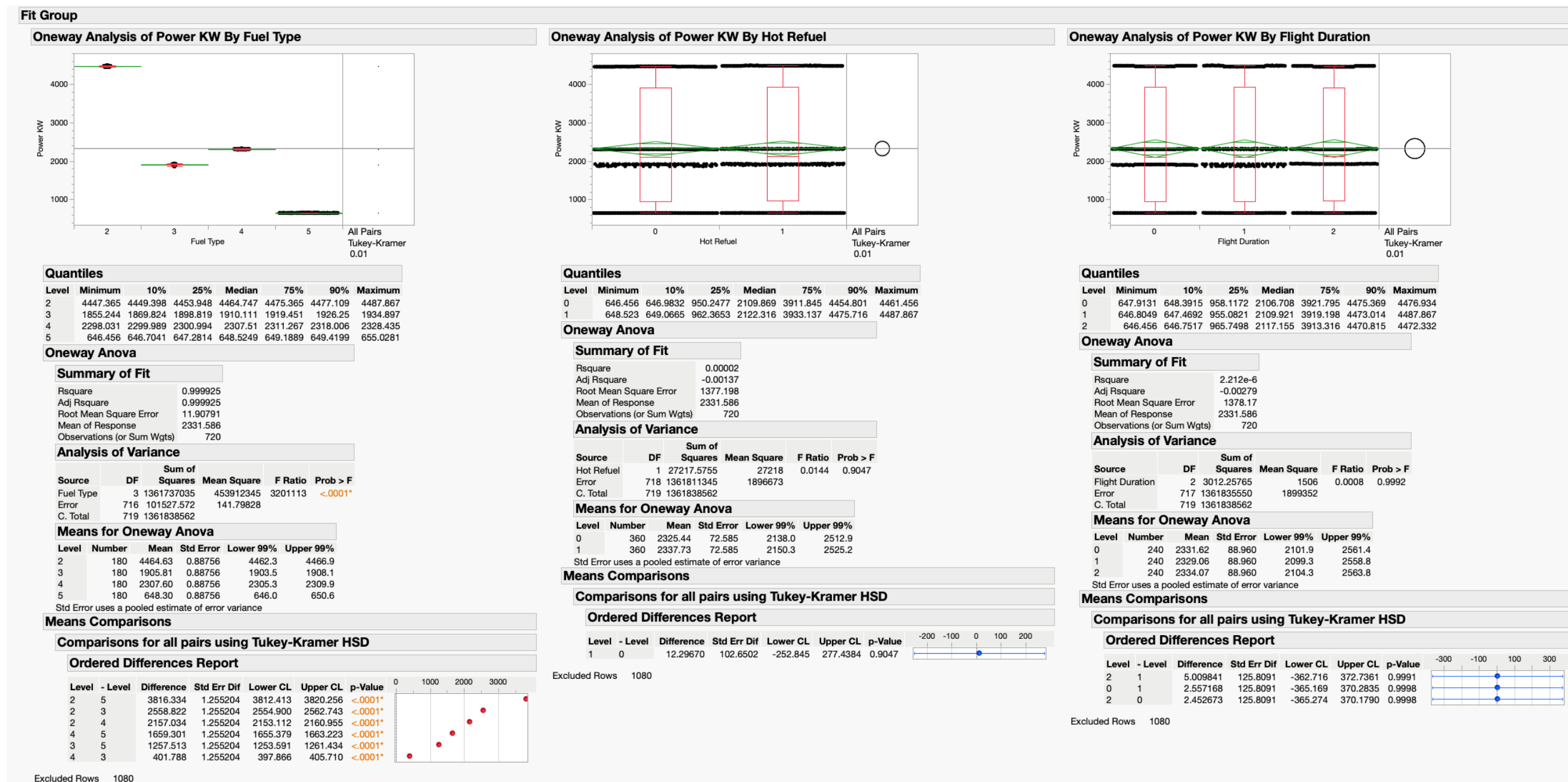
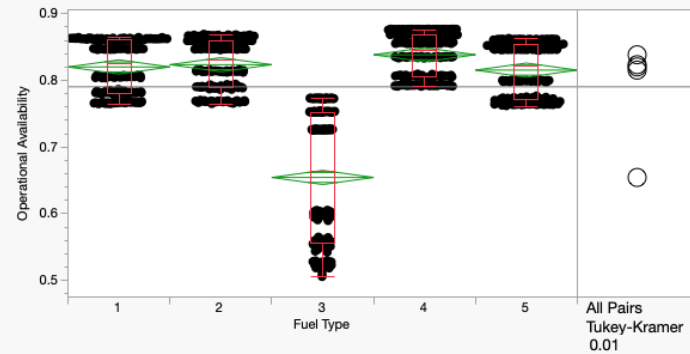




Figure 26. ANOVA and Tukey Test for Flight Hour Per Day Vignette One

Fit Group

Oneway Analysis of Operational Availability By Fuel Type



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
1	0.764029	0.76604	0.780797	0.826	0.860337	0.862096	0.863785
2	0.764208	0.767961	0.788846	0.830106	0.8588	0.865906	0.868494
3	0.504702	0.524941	0.556033	0.664271	0.752139	0.772051	0.772839
4	0.790196	0.79182	0.805795	0.844789	0.868135	0.875883	0.876227
5	0.761065	0.763669	0.770958	0.822054	0.853365	0.860736	0.862231

Oneway Anova

Summary of Fit

Rsquare	0.607393
Adj Rsquare	0.605638
Root Mean Square Error	0.055185
Mean of Response	0.790399
Observations (or Sum Wgts)	900

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Fuel Type	4	4.2167571	1.05419	346.1585	<.0001*
Error	895	2.7256280	0.00305		
C. Total	899	6.9423852			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 99%	Upper 99%
1	180	0.820176	0.00411	0.80956	0.83079
2	180	0.823572	0.00411	0.81295	0.83419
3	180	0.654371	0.00411	0.64375	0.66499
4	180	0.838460	0.00411	0.82784	0.84908
5	180	0.815416	0.00411	0.80480	0.82603

Std Error uses a pooled estimate of error variance

Means Comparisons

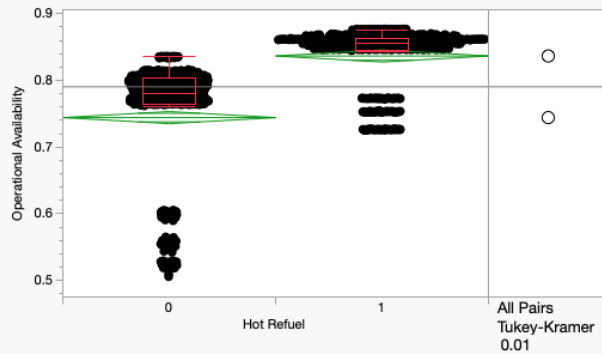
Comparisons for all pairs using Tukey-Kramer HSD

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
4	3	0.1840888	0.0058170	0.165099	0.2030790	<.0001*
2	3	0.1692012	0.0058170	0.150211	0.1881914	<.0001*
1	3	0.1658053	0.0058170	0.146815	0.1847955	<.0001*
5	3	0.1610444	0.0058170	0.142054	0.1800346	<.0001*
4	5	0.0230444	0.0058170	0.004054	0.0420346	0.0008*
4	1	0.0182835	0.0058170	-0.000707	0.0372737	0.0149*
4	2	0.0148876	0.0058170	-0.004103	0.0338778	0.0790
2	5	0.0081568	0.0058170	-0.010833	0.0271470	0.6264
1	5	0.0047609	0.0058170	-0.014229	0.0237511	0.9250
2	1	0.0033959	0.0058170	-0.015594	0.0223861	0.9775

Excluded Rows 900

Oneway Analysis of Operational Availability By Hot Refuel



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	0.504702	0.555902	0.763854	0.7808	0.8037	0.812836	0.835213
1	0.724153	0.752061	0.845487	0.855883	0.861955	0.868142	0.876227

Oneway Anova

Summary of Fit

Rsquare	0.276911
Adj Rsquare	0.276106
Root Mean Square Error	0.074767
Mean of Response	0.790399
Observations (or Sum Wgts)	900

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Hot Refuel	1	1.9224238	1.92242	343.8944	<.0001*
Error	898	5.0199614	0.00559		
C. Total	899	6.9423852			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 99%	Upper 99%
0	450	0.744182	0.00352	0.73508	0.75328
1	450	0.836616	0.00352	0.82752	0.84571

Std Error uses a pooled estimate of error variance

Means Comparisons

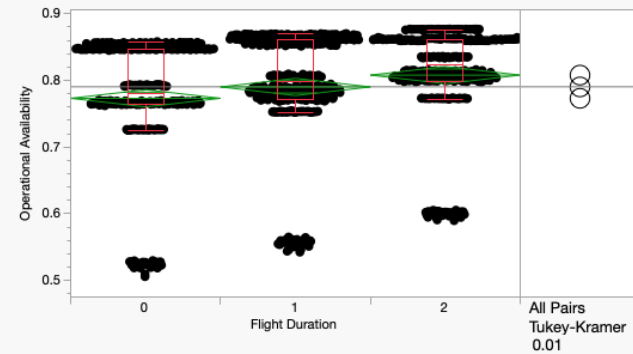
Comparisons for all pairs using Tukey-Kramer HSD

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
1	0	0.0924343	0.0049845	0.0795664	0.1053023	<.0001*

Excluded Rows 900

Oneway Analysis of Operational Availability By Flight Duration



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	0.504702	0.548321	0.763354	0.779848	0.84645	0.854095	0.857321
1	0.541394	0.582798	0.770958	0.798277	0.860337	0.867353	0.869382
2	0.588655	0.621025	0.79837	0.823873	0.860758	0.872845	0.876227

Oneway Anova

Summary of Fit

Rsquare	0.026176
Adj Rsquare	0.024005
Root Mean Square Error	0.086816
Mean of Response	0.790399
Observations (or Sum Wgts)	900

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Flight Duration	2	0.1817263	0.090863	12.0557	<.0001*
Error	897	6.7606589	0.007537		
C. Total	899	6.9423852			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 99%	Upper 99%
0	300	0.773108	0.00501	0.76017	0.78605
1	300	0.790176	0.00501	0.77724	0.80311
2	300	0.807913	0.00501	0.79497	0.82085

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
2	0	0.0348046	0.0070885	0.014099	0.0555102	<.0001*
2	1	0.0177364	0.0070885	-0.002969	0.0384421	0.0335*
1	0	0.0170682	0.0070885	-0.003637	0.0377738	0.0429*

Excluded Rows 900

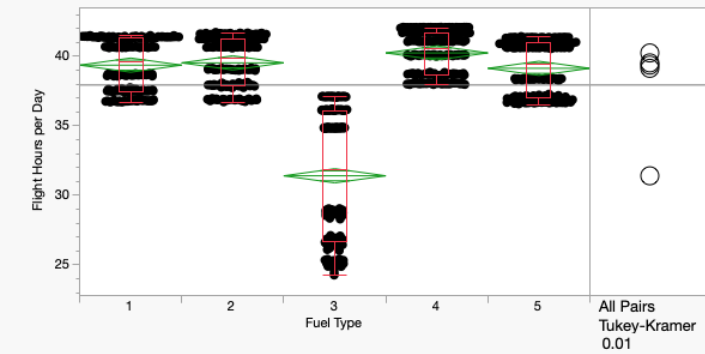
Figure 27. ANOVA and Tukey Test for Ao Vignette Two



Figure 28. ANOVA and Tukey Test for Power Requirement Vignette Two

Fit Group

Oneway Analysis of Flight Hours per Day By Fuel Type



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
1	36.67338	36.76991	37.47825	39.64802	41.29619	41.38061	41.46167
2	36.68197	36.86211	37.86463	39.8451	41.2224	41.5635	41.6877
3	24.22572	25.19716	26.68957	31.88501	36.10269	37.05847	37.09627
4	37.92939	38.00738	38.67814	40.54988	41.67049	42.04241	42.05892
5	36.53111	36.65611	37.00596	39.45859	40.96154	41.31531	41.38707

Oneway Anova

Summary of Fit

Rsquare	0.607393
Adj Rsquare	0.605638
Root Mean Square Error	2.648884
Mean of Response	37.93916
Observations (or Sum Wgts)	900

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Fuel Type	4	9715.408	2428.85	346.1585	<.0001*
Error	895	6279.847	7.02		
C. Total	899	15995.255			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 99%	Upper 99%
1	180	39.3685	0.19744	38.859	39.878
2	180	39.5315	0.19744	39.022	40.041
3	180	31.4098	0.19744	30.900	31.919
4	180	40.2461	0.19744	39.736	40.756
5	180	39.1399	0.19744	38.630	39.650

Std Error uses a pooled estimate of error variance

Means Comparisons

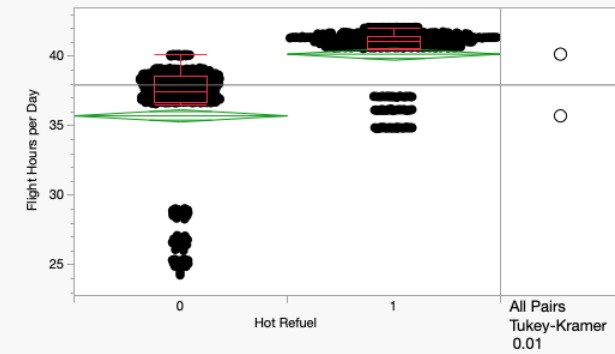
Comparisons for all pairs using Tukey-Kramer HSD

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
4	3	8.836263	0.2792169	7.92473	9.747793	<.0001*
2	3	8.121657	0.2792169	7.21013	9.033187	<.0001*
1	3	7.958655	0.2792169	7.04713	8.870184	<.0001*
5	3	7.730132	0.2792169	6.81860	8.641661	<.0001*
4	5	1.106131	0.2792169	0.19460	2.017661	0.0008*
4	1	0.877608	0.2792169	-0.03392	1.789138	0.0149*
4	2	0.714606	0.2792169	-0.19692	1.626135	0.0790
2	5	0.391525	0.2792169	-0.52000	1.303055	0.6264
1	5	0.228523	0.2792169	-0.68301	1.140052	0.9250
2	1	0.163003	0.2792169	-0.74853	1.074532	0.9775

Excluded Rows 900

Oneway Analysis of Flight Hours per Day By Hot Refuel



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	24.22572	26.68328	36.66499	37.47841	38.57761	39.01611	40.09021
1	34.75933	36.09892	40.58338	41.08238	41.37383	41.67083	42.05892

Oneway Anova

Summary of Fit

Rsquare	0.276911
Adj Rsquare	0.276106
Root Mean Square Error	3.588833
Mean of Response	37.93916
Observations (or Sum Wgts)	900

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Hot Refuel	1	4429.264	4429.26	343.8944	<.0001*
Error	898	11565.991	12.88		
C. Total	899	15995.255			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 99%	Upper 99%
0	450	35.7207	0.16918	35.284	36.157
1	450	40.1576	0.16918	39.721	40.594

Std Error uses a pooled estimate of error variance

Means Comparisons

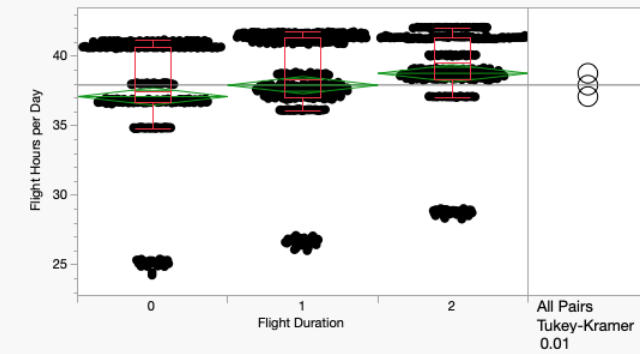
Comparisons for all pairs using Tukey-Kramer HSD

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
1	0	4.436848	0.2392555	3.819185	5.054510	<.0001*

Excluded Rows 900

Oneway Analysis of Flight Hours per Day By Flight Duration



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	24.22572	26.31939	36.64098	37.43273	40.62961	40.99657	41.15139
1	25.9869	27.97431	37.00596	38.31729	41.29619	41.63292	41.73032
2	28.25545	29.80922	38.32178	39.54591	41.31638	41.89655	42.05892

Oneway Anova

Summary of Fit

Rsquare	0.026176
Adj Rsquare	0.024005
Root Mean Square Error	4.167154
Mean of Response	37.93916
Observations (or Sum Wgts)	900

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Flight Duration	2	418.697	209.349	12.0557	<.0001*
Error	897	15576.558	17.365		
C. Total	899	15995.255			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 99%	Upper 99%
0	300	37.1092	0.24059	36.488	37.730
1	300	37.9285	0.24059	37.307	38.550
2	300	38.7798	0.24059	38.159	39.401

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
2	0	1.670621	0.3402467	0.676750	2.664491	<.0001*
2	1	0.851348	0.3402467	-0.142523	1.845219	0.0335*
1	0	0.819273	0.3402467	-0.174598	1.813144	0.0429*

Excluded Rows 900

Figure 29. ANOVA and Tukey Test for Flight Hours per Day Vignette Two

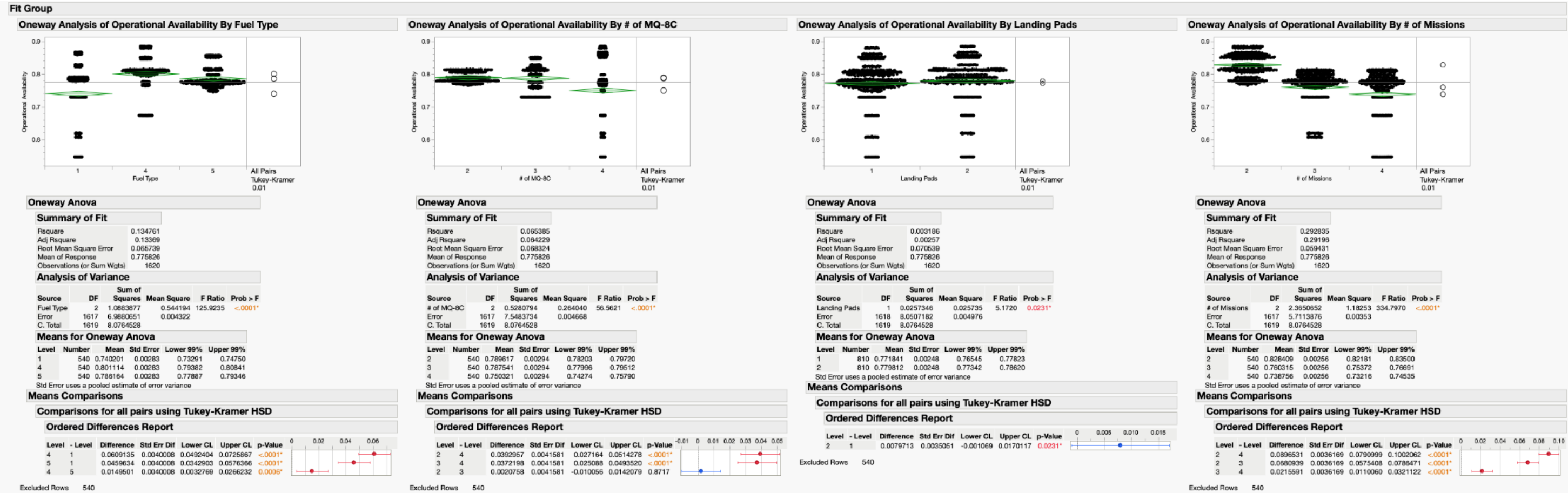


Figure 30. ANOVA and Tukey Test for Operational Availability Phase Two

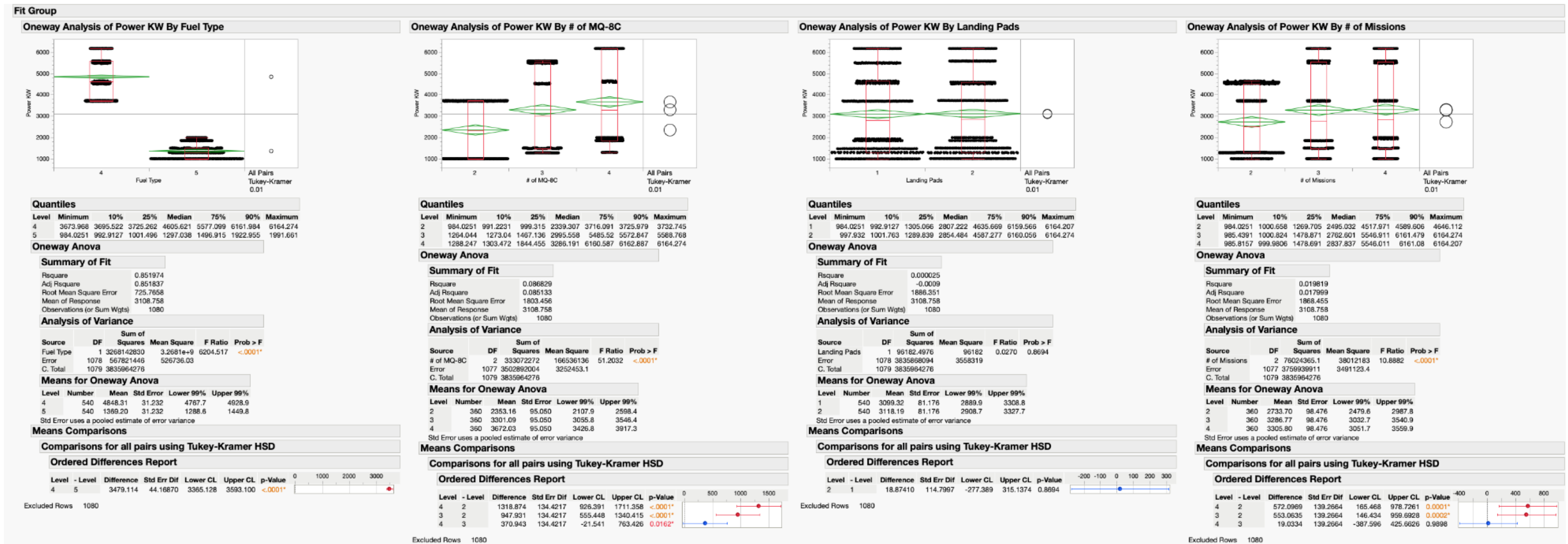




Figure 32. ANOVA and Tukey Test for Flight Hours per Day Phase Two

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