NAVAL
POSTGRADUATE
SCHOOL

MONTEREY, CALIFORNIA

THESIS

SINGLE FUEL CONCEPT FOR MARITIME OPERATIONS: EFFECTS ON TACTICAL AND OPERATIONAL READINESS AND SUSTAINMENT THROUGH SIMULATION AND ANALYSIS

by

Edwin F. Jimenez, John T. Walters, and Dale P. Lessner

June 2020

Thesis Advisor:	Geraldo Ferrer
Co-Advisor:	Ira A. Lewis

Approved for public release. Distribution is unlimited.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2020	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE SINGLE FUEL CONCEPT FOR MARITIME OPERATIONS: EFFECTS ON TACTICAL AND OPERATIONAL READINESS AND SUSTAINMENT THROUGH SIMULATION AND ANALYSIS	**5. FUNDING NUMBERS** W0A18
6. AUTHOR(S) Edwin F. Jimenez, John T. Walters, and Dale P. Lessner	
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) Monterey	**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.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This thesis analyzed the potential operational benefits and force structure reductions to the U.S. Combat Logistics Force provided by the single fuel concept (SFC). We used inventory pooling analysis to examine historical combatant demand patterns for F-76 and JP-5 to determine whether the SFC would expand afloat storage capacity and increase refueling logistics responsiveness through demand variability reduction across fleets. We then developed an unclassified major combat operations (MCO) deterministic scenario involving multiple task groups within the U.S. Indo-Pacific Command area of responsibility. We used a steady-state model to calculate the number of shuttle ships and stations ships required to support the scenario using the SFC, as compared to F-76 and JP-5. This thesis demonstrated adopting JP-5 as the Navy's single fuel would increase maritime refueling service capacity at sea and reduce the number of ships required to support MCOs with long transit distances between defense fuel support points and the area of operations.

14. SUBJECT TERMS single fuel concept, SFC, maritime operations, Indo-Pacific, major combat operations, MCO, F-76, JP-5	**15. NUMBER OF PAGES** 91
	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. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

SINGLE FUEL CONCEPT FOR MARITIME OPERATIONS: EFFECTS ON TACTICAL AND OPERATIONAL READINESS AND SUSTAINMENT THROUGH SIMULATION AND ANALYSIS

Edwin F. Jimenez
Lieutenant Commander, United States Navy
BSBA, Philippine Women's University, 1994

John T. Walters
Lieutenant, United States Navy
BS, Texas A & M University, 2010

Dale P. Lessner
Lieutenant Commander, United States Navy
BS, Indiana University of Pennsylvania, 2006
MBA, Naval Postgraduate School, 2020

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF BUSINESS ADMINISTRATION

from the

NAVAL POSTGRADUATE SCHOOL
June 2020

Approved by: Geraldo Ferrer
Advisor

Ira A. Lewis
Co-Advisor

Eddine Dahel
Academic Associate, Graduate School of Defense Management

ABSTRACT

This thesis analyzed the potential operational benefits and force structure reductions to the U.S. Combat Logistics Force provided by the single fuel concept (SFC). We used inventory pooling analysis to examine historical combatant demand patterns for F-76 and JP-5 to determine whether the SFC would expand afloat storage capacity and increase refueling logistics responsiveness through demand variability reduction across fleets. We then developed an unclassified major combat operations (MCO) deterministic scenario involving multiple task groups within the U.S. Indo-Pacific Command area of responsibility. We used a steady-state model to calculate the number of shuttle ships and stations ships required to support the scenario using the SFC, as compared to F-76 and JP-5. This thesis demonstrated adopting JP-5 as the Navy's single fuel would increase maritime refueling service capacity at sea and reduce the number of ships required to support MCOs with long transit distances between defense fuel support points and the area of operations.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	anti-access/area denial
Ao	operational availability
AOR	area of operational responsibility
API	American Petroleum Institute
AS	submarine tender (United States Navy hull classification)
ASTM	American Society for Testing and Materials
bbl	barrel, 42 U.S. gallons (crude oil and petroleum products)
BLS	U.S. Bureau of Labor Statistics
CG	Ticonderoga-class guided-missile cruiser
CLF	Combat Logistics Force
CNA	Center for Naval Analyses
COMPACFLT	Commander, U.S. Pacific Fleet
CONOPS	concept of operations
CONSOL	consolidated logistics
CHOP	change of operational control
CuNi	copper nickel
Cv	coefficient of variation
CVN	Nimitz-class nuclear aircraft carrier
DDG	Arleigh Burke-class guided-missile destroyer
DFM	Diesel Fuel Marine
DFSP	Defense Fuel Support Point
DLA	Defense Logistics Agency
DMO	distributed maritime operations
DA	U.S. Department of the Army
DoD	U.S. Department of Defense
DoN	U.S. Department of the Navy
DOS	days of supply
DSH-76	Direct Sugar to Hydrocarbon F-76
DSRA	dry-docking selected restricted availability
EIA	U.S. Energy Information Administration
ERQ	economic reorder quantity
F-76	military specification Diesel Fuel Marine
FSII	Fuel Systems Icing Inhibitor
FY	fiscal year
JFTOT	Jet Fuel Thermal Oxidation Test
JP-5	military specification kerosene-based shipboard jet fuel

JP-4	military specification 50–50 kerosene-gasoline blend
JP-8	military specification kerosene-based universal (air and ground) fuel
KG	center of gravity (physics)
kn	knot
LCS	littoral combat ship (United States Navy hull classification)
LEL	lower explosive limit
LHA	landing helicopter assault ship (United States Navy hull classification)
LHD	landing helicopter dock ship (United States Navy hull classification)
LPD	San Antonio-class landing platform dock
LSD	landing ship, dock (United States Navy hull classification)
MARAD	U.S. Maritime Administration
MCO	major combat operations
MGO	marine gas oil
MIL-DTL	defense detail specification
MIL-SPEC	military specification
MJ	megajoule
MSC	Military Sealift Command
MSP	Maritime Security Program
MT	metric ton
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NAVSUP	Naval Supply Systems Command
NF&L CFT	Naval Fuels & Lubricants Cross Functional Team
nmi	nautical mile
NSFO	Navy Special Fuel Oil
NSS	National Security Strategy
NSWCCD	Naval Surface Warfare Center Carderock Division
NWP	Navy Warfare Publication
OPLAN	operational plan
OPORD	operations order
PWRR	Prepositioned War Reserve Requirement
PWRS	Prepositioned War Reserve Stock
RIMPAC	Rim of the Pacific Exercise

SFC	Single Fuel Concept
SDA	Static Dissipative Additive
SPA	Systems Planning and Analysis, Inc.
SS	safety stock
TOS	time-on-station
UEL	upper explosive limit
UNREP	underway replenishment
USAF	United States Air Force
USCENTCOM	United States Central Command
USINDOPACOM	United States Indo-Pacific Command
USMC	United States Marine Corps
USNS	United States Naval Ship
USS	United States Ship
V/E	vehicles and equipment

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

This thesis analyzed the potential operational benefits and force structure reductions to the U.S. Combat Logistics Force (CLF) provided by the Single Fuel Concept (SFC). We used inventory pooling analysis to examine historical combatant demand patterns for F-76 and JP-5 to determine whether the SFC would expand afloat storage capacity and increase refueling logistics responsiveness through demand variability reduction across fleets. We then developed an unclassified Major Combat Operations (MCO) deterministic scenario involving multiple task groups within the U.S. Indo-Pacific Command (USINDOPACOM) area of responsibility. We used a steady-state model to calculate the number of shuttle ships and stations ships required to support the scenario using the SFC, as compared to F-76 and JP-5. This thesis demonstrated adopting JP-5 as the Navy's single fuel would increase maritime refueling service capacity at sea and reduce the number of ships required to support MCOs with long transit distances between Defense Fuel Support Points and the area of operations.

In investigating the impact to maritime refueling operations through the adoption of JP-5 as the single fuel at sea, we address whether the SFC can enhance refueling logistics capabilities at operational and tactical levels of maritime warfare, by answering the following questions:

1. Does the SFC improve afloat fuel inventory postures and reduce afloat fuel demand variability?
2. How many shuttle and station ships are required to support proposed contingency operations within USINDOPACOM using the SFC, and does task force endurance increase, when compared to status quo?

Our analysis shows that the SFC provides measurable operational benefits to the responsiveness and flexibility of maritime refueling logistics, primarily through enhanced CLF capacity to meet customer demand. Additionally, through recent historical analysis, it is estimated that all three primary refueling CLF classes and every numbered fleet would experience afloat storage capacity expansion through inventory pooling effects due

to SFC implementation. Furthermore, under the SFC “Go Big” concept of operations, when compared to the dual fuel concept of operations the Navy currently operates under, fewer fleet oilers and tankers would be required to provide the same level of service and logistics refueling capability during high-intensity operations, and task force endurance would be increased.

The following are the results of our analysis:

1. Inventory pooling effects would improve T-AKE refueling capacity by 20.29 percent, and 12.32 percent for T-AOs.

2. The SFC yields the equivalent additional storage capacity of 1.94 T-AKEs and 1.31 T-AOs, worth $1.61 billion in cost-avoidance.

3. Every number fleet would experience demand variability reduction and improved refueling service capability and responsiveness.

4. We estimate that MSC port visits could have been reduced from anywhere between 4 to 31 fewer annually.

5. Modeled T-AO and tanker requirements to support task group operations were reduced by one each.

6. Modeled task group endurance would increase by up to three days and operational range expands up to 1,080 nmi without sacrificing combatant operations or increasing required CLF force structure.

I. INTRODUCTION

The Secretary of the Navy's *2019 Operational Energy Goals* tasked the Chief of Naval Operations (CNO) and the Commandant of the U.S. Marine Corps (USMC) to enhance the lethality and effectiveness of forces through energy resilience, operational reach, and time-on-station (TOS) for forward-presence naval forces (Department of the Navy [DoN], 2019). Important to this effort is the sustainment and enhancement of the Navy's primary maritime fuel logistics transportation and delivery capability, the Combat Logistics Force (CLF). This thesis aims to detail the inherent operational benefits provided by supply chain simplification via the Single Fuel Concept (SFC).

A. SINGLE FUEL CONCEPT

The United States Department of Defense (DoD) consumed 85 million barrels (bbls) of fuel in fiscal year (FY) 2018, totaling $9.1 billion in annual expenditures, supporting the operational energy demands of all military components making it the largest user of energy in the world (Office of the Under Secretary Defense for Acquisition and Sustainment, 2019). The report goes on to note that DoD is challenged in meeting its operational energy strategy goals because multiple fuels contain unique characteristics required by different DoD components. Additionally, DoD components are required to "minimize the types of bulk petroleum products that must be stocked and distributed, plan to use fuels readily available worldwide, and minimize the military-unique characteristics of DoD fuels" (Joint Chiefs of Staff [JCS], 2017, p. I.2). Also, in line with JCS guidance, the DoN *Business Operations Plan*: *Agility and Accountability Fiscal Year 2020–2022* (2019), outlined strategic plans to improve business processes and "provid [e] forces with the right fuel, in the right place, at the right time," (JCS, 2017, p. I.1) and minimize the impact of military-unique DoD requirements. Therefore, the SFC has the possibility to meet these goals by reducing the number of bulk petroleum products stored and distributed, while still meeting various unique DoN requirements.

Currently, the Navy uses two types of fuel at sea, Naval Distillate Fuel (F-76) for ship's propulsion aboard conventionally powered ships, and Jet Propulsion – 5 (JP-5) for naval aircraft (Tosh et al., 1992). Prior to the late 1960s, the Navy used three types of fuels: Navy Special Fuel Oil (NSFO) for steam boiler plants, Diesel Fuel Marine (DFM) for combustion engines, and Jet Propulsion-5 (JP-5) fuel for Navy aircraft. In 1967, there was a motivation within the Navy to adopt JP-5 as a single fuel at sea (Tosh et al., 1992). In contrast, this strategy was discarded because the cost of JP-5 at that time was double the standard price of NSFO, and it was doubtful that existing worldwide JP-5 refining capacity could meet the projected demand. Thus, multiple fuel utilization continued for powering all non-nuclear ships.

According to research conducted by Garrett (1993), the first motivation for having a single fuel on the battlefield for the U.S. Army and U.S. Air Force (USAF) was in 1986. Originally, Jet Propulsion-4 (JP-4) was used for powering aircraft, and diesel engines of nearly all tactical ground vehicles and equipment (V/E). Then, in 1988, after a series of tests and demonstrations at Fort Bliss to confirm the usability of Jet Propulsion-8 (JP-8), the USAF, Army, and North Atlantic Treaty Organization (NATO) embraced JP-8 as the single fuel, replacing JP-4 and No. 2 diesel fuel. Despite JP-8 being suitable as a single fuel for both aviation and ground use, it is not suitable for maritime use and storage in naval vessels. The primary reason is its lower flash point when compared to JP-5, which will be discussed in detail in *Background: Fuel Descriptions and Characteristics*.

Subsequently, in light of this success using a single fuel on the battlefield for land-based applications, the Navy revisited the SFC (Tosh et al., 1992). In this study, Belvoir Fuels and Lubricants Research Facility (BFLRF) in San Antonio, Texas, recommended a similar policy for the Navy to adopt JP-5. This was due to several benefits, including, "[ease] for tanker and oiler crews in tank cleaning and purging between loads; less possibility of inter-fuel contamination; and less bookkeeping on fuel rotation, etc." (p. 16). The study concluded that converting to "JP-5 would not be detrimental to fleet operational readiness" (p. 26). However, due to the F-76 and JP-5 price differential—then five cents—researchers also identified a projected seven percent annual fuel cost increase, approximately $103 million per year. More recently, a thesis by Sermarini (2000) showed that cost, as well as JP-5 production capacity, remained an issue.

Beginning in 2017, the price differential changed, closing to one cent per gallon, which will remain steady through September 30, 2020, according to McCusker (2019). Although it is hard to determine if the price differential will continue, today, the U.S. is the largest global crude oil producer and JP-5 refiner, enabling domestic control of price and production to support DoD operational energy demands (U.S. Energy Information Administration [EIA], 2018).

B. OBJECTIVE AND RESEARCH QUESTIONS

In investigating the impact to maritime refueling operations through the adoption of JP-5 as the single fuel at sea, we address whether the SFC can enhance refueling logistics capabilities at operational and tactical levels of maritime warfare, by answering the following questions:

1. Does the SFC improve afloat fuel inventory postures and reduce afloat fuel demand variability?

2. How many shuttle and station ships are required to support proposed contingency operations within U.S. Indo-Pacific Command (USINDOPACOM) using the SFC, and does task force endurance increase, when compared to status quo?

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

A. INTRODUCTION

This chapter provides the reader with a general understanding of maritime fuel logistics necessary to assess the impact of the SFC on afloat fuel inventory postures and CLF force structure. Specifically, this chapter contains information on future operational strategy, the fuel logistics supply chain, and types of fuel used by the DoD.

B. KEY SUPPORTING OPERATIONAL CONCEPTS

1. Distributed Maritime Operations

In December 2018, CNO Admiral John Richardson, in *Design for Maintaining Maritime Superiority 2.0 (Design 2.0)* (2018), proposed Large Scale Exercise (LSE) 2020 to test the effectiveness of Distributed Maritime Operations (DMO); the focus of LSE is to conduct simulated major combat operations (MCOs) at the fleet level using multiple carrier strike groups (CSGs) and other military components spread over a vast area. The planned LSE will occur between Guam and Hawaii (Werner, 2019), and as Admiral Richardson indicates, the exercise is similar to the Valiant Shield and Rim of the Pacific (RIMPAC) exercises in the USINDOPACOM AOR, which tests our different military branches' wargame capabilities in response to a wide range of missions at sea, in the air, and on land. According to *Design 2.0,* "the logistics capabilities needed to refuel, rearm, resupply, and repair our operational forces" in support of LSE are paramount to sustaining the fight (CNO, 2018, p. 6). *Design 2.0* goes on to prioritize developing options for more agile and resilient refueling capabilities to strengthen our Naval power projection through DMO. Therefore, the SFC is one option that would provide enhanced inventory postures and improved responsiveness in support of DMO, by simplifying the fuel supply chain with identical or reduced maritime refueling logistics force structure.

2. Naval Refueling Behavior

Navy Warfare Publication: (*NWP*) *Navy Planning* defines an "operations order (OPORD) [as] a directive issued by a commander to subordinate commanders for the purpose of effecting the coordinated execution of an operation." (DoN, 2013, p. 6.4). It goes on to explain that OPORDs allow for commander discretion in carrying out prescribed orders to best accomplish mission objectives. For example, Commander, U.S. Pacific Fleet (COMPACFLT) *OPORD 201* Annex D, which is nearly identical to most other Fleet commander OPORD guidance for fuel, directs naval vessels to fill their fuel tanks at any practicable and available opportunity (2015). This applies to both end-user combatant vessels as well as the CLF, as this requirement is intended to maintain CLF and combatant storage levels to their fullest. While this increases the frequency between refueling events in peacetime, it is meant to ensure that in emergency or contingency situations, stocks are already replenished, and TOS and the available time between future refueling events are extended. This is most notable during warfare operations in contested environments. Since the directive provides commanding officers and ship masters with the operational flexibility to best decide when to refuel, as opposed to mandated inviolate tank levels or scheduled periodicities, average afloat fuel inventory levels are not solely influenced by vessel-specific consumption rates. Instead, varying individual risk tolerances and behavioral patterns, in response to situation-specific requirements, are also influential in determining average fuel inventory postures.

C. MARITIME FUEL LOGISTICS KEY PLAYERS

1. DLA Energy

According to Defense Logistics Agency (DLA) Energy's factsheet, the agency is responsible for sourcing, distributing, and storing fuel in support of DoD requirements around the world (2020). The factsheet goes on to state that DoD petroleum supply chains traditionally begin with domestic and international fuel contracts; specifically, for the Navy's supply chain, DLA Energy contracts were used to procure 9.14 million bbls of JP-5 and 43.1 million bbls of F-76. Terminal operations are next in the chain, with 597 worldwide Defense Fuel Support Points (DFSP), which include ashore facilities and afloat tankage within the hulls of MSC's CLF vessels (2020). Finally, DLA Energy's responsibility typically ends at tactical distribution, such as an underway replenishment (UNREP) between CLF vessels and combatants.

2. Military Sealift Command

The *2017 National Security Strategy* (*NSS*) states that the U.S. "will maintain a forward military presence capable of deterring and, if necessary, defeating any adversary [in the Indo-Pacific area of operational responsibility (AOR)]" (White House, 2017, p. 47). To achieve these ends, U.S. military planners require operational strategies capable of projecting military forces into contested environments over 5,000 nautical miles (nmi) from the contiguous United States. The means often used to achieve these ends are large, fuel hungry CSGs, as shown in Figure 1, which constitute the majority of sea-going military forces. A typical CSG is composed of one Nimitz class nuclear aircraft carrier (CVN) and her associated air wing, composed of 70 aircraft, one Ticonderoga class guided-missile cruiser (CG), several Arleigh Burke class guided-missile destroyers (DDGs), an attack submarine, and one Fast Combat Support Ship (T-AOE). Additionally, to meet the multi-product demands of a CSG, it is necessary to maintain robust, reliable, and uninterrupted lines of communication (LOCs) comprised of supplies, ammunition, and fuel. The primary means to support fuel LOCs is the Military Sealift Command's (MSC) CLF.

Figure 1. CSG-5 and flagship, USS *Ronald Reagan* (CVN 76) on patrol in the Indo-Pacific AOR. Source: Commander, U.S. 7TH Fleet (2016).

a. Fleet Replenishment Oiler

The backbone of the CLF's fuel delivery capabilities is met by 15 Henry J. Kaiser Class fleet replenishment oilers T-AOs, as shown in Figure 2 (MSC, 2020a). According to *NWP: Sustainment at Sea* (DoN, 2007), T-AOs provide underway replenishment fuel to U.S. Navy ships at sea and aircraft assigned to aircraft carriers. Generally, fleet replenishment oilers come in two variants, single hull and double hulled. Currently, the Navy has three ships (T-AO 201, 203 and 204) equipped with double hulls to comply with the Oil Pollution Act of 1990. As a result, the single-hull variant possesses a 90,260 bbls storage capacity for each product; whereas, the double hull configuration only possesses 77,160 bbls of storage capacity for each product. Both port and starboard sides of the ship have refueling stations enabling UNREP of two ships simultaneously, pumping up to 28,571 bbls of F-76 and 17,142 bbls of JP-5 per hour. The ship can steam up to 20 knots (kn) with a maximum operational range of 3,000 nmi. Additionally, T-AOs have the capability to perform fuel consolidated logistics (CONSOL) operations with both long-term and short-term charted commercial tankers (T-AOTs), significantly extending fuel LOCs.

Figure 2. USNS *Henry J. Kaiser* (T-AO 187), the lead ship of her class. Source: MSC (2020b).

b. Fleet Ordnance and Dry Cargo

The fourteen ships in the Lewis and Clark Class (T-AKE) were constructed to provide multi-product cargo and ammunition UNREP capability to U.S. Navy ships and aircraft assigned to aircraft carriers (MSC, 2020c), as shown in Figure 3. According to (DoN, 2007), out of the 14 ships of her class, 12 are designated to provide multi-product support to the Navy fleet while 2 ships are designated to provide support to USMC at sea as part of the Maritime Prepositioning Force. While it was not primarily designed as a fuel carrying vessel, it does possess a cargo F-76 capacity of 7,000 bbls and a JP-5 capacity of 17,000 bbls, and the ship can steam up to 20 kn with a maximum operational range of 14,000 nmi. In contemporary operations, the T-AKEs operate in conjunction with the T-AOs to provide station ship logistics to CSGs.

Figure 3. USNS *Cesar Chavez* (T-AKE 14) performing UNREP operations. Source: MSC (2020d).

c. Fast Combat Support Ship

Similar to T-AKEs, the two ships of the Supply Class (T-AOE) were constructed to provide rapid multi-product cargo and ammunition UNREP to U.S. Navy ships and aircraft assigned to aircraft carriers (DoN, 2007), as shown in Figure 4. Furthermore, T-AOEs can receive ammunition, food, repair parts, store items, and fuel from shuttle ships while simultaneously redistributing these cargos to U.S. combatants. This unique capability reduces the amount of time combatants are alongside; therefore, reducing their vulnerability to attack in a contested environment. According to *NWP: Sustainment at Sea* (DoN, 2007), it can steam up to 25 kn, necessary to keep pace with CSG flanking speed, with a maximum operational radius of 3,000 nmi, and can carry 2,150 tons of ammunition, 500 tons of dry stores, 250 tons of refrigerated stores, and more than 177,000 bbls of oil.

Figure 4. USNS *Rainer* (T-AOE 7) underway in the Indo-Pacific AOR. Source: DoN (2020).

d. Petroleum Tankers

Six T-AOT Tankers under MSC’s Combatant Command Support program, as showcased in Figure 5, deliver petroleum products to DFSPs worldwide (MSC, 2020e). According to *NWP: Sustainment at Sea* (DoN, 2007), T-AOTs have an operational range equal to 6,000 nmi and can carry 118,500 bbls of fuel cargo to support operational fuel requirements.

Figure 5. MT *Empire State* (T-AOT 5193) MSC tanker conducts sea trials off the coast of San Diego. Source: Seal (2000).

Currently, there are two U.S. flag vessels in the U.S. Maritime Administration (MARAD) Maritime Security Program (MSP) (M. Sweeney, email to authors, March 17, 2020). As of March 12, 2020, according to MARAD data statistics, the U.S. currently has 99 tankers eligible for MSP recruitment (Vough, n.d.). According to Sweeney, this program provides DoD access to a versatile fleet of government-owned/controlled or privately-owned, U.S.-flagged vessels that are ready to support a global, intermodal transportation network of terminals, facilities, and logistics management services. Such long-range tankers can carry from 310,000 bbls up to 615,000 bbls of petroleum products (EIA, 2014).

D. FUEL CHARACTERISTICS AND DESCRIPTIONS

1. Flash Point

Flash point is the lowest temperature at which vapors will ignite by an ignition source (DA, 2015). Therefore, the lower the flash point, the more vulnerable combatant ships are to fire and mishaps.

2. Explosive Range

The *Army Techniques Publication 4–43 (ATP 4-43)* states that “a mixture’s lower explosive limit is formed at about the product’s flash point” (2015, p. 3.3). As fuel and air are mixed, a possibly explosive or flammable mixture is created. Any mixture above the upper explosive limit (UEL) value for the gas/vapor is rich to ignite and explode, and any mixture below the lower explosive limit (LEL) is lean and will not ignite, as there is not enough fuel present in the air to burn (DA, 2015). Explosive ranges vary among fuel types and a mixture within the explosive range ignites when in contact with an ignition source. *ATP 4-43* goes on to state that "in open spaces, this causes an intense fire. In enclosed spaces, such as an empty tanker, the mixture explodes… The key point is that an empty or nearly empty petroleum tank, or container is still dangerous due to remaining fuel vapors" (p. 3.3).

3. Volumetric Density

A defining characteristic of fuel types per American Petroleum Institute (API) standards is volumetric density, or the API gravity of a standard mass per volume, at a constant temperature, expressed as kg/L at 15°C (59°C).

4. Energy Density

Individual fuel types have specific energy density profiles. Energy density is a measure of the net heat production at the moment of combustion, or the stored potential energy in a standard mass, expressed as megajoules per kg (MJ/kg).

5. Jet Fuel Additives

Additives in government-owned, military-grade jet fuel stocks can be included during the refining process or injected in pipeline or during discharge at the DFSP (DA, 2015). The standard military-grade additive package for the majority of jet fuels used by DoD include Fuel System Icing Inhibitor (FSII), Static Dissipative Additive (SDA), and Corrosive Inhibitor/Lubricity Improver. First, FSII is an anti-icing additive that reduces the freezing point of water to prevent the formation of ice crystals in fuel lines, which reduces the flow of fuel to the engine (DA, 2015). Additionally, FSII aides in the removal of entrained water molecules during filtration. Second, SDA increases a fuel's electrical conductivity, thereby reducing its likelihood of electrostatic buildup and resultant explosive hazards (DA, 2015). Therefore, this is especially important for the safe operation of rotary wing aircraft during “hot” refueling. Lastly, CI/LI contains an active ingredient called dimer of linoleic acid that “has been shown to reduce corrosion and improve lubricity” in “dryer” fuels (Johnson et al., 2014). Therefore, CI/LI adds lubricity on roller bearings when pumping fuel and an effective anti-corrosion agent in fuel line tubing.

E. FUEL TYPES

1. Fuel Oils

The *ATP* describes fuel oil as a petroleum product obtained through distillation, varying in type as a distillate or as a residual oil classified by different numerical fuel grades (2015). As the *ATP* states, “the term fuel oil is also used in a stricter sense to refer only to the heaviest commercial fuel that can be obtained from crude oil… Broadly speaking, fuel oil is any liquid petroleum product that is burned in a furnace or boiler for the generation of heat or used in an engine for the generation of power” (p. 3.1). While fuel oils are generally stable with safe flash points and explosive ranges, they are not suitable for aviation use due to their higher freeze and cloud points. For example, F-76’s cloud point is -1°C (30°C) (DoD, 2014), which would invite clogging in fuel injection systems at low ambient temperatures, which are present at high altitudes, due to paraffin wax crystallization and coagulation.

a. Marine Gas Oil

Marine Gas Oil (MGO) is approved for use as an alternative bunker fuel [in naval vessels] only when F-76 is not available (Sermarini, 2000, p. 11). Additionally, this type of fuel is not stable over the long-term and must be used before sludge forms in storage tanks, thus requiring considerable filtration. In a telephone conversation with the Energy Plans and Policy Branch, Deputy CNO, Sermarini quotes Roberts (personal communication to author, February 17, 2000) as stating that “Coast Guard maintenance personnel believe that continuous and long-term use of MGO results in greater wear and higher maintenance costs than when F-76 is used” (p. 12).

b. Diesel Fuel

Diesel fuel is a predominant fuel used in an internal compression engine where ignition of the fuel takes place as a result of elevated air temperature in the tank compressed by the piston (Garrett, 1993). Diesel fuel has a flash point of 52°C (126°F), which is lower than F-76 (Monroe, 2016). The most common type of diesel fuel is No. 2 diesel, or DF-2, a middle-distillate used for automobile diesel and gas turbine engines.

c. F-76

Naval distillate fuel, F-76, previously known DFM, is the MIL-SPEC distillate fuel equivalent to No. 2 diesel and delivered on the ship by fleet oilers for ships' boilers and diesel engines (DoD, 2014). F-76's density at 15°C (59°F) is between 0.800 kg/L minimum, and 0.876 kg/L maximum (DoD, 2014). Its flash point is 60°C (140°F) like JP-5, and its explosive range is narrow at 0.6 LEL and 6.5 UEL. (CITGO Petroleum Corporation, 2016). Like JP-5, F-76 must meet tight storage stability requirements.

Notably, *MIL-DTL-16884N* does not require a minimum heating value for F-76. However, *MIL-DTL-16884N* Appendix A does provide a minimum heating value by mass of 43.5 MJ/kg for a related product, Synthesized Paraffinic Diesel (DoD, 2014). This product is dissimilar to F-76 in several ways and thus, a more accurate representation of F-76's heating value required research beyond MIL-DTL standards.

A Naval Fuels & Lubricants Cross Functional Team (NF&L CFT) report detailed fit-for-purpose analysis on traditionally refined F-76 and a potential alternative, Direct Sugar to Hydrocarbon F-76 (DSH-76), colloquially known as "bio diesel," (Weisser & Turgeon, 2013). The report's analysis used 43 MJ/kg as the required minimum heating value benchmark when comparing the two products, which was higher than the observed average 42.7 MJ/kg F-76 sample result.

2. Kerosene Fuels

Kerosene is a mid-weight liquid hydrocarbon chain that is light in color and was once used primarily for lighting in cities before mass electrification (Green, 2017). Today, kerosene is primarily refined into jet fuel, designed for use in gas turbine engine powered aircraft (DA, 2015). Additionally, kerosene products are less volatile and safer to store and transport than Naphtha products, like gasoline, which has a -43°C (-45°F) flashpoint.

a. JP-4

JP-4 fuel is a 30 percent kerosene, 70 percent gasoline mixture with a large concentration of light liquid hydrocarbon chains and weighs less than kerosene, which is a desirable characteristic for aviation (Deziel, 2019). Additionally, it has a low flash point of -23ºC (-9°F), which makes it less safe to store than other jet fuels, but its low freezing point of -58ºC (-72°F) makes it advantageous for use in exceedingly cold environments. Furthermore, JP-4 has a 1.3 percent LEL and 8 percent UEL (Product Safety and Toxicology Group, 2016). Due to JP-4's low flash point and relatively wide explosive range, it is unsafe for storage at sea.

b. JP-8

JP-8 is a widely used complete kerosene blend that is the least expensive for DoD to procure and viewed as an acceptable substitute for No. 2 diesel (Deziel, 2019). Additionally, it is nearly identical to commercial jet fuel variants but includes the standard military fuel additive package. Furthermore, JP-8 has a minimum flash point of 38ºC (100°F), and a minimum energy density of 42.8 MJ/kg, which is slightly higher than JP-5 (DoD, 2015). As JP-8 is cheaper to produce, has an identical explosive range, and stores more potential energy than JP-5, it would seem to be a suitable substitute for maritime aviation. However, while JP-8's flash point is still lower than that of JP-5 or F-76 and is less safe to store at sea.

c. JP-5

JP-5 is a kerosene-based jet fuel first developed in 1952 for use in aircraft aboard naval vessels (Hemighaus et al., 2007) By definition, JP-5's density at 15°C (59°F) is between 0.788 kg/L minimum and 0.845 kg/L maximum and its energy density must meet or exceed 42.6 MJ/kg (DoD, 2016a). Amerada goes on to state that both JP-8 and JP-5 have the same explosive range of 0.7 percent LEL and 5 percent UEL.

The most significant distinction of between JP-5 and all other jet fuels is its high flash point of 60°C (140°F). This distinction makes it safe for use on aircraft carrier flight decks, where ambient temperatures can often exceed 38ºC (100°F) (Sermarini, 2000). In turn, F-76 cannot be safely used in aircraft. For these reasons, JP-5 is the only acceptable substitute for F-76 and historical operations confirm its versatility. Additionally, in 1982 and 1983, during the Iranian crisis, which restricted access to F-76 stores and shipping lanes through the Persian Gulf, JP-5 was used in lieu of F-76 onboard navy vessels in the Indian Ocean without any documented negative consequences (Tosh et al., 1992).

III. LITERATURE REVIEW

The following sections detail prior research and studies related to this thesis. It begins by detailing the Army's successful transition to a single fuel on the battlefield demonstrating simplified fuel logistics and greater service interoperability. Then, we examine research into energy requirements within USINDOPACOM AOR and the DoD's ability to meet them with anticipated force structure and resourcing. Next, we include studies into the cost, operational impacts, and feasibility of the Navy converting to the SFC, and selected associated counterarguments. Finally, we close by specifying how our thesis will contribute to this field of work.

A. SINGLE FUEL ON THE BATTLEFIELD

The executive research project by Garrett (1993) discusses how both the USAF and U.S. Army came to adopt JP-8 as the single fuel on the battlefield due to separately encountered problems. The initial impetus for adopting JP-8 started in 1986 when the USAF and Army agreed to investigate substituting JP-8 for JP-4 and No. 2 diesel. According to Garrett, USAF had determined that JP-4, which has a low flash point, was unsafe and volatile for continued use in their aircraft. Garrett goes on to describe how the U.S. Army's experienced wax crystallization buildup at low temperatures in No. 2 diesel, which clogged fuel lines and caused engine failure in M-1 tanks.

Likewise, in 1988, the U.S. Army Energy Office and the Belvoir Research, Development, and Engineering Center (BRDEC) conducted a comprehensive test and demonstration of JP-8 involving 2,800 diesel-powered V/E and consumed over 110,000 bbls (Butler et al., 1990). The purpose of the demonstration program was to observe compatibility of JP-8; identify mechanical issues; and monitor changes in fuel consumption. Similarly, a separate laboratory evaluation conducted by BRDEC in 1988 to test acceptability and endurance of JP-8 fuel in comparison to No. 2 diesel (Likos et al., 1988). Both demonstrations and laboratory tests revealed no significant impacts on V/E and no significant problems in any engine attributable to JP-8. However, some recommendations were presented that a further study must be conducted on the injection equipment to determine its durability at the maximum fuel temperature when using JP-8, and the development of new operation manual for proper handling of JP-8 and maintenance schedules of V/E.

Subsequently, in 1990, the Army and USAF adopted JP-8 as the SFC on the battlefield, but the Navy abstained because of the flash point issue (Garrett, 1993). Despite skepticism of using JP-8 due to minor mechanical problems encountered by U.S. Army personnel, some advantages were observed on the battlefield such as increased survivability when USAF shifted from JP-4 to JP-8, and simplified fuel logistics when U.S. Army converted from No. 2 diesel to JP-8 as they used this oil for both M-1 and helicopters. Those minor mechanical problems were assessed by BRDEC and found insufficient evidence or no significant mechanical problems of using JP-8. Finally, both branches achieved the DoD's goal to simplify fuel logistics operations on the battlefield and interoperability within our military components including our NATO allies (Le Pera, 2005).

B. REFINED FUEL WITHIN THE INDO-PACIFIC AOR

Folster et al. (2018) developed a model to estimate the number of commercial tankers available for charter to transport fuel to DFSPs within the USINDOPACOM AOR within a given week. Their model computed a mean, a minimum, and maximum of four, two, and seven tankers respectively available for charter on any given week. Then, they computed the number of tankers required to support a major contingency using Desert Storm daily fuel demand as their proxy. Next, using a daily demand of 56,000 metric tons (MT), a cycle-time of 18 days (loading/unloading/transportation time) between three major USINDOPACOM DFSPs, and an average tanker capacity of 36,000 MT, they computed 11 tankers per week were required to support fuel requirements. Using this information, together with the amount of tankers their model computed were available for charter in the USINDOPACOM area, their model was used to determine potential charter tanker shortfalls. By comparing the estimated amount of tankers available for charter against Desert Storm weekly tanker requirements, this demonstrated fuel shortfalls in every major contingency scenario evaluated.

C. OPERATIONAL IMPACT STUDY

The *Single Naval Fuel at Sea Feasibility Study – Phase Two Results* final report (Williams & Leung, 2011) details the findings of previous studies pertaining to seven primary focus areas related to SFC implementation, the first of which was the operational impacts of the SFC. The report states that SFC implementation would fail to yield any significant operational benefits, and the claim was based on the findings from the *Alternative Fuels Study Final Report Unclassified Version (U)*, conducted by Systems Planning and Analysis, Inc. (SPA) (D. Saks, personal communication, April 7, 2020).

The SPA analysis used a linear program to determine the minimum T-AO presence required to meet combatant demand, during peacetime operations within the three AORs. The study's MCO scenario models were constructed using steady-state surge requirements in the same three AORs. In each model iteration, the study assumed that at least three DFSPs were accessible and would remain uncontested, that no tankers were required, with T-AOs serving as shuttle ships, and that there was no variability in demand. Therefore, the study's results showed that proximity to DFSPs within the AOR was the primary driver for CLF composition. The study also concluded that the only combatants projected to experience positive endurance effects under the SFC were amphibious platforms with aviation operations capabilities. As described later in *Recommendations*, this result is due to the relatively large JP-5 storage tanks aboard amphibious warfare platforms, designed to service sustained aerial warfare operations.

D. UNIVERSAL FUEL AT SEA

A Naval Postgraduate School thesis entitled *The Universal Fuel at Sea: Replacing F-76 with JP-5* lists key maritime fuel logistics enablers inherent in the SFC (Sermarini, 2000). It showed that first, the SFC would provide greater flexibility in UNREP and CONSOLs between various CLF assets could be achieved through the use of a single product. Secondly, this work detailed that any efficiencies which the SFC can provide are warranted, as the MSC long-term chartered tanker fleet shrunk from 21 to five in the decade preceding 2000. Lastly, Sermarini points out that the U.S. has increasingly relied on foreign-flagged tankers for strategic petroleum lift transportation to DFSPs during both peacetime and contingency operations. Thus, in future conflicts, these foreign assets could be restricted from U.S. use by their respective governments, and thus, any added flexibility afforded by the SFC might prove critical for sustained operations.

E. TECHNICAL FEASIBILITY COUNTERARGUMENTS

In speaking with fuel professionals during our data collection efforts, several potential impediments to SFC implementation were mentioned. Below are brief descriptions of previous research and analysis conducted on the most notable topics.

1. Engine Performance and Wear

Lubricity has been thoroughly analyzed as a potential impediment to using JP-5 in F-76 based systems. Lubricity is a function of viscosity but not a measurable property (Wilson, 1996). Therefore, to determine a fluid's lubricity, test wear scarring patterns are compared to those produced from fluids with the same viscosity. Often, fluids with different densities will also have different viscosities. Additionally, the rates of change in viscosity between two fluids can vary at matching temperatures. Thus, viscosity requirements are the desired coating behavior of a fluid within a desired operating temperature range.

In terms of lubricity, the Belvoir Fuels and Lubricants Research Facility (BFLRF) detailed how kerosene-derived fuels, such as JP-5, provide less lubricity than F-76 (Tosh et al., 1992). The report goes on to describe that diesel engine components are manufactured with less restrictive spacing tolerances than are turbine engines and therefore are prone to surface contact between internal moving parts such as fuel injection valve components and cylinder walls and pistons. F-76 then provides inherent protection against friction and scarring.

In regard to viscosity, JP-5's must not exceed 7.0 mm^2/s at -20°C (-4°F) (DoD, 2016a). Required F-76 viscosity at 40°C (104°F) must remain between 1.7 mm^2/s and 4.3 mm^2/s (DoD, 2014). DoD is therefore concerned with JP-5's performance in turbines at great altitudes and low ambient temperatures, and with F-76's performance at sea level, where it is not nearly as cold and in turbines that operate for longer durations. By comparison, JP-8's required viscosity must not exceed 8.0 mm^2/s at -20°C (-4°F) (DoD, 2015). *ASTM D975* requires viscosity at 40°C (104°F) for No. 2 diesel, must be at least 1.9 mm^2/s and must not exceed 4.1 mm^2/s (ASTM, 2019). This means that by acceptable tolerances, JP-5 is more viscous and provides more lubricity than JP-8, and should be acceptable for use in F-76 engines.

A BFLRF report also details the inconsequential differences in performance and wear in either diesel engines or previously JP-4 propelled turbine engines upon conversion to JP-8 during field tests (Butler et al., 1990). Thus, the Army concluded that any harm incurred by using JP-8 in diesel engines was not significant enough to prevent widespread use of JP-8 as a preferred substitute according to its Single Fuel Forward initiative.

Likewise, a Naval Surface Warfare Center Carderock Division (NSWCCD) impact study details the effects of JP-5 usage on existing diesel engines in naval service at the time (Guimond, 2007). It concluded that preliminary studies showed minimal negative effects on diesel engines and recommended follow-on studies for newer, small diesel engines coming into service and on LCS class engines. It also recommended that extended JP-5 use trials be conducted on diesel engines to verify the findings of limited use trials. The impact study also drew on numerous instances of U.S. Coast Guard Cutter usage of JP-5 for extended periods of time with no meaningful reports of damage or negative maintenance or performance results.

Similarly, in a letter from the Technical Warrant Holder, Diesel Engines to Commander, Naval Sea Systems Command (NAVSEA), JP-5 use was recommended in LCS classes 1 and 3, both containing Diesel Main Propulsion Engines and auxiliary Services Diesel Generators (Pogarty, 2014). The technical warrant holder concluded that mishap frequency would remain rare and the resulting risk to the engines or generators low. In addition, in response to previous inquiries on the effect of JP-5 use in smaller naval diesel engines, a NF&L CFT report details the results of High Frequency Reciprocating Rig and Wear Scar Diameter tests on such engines (2018). It concluded that no negative performance results or any increased engine wear beyond original equipment manufacturer tolerances were observed due to JP-5 usage.

Lastly, a NSWCCD study detailed the impacts of using JP-5 in F-76 powered naval boiler platforms (Rebold, 2004). The study concluded that long term JP-5 use would produce no negative effects and limited performance degradation.

2. Preventive Maintenance and Filtration

In general, JP-5 burns cleaner and maintains overall fuel storage and piping system cleanliness better than F-76. Thus, there are preventative maintenance benefits to utilizing JP-5 in F-76 systems. For example, the boiler study showed cleaner firesides and would dramatically reduce man-hours for cleaning (Rebold, 2004). The study goes on to show that due to less frequent presence of entrained water in JP-5 than in F-76, flaking rust within piping systems was also reduced and therefore JP-5 usage was found to reduce instances of plugging in narrow diameter pipes such as injections points. Additionally, a Naval Air Systems Command (NAVAIR) report showed that JP-5 usage in ship's propulsion gas turbine engines produced significant savings in consumable components within filtration systems (2006). The report showed a marginal decrease in the number of filter changes in centrifugal purifier systems, a 68 percent reduction in pre-filter element changes, and a 72 percent reduction in filter/particle separator element changes.

3. Ship Stability Profiles

It is known that a ship's center of gravity (KG) is defined as the pivot point about which a ship will heel, or roll laterally due to wind or wave action while floating (Barrass, 2004). To that extent, a ship's basal KG is inherent to its design and will not change unless structural alterations were made to the ship, i.e., increasing the height of the mast would make it top-heavy and elevate its KG, or deepening the keel would lower its KG. Furthermore, a ship will become less stable and more prone to heeling if it is laden with weight above its KG or by lightening the weight of its load below the KG. For naval combatants, heeling is particularly important as these ships are more likely to conduct dynamic maneuvers in response to battle conditions than are commercial cargo and passenger vessels.

Specifically, *NAVSEAINST 9096.3E, Weight and Moment Compensation and Limiting Drafts for Naval Surface Ships*, lists the weight and KG impacts for each class of naval combatant (2005). Most classes of combatants are in a restricted stability status (2) or (3), meaning that a rise of a ship's KG cannot be accepted or must be avoided. Since internal fuel storage tanks aboard vessels are located below the KG, the KG is anticipated to elevate if less dense, lighter fuel is stored.

Likewise, an internal NAVSEA letter from the Technical Warrant Holder, Weight Control and Stability details analysis on the changes in buoyancy and KG for naval surface vessels caused by substituting JP-5 for F-76 (Cimino, 2007). It notes ship classes AS-39, LHA-1, and LHD-1 as most negatively affected pursuant to *NAVSEAINST 9096.3E* guidelines for stability. The letter also states that if SFC implementation is to be seriously considered, further analysis should be conducted to include live combatant trials and possible revisions to stability standards based on observed performance characteristics. This is a significant issue for the SFC, and needs additional attention and consideration by authoritative experts. One possible mitigation strategy is to alter engineering manuals and procedures to laden ships with more ballast water in ships propulsion fuel tanks and ballast tanks to counter balance the decreased weight of JP-5. The written procedures for mechanical onboard pumping and ballasting processes for large deck amphibious aviation platforms will need detailed examination in future research to determine if counter ballasting can overcome KG elevation.

4. Copper Nickel Contamination

Copper Nickel (CuNi) is a frequently used alloy in piping unions and joints aboard maritime vessels. However, hydrocarbons' prolonged exposure to CuNi causes deleterious effects to thermal stability and potential failure of the Jet Fuel Thermal Oxidation Test (JFTOT) per *ASTM 3241* test methods (Putnam, 2018).

As noted by Putnam in a NAVSEA Small Business Innovation Research white paper (2018), Joint Strike Fighter Command identified the adverse impact of copper in JP-5 fuel that "creates maintenance and repair issues, such as coking, for aircraft engines as well as impairs performance capability." (p. 1) Putnam goes on to note that CuNi contamination and JFTOT failure is more frequently observed in JP-5 stored aboard CVNs than aboard T-AOs and T-AKEs. This is primarily due to increased individual stock turnover and thus decreased exposure time aboard refueling ships as compared to combatants (Putnam, 2018).

We note that per *MIL-STD-3004D*, all fuel must pass A-series testing, to include JFTOT for jet fuels, prior to acceptance into DFSPs (DoD, 2016b). As fuel is passed further along the supply chain, less stringent C-series tests, which do not include JFTOT, are performed prior to acceptance from a shore DFSP into a CLF vessel, or from a CLF vessel into a combatant. JFTOT failure then becomes problematic once fuel is downloaded from a combatant back into a DFSP. *MIL-STD-3004D* also states that NAVAIR specifically calls for JFTOT testing in such instances.

Currently, prior to any ship entering dry-docking shipyard restricted availabilities (DSRA), remaining stored fuel is downloaded for future use in the most economical manner (DoD, 2016b). Often, JP-5 is downgraded and blended into F-76 stocks, which does not require JFTOT in A-series testing. Since fuel stored aboard CLF hulls are less likely to suffer CuNi contamination, the SFC is unlikely to prevent downloads back into DLA Energy storage. However, upon SFC implementation, downloads would only be able to be blended into JP-5 stocks.

Currently, no onboard mitigation systems exist, therefore, developing a CuNi contamination prevention, and/or filtration technology JP-5 is important in mitigating the deleterious effects of CuNi.

F. SUMMARY

Our review of the literature indicates that previous studies were focused on technical feasibility, costs, operational impacts, and force structure implications of switching to the SFC. However, there are gaps in evaluating F-76 and JP-5 historical demand to glean operational benefits of adopting the SFC, and gaps in modeling to determine force structure requirements using contemporary assumptions. Therefore, this study analyzes F-76 and JP-5 contemporary demand history, accounting for demand variability, to exploit inventory pooling effects, and perform modeling using contemporary threat, environment, and concept of operations (CONOPS) assumptions to determine force structure requirements based on adopting the SFC.

IV. METHODOLOGY

A. HISTORICAL DATA

Our data was aggregated by Naval Supply Systems Command (NAVSUP) inventory and accounting software, and provided by the Center for Naval Analyses (CNA), with the permission of NAVSUP (R. Fye, email to authors, October 10, 2019). The dataset spanned from April 1, 2014, to September 30, 2019, and included 27,250 data entries for fuel and non-fuel services and products provided by ashore and afloat units. All fuel transactions were originally in gallons but were converted to bbls for consistency throughout our analysis.

The data was filtered to remove all non-fuel transactions, and then segregated by ashore or afloat sources to isolate and analyze only those fuel transactions provided by CLF assets. The unused fuel data constitutes combatant-to-combatant transactions, such as JP-5 transferred from a CVN to a DDG, as well as transactions from ashore DFSPs or partner nation ashore or afloat assets to U.S. combatants. Then the data was partitioned by product type by each CLF ship. This allowed us to monitor combatant demand during each UNREP, the transaction date, and in which Numbered Fleet the UNREP occurred.

When partitioning the data into Numbered Fleets, if all UNREPs between onloads occurred within the same fleet, that demand data was assigned to that Numbered Fleet. If between CLF onload events, UNREPs occurred in two or more fleets, then that demand data was assigned as a change of operational control (CHOP) event. Of note, so few fuel-related UNREPs occurred in 4TH Fleet, that all transactions were added to either 2ND FLT or CHOP transactions, depending on circumstances.

In our analysis, a cycle for each product is defined as the period between CLF onloading events for that product type. The demand quantities for each product type, within each cycle, were then summed and further agglomerated into sub-datasets by CLF type and again by Numbered Fleet. Then, means and standard deviations of demand were produced for each product type within each of the two sub-dataset classifications.

Given that the central premise of this thesis is to analyze the operational impact of SFC implementation, all F-76 transactions were recalculated as η76 values. This enabled us to calculate the prospective quantities of JP-5 that would have been required for ships' propulsion across the dataset time span. Further explanation is provided below as to how our η76 value was calculated and why it is necessary when discussing the SFC.

B. APPLIED ANALYSIS TECHNIQUES

1. CLF Type Calculated Ao

The operational availability (Ao) of the CLF, in concert with the inventory pooling method, will be used in *Results* to estimate potential cost avoidance to the Navy. Per the authors' email correspondence with Commander, MSC headquarters staff (G. S. Palabrica, March 16, 2020), MSC defines Ao as "days available for tasking," which equates to the total number of days each CLF vessel is certified and operationally available during a year. In order to generate a composite Ao for T-AKEs and T-AOs respectively, spanning the dataset timeframe, we summed the annual average Ao for each type for years FY15 through FY19, which equaled 1,452.6 days for T-AKEs and 1,289.0 for T-AOs. Then, we divided these figures by the total number of days within FY15 through FY19, or 1,826 days. Thus, the Ao for the 12 hull T-AKE fleet was 79.6 percent and 70.6 percent for the 15 hull T-AO fleet. Of note, the T-AKEs USNS *Sacagawea* and USNS *Lewis and Clark* are considered prepositioned forces, and as such, no demand data was collected for them. Additionally, we declined to compute this figure for the two presently in-service T-AOEs, as the Navy has no plans for future shipbuilding of this type.

2. Calculating JP-5 Efficiency Loss

To analyze the impacts of the SFC on ship propulsion performance, a standard power output profile was computed to compare JP-5 and F-76. Since the SFC necessitates JP-5 as the single fuel, F-76 demand quantities across our dataset were multiplied by an efficiency value, η, to accurately measure the additional quantity of JP-5 that would have been consumed for ship propulsion in the SFC scenario. Our analysis utilized the 2013 NF&L CFT requirement of 43 MJ/kg for F-76, which is likely more stringent than necessary (Weisser & Turgeon, 2013).

For the purpose of calculation in comparing the energy density differences between JP-5 and F-76, we used the median API gravity profiles for JP-5 as 0.817 kg/L and as 0.838 kg/L for F-76. Then, each API gravity was multiplied by the minimum heating values by mass, 42.6 MJ/kg for JP-5 and 43 MJ/kg for F-76. Thus, the heating value by volume for JP-5 is 34.8 MJ/L at 15°C (59°F) and 36.0 MJ/L at 15°C (59°F) for F-76. JP-5 therefore contains only 96.5 percent of the potential energy of F-76. Stated differently, our computed η value would be equal to 36.0 divided by 34.8, or roughly 1.036. Then, η is multiplied by F-76 demand quantities within the dataset to produce calculated quantities of JP-5 that would be necessary under the SFC; we term these quantities $\eta 76$.

Likewise, previous boiler performance tests were conducted by NSWCCD (Rebold, 2004), and a report by the NF&L CFT (2018) lists the consolidated results of numerous diesel engine performance tests. These tests showed power output decreases that ranged from one to four percent, depending on the platform type and load requirements placed on the engine or boiler. A BFLRF report detailed comparative energy density test results between the two products and showed a 2.6 percent volumetric energy density deficit in JP-5 as compared to F-76 (Tosh et al., 1992).

While the BFLRF findings were derived from laboratory test results and our $\eta 76$ value is computed, we shall use the computed value for several reasons. First, the BFLRF tests were conducted nearly thirty years ago. Changes in the refining industry as well as regional differences between kerosene feed stocks and individual refineries can yield distinct results between samples. Secondly, our computed $\eta 76$ value is still within the one to four percent range confirmed by multiple separate agencies' more recent test results. Third, our computed value is more conservative and less generous to our analysis than using lower efficiency loss values.

Finally, while a three percent efficiency loss may appear significant, as will be shown in *Results*, upon applying our chosen analysis technique, the net "savings" to naval operational readiness will actually overcome the additional JP-5 required for ship propulsion.

3. Inventory Pooling Method

Inventory pooling, sometimes referred to as risk pooling, is a supply chain management technique widely used to mitigate demand uncertainty and lower overall inventory levels by consolidating stock points or reducing the variety of offered products. It is most beneficial where demand is varied and not positively correlated (Eppen, 1979). Supply managers retain certain levels of safety stock (SS) above those levels that are required to meet mean (μ) demand between resupply deliveries. Therefore, SS is only utilized when demand is greater than average, before stocks are replenished again. Conversely, if demand falls below average, then SS goes unutilized and unnecessary holding costs are incurred during that cycle. The ability to satisfy customer demand is known as the desired service level, and is more difficult to maintain, as variability in demand between cycles increases as some cycles may unexpectedly experience unusually high customer demand before resupply. The size of SS levels is calculated as a product of the desired service level and the standard deviation (σ) of demand variability during a cycle. Thus, if supply managers desire to maintain current service levels, but also reduce SS levels, then the variability in demand must decrease. Conversely, if SS levels remain unchanged, but supply managers desire to increase service levels, then again, the variability in demand must decrease.

If the demand for two products, in this case F-76 and JP-5, were pooled into demand for a single product under the SFC, the potential for lower demand for one product within a given time period may then offset the potentially higher demand for the second product. Thus, the pooled mean demand under the SFC is calculated as the sum of the of the averages of the two formerly distinct products and expressed as

$$\mu_{SFC} = \mu_{F-76} + \mu_{JP-5} .$$

Furthermore, the pooled risk in consolidating demand under the SFC is calculated by deriving the square root of the summed demand variances, or squared standard deviations, assuming demand is uncorrelated, during a cycle and is expressed as

$$\sigma_{SFC} = \sqrt{\sigma_{F-76}^{2} + \sigma_{JP-5}^{2}}\,.$$

Thus, SS and average inventory levels can be reduced, while maintaining service levels to meet the same consolidated mean demand, if the standard deviation of demand is reduced during a cycle (Eppen, 1979).

Inventory savings can then be directly measured by calculating the difference between the combined standard deviation for the single product and the sum of standard deviations across the distinct products and expressed as

$$\text{Inventory savings} = \left(\sigma_{F\text{-}76} + \sigma_{JP\text{-}5}\right) - \sigma_{SFC}\,.$$

A final way to measure performance improvements within a supply system is to look at the coefficient of variation (Cv). Cv is the ratio of the standard deviation relative to mean demand and expressed as

$$\text{Cv} = \frac{\sigma}{\mu}\,.$$

To measure performance improvement after inventory pooling, the combined Cv is compared to the individual Cv of separate markets. Cv analysis will be used to compare SFC implementation effects amongst Numbered Fleets and detailed in *Results*.

4. Calculated Mean and Standard Deviation of Demand

Before the inventory pooling technique can be applied to fuel demand, we first calculated the mean and standard deviation of demand for each product type, by each CLF type from our dataset. All F-76 demand quantities were multiplied by our computed SFC efficiency loss, η, before any other computations. Table 1 contains our results.

Table 1. Mean and standard deviation of demand by product and CLF type

		T-AKE (bbls)	**T-AO (bbls)**	**T-AOE (bbls)**
η76	**μ**	15,198	42,734	40,580
	σ	10,951	30,224	43,827
JP-5	**μ**	4,857	30,919	25,863
	σ	7,861	47,113	22,585

5. SFC Inventory Pooling Adaptation

Our analysis differs from traditional inventory pooling analysis by redefining cycle periodicities and reinterpreting inventory savings in this context. As will be shown, both deviations from traditional practices are driven by and necessary to accommodate the unique nature and requirements of maritime refueling operations.

First, unlike resupply to commercial facilities, which are often triggered by timed deliveries, CLF vessels onload at irregular intervals, and as often as practicable in compliance with *OPORD 201* guidance. Additionally, CLF service to combatants is flexible. For example, within a month, a CLF acting as the station ship for a CSG may be detached from regular duties to travel vast distances, in support of an independent-deployer combatant, to then CHOP and service a new AOR. Likewise, demand on CLF fuel stores is driven by the same OPORD guidance. For example, a combatant and CLF may UNREP again after only two or three days, if the combatant received unexpected orders to travel to an AOR without CLF coverage, and its next UNREP is unknown. For these reasons, our analysis treats a cycle as the period between onloads for each product type, instead of a fixed time period.

Secondly, whereas a goal for commercial facilities is to reduce inventory while maintaining service level, *OPORD 201* guidance mandates that CLF assets shall refill to their maximum allowable storage capacity as often as practicable. Thus, the reduction in standard deviation of demand during cycles may then be viewed as supplemental fuel brought into the battle space, and an increase in service level. Stated differently, under the SFC, the CLF could meet all combatant demand and transport less fuel; however, since they will remain as full as possible, at any given time, this excess fuel may be viewed as increased potential responsiveness, or as additional maritime refueling capacity at sea.

THIS PAGE INTENTIONALLY LEFT BLANK

V. SCENARIO

To define the maritime operational environment, the unclassified scenario developed for this thesis uses a fictitious conflict with the People's Republic of China. This scenario was determined relevant in light of what the *2017 NSS* identified as China's efforts to "build and militarize outposts in the South China Sea," which "endanger the free flow of trade, threaten the sovereignty of other nations, and undermine regional stability" (White House, 2017, p. 46). This scenario demonstrates increased CLF utilization by switching to the SFC in a contested environment, in line with the Secretary of Defense's goal of "Building a More Lethal Force" (DoD, 2018, p. 5). The order of battle modeled in this scenario was not based on actual military planning documents. Instead, we chose forces which represent typical combatant ship combinations, and known commodity usage rates, to determine the logistics necessary to maintain continuous combat operations.

A. CONTESTED ENVIRONMENT

Currently, China uses anti-access/area denial (A2/AD) capabilities to deter and compete in the Pacific Ocean; among the various weapon systems used to support China's A2/AD strategy, this scenario is primarily concerned with the DF-26 Intermediate-Range Ballistic Missile and DF-21D Medium-Range Ballistic Missile threats. The DF-26 is a road-mobile, nuclear and conventional capable missile with a range of approximately 4,000 km (OSD, 2019). This is an important modeling assumption as the threat range of this missile envelopes DFSPs within the AOR, potentially restricting current U.S. fuel supply access. The DF-21D is an anti-ship ballistic missile, touted as a carrier killer, with a range of approximately 1,500 km (Office of the Secretary of Defense [OSD], 2019). Knowing that the U.S. has historically used CSGs as the primary instrument to establish maritime and air superiority, China developed this missile to shape the operating environment in their favor by attempting to deny U.S. naval ships access within the first island chain. This is an important modeling assumption as it shapes the environment that the CLF can operate in.

B. SCENARIO DESCRIPTION

The U.S. is drawn into conflict with China as a result of Chinese aggression against the U.S. and its regional allies. U.S. forces have sortied to their designated areas of operations and have resupplied all fuel, ordnance, and stores to maximum inventory levels. Sustained combat operations begin in the morning and provide the basis of our steady-state analysis.

In response to U.S. and its allies' rhetoric and force positioning, China deploys its DF-21D and DF-26 missile systems, and U.S. intelligence experiences difficulty tracking mobile missile movements. However, the intelligence community has provided the following DF-21D and DF-26 threat assessments, Figure 6 and Figure 7, with high confidence.

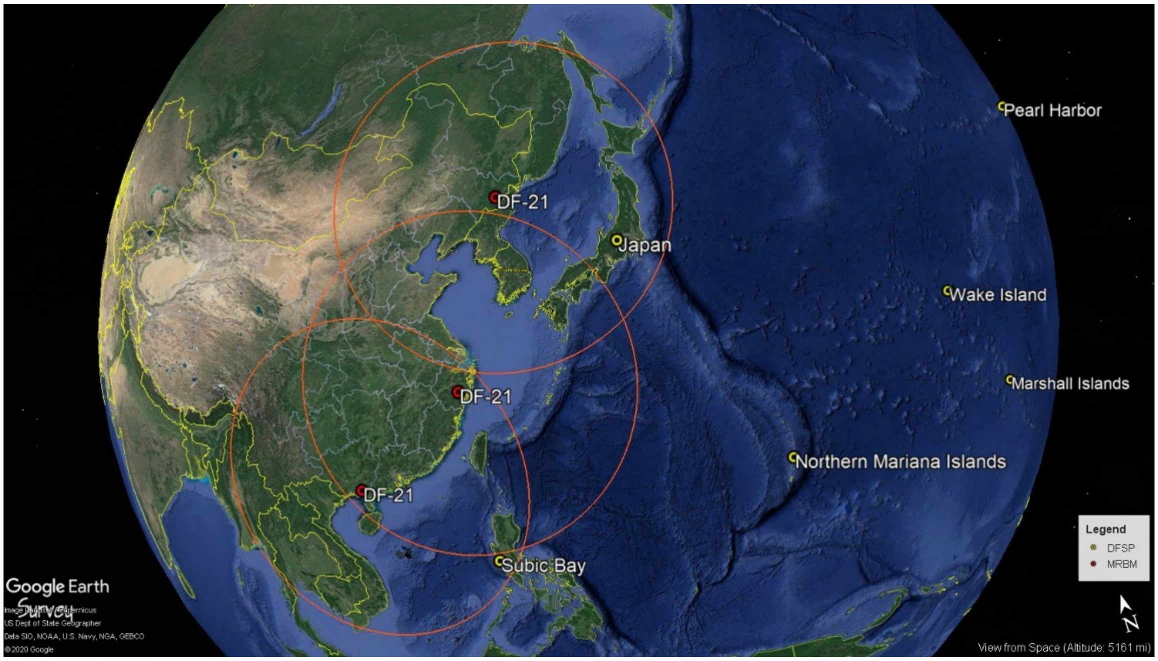

Figure 6. DF-21D threat based on intelligence sources

It can be determined from Figure 6 that Chinese missile placement effectively denies U.S. naval forces and CLF from entering the first island chain, as well as access to

DFSPs located in the Philippines and Japan. These are critical factors when considering the flow of fuel into theater.

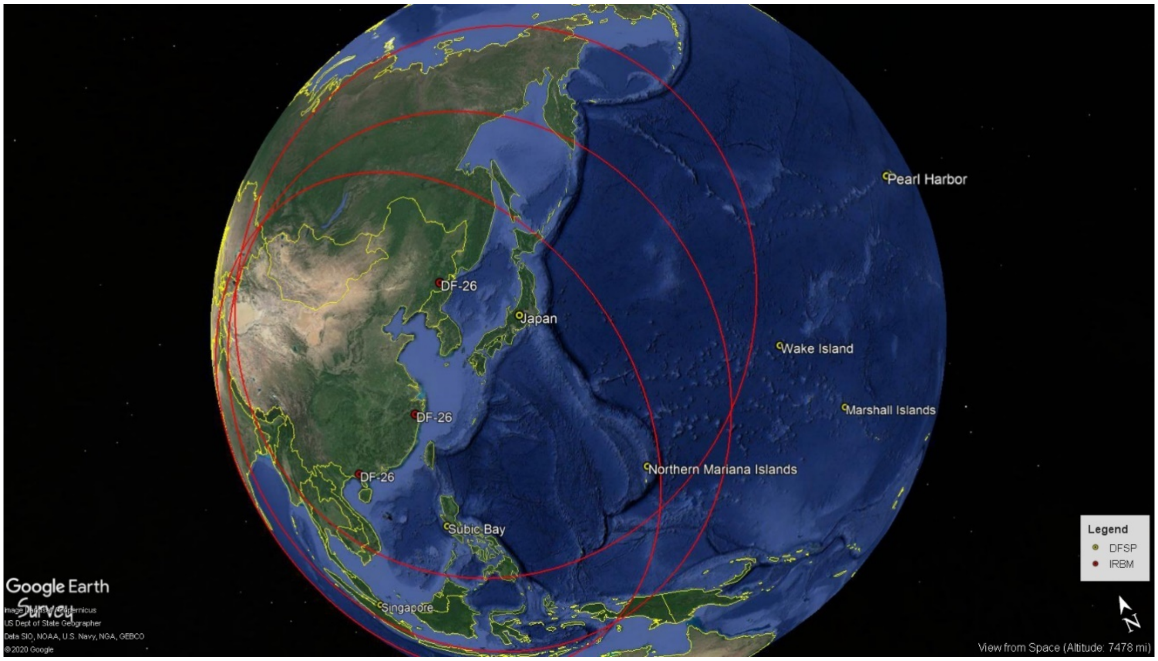

Figure 7. DF-26 threat based on intelligence

It can also be determined from Figure 7 that Chinese missile placement enables targeting DFSPs located in Guam and Singapore (bottom left of figure). Accordingly, this leaves fuel available at DFSPs at Wake Island, the Marshall Islands, and Pearl Harbor, Hawaii.

C. SCENARIO CONCEPT OF OPERATIONS

The CONOPS chosen to provide the fuel logistics necessary for sustained combat operations is based on what the Center for Strategic and Budgetary Assessments termed “Go Big” (Walton et al., 2019, p. 41). Under this concept, CONSOL tankers would shuttle cargo fuel from DFSPs to replenish station ships—T-AOs, T-AOEs, or T-AKEs—underway. This CONOPS was chosen due to three distinct advantages: more cargo fuel storage, ease to modify CONSOL tankers to gain UNREP capability, and greater operational range when compared to current MSC CLF shuttle ships.

First, tankers can store significantly more cargo fuel than CLF oilers. For example, MSC's tanker MT *Empire State* can store nearly double the cargo fuel USNS *Henry J. Kaiser* (T-AO 187) class fleet oiler. This enables more fuel to be stored at sea; thereby decreasing the number of times a fleet oiler has to return to port. This decreases opportunities for the enemy to locate and target the CLF. Additionally, the use of tankers brings the source of fuel closer to the combatants, enabling quicker access to cargo fuel.

Second, tankers can be easily modified to connect to the CLF underway, on either two or four stations, in order to support Navy CLF operations (Walton et al., 2019). This enables tankers to CONSOL with MSC fuel cargo ships underway, as proven through CONSOL operations involving the USNS *Rainier* and the MT *Empire State* during RIMPAC 2016 (Burford, 2016).

Third, and most important to this scenario, the tankers' operational range is in excess of 6,000 nmi, when compared to 3,000 nmi for T-AOs and T-AOEs. While the Marshall Islands and Wake Island are within the operational range of all three ship types, these DFSPs are relatively small with the largest quantity of either product, totaling 104,288 bbls. For this reason, all fuel will be transported from the DFSP located at Pearl Harbor, Hawaii in this scenario.

Finally, using tankers leverages MSC's CLF as station ships with their associate combatants, as originally intended. In the scenario, CLF ships will enter and exit the contested environment, as necessary, in order to CONSOL with tankers positioned at a designated location outside of the contested environment. This CONOPS mitigates the tankers' risk of exposure to the enemy while providing timely and responsive delivery of cargo fuel to the combatants.

Two scenarios were modeled to contrast the existing system using two fuels to only using JP-5 – the SFC. Both scenarios use the same combatant composition outlined in Table 2. Scenario 1 represents the status quo of using two fuels, F-76 and JP-5, to satisfy combatant fuel demands. Furthermore, CLF and CONSOL tanker fuel cargo holds were configured to best support operational demand by task force. For example, when operations in task force 17.1 demanded 66 percent JP-5 and 34 percent F-76, cargo fuel holds in the

CLF and CONSOL tankers were configured to support using a 70/30 JP-5 to F-76 split. Scenario 2 uses only JP-5 to satisfy both F-76 and JP-5 aviation and ship propulsion fuel requirements. What the scenarios demonstrate are fewer required CLF and charter tankers to support the same operations under the SFC and an increase in task force endurance.

Table 2. Task Force composition

Forces Involved	**Task Force 17.1**	**Task Force 17.2**	**Task Force 17.3**	**Task Force 17.4**
CVN	1 CVN	2 CVN	2 CVN	None
Escorts	1 CG 3 DDG	2 CG 12 DDG	2 CG 6 DDG	1 CG 3 DDG
Station Ship	1 T-AO* 1 T-AKE	2 T-AO* 2 T-AKE	2 T-AO*/** 2 T-AKE**	1 T-AO 1 T-AKE
Amphibious Forces	None	None	None	1 LHD 1 LPD 1 LSD Embarked MEU

* T-AO 187 class oiler is the single hull variant

** Two T-AO/T-AKE pair for Scenario 1 and one T-AO/T-AKE pair for Scenario 2

Additionally, both scenarios use tanker CONSOL points for each task force located 3,500 nmi from Hawaii; as illustrated in Figure 8. It can be noted that a range of tanker CONSOL points located closer to mainland China, such as the South China Sea, could be considered based on the tanker's 6,000 nmi operational radius. Our tanker CONSOL point was chosen because at this location, the T-AO has the operational radius, based on the CONOPS chosen, to operate inside the first island chain supporting combat operations as necessary. Tanker CONSOL points located at varying distances from Hawaii would most certainly be chosen in a real-world operation. However, for the sake of demonstrating the benefits of the SFC, a single tanker CONSOL point distance of 3,500 nmi was chosen.

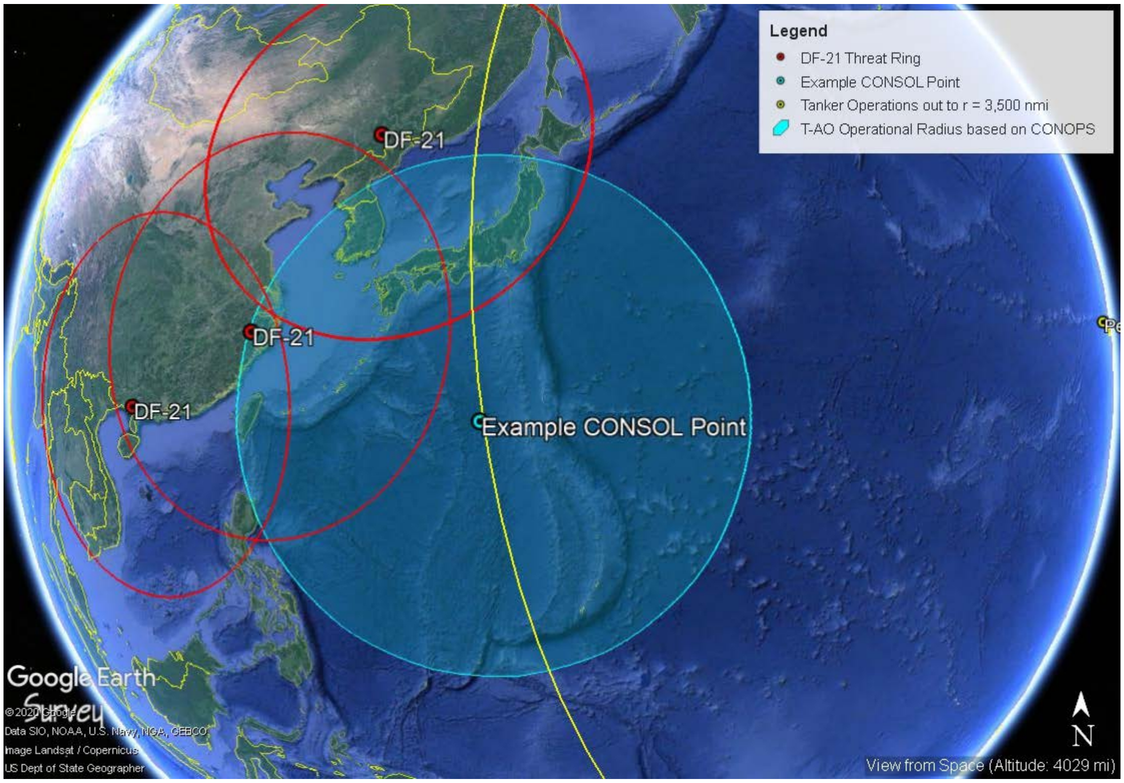

Figure 8. Tanker CONSOL point

D. LOGISTICS PLANNING FACTORS

The logistics planning factors used in both scenarios were referenced from *NWP: Sustainment at Sea* (DoN, 2007). Both scenarios' daily assault rate fuel consumptions and ship capacities were referenced to determine aggregate task group consumption and capacity. Table 3 summarizes the two fuel types referenced by ship class. Additionally, ship speeds and operational radii for T-AOs and tankers were referenced from this publication, summarized in Table 4.

Table 3. Combatant F-76 and JP-5 capacities and daily assault rate consumption values by ship type

	JP5 (bbls)		**F-76 (bbls)**	
Class	**Capacity**	**Daily usage**	**Capacity**	**Daily usage**
CVN	74,642	5,000	0	0
CG	475	39	15,032	757
DDG	475	34	10,518	646
LHD	14,452	759	43,091	1,071
LPD	6,700	324	23,750	528
LSD	1,144	81	19,150	346

Table 4. T-AO and Tanker general capabilities

Ship	**Speed (kn)**	**Max Speed (kn)**	**Op Radius (nmi)**	**Cargo Fuel (bbls)**
T-AO	17	20	3,000	180,000*
T-AKE	20	24	14,000	23,450*
T-AOT	15	20	6,000	300,000*

* Can be configured for 50/50, 30/70, or 70/30 F-76 and JP-5 split

THIS PAGE INTENTIONALLY LEFT BLANK

VI. MODEL DESCRIPTION

A. RATIONALE FOR DETERMINISTIC MODELING

We chose a steady-state deterministic model to find the number of T-AOs and tankers required to support combat forces in the scenario, where steady-state is defined as the station ship supplying, on-average, what the task force consumed, on-average. Stochastic simulation was also considered, but it was determined that introducing randomness would provide little value until a complete deterministic solution was found. Ultimately, we sought a tractable model that would provide rapid, meaningful interpretation.

B. ASSUMPTIONS

Within the above scenarios, we assumed the following:

1. Daily time resolution is adequate to compute the number of T-AOs and tankers required to support our scenario. Daily time resolution was chosen because it aligns with most fleet logistics planning factors used to prepare time-phase force deployment planning methods.

2. Daily commodity demand was aggregated for whole task groups. Under this assumption, in the short-run, there is some fidelity lost in tracking T-AO daily commodity levels. However, in the long-run, it does not affect determining on what day the T-AO reached critical commodity levels. It was assumed that, even under a DMO concept, combatants would schedule an UNREP when they reach critical fuel levels, and the T-AO would be able to provide uniform replenishment to full inventory while cargo fuel exists.

3. Fuel inventory was the primary constraint driving T-AO and tanker fuel replenishment events. Therefore, when calculating the number of tankers to support operations, only F-76 and JP-5 fuel critical inventory levels in DOS were considered. For example, if combatant ordnance and/or stores

demand depleted a T-AKE's DOS for that commodity before fuel inventory critical levels were reached, our analysis would only generate a CONSOL for the latter. Consideration of ordinance and stores' inventory levels would likely need to be included in future analysis to determine a CONOP to support their logistical demands.

4. Each task group was assigned one or more T-AO/T-AKE pairs based on fuel demand and would act as a station ship or shuttle ship when necessary. The T-AO/T-AKE pair was considered to be a shuttle ship when in transit to the tanker CONSOL point.

5. Time to reload a tanker in-port would take approximately 2.5 days. While refueling a tanker would likely take less time than this approximation, we gave allowances for minimal in-port scheduled and unscheduled ship maintenance and stores loading/unloading.

6. Time for T-AO/T-AKE pair to CONSOL with tanker was one day.

7. Combatant fuel critical levels were set at 50 percent total capacity. Each task group would operate on a maximum six-day replenishment cycle. As a result, the distance from the center of each task group's operations area to CLF/tanker CONSOL point would be no greater than 2.5 days' travel in one direction.

8. All current CLF F-76 cargo fuel space would be converted for JP-5 cargo fuel storage under the SFC concept.

9. Minimum DOS required per task group was set at 12. Doing so minimized the number of tanker CONSOLs in order to reduce the opportunity for enemy detection.

C. LIMITATIONS

The model is limited by the following factors:

1. The model did not include stochastic variation. It would be useful to know combatant fuel usage variability as a function of operations, dispersion, and tactical maneuvering and its effects on T-AO and CONSOL tanker requirements. This would enable decision makers to quantify combatant logistics risk.

2. *NWP Sustainment at Sea* planning factors for fuel usage rates are 12 years old and reflect counterinsurgency-based operations. If contemporary demand values were known that better reflected MCOs, the model could better determine T-AO and CONSOL tanker requirements.

3. Transient stages were not captured. T-AO and CONSOL tanker requirements would certainly be different as function of operational phase. Pre-assault F-76 usage rates would almost double the F-76 usage rates during the assault phase for CG and DDG combatants and would demand increasing T-AO and CONSOL tanker requirements as a function of the distance from Hawaii.

4. CLF ship attrition was not considered. Accounting for attrition, based on historical data or war simulation, and rounding up to whole ships would increase the number of T-AOs and possibly CONSOL tankers required to support operations.

D. MODEL

The steady-state model we created was largely based on a similar model produced by CNA to determine the number of T-AKE class ships required in several AORs. At the time, T-AKEs were known as the planned T-ADC(X) class auxiliary dry cargo carrier and were required to support wartime requirements, based on the 1997 versions of the Non-Nuclear Ordnance Requirements, the Naval Planning Scenarios, and the Defense Planning Guidance. The CNA defines steady-state as “one in which the CLF delivers, on average, what the combatants consume, on average.” (John, 1998, p. 6). The CNA modeled the combatant’s initial inventory of stores, ordnance, and fuel as “sumps.” As John writes, “Demand is satisfied by the sumps, and the CLF resupply side replenishes the sumps.” (John, 1998, p. 6). Variability in sump daily demand was not considered because the model analyzed was said to be in steady-state—supply for stores, ordnance, and fuel equals demand for the same. A visual representation of the model is included in Figure 9.

Key differences in our model were the choice in shuttle ship – using CONSOL tankers to resupply oilers, using T-AOs to act in both a shuttle ship and station ship capacity, and using one fuel to satisfy combatant demand. Critical inputs to the model were the considerations of supply and demand.

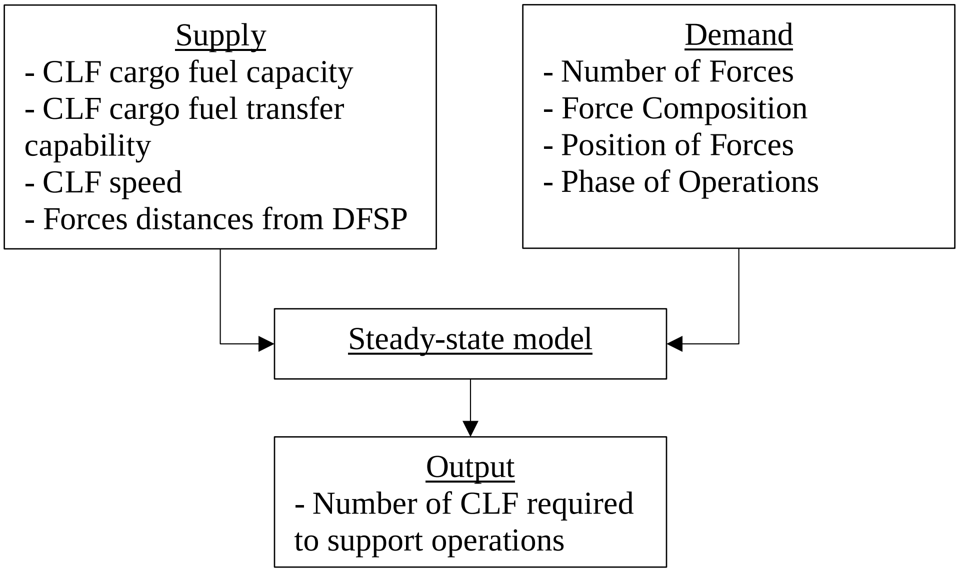

Figure 9. Basic steady-state model overview

1. Supply

To meet the demands of the task force, CONSOL tankers had to replenish their cargo fuel at the Pearl Harbor, Hawaii DFSP, transit from the DFSP to a CONSOL point, perform underway CONSOL operations, and then transit back to the DFSP for resupply. The time to complete this process was considered the process cycle-time. The primary variable driving cycle-time was the transit distance between the DFSP and CONSOL point.

Transit time was computed using the elementary relationship between speed, time, and distance. As previously stated, the constant for tanker loading time was assumed to be 2.5 days and the constant for CONSOL time was assumed to be one day.

In one cycle, the shuttle ship delivers its fuel cargo in the total cycle time computed. This amount of bbls per day represents the shuttle ship's capacity to deliver either quantity of cargo fuel – F-76 or JP-5. It should be noted the shuttle ship's cargo fuel capacity is limited by the station ship's cargo fuel capacity for any given fuel type, in order to avoid a virtual surplus in station ship cargo fuel.

2. Demand

Fuel demand was calculated for the forces listed in Table 2. Scenario 1 involves two fuels – F-76 and JP-5. In this scenario, the CONSOL requirement was driven by the fuel with the least DOS available. In Scenario 2, which used solely JP-5 under the SFC, the CONSOL requirement was driven by JP-5 cargo fuel DOS. In Scenario 1, the more closely that F-76/JP-5 cargo fuel split aligned with fuel demand, relative to storage capacity, then the more closely the outcomes of Scenarios 1 and 2 would resemble each other.

3. Steady-state Model Formula

The model used to calculate the number of T-AOs and tankers required to support the task force is expressed as

$$\text{Number of TAOs} = \frac{12\text{ days} \times \text{Task group usage (bbls/day)}}{\text{TAO cargo fuel capacity (bbls/tanker)}}\text{, and as}$$

$$\text{Number of CONSOL tankers} = \frac{\text{Task force demanded (bbls/day)}}{\text{Tanker cargo fuel delivered (bbls/day)} \times \text{Cycle-time(days/tanker)}} \cdot$$

The output of the model was a fractional number of T-AOs and CONSOL tankers required to supply the task force fuel demand. For our results, outputs were rounded up to the nearest whole number of station and shuttle ships. For example, if the output was 1.1 ships, we rounded up to 2 ships.

VII. RESULTS

A. HISTORICAL DEMAND ANALYSIS

1. Capacity Augmentation by CLF Type

As described under *Methodology*, the reduction in variability produced by the SFC cannot be directly translated into inventory savings for the CLF. Instead, the impact of SFC implementation is viewed in terms of increased service level or additional CLF refueling capacity. Since the average storage capacities for each CLF type, as shown in Table 5, are functions of each fleets' composition, these figures will only change when ships are commissioned or decommissioned. Thus, these figures change slowly and infrequently and can be used to calculate potential refueling capacity expansion under the SFC.

When the means and standard deviations of demand for each product type are combined per the inventory pooling technique, as described in *Methodology*, our research shows that the CLF's capacity to refuel combatants would improve as detailed in Table 5. Additionally, this capacity expansion can be expressed as a percent increase when divided by the average total combined product storage capacity, by CLF type.

Table 5. Storage capacity expansion via SFC by CLF type

	T-AKE	**T-AO**	**T-AOE**
Average Total Capacity (bbls)	26,273	173,353	166,585
SFC Capacity Expansion (bbls)	5,332	21,363	17,108
Capacity Expansion (%)	20.29%	12.32%	10.27%

This means that under the status quo, a dual fuel Navy, in order to acquire the same augmented service level and afloat refueling capacity at any given time that the SFC provides, every currently operationally available T-AKE, for example, would need retrofitted with a 5,332 bbl auxiliary cargo fuel tank. Stated differently, without making alterations to any existing hulls, under the SFC every T-AKE available for tasking could carry 20.29 percent more cargo fuel than at present. Of note, these figures account for the additional quantities of JP-5 required for ship propulsion, due to its lower energy density value, under the SFC.

2. Potential for Cost Avoidance

To analyze the inventory pooling method's effect on CLF size and any inherent monetary savings, Ao for each CLF type fleet was considered. Therefore, by multiplying the number of hulls in each ship type by its respective Ao as computed in *Methodology*, and then again by the respective CLF type afloat capacity expansion percentage, our analysis indicates that the SFC yields the equivalent additional storage capacity of 1.94 T-AKE hulls and 1.31 T-AO hulls at sea, at any given time.

Lastly, we can estimate potential cost avoidance derived by ship type. According to a 2019 Congressional Research Service report, the next T-AO hull, slated for commission in FY20, will cost $528.1 million (O'Rourke, 2019). Per the authors' email correspondence with NASSCO program managers, the two most recent T-AKE hulls, commissioned in FY11, averaged $412.5 million (T. Wetherald, March 4, 2020). Then, using the U.S. Bureau of Labor Statistics (BLS) Consumer Price Index inflation calculator, this would be worth $476.5 million in FY20 (BLS, n.d.). Thus, when the dollar figures above are multiplied by the representative number of additional hulls that our computed storage capacity expansion yields, SFC implementation would realize immediate afloat storage capacity benefits, while also avoiding costs equal to more than $1.61 billion.

3. Cv Improvement by Numbered Fleet

Compared to total CLF fleet storage capacity, afloat storage capacity within Numbered Fleets is dynamic, since CLF assets CHOP in and out constantly, but irregularly. Thus, Cv improvement, instead of capacity expansion, was used to compare the Numbered Fleets. Figure 10 shows the ranked differences between the Cv of each product type by Fleet and the Cv under the SFC.

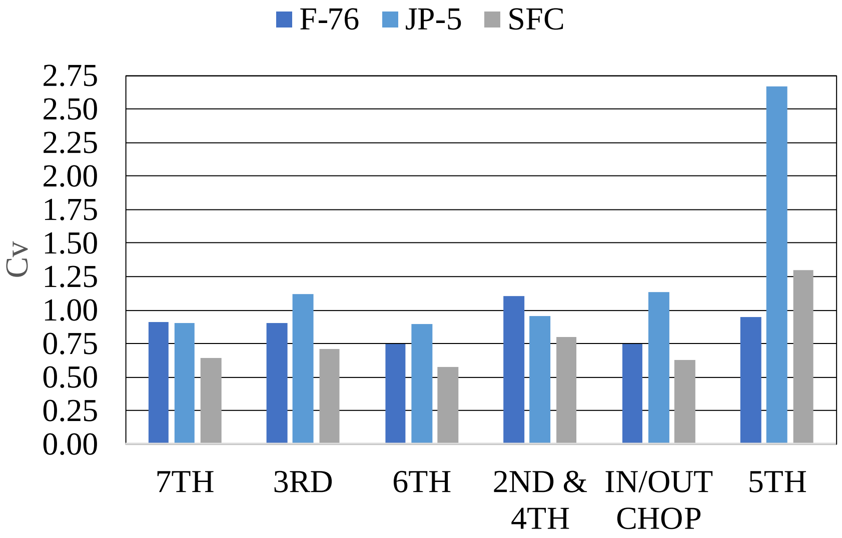

Figure 10. Coefficient of variation (Cv) improvement by Fleet

Since the SFC eliminates one type of fuel, but not the associated activity that generates demand—ship propulsion or aviation—the benefit of decreased variability is only as good as the Cv reduction for either product which experiences the least reduction. Therefore, the Fleets were ranked from left to right in terms of the most significant Cv reduction on the product least benefitted by the SFC.

As shown, every Fleet would have experienced a reduction in demand variability for both product types, except for 5TH. The CLF in 5TH Fleet would experience a drastic increase in its ability to meet aviation fuel demand, but only at the expense of its ability to meet surface propulsion fuel demand. We speculate that this is driven mainly by the relatively high operational tempo of naval aviation operations, and tight concentration of forces within a confined operating area, which requires less transient ship steaming relative to aviation operations. Meanwhile, the vast distances covered in 7TH and 3RD Fleets require more ship propulsion before aviation operations can commence, as illustrated in Figure 11.

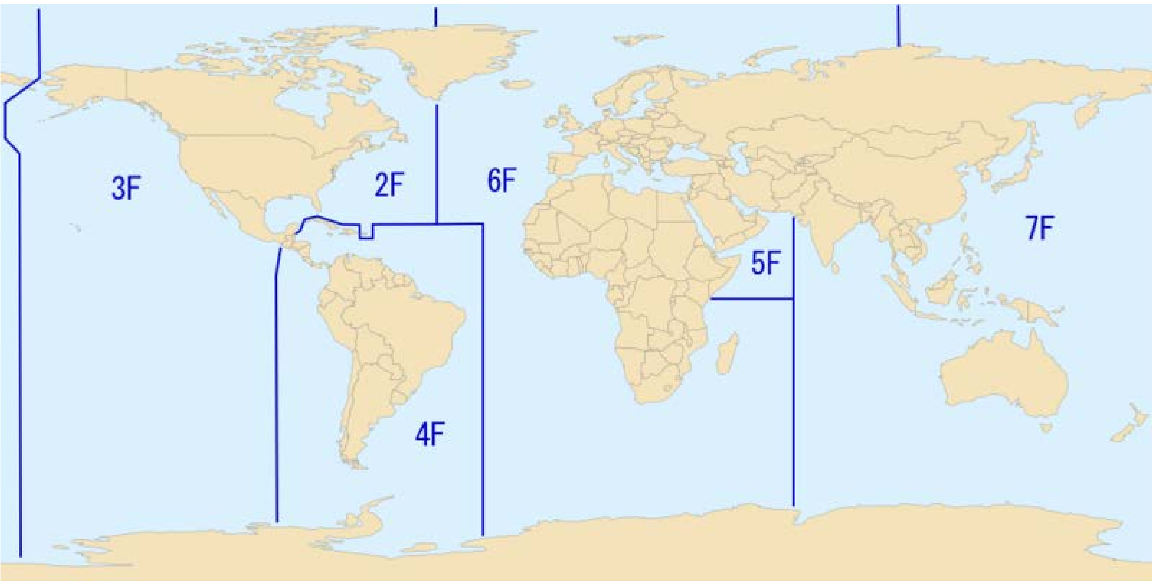

Figure 11. U.S. Navy numbered Fleet commanders' AORs. Source: Wikimedia Commons (2009).

This notion would express itself in the Cv equation for JP-5, as the numerator σ grows relative to the denominator µ. Since ships steam continually, but aviation operations are episodic, with high-intensity demand, the standard deviation of demand for F-76 will nearly always be lower than for that of JP-5. Furthermore, since we defined a cycle as the period between CLF fuel-onloads, and given the perpetually close proximity between any point within 5TH Fleet's small AOR and a DFSP, CLF ship masters can be more confident in satisfying larger demand quantities before resupplying. Thus, due to the frequency of sporadic, high-intensity JP-5 demand, with nearly constant CVN presence in the AOR, 5TH Fleet's standard deviation is much larger than its mean, when compared to other Fleets.

As shown above, the differences in the nature of operations conducted between fleets are as important to our analysis as the quantities of fuel demanded. To better understand how Cv improvement would benefit each Fleet, a value relative to global demand was constructed to better represent SFC's impact within each fleet. Therefore, we created Table 6 to demonstrate the percentage of each product type proportional to total combined global demand.

Table 6. Product type demanded by Fleet as a percentage of total combined global demand

Fleet	F-76 (%)	JP-5 (%)	Total (%)
7TH	16.9	5.6	22.5
3RD	12.8	4.5	17.3
2ND & 4TH	11.5	1.4	12.9
IN/OUT CHOP	11.3	3.7	15.0
6TH	5.4	0.9	6.3
5TH	19.7	6.1	25.9
Total	77.6	22.4	100.0

The Cv reduction value for each product in each numbered fleet was then multiplied by its respective percentage of total global demand for both products. Figure 12 shows the fleets ranked again from left to right, but now by throughput-weighted Cv improvement, where the benefit (or detriment) from the SFC for both ship propulsion and aviation demand is added.

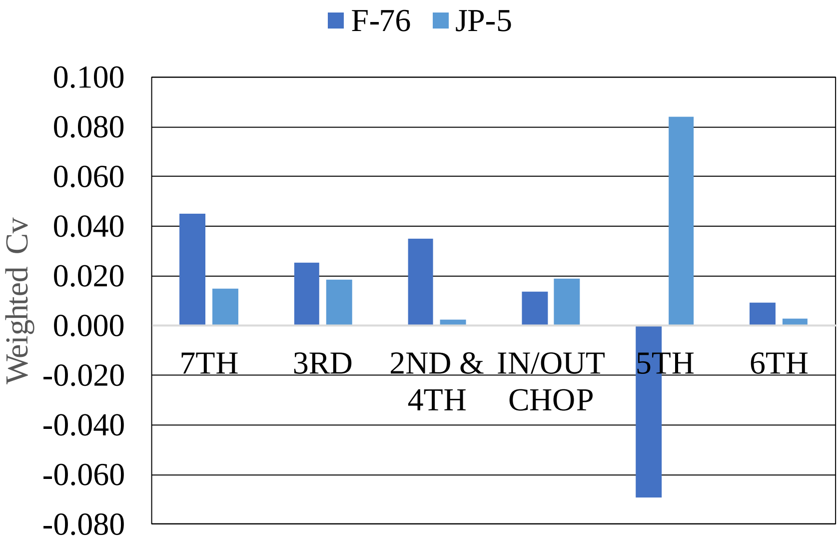

Figure 12. Fleet Cv improvements weighted by demand

The figures above provide a broad approach to understanding the impact of the SFC across geographical areas. Thus, if demand trends for future fuel are similar to those across the dataset, then numbered fleet commanders should see improved refueling service capability and responsiveness like the figures above if the SFC was adopted. Decision makers may therefore choose to use this information to geographically prioritize and phase-in implementation if the SFC were adopted.

4. Reduced Port Visits

An ancillary benefit of the SFC is the potential to reduce the number of expected port visits, and the related charges, for CLF cargo fuel-onloading each year. As shown in Table 7, we counted the number of fuel-onload port visits made by each ship type according to one of four categories: F-76 only, F-76 driven, JP-5 driven, and JP-5 only. Each categorization describes whether the ship loaded a single product or loaded more of one product than the other, relative to that product's storage capacity of each product.

Table 7. Port visits by product and CLF type

	T-AKE		**T-AO**		**T-AOE**	
	Average	**Total**	**Average**	**Total**	**Average**	**Total**
F-76 only	26.9	403.0	44.9	494.0	18.3	55.0
F-76 driven	15.7	236.0	5.1	56.0	11.7	35.0
JP-5 driven	5.8	87.0	1.3	14.0	15.7	47.0
JP-5 only	1.0	15.0	0.5	5.0	0.7	2.0

In order to fairly account for the port visits, the USNS *Charles Drew* (T-AKE 10) was excluded from the dataset for this analysis only, as it was converted to solely carry JP-5, prior to its 7TH/5TH Fleet deployment in 2018. Were it included, JP-5 only and JP-5 driven port visit tallies, and T-AKE fleet averages would have been higher. As is evident by the data, F-76 demand is the primary driver for all three CLF type port visits. However, we estimate that if inventory pooling effects were in place, the number of port visits could have been reduced by at least 22 and at most 170 over the dataset's 66-month time span. This averages from anywhere between 4 to 31 fewer MSC port visits annually, depending on whether JP-5 driven instances are included.

Thus, this calculation is an inexact science, since port visits are driven by ship masters’ behavior in compliance with AOR-specific *OPORD 201* directives, and not by defined inventory levels or time-related policies. Regardless, since the SFC yields higher combined inventory postures than the status quo, it should be recognized that ship masters would be compelled to pull into port less frequently than current demands dictate.

B. SCENARIO

1. T-AO and CONSOL Tanker Requirements

The results of the steady-state model estimated how many T-AOs and CONSOL tankers were required to support the two scenarios given by task group. By summing the number of T-AOs and CONSOL tankers over all the task groups we calculated the number of in-service ships required to support either scenario. Assuming a 71 percent Ao for the T-AOs, we calculated the number of additional CLF ships needed to maintain the in-service requirement due to scheduled and unscheduled maintenance. It is likely that the Ao for T-AOs would be larger during a wartime environment. Conversely, Ao was not considered for CONSOL tankers because the in-service requirement would be met by a time charter tanker for the duration and be capable of meeting the capacity requirements. Adding the number of in-service and in-maintenance ships yielded the total number of T-AOs and CONSOL tankers required to support either scenario, illustrated in Table 8. Using traditional CONOPs – Scenario 1, the total number of T-AOs required was nine with seven CONSOL tankers. Under the SFC – Scenario 2, the total number of T-AOs required was reduced to eight with six CONSOL tankers.

Table 8. CLF ships and CONSOL tankers required to support scenarios

	Scenario 1		Scenario 2	
Task Force	**T-AO**	**Tanker**	**T-AO**	**Tanker**
17.1	1	2	1	1
17.2	2	2	2	2
17.3	2	2	1	2
17.4	1	1	1	1
In service	6	7	5	6
Maintenance*	3	0	3	0
Total	9	7	8	6

* Assumed 71 percent operational availability

Comparing these values against the 15 T-AOs available in CLF inventory and the six tankers on long-term charter by MSC, we can identify any potential shortfalls the DoD may encounter during the scenarios. Therefore, there is a surplus of six and seven CLF ships for Scenarios 1 and 2 respectively. It also follows that scenario one results in a shortfall of one tanker, and scenario 2 would require the use of all six long-term charter tankers. This assumes that in order to support either scenario, MSC would pull tanker resources from other operational requirements worldwide.

2. Task Force Endurance

The metric chosen to measure endurance was DOS, wherein each task group's DOS was computed by dividing its average CLF cargo fuel amount by combatant daily demand for each product. This resulted in a fractional number of DOS available before the CLF exhausted its cargo fuel requiring a tanker CONSOL event. Finally, task force endurance was demonstrated by comparing DOS for each scenario, as illustrated in Figure 13.

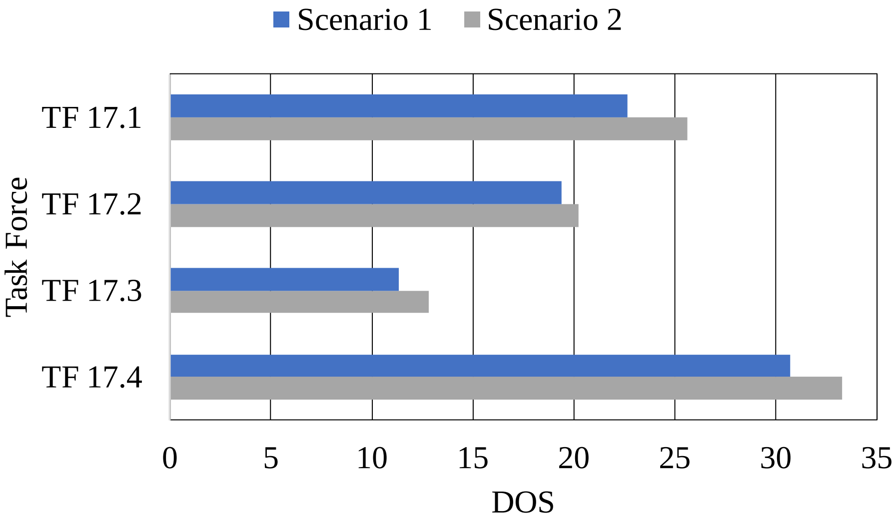

Figure 13. Task force endurance

As can be determined from Figure 13, Scenario 2, using the SFC increases supply for every task group, and ultimately, the entire task force. This would provide greater operational flexibility for the Task Force Commander. The marginal DOS increase between the two scenarios is illustrated in Figure 14.

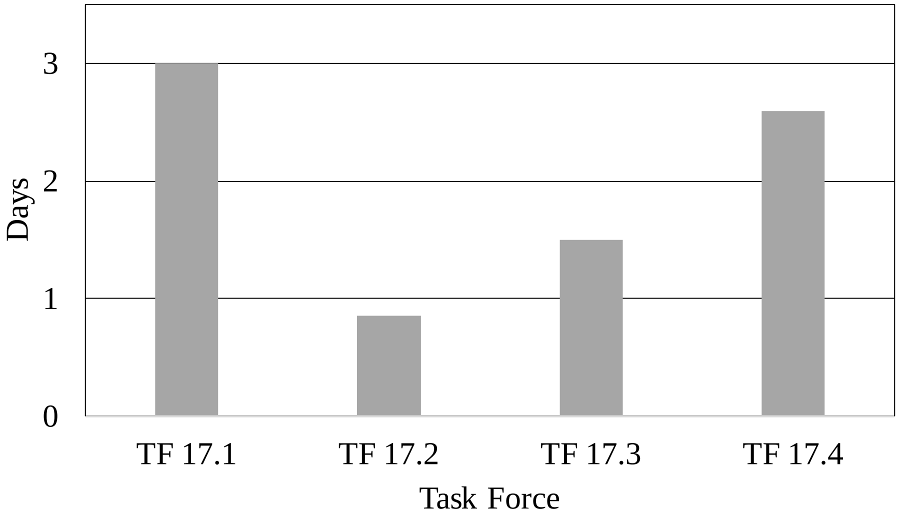

Figure 14. Increase in DOS by adopting SFC

While a one to three-day increase in DOS may not appear significant, it can meaningfully affect an operation’s logistics supportability given the relationship between the number of CONSOL tankers required to support operations and logistics cycle-time. As cycle-time increases, the number of CONSOL tankers required to support operations increases. Put another way, for every full day increase in DOS, the fight can move 360 nmi closer to the enemy without increasing the number of CONSOL tankers required to support operations without degrading operations. Finally, the added time allows for more circuitous navigation or tactical evasion due to enemy threats without sacrificing combatant operations or increasing CLF force structure requirements.

VIII. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

Our analysis shows that the SFC provides measurable operational benefits to the responsiveness and flexibility of maritime refueling logistics, primarily through enhanced CLF capacity to meet customer demand. Additionally, through recent historical analysis, it is estimated that all three primary refueling CLF classes and every numbered fleet would experience afloat storage capacity expansion through inventory pooling effects due to SFC implementation. Furthermore, under the SFC "Go Big" CONOPS scenario, when compared to the dual fuel CONOPS the Navy currently operates under, fewer fleet oilers and tankers would be required to provide the same level of service and logistics refueling capability during high-intensity operations, and task force endurance would be increased.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

Given our analysis and results, the following are a few related research areas that we feel need further attention and would enable DoD decision-makers to better deliberate the impacts of SFC implementation.

1. Amphibious Operational Impact Study

While our study focused on the SFC operational impact on CLF assets' ability to provide refueling logistics support to combatants, our study did not address the impact on combatants themselves. As discussed in our *Literature Review*, most engineering and technical specification concerns have been evaluated, and would not prohibit SFC implementation. Our central premise is that the SFC provides operational benefits by simplifying maritime fuel logistics and enhancing average battle group inventory posture. For most combatant platforms, the operational benefits stop at the increased flexibility of the CLF to meet combatant demand. For example, CVNs use nuclear propulsion and therefore already only store JP-5 aboard, and while DDGs and CGs store both products, F-76 is stored in seawater-compensating tanks for ship stabilization purposes (NAVAIR, 2006). Thus, while it is mechanically possible to transfer fuel from an existing F-76 storage tank to the JP-5 service tank, this is procedurally forbidden for the sake of aircraft safety precautions.

Prior research also identified that amphibious platforms such as LHA/LHDs, and LPDs, unlike other surface combatants, may experience increased endurance benefits under the SFC (D. Saks, personal communicaiton, April 7, 2020). These platforms are designed with ballast tanks in lieu of seawater-compensating tanks (NAVAIR, 2006) and therefore may be able to transfer fuel from F-76 storage to JP-5 service tanks, without sullying JP-5 for aviation use. Furthermore, since these platforms have much higher aviation fuel demand, relative to ship propulsion fuel, than other surface combatants, their JP-5 storage capacities relative to F-76's are far larger. Therefore, amphibious platforms have the potential to experience the most significant benefits of the SFC at the tactical level of warfare.

To test this theory, we used our historical dataset and factored in previously unutilized fuel demand serviced by DFSPs and foreign sources under Acquisition and Cross Service Agreements. Next, the means and standard deviations of LHA/LHD and LPD demand for each fuel type were calculated. After applying the inventory pooling method, our cursory analysis showed a 6.17 percent storage capacity expansion for LHA/LHDs and 3.15 percent for LPDs. While these figures appear modest, two points should be noted: first, these figures already account for η loss, and second, these figures include peace-time steaming and inter-theater transit fuel demand, which constitutes the bulk of F-76 usage. Therefore, the SFC may provide even greater benefits during MCOs with high aviation operational tempo.

Further research is also needed to ensure that LHA/LHDs and LPDs have not been converted to include seawater-compensating fuel storage systems, per SHIPALT 941. If this is true, utilizing the inventory pooling method and the η76 value, analysis would be required on fuel consumption by type, compared to onboard storage capacity, as captured in daily engineering logs during real-world kinetic operations and exercises. From this, additional DOS for aviation requirements and TOS during air assault phases of battle could be computed.

2. Changes to DoD Prepositioning Requirements

As we observed, the inventory pooling method is more easily applied to ashore DFSP demand in a traditional fashion than to afloat storage units; however, further research is needed to calculate potential inventory and cost reductions globally. Unlike traditional commercial inventory safety stock policies, stockage levels at DFSPs include Prepositioned War Reserve Stock (PWRS) when feasible. PWRS levels are driven by the Prepositioned War Reserve Requirement (PWRR), and "sized to satisfy the most demanding [operational plan (OPLAN) fuel] requirements at each DFSP" within a theater of operations (DoD, 2009, p. 6). This means that PWRS is not supposed to satisfy the requirements for every OPLAN, and instead is only for the largest or most restrictive requirement amongst OPLANs for that theater, and is intended for use only upon OPLAN execution.

Thus, if the largest Army, USAF, and USMC aviation PWRR could be met via JP-5, then the potential exists at numerous DFSPs where the SFC would produce a far greater JP-5 PWRS and thus satisfy jet fuel variant PWRRs. However, a future research project would need to verify that there are no procedural impediments for JP-5 use in ground V/E and aircraft that traditionally consume jet fuel variants during contingency situations. If this were so, then we recommend that these impediments were analyzed and challenged, such as in this thesis' *Literature Review: Counter Feasibility Arguments*.

Additionally, *The Single Naval Fuel at Sea Feasibility Study – Phase Two – Task Five, Supply System Impact* report (2005), identified a reduction in economic reorder quantity (ERQ) as the only inventory reduction benefit from the SFC, assumed that jet fuel variant PWRS levels could not be amended. The report went on to state that the potential reduction in ERQ quantities, and the associated holding cost savings, would not be large enough to warrant SFC implementation.

Opportunities also exist to address the potential for hypothetical total PWRS reductions at DFSPs by reducing jet fuel variant inventory levels where they are collocated with JP-5 stocks. Additionally, nine such DFSPs have F-76 stock collocated with jet fuel variants other than JP-5. This means that opportunities may exist at those locations for potential ERQ and PWRS reductions. Table 9 displays commingled fuel DFSPs and is derived from the FY20 Inventory Management Plan (IMP) (W. Jakubowicz, email to authors, October 23, 2019). The IMP is updated each year and changes in planned inventory requirements or wholesale changes in storage locations are infrequent.

Table 9. Potential inventory reductions by product type and DFSP location.

	ERQ **F-76/JP-5**	**PWRS** **Jet variant/JP-5**	**ERQ & PWRS** **F-76/Jet variant/JP-5**
CONUS	Colonial Pipeline	DFSP Selma	DFSP Craney Island
	DFSP Jacksonville	DFSP Houston	DFSP Puget Sound
	DFSP Mayport	DFSP Selby	-
	Miramar Station	-	-
	DFSP Point Loma	-	-
OCONUS	DFSP Guantanamo Bay	St. Theodori	Lajes Field*
	Augusta Bay	-	Rota
	Souda Bay	-	DFSP Okinawa
	DFSP Fujairah	-	DFSP Hakozaki
	DFSP Jebel Ali	-	DFSP Guam
	DFSP Salalah	-	Wake Island
	DFSP Djibouti	-	DFSP Pearl Harbor
	DFSP Diego Garcia	-	-
	DFSP Singapore	-	-
	DFSP Subic Bay	-	-
	Sasebo	-	-
	Marshall Islands	-	-

*F-76 & JP-8

Once potential PWRS and ERQ inventory quantity reductions are derived, the costs avoided by the elimination of excess contracted tankage and holding costs for fuel savings can be calculated per *Office of Management and Budget Circular No. A-94* guidelines to project future budget reductions.

3. Storage Transition Costs and Phased Roll-out Plan

As part of the transition to JP-5, further research is also needed on the total cost and timing required to clean, certify and make ready all applicable afloat and ashore fuel handling infrastructure. Additionally, cost avoidance and schedule deconfliction methods need to be crafted to mitigate budget overruns and a reduction in Ao of fuel storage assets. As noted in our *Literature Review*, CuNi contamination, and potential JFTOT failure during A-series testing for combatant fuel downloads into DFSPs prior to DSRAs, are a significant issue under SFC conditions. Additionally, entrained water in JP-5 used for ships propulsion in F-76 seawater-compensating fuel tanks aboard surface combatants would pose the same issue.

Therefore, future analysis should include the cost of establishing minimal auxiliary JP-5 storage for the instances previously stated. Likewise, current shore-based F-76 storage tanks or dedicated refueling barges could constitute this auxiliary storage. Under the SFC, this JP-5 could not be reloaded into MSC vessels, baring extensive filtration and treatment, but could be reserved for in-port loading into surface combatant ship propulsion storage tanks. Furthermore, the analysis should identify the most cost-effective method, with the least negative impact to maritime operations, by incorporating all planned contracted maintenance at DFSPs with currently collocated JP-5 and F-76 stocks and selected restricted availabilities for deployable vessels. It is vitally important to implement a phased roll-out plan that incorporates a timeline for the drawdown and repositioning of current F-76 stocks globally. This timeline would be important to DLA Energy contracting time horizons for refinery solicitations, as some contracts may require two years from requirements planning to product delivery.

4. Total Fuel Supply System Transition Cost

Lastly, an initial goal of our research was to analyze the operational impact of the SFC on procurement and land-based distribution and storage systems in addition to its impact on CLF assets. Unfortunately, we were unable to secure procurement information or inventory data for all DFSPs. While we have shown potential operational benefits of SFC implementation, this information will significantly alter the primary cost driver for naval fuel consumption, that is, the procurement cost for the fuel itself. Additionally, further research is needed to analyze the major potential DoD and contracted infrastructure, stock positioning, and global fuel distribution network changes. To do so would first require obtaining historical pricing trends from DLA Energy's primary and frequent JP-5 refineries or providers. Since 2014, the availability of high quality, light/sweet crude oil produced domestically has dramatically increased (EIA, 2019a). Lighter and sweeter feeder stocks are more conducive to producing lighter end products, such as kerosene, rather than heavier end products, such as fuel oil (EIA, 2019b). Thus, pricing trends in the domestic U.S. refining industry must be analyzed to confirm if continued downward pressure on the price for kerosene-based products will result from a continued increase of appropriate feeder stock supply. Supplemental analysis is also needed to determine if JP-5 procurement prices would rise, due to the greatly increased annual demand caused by the SFC, or would fall due to economies of scale in batching by refineries.

Secondly, it is assumed that the majority of JP-5 would be refined in the United States and transported to OCONUS DFSPs requiring additional T-5 tanker deliveries. If the SFC were adopted, any additional T-5 tanker resupplies and associated transportation costs would need to be calculated. Through this analysis, a breakeven price could be determined that balances procurement versus transportation costs. Once these two areas are analyzed, a cost-benefit analysis should be conducted, to include areas of potential savings identified within this thesis and in concert with the research results from Recommendation 2 and Recommendation 3. We feel this will give a final, and fully scoped evaluation of a Single Fuel Concept.

LIST OF REFERENCES

American Society of Testing and Materials. (2019). *Standard specification for diesel fuel* [ASTM D975-19c]. https://www.astm.org/DATABASE.CART/HISTORICAL/D975-19C.htm

Barrass, B. (2004). *Ship design and performance for masters and mates.* Elsevier/Butterworth-Heinermann.

Burford. (2016, July 18). *MSC ships USNS Rainier and MT Empire State conduct CONSOL-at-sea during RIMPAC 2016*. https://mscsealift.dodlive.mil/2016/07/18/msc-ships-usns-rappahannock-and-mt-empire-state-conduct-consol-at-sea-during-rimpac-2016/

Butler Jr., W. E., Alvarez, R. A., Yost, D. M., Westbrook, S. R., Buckingham, J. P., & Lestz, S. J. (1990). *Field demonstration of aviation turbine fuel MIL-T-83133C, Grade JP-8 (NATO Code F-34) at Fort Bliss, TX* [Interim Report No. 264]. Belvoir Fuels and Lubricants Research Facility. https://apps.dtic.mil/dtic/tr/fulltext/u2/a233441.pdf

Product Safety and Toxicology Group. (2016). *JP-4 fuel (MIL-T-5624)* Chevron Phillips. http://www.cpchem.com/msds/100000014035_SDS_US_EN.PDF

Chief of Naval Operations. (2018). *A design for maintaining maritime superiority version 2.0*. https://www.navy.mil/navydata/people/cno/Richardson/Resource/Design_2.0.pdf

Cimino, D. (2007). *Naval fuels and lubricants IPT* [NSSC-05H/00X]. Naval Sea Systems Command.

CITGO Petroleum Corporation. (2016). *F-76 military diesel* [Material safety data sheet: 13176]. CHEMTREC. http://www.docs.citgo.com/msds_pi/13176.pdf

Commander, U.S. 7TH Fleet. (2016, November 20). *Carrier Strike Group 5 returns to Yokosuka after patrol.* https://www.c7f.navy.mil/Media/News/Display/Article/1009446/carrier-strike-group-5-returns-to-yokosuka-after-patrol/

Commander, U.S. Pacific Fleet. (2015). *Operations Order* [OPORD 201-15]. Department of the Navy.

Defense Logistics Agency-Energy. (2020). *Fiscal year 2019 fact book.* https://www.dla.mil/Portals/104/Documents/Energy/Publications/FactBookFiscalYear2019_lowres.pdf?ver=2020-01-21-104015-803

Department of Defense. (2014). *Detail specification: Fuel, Naval distillate* (MIL-DTL-16884N). everyspec.com: http://everyspec.com/MIL-SPECS/MIL-SPECS-MIL-DTL/MIL-DTL-16884N_50645/

Department of Defense. (2015). *Detail specification: Turbine fuel, aviation, kerosene type, JP-8 (NATO F-34), NATO F-35, and JP-8+100 (NATO F-37)* [MIL-DTL-83133J]. everyspec.com: http://everyspec.com/MIL-SPECS/MIL-SPECS-MIL-DTL/MIL-DTL-83133J_53582/

Department of Defense. (2016a). *Detail specification: Turbine fuel, aviation, grades JP-4 and JP-5* (MIL-DTL-5624W). everyspec.com: http://everyspec.com/MIL-SPECS/MIL-SPECS-MIL-DTL/MIL-DTL-5624W_55741/

Department of Defense. (2016b). *Standard practice quality assurance/surveillance for fuels, lubricants and related products* (MIL-STD-3004D Change 1). everyspec.com: https://www.dla.mil/Portals/104/Documents/Energy/Quality%20and%20Technical%20Support/E_MilSTD3004_1603.pdf

Department of Defense. (2016b). *Standard practice quality assurance/surveillance for fuels, lubricants and related products* (MIL-STD-3004D Change 1). everyspec.com: http://everyspec.com/MIL-STD/MIL-STD-3000-9999/MIL-STD-3004D_CHG-1_54230/

Department of Defense. (2018, January 19). *National Defense Strategy*. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

Department of Defense. (2009). *Chapter 11: Management of peacetime operating stock (POS) and pre-positioned war reserve (PWRS) Levels* (DoDM 4140.25-M). https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/414025m/414025-m-vol2-chapter11.pdf

Department of the Army. (2015). *Petroleum supply operations, Army techniques publication No. 4-43* (ATP 4-43). https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/atp4_43.pdf

Department of the Navy. (2007). *Naval warfare publication: Sustainment at sea* [NWP 4-01.2]. Government Publishing Office.

Department of the Navy. (2013). *Navy warfare publication: Navy planning* [NWP 5-01]. Government Publishing Office.

Department of the Navy. (2019). *Business operational plan: Agility and accountability 2020-2022.* https://www.secnav.navy.mil/donhr/Site/SECNAV%20Strategic%20Documents/DON%20Business%20Operation%20Plan%20FY20-FY22.pdf

Department of the Navy. (2020, February 24). *Fast combat support ships T-AOE.* https://www.navy.mil/management/photodb/photos/041221-N-1229B-029.jpg

Deziel, C. (2019, March 8). *The differences between kerosene & jet fuel.* Itstillruns: https://itstillruns.com/the-differences-between-kerosene-jet-fuel-12003828.html

Eppen, G. D. (1979). *Effects of centralization on expected costs in a multi-location newsboy problem.* (Management Science, *25*(5), 498-501). https://doi.org/10.1287/mnsc.25.5.498

Folster, A., Eggers, D., & Sawko, R. (2018). *Availability of refined fuel within the Indo-Pacific area of responsibility.* [Master's thesis, Naval Postgraduate School]. NPS Archive: Calhoun. http://hdl.handle.net/10945/61366

Garrett, R. K. (1993). *Is a single fuel on the battlefield still a viable option?* The Industrial College of the Armed Forces. https://apps.dtic.mil/dtic/tr/fulltext/u2/a276757.pdf

Green, M. L. (2017). *Kerosene: the advantages & disadvantages.* Itstillruns https://itstillruns.com/kerosene-advantages-disadvantages-8319651.html

Guimond, D. P. (2007). *Single Naval fuel at sea diesel engine impact study* (NSWCCD-98-TR-2004/22). Naval Surface Warfare Center, Carderock Division.

Hemighaus, G., Boval, T., & Bacha, J. (2007). *Aviation fuels technical review.* Chevron. https://www.chevron.com/-/media/chevron/operations/documents/aviation-tech-review.pdf

John, I. (1998). *TADC(X) Wartime force levels: Steady-state analysis* (CRM 98-69). Center for Naval Analyses. https://fas.org/man/dod-101/sys/ship/docs/adc_1855-1.htm

Johnson, D. W., Flake, M., & Adams, R. (2014, July 1). *Determination of corrosion inhibitor lubricity improver in jet fuel by liquid chromatography-electrospray ionization mass spectrometry*. University of Dayton, Department of Chemistry. https://ecommons.udayton.edu/cgi/viewcontent.cgi?referer=https://search.yahoo.com/&httpsredir=1&article=1041&context=chm_fac_pub

Joint Chiefs of Staff. (2017). *Joint bulk petroleum and water doctrine* (JP 4-03). https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp4_03pa.pdf?ver=2018-02-08-091424-107

Le Pera, M. (2005). *The reality of the single fuel concept* (PB 700-05-2 Volume 37). Army Logistician, Professional Bulletin of Unted States Army Logistics. https://alu.army.mil/alog/issues/MarApr05/reality.html

Likos, W. E., Owens, E. C., & Lestz, S. J. (1988). *Laboratory evaluation of MIL-T-83133 JP-8 Fuel in Army Diesel Engines* (Interim Report No. 232). Belvoir Fuels and Lubricants Research Facility. https://apps.dtic.mil/dtic/tr/fulltext/u2/a205281.pdf

McCusker, E. (2019). *Fiscal Year 2020 fuel price change* [Memorandum]. Department of Defense. https://www.dla.mil/Portals/104/Documents/Energy/Standard%20Prices/Petroleum%20Prices/E_2019Oct1PetroleumStandardPrices_190928.pdf?ver=2019-09-30-072433-663

Military Sealift Command. (2020a, April 11). *Fleet Oiler (PM1)*. https://www.msc.navy.mil/pm1/

Military Sealift Command. (2020b, February 2). *Ship inventory*. https://www.msc.navy.mil/inventory/images/photos/160805-N-AI605-006.jpg

Military Sealift Command. (2020c, April 11). *Fleet ordnance and dry cargo (PM6)*. https://www.msc.navy.mil/PM6/

Military Sealift Command. (2020d, February 24). *Ship inventory*. https://www.msc.navy.mil/inventory/images/photos/160614-N-YR245-040.jpg

Military Sealift Command. (2020e, April 11). *Dry cargo and tankers*. https://www.msc.navy.mil/PM55/

Monroe, D. (2016). *Diesel Fuel Properties* (S6P4). Mining Diesel Emissions Counsel. https://mdec.ca/2016/S6P3_monroe.pdf

Naval Air Systems Command. (2006). *Impact on shipboard fuel handling equipment: JP-5 single naval fuel at-sea feasibility study phase two* (NAVAIRSYSCOM Report 445/05-007). Naval Fuels & Lubricants IPT.

Naval Fuels & Lubricants Cross Functional Team. (2018). *Assessment of JP-5 for extended use in shipboard diesel engines* (NF&L CFT Report 19-008). Naval Air Systems Command, NAVAIR-4.4.5.1.

Naval Sea Systems Command. (2005). *Weight and moment compensation and limiting drafts for Naval surface ships* (NAVSEA INST 9096.3E). Government Publishing Office.

Office of the Secretary of Defense. (2019). *Annual report to Congress, military and security developements involving the People's Repulic of China 2019.* Government Publishing Office.

Office of the Under Secretary Defense for Acquisition and Sustainment. (2019). *Fiscal year 2018 operational energy annual report.* https://www.acq.osd.mil/eie/Downloads/OE/FY18%20OE%20Annual%20Report.pdf

O'Rourke, R. (2019). *Navy John Lewis (TAO-205) Class oiler shipbuilding program: Background and issues for Congress* (CRS Report No. R43546). Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R43546/58

Pogarty, R. P. (2014). *Use of JP-5 fuel on LCS 1 and 3 ship service diesel generators (SSDG) and main propulsion diesel engines (MPDE), NAVSEA 05Z21 Risk Assessment* [NSSC-05D/103]. Naval Sea Systems Command.

Putnam, D. (2018). *Eliminating adverse impact of copper contamination in jet propellant 5 (JP-5)* [SBIR 2018.1 - Topic N181-071]. Navy Small Business Innovation Research Program Office.

Rebold, M. (2004). *Use of JP-5 aviation turbine fuel as the primary fuel for USN propulsion boilers* (NATO Code F-44). Naval Surface Warfare Center, Carderock Division.

Seal, L. M. (2000). *MSC tanker fleet adds first of two new ships; retires two*. msc.navy.mil: https://www.msc.navy.mil/publications/pressrel/press10/press56.htm

Sermarini, J. T. (2000). *The universal fuel at sea: Replacing F-76 with JP-5.* [Master’s thesis, Naval Postgraduate School]. NPS Archive: Calhoun. http://hdl.handle.net/10945/7730

Tosh, J. D., Moulton, D. S., & Moses, C. A. (1992). *Navy fuel specifications standardization interim report* (Interim Report No. 225). Belvoir Fuels and Lubricants Research Facility. https://apps.dtic.mil/dtic/tr/fulltext/u2/a248542.pdf

U.S. Bureau of Labor Statistics. (n.d.). *CPI inflation calculator*. Retrieved January 22, 2020, from https://www.bls.gov/data/inflation_calculator.htm

U.S. Energy Information Administration. (2014, September 16). *Oil tanker sizes range from general purpose to ultra-large crude carriers on AFRA scale*. https://www.eia.gov/todayinenergy/detail.php?id=17991

U.S. Energy Information Administration. (2018, September 12). *The United States is now the largest global crude oil producer.* https://www.eia.gov/todayinenergy/detail.php?id=37053

U.S. Energy Information Administration. (2019a, August 23). *The United States tends to produce lighter crude oil and import heavier crude oil*. https://www.eia.gov/todayinenergy/detail.php?id=41033

U.S. Energy Information Administration. (2019b, October 23). *Oil: crude and petroleum products explained*. https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil-inputs-and-outputs.php

Vough, M. (n.d.). *Maritime Law Center*. The Jones Act. Retrieved February 18, 2020, from http://www.maritimelawcenter.com/html/the_jones_act.html

Walton, T., Boone, R., Schamm, H. (2019). *Sustaining the fight resilient maritime logistics for a new era.* csbaonline.org: https://csbaonline.org/research/publications/sustaining-the-fight-resilient-maritime-logistics-for-a-new-era/publication/1

Weisser, K. L., & Turgeon, R. T. (2013). *50/50 F-76/DSH-76 specification and fit-for-purpose level I test results* (NAVAIRSYSCOM Report 441/13-012). Naval Fuels & Lubricants Cross Functional Team.

Werner, B. (2019). *Navy to hold large scale fleet exercises in summer 2020.* news.usni.org: https://news.usni.org/2019/12/05/navy-to-hold-large-scale-fleet-exercises-in-summer-2020

White House. (2017, December). *National Security Strategy of the United States of America.* https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

Wikimedia Commons. (2009). *USN Fleets (2009).* https://commons.wikimedia.org/wiki/File:USN_Fleets_(2009).png

Williams, S., & Leung, R. (2011). *Single fuel at sea: Phase II results* (Report 441/11-002). Naval Fuels & Lubricants Cross Functional Team.

Wilson, B. (1996, February 1). *Fuel lubricity* (48(1), pp. 10-14). Industrial Lubrication and Tribology. https://www.deepdyve.com/lp/emerald-publishing/fuel-lubricity-MwoBmooNjw

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California