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THESIS

**OPERATIONAL CONCEPT FOR HYDROGEN
FUEL-BASED FULLY UNMANNED CARRIER
AVIATION**

by

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March 2022

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**OPERATIONAL CONCEPT FOR HYDROGEN FUEL-BASED FULLY
UNMANNED CARRIER AVIATION**

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Submitted in partial fulfillment of the
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ABSTRACT

Efforts to reduce dependence on existing fossil fuels and decouple from logistics trains are becoming critical for the U.S. military. Hydrogen, a potential alternative fuel, offers three interesting characteristics: it is the most energy-dense source short of a nuclear reaction; it can be used in ways that do not generate heat or harmful chemical substances; and it can be made from seawater. This study defines an operational concept for an unmanned carrier with unmanned aerial vehicles (UAVs) fueled by hydrogen and models this system to ascertain operational implications for a future fleet executing Distributed Maritime Operations as a hybrid force. An ExtendSim model is developed and used to analyze the operational concept with the proposed carrier's physical and functional attributes while assuming existing UAV technology. Operational availability is used as the fundamental comparison. The resulting analyses highlight three major findings. UAV maximum endurance is the most important factor in increasing operational availability. The second most important but closely related factor is fuel type, with liquid hydrogen fuel showing a 7% increase in operational availability over JP-5 for the explored scenarios. The third most important factor is the number of UAV maintenance bays. These three factors account for more than 80% of the statistical variability in the model and are important design points for operationalizing hydrogen as a future carrier aviation fuel.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	Anti-Access/Area Denial
AFP	Adaptive Force Package
Ao	Operational Availability
ATJ	Alcohol-To-Jet
CL-UAV	Carrier-Launched Unmanned Aerial Vehicle
CSBA	Center for Strategic and Budgetary Assessment
CVL	Aircraft Carrier Light
CVQ	All-UAV Aircraft Carriers
DMO	Distributed Maritime Operation
DOD	Department of Defense
DOE	Design of Experiment
DON	Department of Navy
ESB	Expeditionary Sea Base
ISR	Intelligence, Surveillance, and Reconnaissance
MDT	Mean Maintenance Down Time
MOE	Measures of Effectiveness
MOP	Measures of Performance
MTBM	Mean Time Between Maintenance
NPS	Naval Postgraduate School
RDT&E	Research, Development, Test, and Evaluation
SOI	System-Of-Interest
SUW	Surface Warfare
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Air Vehicle
USS	Unmanned Surface Systems
UUS	Unmanned Underwater Systems
UVC	Unmanned Vehicle Carrier
UXV	Unmanned Vehicles (ground, air, surface, or undersea)

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EXECUTIVE SUMMARY

Efforts to reduce dependence on existing fossil fuels as well as to decouple from logistics trains will become more important as the U.S. Navy seeks to implement future operating concepts. Against this backdrop, hydrogen is a potential alternative fuel that has three interesting characteristics: it is the most energy-dense source of energy short of a nuclear reaction; it can be used in ways that do not generate heat or harmful chemical byproducts; and it can be made from seawater. One major disadvantage associated with hydrogen, however, is the lack of infrastructure to facilitate its implementation. Despite this drawback, the implementation of hydrogen as an alternative fuel might be possible for naval applications not only because the U.S. Navy develops its own ships but also because the existing technology for naval platforms could harvest hydrogen from seawater, bringing with it the secondary advantage of reduced operational logistics requirements.

A. LITERATURE REVIEW

As evident in its energy strategy published in 2015, the U.S. Department of Defense (DOD) recognizes energy as a key role in the military mission (Office of the Assistant Secretary of Defense for Energy, Installation and Environment 2015). This recognition is reflected in several efforts. The Office of the Assistant Secretary of Defense for Energy, for example, has set goals to improve the training and education of DOD members and to enhance policy support. Also, the U.S. Department of the Navy's Installation Energy Resilience Strategy has established criteria for energy operation on three major axes: Resilience, Reliability, and Efficiency. The research and development (R&D) budget of DOD provides another insight into the Department's commitment to pursuing alternative sources of energy. DOD's overall project scale increased from \$2.975M in 2019 to \$3.871M in 2020 (Office of the Under Secretary of Defense for Acquisition and Sustainment 2021). Specifically, the project size for alternative energy increased by 273%, from \$2.83M in 2019 to \$7.72M in 2020 (Office of the Under Secretary of Defense for Acquisition and Sustainment 2021). These energy-related policies show DOD's effort to

seek new energy sources different from existing fuels and to make more efficient utilization of existing energy to address energy-related challenges.

A specific area of emphasis within this increased investment in alternative energy is human-machine interaction. Due to the rise in power of competitors and the spread of anti-access/area denial (A2/AD) capabilities, U.S. naval forces may need to make changes in carrier operation. To this end, extending the role of unmanned aerial vehicles (UAVs) as Unmanned Combat Air Vehicles (UCAVs) is being considered. This idea is reflected in the Navy's RDT&E plan and its conceptual visions. Nevertheless, there is cultural resistance to including UAVs in existing carrier operations and insistence on limiting UAVs to ISR (intelligence, surveillance and reconnaissance) missions with a relatively high risk of loss of life. While the United States is slowing down the introduction of an unmanned carrier, other countries are leading in this area. Turkey's *Anadolu*, for example, which operates TB-2/3 UAVs, will join the fleet in 2022.

The literature points out that the pursuit of alternate energy platforms is not new. In fact, the U.S. Navy has studied hydrogen as an alternative fuel since 1974. Hydrogen's low fuel density and economic feasibility were pointed out as disadvantages at that time. However, current technologies and circumstances mitigate those disadvantages. In addition, hydrogen-related supply and production facilities in the United States are expected to grow and have substantially more capability in the near future. Hydrogen-related military research is also in progress, and in particular, research on the application of hydrogen fuel to UAVs is being actively conducted around the world.

B. DESIGN OF MODEL

To explore the feasibility of hydrogen-fueled military applications, this thesis designed a model to analyze alternative concepts of operation (CONOPS) for a UVC. Functional and physical models were built in Cameo Enterprise Architect to describe UVC behavior and structure. Based on those Cameo Enterprise Architect models, an ExtendSim Model was used to analyze the operational concept in terms of physical and functional attributes of the proposed carrier, assuming existing UAV technology. The MQ-8 Fire Scout and RQ-21 BlackJack were chosen for the model. To examine the impact of

alternative fuels, five variants of each existing UAV were modeled: the traditional JP-5, gaseous and liquid hydrogen fuel of the same volume as the conventional fuel tank, and gaseous and liquid hydrogen fuel of the same weight as the traditional fuel tank. The activities of the simulation model included Launch, Mission, Recovery, Refuel, Maintenance, and Weapon Resupply. To measure the efficiency of UAVs using hydrogen, this thesis used Operational Availability as the primary Measures of Effectiveness (MOE).

C. ANALYSIS OF MODEL

A Latin Hypercube design was generated that examined not only the design of the UVC, but also operational and environmental considerations. Simulations for 90 trials with different UVC design points were conducted for five different fuel types, and simulations were repeated 30 times to account for the stochastic nature of the simulation model and to aggregate the statistical mean of operational availability.

The resulting analyses highlighted three major findings. The most important factor related to operational availability was UAV maximum endurance. The second most important, but closely related, factor was fuel type, with liquid hydrogen fuel showing a 7% increase in operational availability over JP-5 for the scenarios explored. The third most important factor was the number of UAV maintenance bays on the UVC. Taken in aggregate, these three factors accounted for more than 80% of the statistical variability in the model and are important design considerations for operationalizing hydrogen as a future carrier aviation fuel. This work applied practitioner standards and systems engineering techniques to inform the development of a desired capability. Related to this research, future work by a capstone team at the Naval Postgraduate School will include the architectural and engineering design of an unmanned UAV carrier using hydrogen as aviation fuel.

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Office of the Under Secretary of Defense for Acquisition and Sustainment. 2021. *Fiscal Year 2020 Operational Energy Annual Report*. Washington, DC: Department of Defense.
<https://www.acq.osd.mil/eie/Downloads/OE/FY20%20OE%20Annual%20Report.pdf>.

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I. INTRODUCTION

A. BACKGROUND

In the fiscal year 2020, the U.S. Department of Defense used about \$9.2 billion in fuel, of which 48% was imported from abroad (Office of the Under Secretary of Defense for Acquisition and Sustainment 2021). Accordingly, discussions on reducing energy consumption and using alternative energy in the military continue (Office of the Assistant Secretary of Defense for Energy; Installation and Environment 2015; Office of the Under Secretary of Defense for Acquisition and Sustainment 2021). Efforts to reduce dependence on existing fossil fuels and use alternative energy will continue to accelerate in the future.

There are many alternative energies, but among them, hydrogen is well known as a potential fuel and has been actively researched by the U.S. Navy. Due to the nature of the Navy operating in the sea, seawater is an easily accessible source of potential energy. U.S. Navy researchers have developed a method of separating hydrogen from carbon dioxide and converting it into liquid hydrogen fuel (Petro 2020).

There are two main advantages of hydrogen fuel over other energies. First, the energy density is high. Since hydrogen energy has fewer power generation stages than conventional power generation methods, the energy loss incurred in the process is significantly less. Hydrogen fuel has the highest energy density, exceeded only by nuclear fuel. Second, hydrogen fuel does not generate heat and chemical substances. It can be considered as an advantage not only in terms of the environment but also in terms of handling and storage costs related to the generation of toxic substances, and in terms of military aspects, it can be considered as an advantage in survivability (*LENR & Cold Fusion News* 2014; Jeong et al. 2015 3173–3180; *Nature Energy* 2016).

One area where hydrogen fuel may provide an operational benefit to the U.S. Navy is in the operation of unmanned systems. The U.S. Navy's future 2035 and 2045 battlefield description proposes an unmanned aerial vehicle (UAV) carrier which may be an alluring option for the use of hydrogen fuel (Shugart 2017; Department of the Navy 2017). Researchers continue to consider hydrogen as the main source of fuel for UAVs mounted

on a carrier (Ciaravino 2003). Additional research has been conducted at the Naval Postgraduate School (NPS) using only hydrogen energy on a destroyer as well as for aviation fuel (Total Ships Team 2018). In addition, condensate storage facilities were built in 2017 by an NPS student (Fosson 2017). Other research continues to use hydrogen fuel for UAVs and evaluate its effectiveness (Pollman, Hobson, and Clay 2021; HES Hycoper 2021).

Based on the previously mentioned background, the purpose of this study is to develop an operating concept of UAVs in carriers operated only by hydrogen fuel. In the 2016 Operational Energy Strategy of the U.S. Department of Defense (DOD), it is also stressed that “systems under development need to be evaluated for their effectiveness and supportability in the types of combat scenarios in which they are expected to be used” (Office of the Assistant Secretary of Defense for Energy 2015, 10). Therefore, based on the operational concept developed in this paper, the use of hydrogen as a fuel source for UAVs can be operationalized. In other words, the aim of this thesis is to develop an operational concept to determine whether hydrogen fuel can be used in the U.S. Navy to improve the operational effectiveness of unmanned systems.

B. BENEFIT OF STUDY

This thesis research is designed to support the Deputy Assistant Secretary of the Navy for Operational Energy. The approach supports a mission engineering approach to transitional operational energy. Through the design and development of a simulation model, this thesis contributes to the appropriate integration of new technologies. The operational concept developed and assessed in this study establishes initial requirements for an unmanned carrier for aviation and assesses the impact on effectiveness that results from the employment of hydrogen fueled UAVs.

C. SCOPE AND METHODOLOGY

This thesis uses the experimental approach, as described by Giachetti (2016). The primary research objective is to assess whether unmanned carrier aviation using hydrogen fuel can be more effective than aviation concepts that do not utilize hydrogen fuel.

To accomplish that research objective, this thesis is organized into five chapters. Chapter I has presented the background of the study. Chapter II reviews the existing research into hydrogen fuel, the U.S. Navy's future battlefield, and relevant energy policies. Chapter III presents a simulation model that is used to answer the primary research objectives and explains the design of the simulation model. The results of the simulation and associated analysis are discussed in Chapter IV. Finally, Chapter V summarizes the modeling and analysis efforts and presents a conclusion for operationalizing hydrogen as a fuel source as well as recommendations for future research tasks.

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II. LITERATURE REVIEW

Each section of this chapter highlights one of the three areas of existing research related to this thesis. The first section examines the direction of the DOD's energy strategy. The second part examines the relevant research on the unmanned carrier discussed in this paper and the U.S. Navy's related initiative. The last part reviews existing and recent studies on hydrogen fuel and examines the feasibility of utilizing hydrogen as a fuel for unmanned carrier operations.

A. DOD'S ENERGY STRATEGY

DOD's energy strategy was first published in 2011 and was recently reissued in 2015 (Department of Defense 2011; Office of the Assistant Secretary of Defense for Energy, Installation and Environment 2015). Through these documents, the Department of Defense recognizes energy as essential in the military's mission.

In response to emerging anti-access/area denial (A2/AD) strategy and hybrid threats, next-generation weapons are being developed, and it is assumed that they will require more energy and will be supplied those energies smoothly. To support the increased use of next-generation weapons, the energy use of current equipment may require improvements. This effort will also require improvements in the training and education of DOD members as well as enhanced policy support. Accordingly, the Office of the Assistant Secretary of Defense for Energy presents the following three goals:

1. Increase future warfighting capability by including energy throughout future force development.
2. Identify and reduce logistics and operational risks from operational energy vulnerabilities.
3. Enhance mission effectiveness of the current force through updated equipment and improvements in training, exercises, and operations. (Office of the Assistant Secretary of Defense for Energy, Installation and Environment 2015)

Similarly, the U.S. Department of the Navy's (DON) Installation Energy Resilience Strategy, published in February 2020, accepts this stance and embodies it at the installation level (Department of Navy 2020). DON has established evaluation criteria for energy

operation on three major axes: Resilience, Reliability, and Efficiency. Resiliency is defined as the ability to adapt to and recover from utility outages. Reliability is defined as the ability to prevent and respond to utility outages, and Efficiency is defined as the ability to reduce utility demand and costs (Department of Navy 2020). The focus of this paper is the analysis of systems in terms of efficiency.

Review of the DOD research and development (R&D) budget is useful to gain insight into expenditures for energy policy and technology. The Operational Energy Annual Report summarizes DOD's operational energy-related efforts and, among others, the investment in alternative fuels to replace petroleum fuels (Office of the Under Secretary of Defense for Acquisition and Sustainment 2021).

To understand the level of commitment related to energy policy and technology, it is important to note the overall scale of projects initiated within DOD, which increased by 131% from \$2.957 million in 2019 to \$3.871 million in 2020 (Office of the Under Secretary of Defense for Acquisition and Sustainment 2021). Among them, the project size for alternative energy increased by 273%, from \$2.83 million (0.1% of total annual budget) in 2019 to \$7.72 million in 2020 (0.2% of total annual budget). These projects spanned multiple categories, from developing Alcohol-To-Jet (ATJ) blends to capturing carbon dioxide and hydrogen from seawater. Of particular relevance to this research is a project from 2020 that extracts hydrogen from carbon dioxide from seawater and the atmosphere.

The aforementioned DOD energy-related policies show the need not only to seek new sources of fuel but to increase the efficient use of existing energy according to energy-related challenges.

B. NAVY'S OPERATIONAL BATTLESPACE

The third offset strategy can be defined as a set of strategies aimed at leveraging new technology advancements and operational ideas to counteract rising technological parity between the United States and its competitors while preserving Washington's capacity to project conventional power (Fiott 2016). The third offset strategy essentially emphasizes human-machine interaction. It has been more than 100 years since Josephus Daniels, a former U.S. Navy secretary, first approved investment in naval drone projects

(Smith 2017). Since then, the use of unmanned aerial vehicles has made substantial progress, and now the marine unmanned air supply MQ-25 Stingray is preparing for service. This paper discusses unmanned carrier aviation in detail; as a basis for that discussion this section reviews several previous studies on unmanned carrier operations.

Smith (2017) points to the need for a change in carrier operation, which has been the center of U.S. power projection for about 75 years. The change is prompted by the rise of power competitors and the spread of A2/AD capabilities. To this end, he emphasizes the role of UAVs as unmanned combat air vehicles (UCAVs) rather than only as existing ISR (intelligence, surveillance, and reconnaissance) assets. Additionally, unmanned air vehicles mounted on a carrier, referred to as carrier-launched UAVs (CL-UAV), emphasize the need for organizational changes and the creation of a research environment for the efficient operation of CL-UAV (Smith 2017).

Shugart (2017) proposes an assisting role for employing UAVs on carriers rather than replacing traditional carriers. Specifically, this platform is called an all-UAV aircraft carriers (CVQ), and Shugart proposes to utilize the new platform that can utilize advanced technologies currently being developed. He also argues that CVQs can replace the role of the aircraft carrier light (CVL). These CVQs may support multiple missions, such as Strike, Surface Warfare (SUW), and ISR, as a part of deterrence forces, as specified in a study by the Center for Strategic and Budgetary Assessment (CSBA) (Shugart 2017).

Based on the difference between the two previous studies, there is a tendency to limit the role of UAVs in areas where they have been operated. This tendency is due to cultural resistance to including UAVs in existing carrier operations (Shugart 2017) and preference for limiting UAVs to ISR missions in close areas with a relatively high risk of loss of life (Smith 2017).

Winston Arnold, Craig Fletcher, Richard McCann, Jeffrey Patel, and Jairus Potts (2021) also conducted a study proposing the need for an unmanned vehicle carrier (UVC). The UVC can support the Adaptive Force Package (AFP) performing Distributed Maritime Operation (DMO). Furthermore, the UVC increases the sustainability of the existing Expeditionary Sea Base (ESB) with maintenance, refueling, and rearmament facilities that

support the UAS. Through this, it was shown that the operational availability of UAS can be increased through the integration of a UVC with conventional forces.

While the United States is slowing down the introduction of an unmanned carrier, Turkey is pushing ahead in this area, with its own TB-2/3 UAVs on the *Anadolu*, its assault ship. It will simply use the winch-and-pulley system without catapults and gantry. Turkey's *Anadolu* will be close to the concept of the CVQ mentioned earlier by Shugart. Although the TB-2/3 UAV does not have air-to-air combat capabilities, it has precise strike and ISR capabilities. Turkey expects to operate about ten UAVs at the same time and mount 30~50 units on the *Anadolu*. Figure 1 shows the *Anadolu*, which will join the Turkish fleet in 2022 (Axe 2021).

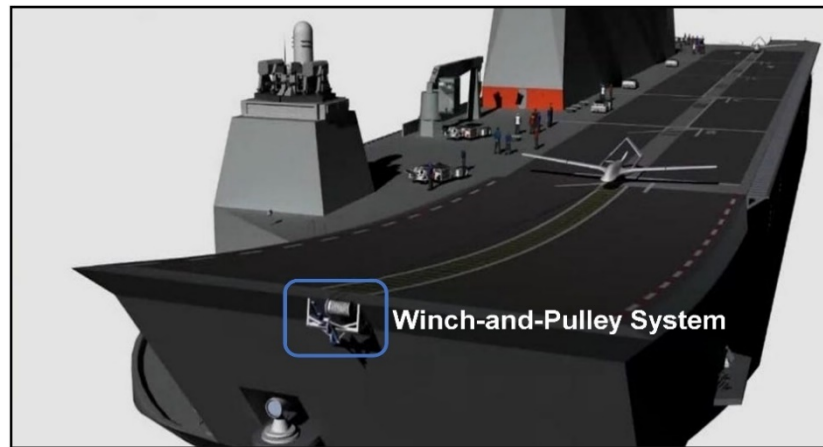
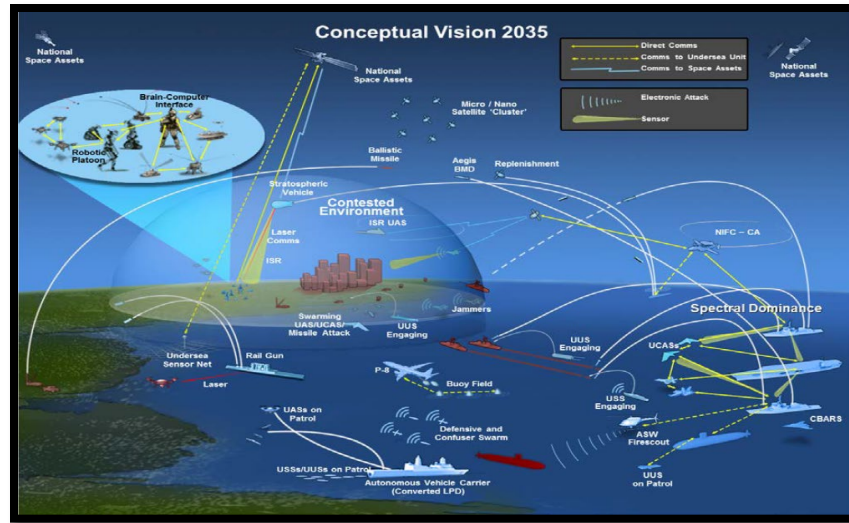
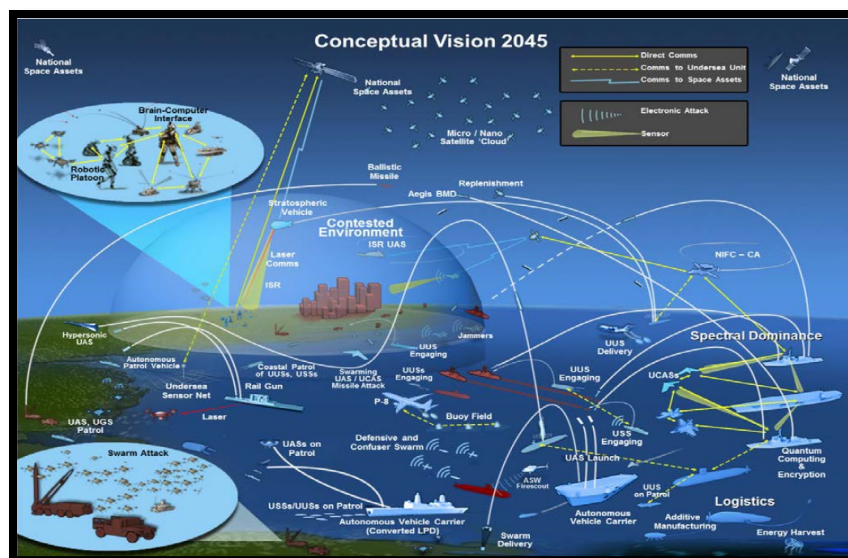


Figure 1. Illustration of the “Anadolu.” Adapted from Axe (2021).

The aforementioned ideas are somewhat reflected in the Navy's research, development, test, and evaluation (RDT&E) plan (Department of the Navy 2017). As shown in Figures 2 and 3, the Navy's conceptual vision plans for 2035 and 2045 shows the appearance of mounting UAVs on a converted amphibious transport dock (LPD).



The unmanned carrier, referred to as the Autonomous Vehicle Carrier, is not described in detail, but the following can be inferred from the figure. First, not only UAVs but also unmanned surface systems (USS) and unmanned underwater systems (UUS) are comprehensively operated in the envisioned platform. Second, we can assume that unmanned carrier vehicles will mainly operate in coastal areas, performing tasks such as land support ISR.



Some differences can be found in the 2045 conceptual vision. The Conceptual Vision 2045, for example, shows CL-UAVs, as described by Smith (2017). It also shows a UVC launching a swarm of UAVs and UUSs. For context, this thesis focuses on the design of an autonomous vehicle carrier as depicted in the U.S. Navy’s conceptual vision 2035. The concept of operations (CONOPS) of the unmanned carrier is specified in Chapter III.

C. HYDROGEN FUEL STUDIES

In fiscal year (FY) 2020, the U.S. Navy used 27.9 million barrels of petroleum. Although the estimated demand for operational energy is going to decrease, the Navy still needs 25.3 million barrels in FY21 and FY22 (Office of the Under Secretary of Defense for Acquisition and Sustainment 2021). Therefore, the need for research on alternative energy continues to increase. In particular, the U.S. Navy's energy research report shows substantial research and development on alternative (non-petroleum) energy focused on hydrogen in 2019 and 2020.

Research on hydrogen in the Navy is not sudden. Hydrogen has been studied as an alternative fuel since 1974. At that time, high fuel efficiency was pointed out as an

advantage, but low fuel density was highlighted as a disadvantage. In addition, because the hydrogen gas storage tank needs to hold hydrogen compressed at high pressure, it poses an increased risk of explosion. On the other hand, the existing petroleum-based fuel, with its relatively low ignition point, was easy to utilize and store. The 1974 study predicted that the economic feasibility of hydrogen fuel would improve due to the increase in crude oil prices and the decrease in oil reserves in the future (Carhart et al. 1974). The drawbacks of hydrogen mentioned here have been partially mitigated by current technological advances. In particular, liquid hydrogen, which compensates for the shortcomings of gaseous hydrogen, is nearing commercialization, which may offset the disadvantages associated with low fuel density and risk of explosion.

The domestic hydrogen production and supply capacity is already substantial and is expected to grow in the future. According to the Department of Energy's (DoE) Hydrogen Program, released in November 2020, the United States has 1,600 miles of hydrogen pipelines, three caverns capable of storing thousands of tons of hydrogen, and eight liquid hydrogen production plants capable of producing more than 200 metric tons per day (Beckman 2021).

Research to utilize hydrogen in the military is also being actively conducted. Previous studies have considered hydrogen as the main fuel of UAVs mounted on carriers. The research said that although hydrogen accounts for 4.15 times the volume of JP-5, hydrogen can improve mission performance by accounting for only 80% of the weight compared to the JP-5 (Ciaravino 2003).

NPS has also conducted a study on the development of a destroyer using only hydrogen fuel. In the study, high energy density and the possibility of a continuous supply of hydrogen fuel were suggested as the advantages. In other words, the development of the technology for extracting hydrogen through electrolysis from seawater suggests the possibility of utilization (Total Ships Team 2018).

An additional study examined condensed storage facilities for hydrogen fuel. This study suggested the possibility of storage and utilization of condensed hydrogen gas in the sea (Fosson 2017). In 2019, the U.S. Navy's first UAV, which is supplied with electricity

from a hydrogen fuel cell, was successfully tested (Pollman, Hobson, and Clay 2021). Additionally, a study is underway in which a mobile device is used to collect air and decompose hydrogen to UAVs (Hoag 2021).

The implementation of UAVs that use hydrogen as fuel is also being actively pursued in the civilian sector. Boeing's subsidiary, Insitu, completed its first UAV using hydrogen fuel cells in December 2020 and tested another UAV that uses liquid hydrogen as fuel in February 2021. The study was conducted by Hydrogen Properties for Energy Research (HyPER) at Washington State University, and the team was supported by a \$1.8 million grant from the U.S. Army (Vodnala 2019). In 2019, a South Korean company, MetaVista, flew a UAV for 12 hours and 7 minutes using 390 grams of liquid hydrogen and was listed in the Guinness World Records (Inside Unmanned Systems 2019). MetaVista's UAV is shown in Figure 4.



Figure 4. MetaVista's UAV Using 390 Grams of Liquid Hydrogen.
Source: Inside Unmanned Systems (2019).

Research using hydrogen fuel has been conducted for nearly 50 years, but the technology has not been actively used due to technical difficulties and limited practicality.

However, considering the continuously conducted research and cases of technology development and practical use, the possibility of future use looks increasingly likely.

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III. DESIGN OF MODEL

This chapter traces the design of the developed simulation model, which is used in this thesis to evaluate an unmanned carrier utilizing hydrogen energy in the future. After specifying the operational environment in which the system will be used, it is analyzed in terms of physical and functional aspects of the system. Based on this, the model design is specified by distinguishing the characteristics of a hydrogen energy-using UAV from the existing UAV.

A. OPERATIONAL ENVIRONMENT FOR SCENARIO DEVELOPMENT

The first step in developing the model configurations of the unmanned carrier equipped with hydrogen UAVs is to construct the baseline operational concept for the system model. Figure 5 shows an operational graphic in which the unmanned carrier operates.

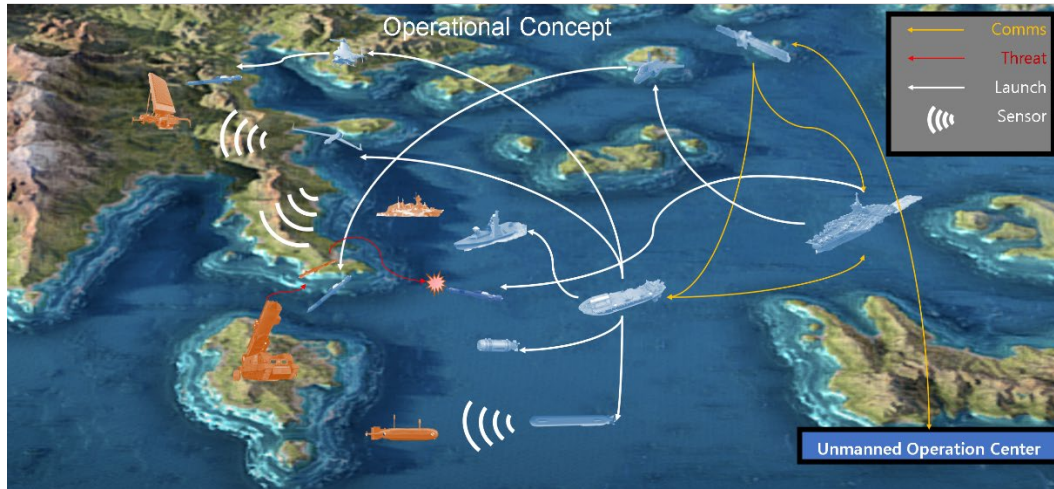


Figure 5. OV-1 of Unmanned Vehicle Carrier

This scenario happens in the archipelago close to the continent. The red country has fortified military bases by intensively deploying anti-ship and anti-aircraft missiles along the archipelago and mainland coasts. These measures pose a significant threat to military operations by neighboring allies and the Navy. In particular, these factors restrict aircraft

carriers' access within the missile range and significantly limit the operation and support of aircraft payloads. The unmanned carrier is operated about 50–100 miles away from the coastline and archipelago and will be utilized to ensure the efficient operation of friendly aircraft carriers. The unmanned carrier communicates with a traditional carrier and unmanned operation center through the satellite. UASs deployed from the unmanned carrier carry out their respective reconnaissance and strike missions. In particular, the unmanned carrier operates strike missions by identifying enemy communication facilities and missile launchers located near the archipelago to strike directly or share the location with nearby fleets. The specific operational concept enables the identification of the unmanned carrier's operation and understanding of the physical and functional structure.

B. MODEL STRUCTURE

To elaborate the general operational concept described in the previous section, this section details the functional and physical aspects of the unmanned carrier system.

1. Functional Analysis

Functional analysis is a procedure to better identify specific functions a system must perform to deliver the desired capability. This section describes the basic behaviors of the UVC, largely decoupled from the design of the UVC itself, to establish a starting point for the definition of behavior within a more detailed simulation model.

To that end, the following paragraph analyzes the system's function through a functional hierarchy organized according to the system's higher functions and their sub-functions. After that, the chapter explains how these combinations work through the functional flow analysis.

a. Functional Hierarchy

The following functional diagram details the main functions of the unmanned carrier. A sequence diagram was developed using Cameo Enterprise Architect that describes the high level functions shown generally in the OV-1. The two main functions of the unmanned carrier are: Prepare Unmanned Carrier Mission, and Perform Unmanned Carrier Operation. There is also a loop where the UVC engages in a loop with an enemy

and defends against enemy attacks. Figure 6 shows how the functions are associated with the parts of the unmanned carrier.

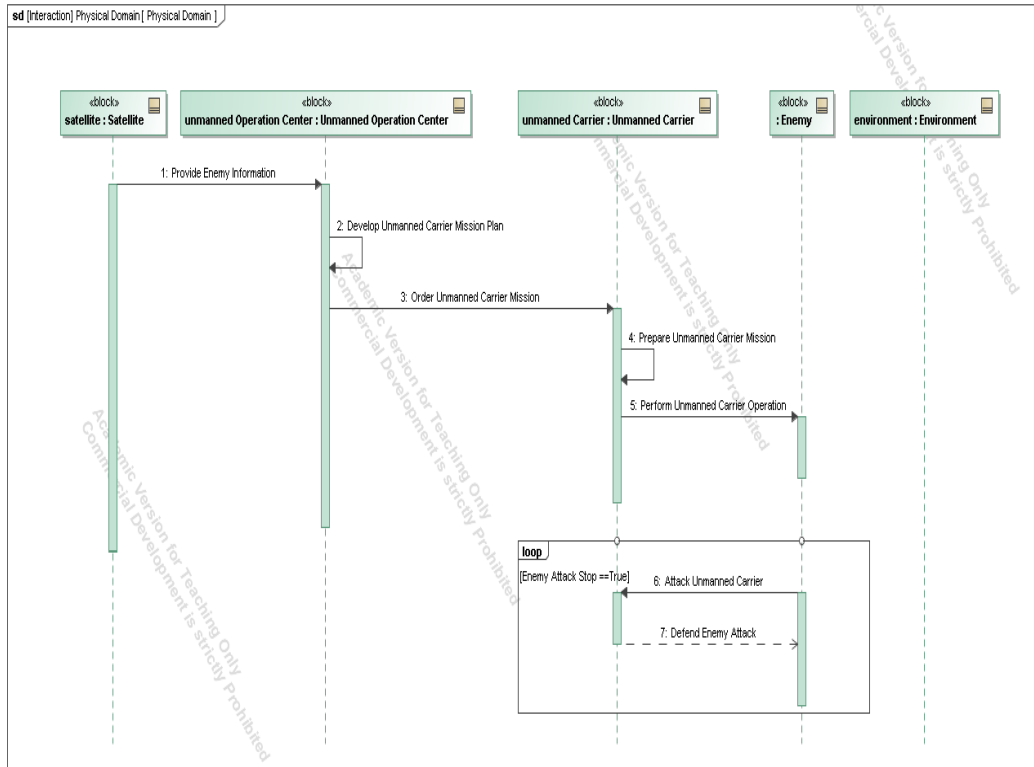


Figure 6. SysML Sequence Diagram for UVC Operational Concept

b. Functional Flow

Figure 7 shows a more detailed sequence diagram for the Perform Unmanned Carrier Operation function. This sequence diagram provides a description of how each part inside an unmanned carrier works to perform the corresponding function. Notice that the UVC is composed of eight major components, each of which has allocated behaviors. The development and identification of those components are described in more detail in the next section.

The control system develops a mission plan and transmits the mission to the UAV. The UAV moves to the launch position and is deployed by the launch system after the launch order. After the mission, the UAV recovers according to the characteristics of the

recovery system and reports mission completion to complete the mission. Also, the UAV performs fueling, maintenance, and weapon resupply activities before and after the mission.

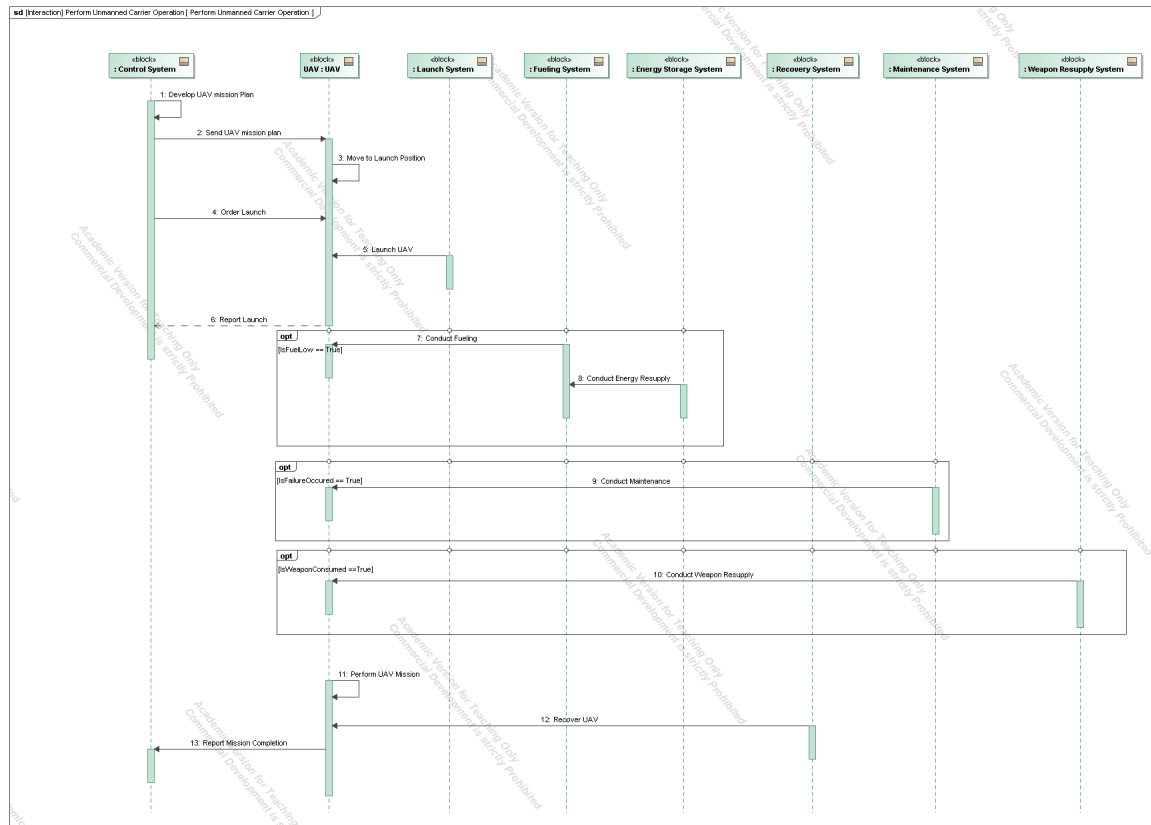


Figure 7. SysML Sequence Diagram for Perform Unmanned Carrier Operations

2. Physical Structure

Following the definition of the operational concept and functional analysis, the physical structure of the system is proposed to allow for the assessment of consistency with system behaviors. Development of the physical structure begins with the identification of external systems that describe contextual interactions between system-of-interest (SOI) and external systems. System decomposition describes how the internal system is composed and how each part works.

a. External Systems of Unmanned Carrier

Figure 8 shows the physical domain of the unmanned carrier and the elements that compose it. In addition to the unmanned carrier, a satellite that supports communications and data and an enemy that has been the subject of operations exist in this domain. In addition, the operational environment and the unmanned operation center, which controls and supports unmanned systems, make up its components. For the purpose of this thesis, the external systems are not described in detail. However, identification of these systems is important because they provide inputs to the UVC and accept outputs from the UVC, which is an important structure for the development of the operational simulation model.

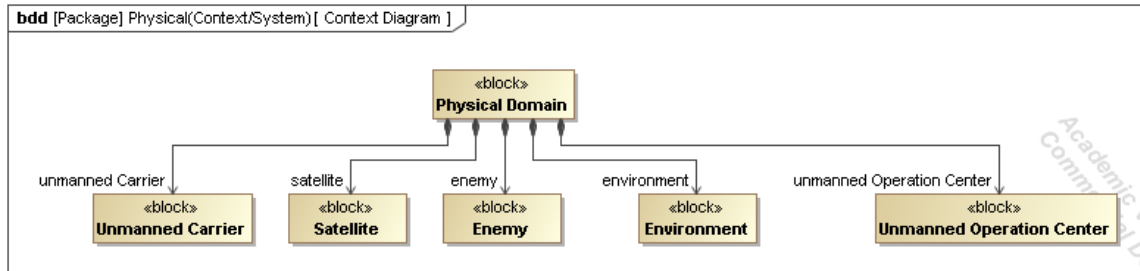


Figure 8. SysML Block Definition Diagram for External Systems of Unmanned Carrier

b. Unmanned Carrier System Decomposition

Figure 9 shows the composition of elements operating inside the unmanned carrier. In addition to the components included in the diagram, there may be other sub-elements, but only the components necessary to evaluate the operation of the UAS evaluated in this paper are included. As with the external systems, the internal components are not described in detail. However, identification of these systems is important because they execute the behaviors that the UVC will perform in the operational simulation model and must be defined and identified prior to the development of the model.

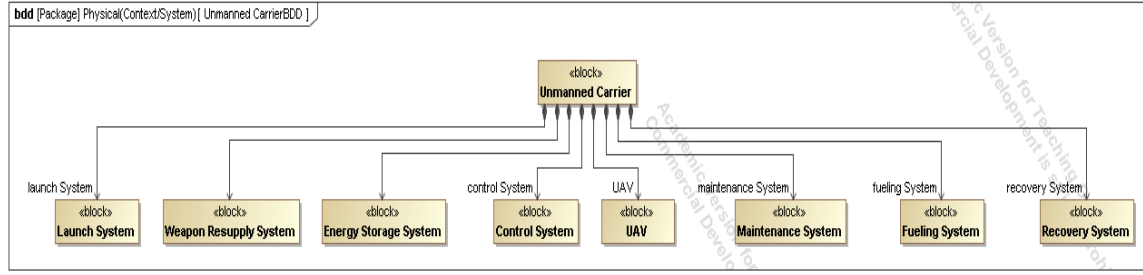


Figure 9. Unmanned Carrier System Decomposition

C. DESIGN OF SIMULATION MODEL

This section details the design of the simulation model with respect to the characteristics of UVC and UAVs, MOE and MOP, description of the model, and assumptions and limitations of the model.

1. UVC and UVC Characteristics

This paper aims to evaluate the characteristics of an unmanned carrier and the consumption of hydrogen fuel within the given operational concept. Prior to definition of the UVC, the characteristics of the UAVs that may operate on the UVC were defined. Those characteristics are based on two existing platforms: the MQ-8 Fire Scout and the RQ-21 Blackjack.

Tables 1 and 2 compare the characteristics and the hydrogen fuel consumption of the UAVs Type 1 (based on the MQ-8 Fire Scout) and Type 2 (based on the RQ-21 Blackjack) used in the model. Some of the characteristics refer to the model design used in the research of Arnold et al. (2021). For the mission duration, the energy of JP-5 of the existing model was compared with the energy of hydrogen fuel. That is, JP-5 has an energy of 35MJ/L, and hydrogen has an energy of 5.7MJ/L (700 Bar pressured), and liquid hydrogen has an energy of 8MJ/L (Office of Energy Efficiency & Renewable, 2014).

Accordingly, this paper assumes the existing fuel tank may be expanded when the configuration is changed from the existing model using JP-5 to the model using hydrogen. This expansion is enabled by securing space for the engine of the current internal combustion model and the lightness of hydrogen fuel. Therefore, this thesis proposes three

alternative configurations for the MQ-8 Fire Scout. The baseline configurations use traditional JP-5 (column 1 of Table 1). The second configuration (column 2 of Table 2) proposes an alternative where hydrogen fuel is used but is constrained by the volume of the existing MQ-8 fuel tank. The third configuration (column 3 of Table 1) proposes an alternative where hydrogen fuel is used but is constrained by the weight of the existing MQ-8 fuel tank.

Similarly, this thesis proposes three alternative configurations for the RQ-21 Blackjack. The baseline configurations use traditional JP-5 (column 1 of Table 1). The second configuration (column 2 of Table 2) proposes an alternative where hydrogen fuel is used but is constrained by the volume of the existing RQ-21 fuel tank. The third configuration (column 3 of Table 1) proposes an alternative where hydrogen fuel is used but is constrained by the weight of the existing RQ-21 fuel tank.

Table 1. UAV 1 Characteristics

	MQ-8 Fire Scout	MQ-8 Fire Scout (H2/LH2)	MQ-8 Fire Scout (H2/LH2)
MTBM (Planned Interval)	25 hours ¹	25 hours ²	25 hours ²
MTTR Planned	1.6 hours	1.6 hours	1.6 hours
Mean Time Between Failure (MTBF)	30 flight hours ¹	30 flight hours ²	30 flight hours ²
MTTR Corrective	2.5 hours ¹	2.5 hours	2.5 hours
TOS (Total Endurance)	12 flight hours ¹	1.7 / 2.9 flight hours	33.5 flight hours
Time for Weapon Resupply	0.75 hours	0.75 hours	0.75 hours
Time for Refuel	0.75 hours	0.8 / 0.4 hours ³	15.4 / 4.8 hours ³
Launch Time	0.5 hours	0.5 hours	0.5 hours
Recovery Time	0.5 hours	0.5 hours	0.5 hours
¹ (Anderson 2016)			
² The value entered here was based on the assumptions in the “Assumptions and Limitations” presented later.			
³ The value entered here was calculated based on the research and DOE objective value.			

Table 2. UAV 2 Characteristics

	RQ-21 Blackjack	RQ-21 Blackjack (Hydrogen Fuel/Liquid Hydrogen)	RQ-21 Blackjack (Hydrogen Fuel/Liquid Hydrogen)
MTBM (Planned Interval)	100 hours ¹	100 hours	100 hours
MTTR Planned	3.5 hours	3.5 hours	3.5 hours
Mean Time Between Failure (MTBF)	45 flight hours ¹	45 flight hours	45 flight hours
MTTR Corrective	0.5 hours ¹	0.5 hours	0.5 hours
TOS (Total Endurance)	10 flight hours ¹	1.4 / 2.4 flight hours	27.9 flight hours
Time for Weapon Resupply	0.75 hours	0.75 hours	0.75 hours
Time for Refuel	0.3 hours	0.2 / 0.1 hours ³	0.1 hours ³
Launch Time	0.5 hours	0.5 hours	0.5 hours
Recovery Time	0.5 hours	0.5 hours	0.5 hours
¹ (Anderson 2016)			
² The value entered here was based on the assumptions in the “Assumptions and Limitations” presented later.			
³ The value entered here was calculated based on the research and DOE objective value.			

2. Measures of Effectiveness and Measures of Performance

Tables 3 and 4 show the measures of effectiveness (MOE) and measures of performance (MOP) for the research. The MOEs and MOPs structure analysis, which is focused on the improvement to the number of flight hours for the UAVs in the model that results from the employment of hydrogen fuel as well as alternations to the UVC design. Because the UVC is intended to augment the capabilities of existing forces, the primary MOE captured in the model was based on the availability of the UAVs in the model.

Operational availability (Ao) is the probability of availability in the actual operating environment (Blanchard and Fabrycky 2011, 493). Ao is the ratio of uptime (Mean Time Between Maintenance, MTBM) to total maintenance downtime (Mean Maintenance Down Time, MDT). This MOE serves as the criterion for judging whether a UAV applied with hydrogen fuel can operate more effectively than an existing UAV.

Table 3. Measure of Effectiveness (MOE)

MOE	Description
Operational Availability (A_O)	Defined as $A_O = \frac{MTBM}{MTBM+MDT} = \frac{Uptime}{Uptime+Downtime}$

Multiple MOPs were captured to aid future model development and to verify model functionality. Those MOPs include downtime, total mission time, and utilization for each function in the model.

Table 4. Measures of Performance (MOPs)

MOP	Description
Mission Time	The total time the UAV is conducting a mission.
Downtime	The total time that the UAV is not conducting a mission. (UAV is waiting in a queue, launching, recovering, refueling, and being maintained and supplied.)
Launch Position Utilization	Defined as the time used divided by the entire time.
Maintenance Bay Utilization	
Recovery Location Utilization	
Refuel Location Utilization	
Weapon Resupply Spot Utilization	

3. Model Description

Based on the behaviors and physical components described earlier, an operational simulation model was developed in the discrete event simulation program ExtendSim 10. Through the construction of the ExtendSim10 simulation, it is possible to evaluate the behaviors of UVCs that support the application of hydrogen energy in UAVs. Since the application of UAVs with hydrogen energy is still in the experimental stage, there are limitations in evaluating the behavior in the operational stage. Through simulation, the operation of the UVC can be evaluated.

Figure 10 shows the structure of the model. Note that these simplified blocks are modeled in detail in ExtendSim 10. To aid in the understanding of the model structure, these blocks are shown in lieu of a screenshot of the ExtendSim model itself. The simulation model starts when the UAV items are created. The generated items move through the activity blocks of Launch, Mission, Recovery, Refuel, Maintenance, and Weapon Resupply, and the items return to the Launch Queue block.

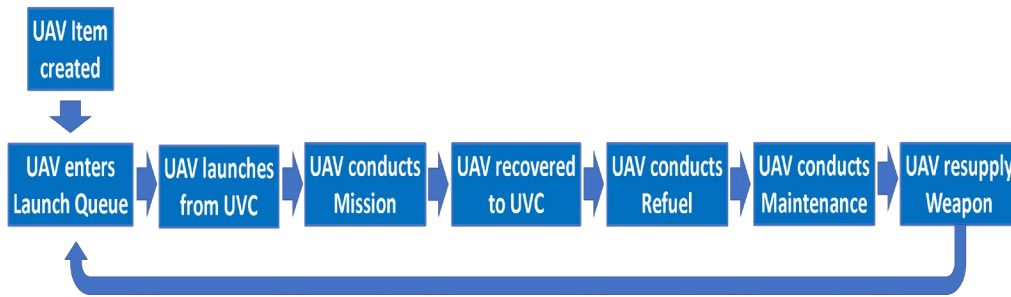


Figure 10. ExtendSim10 Model Structure

In this model, the UAV item has the characteristics of the MQ-8 Fire Scout and the RQ-21 Blackjack previously defined in Tables 1 and 2. These attributes are given to each item after initial creation. Also, as a characteristic of the UVC, the resource pool of each activity is limited. This is classified as a design factor of the model in the next chapter.

4. Limitations and Assumptions

Modeling close to reality is necessary for a more accurate depiction of the real world. However, several limitations were identified based on software limitations or unknown system characteristics. As mitigation for this, several assumptions were identified.

a. Limitations

A total of six limitations were identified. Table 5 lists the identified limitations of the model, their descriptions, and the corresponding assumptions as mitigations.

Table 5. Model Limitations

Limitation	Description	Mitigation
L1	The detailed description of failures that occur during the mission is limited.	A1
L2	The depiction of the loss of friendly UAVs to enemy threats during missions is limited.	A2
L3	Detailed data of UAV is limited.	A3
L4	UVC specifications have not been confirmed.	A4
L5	The difference in the charging speed according to the hydrogen fuel storage method and charging environment gives significant complexity to the model.	A5
L6	Thermal efficiency varies depending on whether an existing internal combustion engine or a fuel cell using hydrogen fuel is used. In general, the latter shows about twice the efficiency of conventional internal combustion engines using fuel cells (Thomas 2000). However, it is difficult to know the details of the thermal efficiency of an undeveloped hydrogen fuel engine.	A7

b. Assumptions

Table 6 describes the assumptions made as mitigation measures for the model's limitations. Some assumptions are reflected in the activity procedure in the simulation, and the remaining assumptions affect the base specifications for the model.

Table 6. Model Assumptions

Assumptions	Description
A1	Decide the failure of UAVs before the mission, based on the reliability of the UAV (for the given mission time). Failure of UAV does not mean loss. Assume all failed UAVs are repairable.
A2	Adjust the mission time by reflecting the coefficient according to the enemy's threat level.
A3	Specifications were acquired through DOD documents and interviews, and some restricted items were based on assumptions. Details are shown in Table 1 and Table 2.
A4	UVC can accommodate the UAVs used in the model. Unknown characteristics are treated as design variables in Chapter IV.
A5	In this paper, we assume 700 Bar pressure as it is an advanced technology and more common these days. Also, hydrogen charging

Assumptions	Description
	meets the T40 condition according to Protocol SAE J2601 (between -40 and 60 degrees Celsius). Also, minimum refueling time for small size of fuel tank was assumed as 0.1 hour.
A6	We assume 100% energy conversion efficiency.
A7	UAV has a separate recovery location according to its type. However, maintenance teams can service different types of UAVs.
A8	We assume that each activity follows normal distribution with 0.1 standard deviation.

IV. ANALYSIS

This chapter is divided into three main sections. In the first section, the analysis approach, the goals, responses, and the design of experiment are discussed. The second section briefly discusses how the simulation results were analyzed using JMP PRO. Finally, a detailed analysis of the results and their implications are presented.

A. ANALYSIS APPROACH

The approach for analysis is focused on determining the viability of hydrogen as an alternative fuel as well as the characteristics of the UVC that have the largest impact on operational effectiveness. To support this approach, five distinct variants of the ExtendSim 10 model are built and analyzed based on the fuel type employed by both the Fire Scout and the Blackjack. The first model uses JP-5, the second model uses gaseous hydrogen that is constrained by the volume of the UAV fuel tank, the third model uses liquid hydrogen that is constrained by the volume of the UAV fuel tank, the fourth model uses gaseous hydrogen that is constrained by the weight in the UAV fuel tank, and the fifth model uses liquid hydrogen that is constrained by the weight in the UAV fuel tank. An experimental design approach is developed to systematically vary the characteristics of the UVC and is implemented in each of the five models.

1. Goal

The goal of the analysis model is to determine the characteristics of the UVC and UAV fuel types that have the largest impact on Ao.

2. Response

Analysis was performed based on Ao, with an emphasis on identifying the factors that had a statistically significant impact on Ao variability.

3. Design of Experiment Factors

The following variables were selected as input variables to define UVC characteristics in ExtendSim. Table 7 describes the variables and shows the minimum and maximum values in the design.

Table 7. DOE Factors

Factor	Min	Max	Description
Number of Fire Scout	40	100	The number of Fire Scout UAVs mounted on the UVC
Number of BlackJack	40	10	The number of BlackJack UAVs mounted on the UVC
Number of Fire Scout Launch Locations	3	8	The number of launch locations for Fire Scout UAVs on the UVC
Number of BlackJack Launch Locations	5	10	The number of launch locations for BlackJack UAVs on the UVC
Number of Maintenance Bays	5	10	The number of maintenance bays supporting UAVs
Number of Fire Scout Recovery Locations	3	8	The number of recovery locations supporting Fire Scout UAV recovery
Number of BlackJack Recovery Locations	3	5	The number of recovery locations supporting Blackjack UAV recovery
Number of Refuel Locations	3	10	The number of refuel locations supporting UAVs
Number of Weapon Resupply Spots	5	10	The number of weapon resupply spots supporting UAVs

4. Design of Experiment Approach

A Latin Hypercube design was generated to systematically vary nine factors, each having a minimum and maximum value. Latin Hypercube designs are well suited to simulation experiments due to their ability to fill in large portions of the system design space without requiring the large run numbers associated with more traditional experimental designs. Using the DOE menu within JMP Pro 16, a Latin Hypercube design with 90 trials was generated for the nine factors from Table 7. Values with decimal points were rounded off to the nearest integer using Excel to ensure that all factors were restricted to integer values (Appendix A). A correlation matrix was generated using JMP Pro 16 to assess the quality of the design matrix; Appendix B presents the assessment of the design matrix. The highest correlation between any two variables was -0.1451, which was the Number of Maintenance Bays and the Number of BlackJack Recovery Locations. This was assumed to be acceptable in this study. Also, the scatterplot shows that the selected design point reflects the entire design space well (Appendix C).

B. ANALYSIS METHOD

Each design point was repeated 30 times to capture the variability in the ExtendSim 10 model. Accordingly, the set of 2,700 runs was constructed ($30 \times 90 = 2,700$). The full 2,700 run design matrix was examined for each of the five different fuel types. A total of $2,700 \times 5 = 13,500$ simulation runs were conducted, and the Ao of UAVs for each trial was aggregated for analysis.

The mean and distribution of Ao according to each fuel type were analyzed through JMP. A decision tree was developed for additional analysis. The statistical analysis according to the simulation result and its implications are discussed below.

C. RESULTS AND ANALYSIS

This section details the result from the simulation and its analysis.

1. Mean of Ao for Each Fuel Type

Table 8 shows the Ao of each UAV classified only by fuel type, not subdivided by UVC characteristics. In all cases, the high efficiency is shown in the order of weight constraint liquid hydrogen > weight constraint gas hydrogen > JP-5 > volume constraint liquid hydrogen > volume constraint gas hydrogen.

Notably, the volume constraint model is the lowest performing regardless of other characteristics. Conversely, the weight constraint model is the highest performing alternative as well as an Ao of up to 0.78 depending on the use, according to the UVC characteristics. Appendix D presents histograms that describe the range of Ao values for each fuel type.

Table 8. Ao of UAVs by Fuel Type

Fuel Type	Fire Scout Ao	BlackJack Ao
JP-5	0.194	0.211
Volume Constraint Gas Hydrogen	0.049	0.053
Volume Constraint Liquid Hydrogen	0.071	0.078
Weight Constraint Gas Hydrogen	0.212	0.221
Weight Constraint Liquid Hydrogen	0.266	0.288

2. Variables Affecting Fire Scout Ao

To find out which variables have an important effect on Fire Scout Ao, a decision tree was developed using the partition modeling of JMP Pro. A total of four splits were performed until the R-square value did not increase substantially. The R-square value indicating the explanatory power of the model was 0.803, which was high (denoted as 1 in Figure 11). Based on Figure 11, three major observations are important.

First, Maximum Endurance was found to be the most important factor. When Maximum Endurance was greater than 12 (Ao=0.224), it showed a statistically significant difference than when it was lower than 12 (Ao=0.06) (denoted as 2 in Figure 11).

Second, the number of Maintenance Bays was identified as the second most important factor. When the number was larger than 7 (Ao=0.248) or smaller than 7 (Ao=0.169), there was a statistically significant difference of about 7% (denoted as 3 in Figure 11).

Finally, fuel type was identified as the third most important factor. When Weight Constraint Liquid Hydrogen was used (Ao=0.299), there was a statistically significant difference than when it was not used (Ao=0.222) (denoted as 4 in Figure 11).

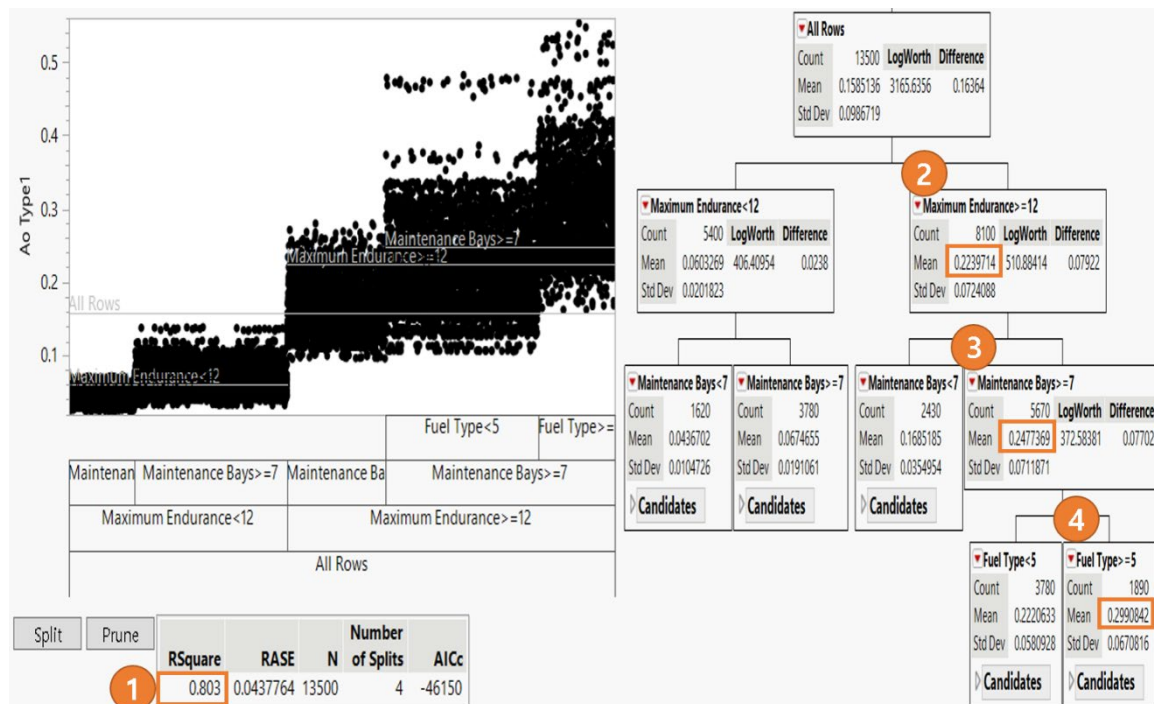


Figure 11. Fire Scout Ao Decision Tree

3. Variables Affecting BlackJack Ao

As was done for the Ao of the Fire Scout UAV, a decision tree was developed to find out which variables have an important effect on the BlackJack's Ao. A total of four splits were performed until the R-square value no longer increased substantially. The R-

square value indicating the explanatory power of the model was 0.743, which was high (denoted as 1 in Figure 12).

First, Maximum Endurance was found to be the most important factor in the BlackJack UAV as it was for the FireScout. When the Maximum Endurance was greater than 10 ($Ao=0.24$), it showed a statistically significant difference than when it was lower than 10 ($Ao=0.065$) (denoted as 2 in Figure 12).

Second, fuel type was identified as the second most important factor. When Weight Constraint Liquid Hydrogen was used ($Ao=0.288$), there was a statistically significant difference than when it was not used ($Ao=0.216$) (denoted as 3 in Figure 12).

Finally, the number of UAVs was identified as the third most important factor. When the number was restricted to less than 64 ($Ao=0.427$), and when it was more than 64 ($Ao=0.200$), there was a statistically significant difference (denoted as 4 in Figure 12).

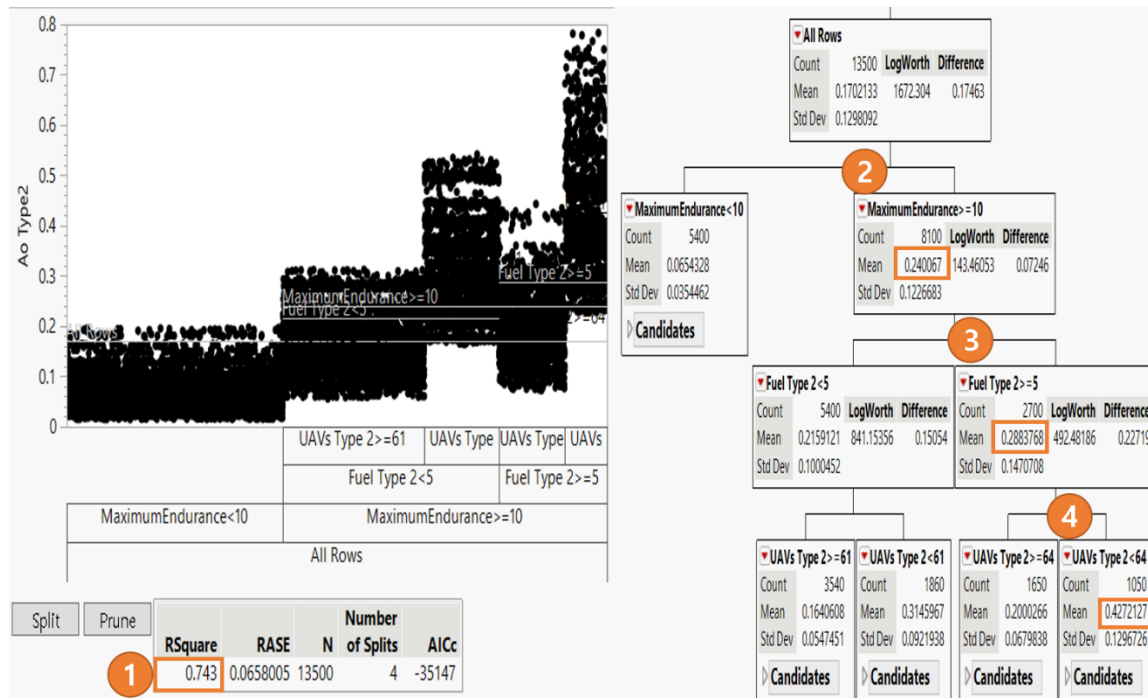


Figure 12. BlackJack Ao Decision Tree

4. Summary of Findings

Overall, Ao was most affected by the changes to Maximum Endurance of individual UAVs. Therefore, the volume constraint hydrogen models, which are associated with lower maximum endurance, results in low performance. Similarly, the liquid constraint hydrogen models, which may enable higher maximum endurance, result in high performance. In other words, the design premised on using the existing fuel tank was not recommended, and it was shown that the UAV using hydrogen fuel should presuppose the configuration change of the fuel tank. The analysis quantified the impact of this change, the analysis showed that the use of hydrogen fuel increased Ao by 7% when the Maximum Endurance had a low or high value.

Secondly, to increase Ao of the overall UVC/UAV system, securing sufficient quantity of maintenance bays was recommended. The ExtendSim model in this paper assumed the same MTBM as the UAV using the existing JP-5. Accordingly, an increase in mission time, which may be possible when using hydrogen fuel, may lead to an increase in the failure rate. Therefore, in the case of the Fire Scout UAV, securing sufficient maintenance facilities was identified as an important factor.

Thirdly, analysis showed a statistically significant reduction to Ao when there are too many UAVs aboard the UVC (greater than approximately 60). This suggests that there are negative consequences associated with unconstrained increase to the number of UAVs employed on the UVC. Mounting more UAVs might be an alluring option. However, increasing the number of UAVs overloaded the system and lowered Ao. Therefore, it is suggested to lower the number of UAVs when sufficient Maximum Endurance is secured.

Finally, using the weight constraint liquid hydrogen could show a statistically significant improvement to overall Ao. Although it was the second most important factor in the Fire Scout UAV and the third most important factor in the BlackJack UAV, in both cases, liquid hydrogen was shown to increase Ao by about 7% when compared to other fuel types. Therefore, it was found that the use of liquid hydrogen could lead to a significant increase in Ao.

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V. CONCLUSIONS AND IMPLICATIONS

A. SUMMARY

Through the simulation presented in this study, it was possible to analyze the operational feasibility of UAVs using hydrogen fuel. The most important factor to increase Ao of UAVs aboard a UVC was the maximum endurance of the individual UAVs. Based on the five different fuel types implemented in this thesis, the preferred strategy for increasing the maximum endurance of individual UAVs is through the use of liquid hydrogen as a fuel source and a UAV configuration that employs a modified fuel tank that is constrained by the weight of the liquid hydrogen fuel. When liquid hydrogen fuel was used as the weight constraint model, it was found to increase the Ao by 7%. On the other hand, the volume constraint hydrogen model using the existing fuel tank showed lower efficiency than the JP-5.

In addition, some reference points for designing the UVC are presented. Since the use of hydrogen fuel would increase the maximum endurance of UAVs, increasing the system's maintenance capability or unloading the system itself is recommended. The Fire Scout UAV's efficiency is improved when the number of maintenance bays is seven or more. In the case of the BlackJack UAV, it was found that efficiency was improved by limiting the number of UAVs to 64 or fewer. These design reference points can be referred to in designing ships operating UXVs in the future.

B. FUTURE RESEARCH

This section details future research that is beyond the scope of this paper or to supplement the analysis.

1. Combat Loss

Although the model describes losses from failure rate, losses from enemy threats were not. For example, UAVs' vulnerability from electronic warfare or different types of engagement was not described. While this may bring the overall numbers closer to the operational reality, the general trends in terms of the preferred fuel type are unlikely to

change. However, increased attrition may result in revisions to the recommended number of maintenance bays and total UAVs employed on the UVC.

2. Hydrogen Fuel Specification

Relevant specifications such as the refueling speed of hydrogen fuel are affected by the operating environment and the level of the facility. In future research, it is necessary to analyze the hydrogen fuel specifications according to temperature and detailed facility alternatives as an alternative.

3. Advanced Fuel Technology

Energy-related technology is developing day by day. Although liquid hydrogen charging technology was presented as the most advanced technology in the model, advanced technologies such as the commercialization of capturing hydrogen could not be considered.

4. UVC Design

This thesis was written based on assumptions about UAVs and UVCs that have not yet been designed. Future work will include architectural and engineering design of an unmanned UAV carrier using hydrogen as aviation fuel by a capstone team at the Naval Postgraduate School.

C. CONCLUSIONS

This paper analyzed the feasibility of the unmanned carrier with UAVs fueled by hydrogen. The paper defined an operational concept for the unmanned carrier with UAVs fueled by hydrogen. An ExtendSim model was developed and used for analysis to ascertain the primary drivers of operational availability. Analysis to identify characteristics that impact operational availability showed statistical explanatory power of over 80%. The most important factor to increase operational availability was UAV maximum endurance. The second most important, but closely related, factor was fuel type, with liquid hydrogen fuel showing a 7% increase in operational availability over JP-5 and alternative implementations of hydrogen fuel for the scenarios explored. The third most important

factor in analysis is ensuring that the UVC is designed with a minimum of seven maintenance bays that are capable of operating in parallel.

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APPENDIX A. DOE TRIALS

Run	UAVs Fire Scout	UAVs BlackJack	Fire Scout Launch Locations	BlackJack Launch Locations	Maintenance Bays	Fire Scout Recovery Locations	BlackJack Recovery Locations	Refuel Locations	Weapon Resupply Spots
1	83	68	4	10	8	6	4	8	5
2	71	81	3	6	9	5	4	9	6
3	43	46	5	7	5	4	5	4	7
4	51	84	3	9	7	3	4	8	8
5	89	43	6	7	8	5	3	6	5
6	97	83	3	8	8	5	4	3	8
7	95	64	4	10	6	5	4	4	5
8	73	84	5	9	7	4	5	6	5
9	54	66	6	8	8	7	3	8	10
10	80	44	4	8	5	5	4	3	9
11	53	82	4	8	10	4	4	3	7
12	63	45	4	5	5	7	4	6	8
13	90	89	7	9	9	7	5	7	8
14	68	48	4	7	9	7	3	7	6
15	50	56	8	10	7	8	5	7	8
16	45	88	6	10	10	6	4	8	8
17	67	45	4	6	9	7	5	10	7
18	81	76	5	9	9	8	4	5	9
19	60	59	5	6	9	6	5	6	8
20	60	61	7	9	10	7	4	4	6
21	65	51	6	10	7	7	3	3	9
22	66	73	8	9	6	6	3	9	6
23	76	93	5	7	10	5	3	9	9
24	44	41	7	9	9	4	4	10	8
25	84	77	6	6	6	8	4	4	8
26	85	97	5	9	9	4	3	7	6

Run	UAVs Fire Scout	UAVs BlackJack	Fire Scout Launch Locations	BlackJack Launch Locations	Maintenance Bays	Fire Scout Recovery Locations	BlackJack Recovery Locations	Refuel Locations	Weapon Resupply Spots
27	59	93	7	10	8	6	4	5	10
28	55	49	4	5	7	5	4	9	9
29	40	56	7	6	7	4	3	6	7
30	99	97	5	5	6	5	5	5	6
31	64	68	6	6	6	7	5	5	5
32	93	53	7	10	9	6	4	9	10
33	98	60	6	7	9	5	4	9	7
34	79	53	7	5	9	4	3	8	9
35	75	42	5	8	9	4	5	5	7
36	48	85	4	8	8	5	3	8	6
37	49	66	7	6	6	4	4	8	9
38	74	74	3	6	5	5	3	7	7
39	70	87	8	6	9	6	5	9	9
40	94	64	7	5	7	4	4	5	9
41	72	50	8	7	8	7	4	6	9
42	92	79	7	8	8	8	3	5	6
43	78	72	8	6	6	3	4	7	6
44	56	57	4	7	7	3	4	9	6
45	74	52	7	9	7	4	5	10	7
46	53	91	6	7	5	8	4	9	7
47	51	78	5	7	9	3	5	10	9
48	91	78	5	6	8	8	3	9	7
49	95	96	7	8	6	6	4	7	9
50	58	91	3	9	6	7	5	6	6
51	41	75	3	8	8	7	4	4	7
52	47	89	5	5	7	5	4	5	7
53	43	76	6	6	10	7	3	6	8
54	47	87	7	7	6	6	3	4	8
55	91	55	7	9	8	3	4	7	7
56	72	40	6	8	5	7	4	8	7

Run	UAVs Fire Scout	UAVs BlackJack	Fire Scout Launch Locations	BlackJack Launch Locations	Maintenance Bays	Fire Scout Recovery Locations	BlackJack Recovery Locations	Refuel Locations	Weapon Resupply Spots
57	56	86	8	9	8	3	4	5	7
58	49	58	6	5	8	7	4	4	5
59	57	94	6	8	8	6	5	10	6
60	52	58	7	6	8	6	4	10	6
61	45	47	4	9	7	5	5	6	10
62	70	90	7	5	6	5	3	8	8
63	97	51	4	7	7	7	4	4	7
64	88	67	4	9	10	5	4	8	9
65	78	65	6	6	5	6	5	9	8
66	58	43	4	5	9	4	4	4	8
67	86	80	8	7	10	4	4	4	10
68	68	99	6	7	8	7	5	3	8
69	87	62	6	8	7	7	5	3	10
70	62	47	7	8	8	4	4	4	10
71	62	92	8	7	9	6	4	7	5
72	42	71	8	7	8	4	5	7	6
73	77	98	5	8	5	5	4	10	8
74	84	72	4	6	7	8	4	8	10
75	61	62	5	10	10	4	3	5	8
76	93	49	5	6	5	4	5	6	6
77	87	80	6	8	6	4	3	5	9
78	100	41	5	8	7	6	3	7	10
79	99	82	5	6	9	5	3	5	7
80	76	74	3	9	6	8	3	7	7
81	82	60	5	9	6	3	4	9	9
82	80	99	7	9	6	6	4	4	5
83	64	70	3	7	7	6	3	3	9
84	69	95	4	7	9	7	3	4	5
85	66	63	6	6	10	3	4	6	6
86	82	100	6	8	7	3	4	6	9

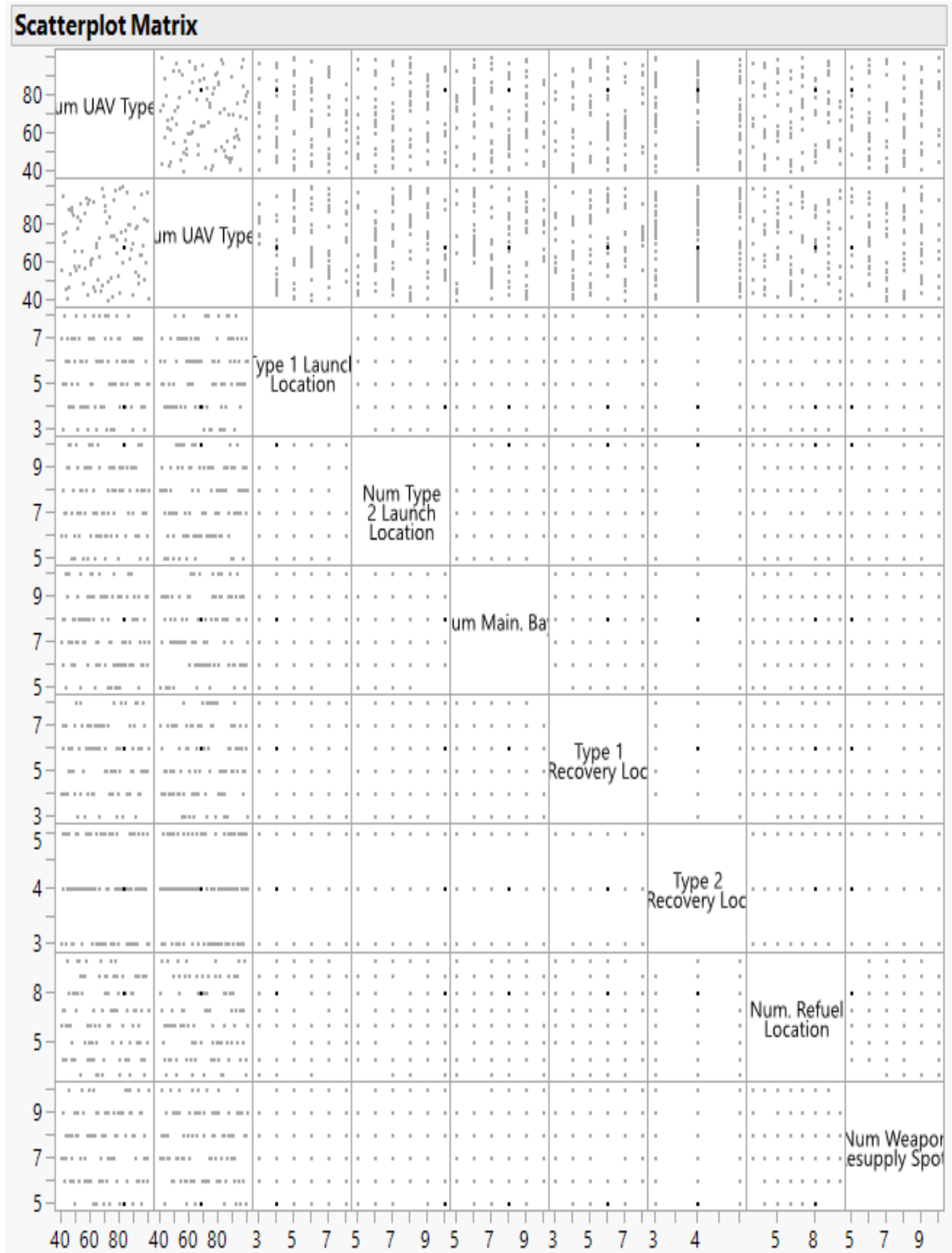
Run	UAVs Fire Scout	UAVs BlackJack	Fire Scout Launch Locations	BlackJack Launch Locations	Maintenance Bays	Fire Scout Recovery Locations	BlackJack Recovery Locations	Refuel Locations	Weapon Resupply Spots
87	89	70	3	9	6	6	5	8	8
88	46	54	4	10	7	5	4	6	6
89	96	69	4	7	6	8	5	9	6
90	41	95	5	8	6	6	5	7	9

APPENDIX B. DOE CORRELATIONS

Correlations									
	Num UAV Type 1	Num UAV Type 2	Type 1 Launch Location	Num Type 2 Launch Location	Num Main. Bays	Type 1 Recovery Loc.	Type 2 Recovery Loc.	Num. Refuel Location	Num Weapon Resupply Spots
Num UAV Type 1	1.0000	0.0194	-0.0482	0.0118	-0.0824	0.0685	-0.0647	-0.0391	0.0406
Num UAV Type 2	0.0194	1.0000	0.0511	0.0566	0.0270	0.0714	-0.0337	-0.0112	-0.1006
Type 1 Launch Location	-0.0482	0.0511	1.0000	-0.0123	0.1111	-0.0765	0.0207	0.0655	0.0914
Num Type 2 Launch Location	0.0118	0.0566	-0.0123	1.0000	0.0864	0.0123	0.0311	-0.0265	0.0519
Num Main. Bays	-0.0824	0.0270	0.1111	0.0864	1.0000	-0.0864	-0.1451	0.0018	0.0420
Type 1 Recovery Loc.	0.0685	0.0714	-0.0765	0.0123	-0.0864	1.0000	-0.0207	-0.0655	-0.0222
Type 2 Recovery Loc.	-0.0647	-0.0337	0.0207	0.0311	-0.1451	-0.0207	1.0000	0.0891	-0.0311
Num. Refuel Location	-0.0391	-0.0112	0.0655	-0.0265	0.0018	-0.0655	0.0891	1.0000	-0.0018
Num Weapon Resupply Spots	0.0406	-0.1006	0.0914	0.0519	0.0420	-0.0222	-0.0311	-0.0018	1.0000

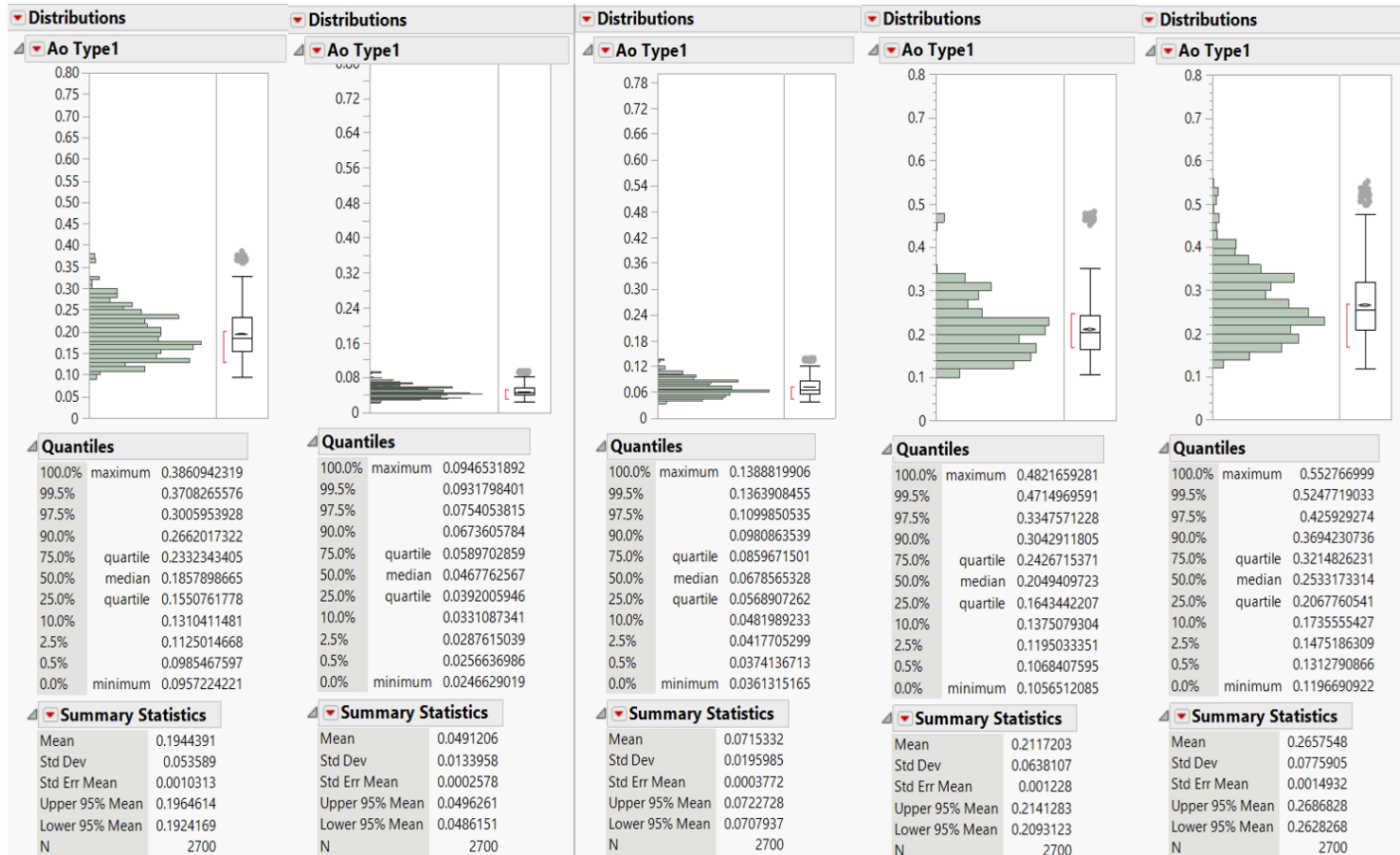
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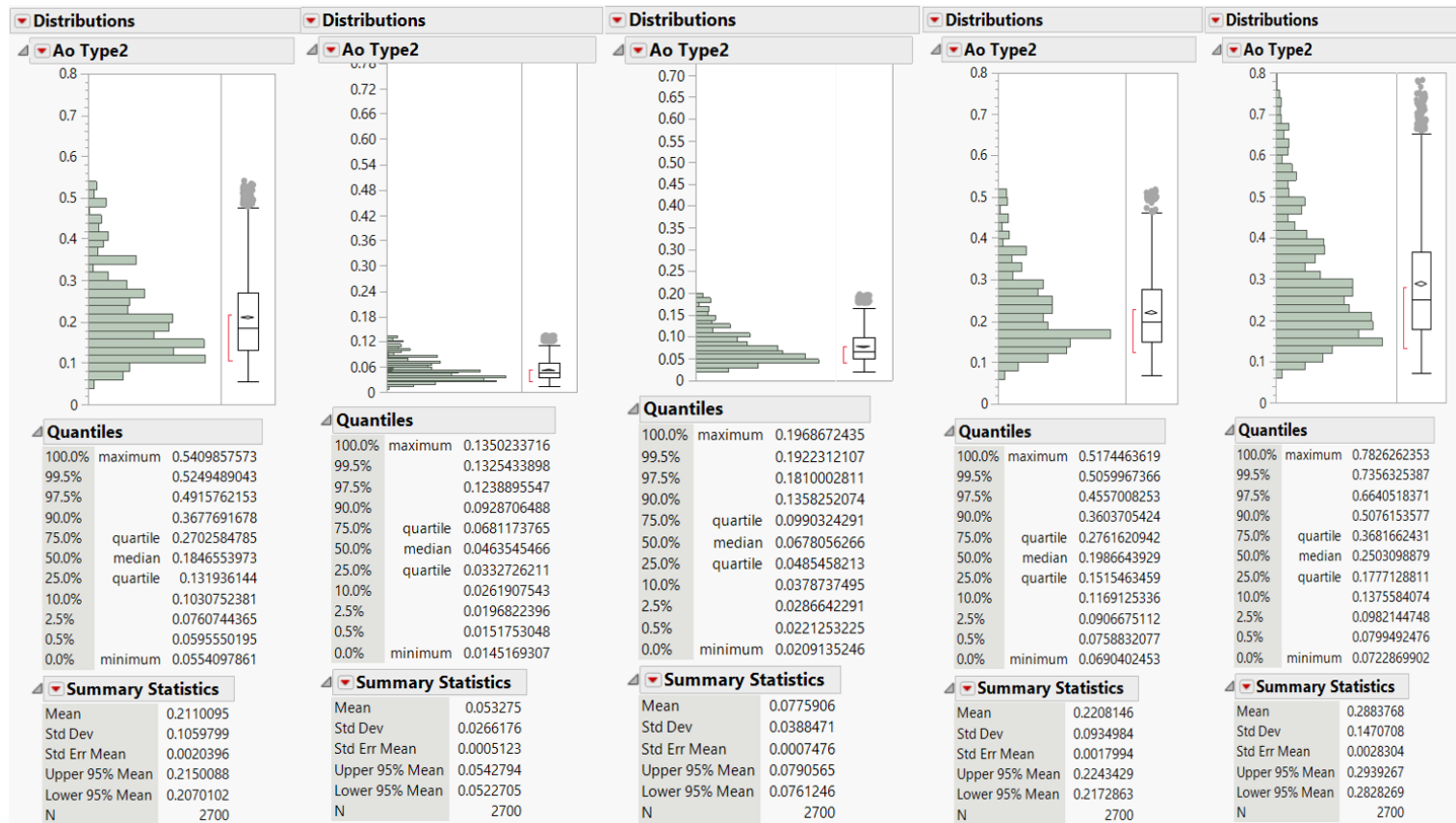
APPENDIX C. DOE SCATTERPLOT MATRIX



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APPENDIX D. DISTRIBUTION OF AO (BY FUEL TYPES)





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