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Resilient Aerial Refueling: Safeguarding the US Military's Global Reach

TIMOTHY A. WALTON & BRYAN CLARK
CENTER FOR DEFENSE CONCEPTS AND TECHNOLOGY, HUDSON INSTITUTE

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Cover Photo: A Hawaii Air National Guard F-22 Raptor approaches a Wisconsin Air National Guard KC-135 Stratotanker to receive aerial refueling December 11, 2018, over the Pacific Ocean, near the Hawaiian Islands. (John Linzmeier/US Air National Guard)

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EXECUTIVE SUMMARY

The US military's ability to promptly project power over intercontinental distances and sustain operations at theater scales is one of its most significant advantages. Aerial refueling is arguably the most important contributor to this uniquely American capability. By enabling aircraft to refuel without landing, the US aerial refueling architecture of tanker aircraft, airfields, and bulk fuel storage and distribution provides US forces global reach. In concert with other elements of military logistics, aerial refueling has helped the United States deter and defeat aggression against its worldwide network of allies and partners.

However, what has been a US strategic strength now risks becoming a major weakness. During the 30 years since the end of the Cold War, tankers have tirelessly operated around the globe, supporting wartime campaigns and peacetime deployments. US Department of Defense (DoD) decisions aggravated the stress on refueling aircraft by shrinking the US Air Force fleet from 701 to 473 tankers while adopting a more expeditionary US force posture and reducing the overseas infrastructure of airfields and bulk fuel storage and distribution.[1] Today, refueling aircraft sustain such an extraordinary pace of "normal" operations that they have little spare capacity to handle new missions that might arise as peacetime competitions with the People's Republic of China (PRC) or Russia intensify.[2] And readiness of the tanker fleet, which is 52 years old on average, may only worsen in the near term as delays in fielding the new KC-46A will likely lead to retirements of aging KC-10 and KC-135 aircraft before KC-46As and their crews are fully ready for operations.

US aerial refueling is also under increased threat as adversaries—especially the PRC—are increasingly capable of attacking aircraft and airbases. In addition to disrupting the tightly choreographed and brittle aerial refueling architecture developed during 30 years of uncontested operations, threats to aircraft and airbases will increase air forces' dependence on tanking to reach targets from distant airfields. And regardless of where they are based, air forces will require the greater endurance provided by tankers to orchestrate more complex, distributed operations to improve survivability and defeat targeting by enemy air defenses.

Deficiencies in the aerial refueling enterprise pose three major challenges.[3] First, logistics weaknesses hinder US forces' ability to swiftly and sustainably deploy during peacetime competition that could also undercut deterrence by signaling a lack of US preparedness for conflict. Second, logistics capacity constraints hinder the ability of the Joint Force to adopt novel concepts of operation (CONOPS) that leverage distribution and tempo to impose dilemmas on adversaries. Third, and most sobering, aerial refueling capability gaps could cause the United States to be incapable of sustaining combat in defense of US allies and partners.

In 2021 the US aerial refueling enterprise is losing altitude. It must evolve, but the increasing operations and support (O&S) costs of the current geriatric fleet and other competing procurement programs amidst a likely flat defense budget raise the specter that change will not be possible, and that the US Air Force will be left with a smaller and weaker aerial refueling force, and, in turn, a weaker Joint Force.

There are fiscally viable opportunities to shift to an aerial refueling architecture that is more operationally effective and supports US strategy. To do so in a relevant time frame, however, the US Air Force will need to commit itself to cross-portfolio trades that appropriately accelerate and fund high-impact investments across the entire aerial refueling enterprise.

Options for the Aerial Refueling Architecture

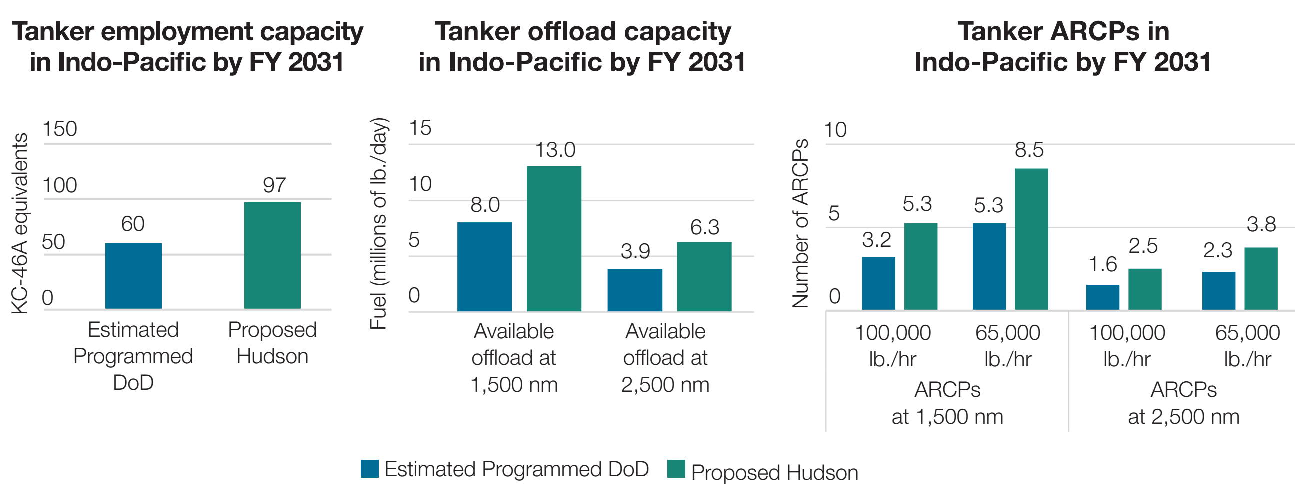
This study assessed the aerial refueling portfolio as an operational system comprised of three main elements: the surface infrastructure of airfields and fuel storage and distribution systems; command, control, and communications (C3); and tanker aircraft. The study focused on the contributions of the US Air Force aerial refueling fleet but also accounted for the roles played by Navy and Marine Corps tanker aircraft.

Guided by national strategy and service and joint warfighting concepts, the study examined threats and demands facing the force through a range of scenarios. These included large conflicts against the PRC and Russia consistent with the most stressing scenarios used in DoD's 2018 Mobility Capabilities Requirements Study (MCRS).[4] The study also assessed challenging, protracted low-to-moderate-scale scenarios and ongoing operations that test the sustainable employment of the force. The study used threat scenarios to assess different investment portfolios for the refueling enterprise that would support the requirement of 479 tankers as established by the 2018 MCRS; this study used the MCRS requirement to provide a basis for comparison between the recommendations below and DoD plans. The investment portfolios considered in this study differed in terms of the types, sizes, and mix of tankers and the extent and nature of improvements to refueling infrastructure and C3.

This study's analysis concludes that any effective plan should fund improvements across the entire aerial refueling enterprise, rather than focusing only on tankers. On the ground, plans should change refueling aircraft posture and augment the surface distribution architecture. In the air, plans should modernize C3, field a capable Bridge Tanker that can support long-range, high-capacity offloads, and accelerate the development of a future K-Z tanker.

The most important changes needed in the aerial refueling enterprise are on the ground. Absent reform, in a conflict with China the tanker fleet may be confined to about a dozen airfields where US forces would have political access and sufficient runway, ramp space, and fuel stores to support refueling operations. Such a force could only support relatively few aircraft in the air and would be more vulnerable to attack compared to a more-dis-

Figure 1: Current and proposed tanker capacity in the Indo-Pacific



Proposed surface architecture investments would increase effective tanker capacity in the Indo-Pacific by 63% within a decade and approximately double it by 2041. Alternatively, greater airfield capacity could enable a higher degree of tanker dispersion. Please see the section "Shifts in Strategy, Threats, and Demands with Implications for the Aerial Refueling Force: Scenario Assessment," for an explanation of the chart's methodology.

Source: Report authors.

tributed fleet. Similar airfield and fuel challenges could be faced in other scenarios, as was observed during the 2011 North Atlantic Treaty Organization (NATO)–led campaign in Libya.

Enhancing the capacity and resilience of its surface architecture should be a top priority for the US Air Force—even if it comes at the cost of tanker procurement—because it will yield a greater increase in the number of tankers available and a greater amount of fuel delivered even if fewer new tankers are in the overall fleet. DoD should improve the architecture's resilience by evolving today's brittle posture to a more-distributed one that leverages clusters of mutually supporting military and civil airfields on US, allied, and partner territory, consistent with the US Air Force's Agile Combat Employment concept. This approach would also better protect fuel stores and secure access to capabilities such as maritime tankers and over-the-shore fuel delivery systems that would be needed to distribute fuel at scale. Allocating an additional $633 million per year over the next 10 years (and $400 million thereafter) to Indo-Pacific posture and bulk fuel distribution could boost employable tanker capacity in the theater by 63% within a decade (as shown in Figure 1) and greatly improve operational resilience. These investments would complement planned DoD actions and elements of the proposed Indo-Pacific Deterrence Initiative.

Beyond the surface architecture, C3 improvements could greatly improve the tanker fleet's efficiency and ability to support emerging DoD operational concepts. During peacetime competition, new command and control (C2) and fleet optimization tools could improve tanker availability, lower costs, and enable higher tanker fleet readiness. During crises or conflicts, C2 and communications enhancements will be essential to enhance tanker survivability and allow tankers to support emerging operating concepts that entail greater distribution and agility on the ground and in the air. As part of these concepts, new C3 tools would allow the tanker community to execute more sophisticated force extension operations, dynamic refueling control points, and other approaches that maximize optionality for the force and impose complexity on adversaries. The technologies for C3 enhancements are largely mature and could be adopted by the tanker fleet during the next five years.

In terms of aircraft, the US Air Force should embrace new concepts of employment and evolve the tanker fleet through the Bridge Tanker and K-Z programs. The top candidates for the Bridge Tanker program are the Boeing KC-46A and the Lockheed Martin Next Generation Tanker (LMXT), which is a modified version of the Airbus A330 Multi Role Tanker Transport (MRTT). The LMXT provides greater offload capacity than the KC-46A, which could allow it to support missions with fewer aircraft, thus saving operating costs on some missions during peacetime competition and reducing operational complexity during crises or conflicts. Additionally, like the KC-10 that is being retired, the LMXT excels at long-range, high-capacity offloads necessary for supporting large operations from distant airfields, such as those found throughout the Indo-Pacific. The smaller KC-46A's generally higher fuel offload to ramp space ratio means that for a given airfield, KC-46As may be able to deliver more aggregate fuel capacity and booms in the air than LMXTs, albeit by relying on more tankers and associated ground and air personnel. The KC-46A costs less to procure and operate than the LMXT, and the US Air Force could avoid incurring some costs by selecting the KC-46A and increasing commonality throughout the fleet.

To ensure the Bridge Tanker paves the way for a new tanker, throughout the 2020s, the US Air Force can methodically fund technology maturation, design, and prototyping efforts for capabilities to enhance the survivability of existing tankers and can launch the follow-on K-Z program. The K-Z tanker should likely be a dedicated medium tanker, termed K-Z(M), that is efficient in terms of fuel consumption, fuel offload to ramp space ratio, and lifecycle costs and is capable of offloading fuel at range. A 95,000-pound (lb.) empty weight K-Z(M) with 140,000 lb. of fuel appears to be a promising design that could offload relevant quantities of fuel to packages of small aircraft or one or more larger aircraft and would be capable of operating from a wide range of airfields near and far from fuel delivery areas. By adopting a balanced approach to survivability, the K-Z(M) could leverage a medium-sized fuselage, signature management best practices, and robust protection systems to allow it to operate slightly inside contested areas. Because it would remain outside highly contested areas and could defend itself against some missile threats, the K-Z(M) would not require a highly stealthy design, and its RDT&E and procurement costs could be reduced relative to a more sophisticated aircraft. If the necessary technologies are matured, making the K-Z(M) a highly automated unmanned aircraft would confer significant operational and lifecycle cost benefits.

This analysis finds two classes of tanker designs would be poor fits for US Air Force requirements. Small and very small tankers would carry insufficient fuel to support likely formations of fighter aircraft or small numbers of large aircraft. These "tactical tankers," or "shuttle tankers," would reduce flexibility for US forces by either requiring beddown at contested forward airfields or by binding larger tankers to support them. Instead of opting for these design attributes, the K-Z(M) should hold enough fuel to independently support a range of receivers and flexibly operate throughout a theater, while still receiving onloads from larger tankers when appropriate. To maximize efficiency, larger tankers such as the KC-46A or the LMXT could focus on refueling larger aircraft, while K-Z(M) could focus on refueling packages of smaller aircraft closer to contested areas.

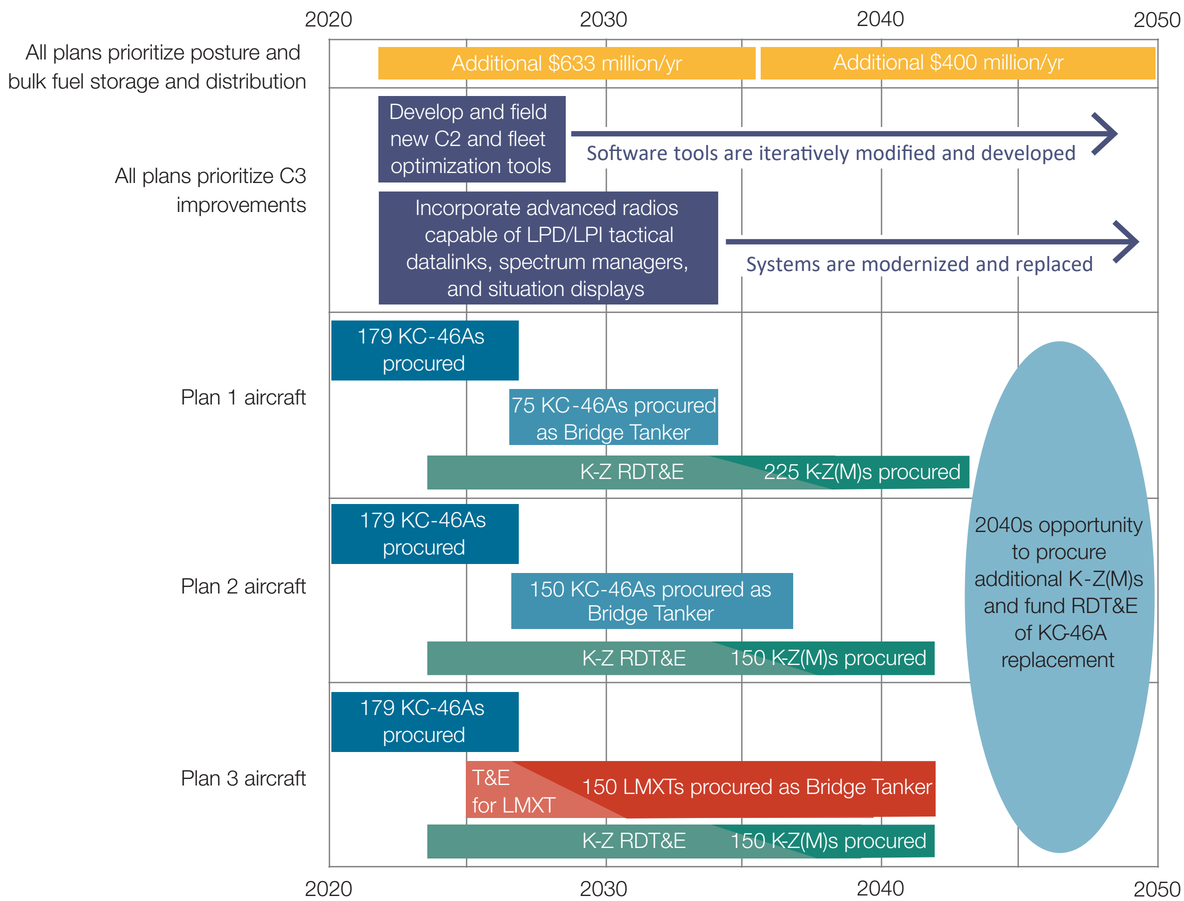
Another unpromising tanker design concept is a very low observable tanker. Apart from the challenges in designing a tanker that could remain undetected while refueling other aircraft in highly contested environments, such a tanker would be costly to develop and procure. Those costs would likely crowd out investments in the surface architecture, C3 and self-defense features for widebody tankers, and new fuel transfer technologies. Instead, better value would be gained by procuring a moderate-cost K-Z(M) that could stand-in a conservative distance, funding other elements of the aerial refueling architecture, and dedicating remaining funds to munitions and long-range systems, such as the B-21 bomber and the Next Generation Air Dominance (NGAD) family of systems that could achieve desired effects when tanking at the edge of contested zones.

New concepts and capabilities outside of the tanker force can play a major role in reducing tanker demands, increasing operational flexibility, and lowering lifecycle costs. Some of these, such as Forward Arming and Refueling Point (FARP)–enabled shuttle missions, can be embraced in the near term, while others requiring the fielding of new Defensive Counter-Air (DCA) capabilities or engine technologies will take more time to proliferate throughout the force. By articulating the opportunities generated and risks mitigated by the adoption of these concepts and capabilities, the tanker community can play an important role in their adoption.

To evaluate potential procurement options, this study developed notional plans that illustrate the choices available to DoD. All three plans (summarized in Figure 2) prioritize funding investments in Indo-Pacific posture and bulk fuel storage and distribution and C3 improvements. In terms of aircraft, each plan advances the development of K-Z(M) during the 2020s, resulting in the delivery of the first K-Z(M)s by Fiscal Year (FY) 2035. By acquiring K-Z(M)s at rates of 18-24 tankers per year, the plans retire aging KC-135s sooner than anticipated by the US Air Force, which reduces fleet O&S expenditures, and frees up funding for procurement of K-Z(M) or continued improvements to the surface architecture.

The three plans differ in their approach to the Bridge Tanker. One truncates the Bridge Tanker program with a buy of 75 additional KC-46As; another acquires 150 KC-46As; and the third acquires 150 LMXTs. All three plans deliver more offload capacity and can sustain more aerial refueling points than the current force. The plan that acquires LMXT confers 11-12% more offload capacity at 2,500 nautical miles (nm) than the alternative plans and would provide 8-10% more points that deliver 65,000

Figure 2: Summary of aerial refueling architecture plans



Source: Report authors.

lb. and 100,000 lb. of fuel per hour at 2,500 nm (a good measure for booms in the air for fighters and transports/bombers, respectively), but it would require 8-16% more ramp space. Beyond the nominal performance of the force, however, as shown in Figure 1, all three plans' investment in the necessary surface architecture would greatly increase their effective capacity in the Indo-Pacific.

In terms of total RDT&E, procurement, O&S, and surface architecture costs, the first plan mostly stays within the funding levels established in the President's Fiscal Year 2022 budget proposal, adjusted for inflation, over the next 30 years—even though (like the other two plans) it spends $14 billion on additional posture and bulk fuel distribution investments. The plans acquiring 150 KC-46A or LMXT Bridge Tankers would cost $7.5 and $17.6 billion more than the first plan, respectively.

Overall, the US Air Force should take a comprehensive approach to aerial refueling force design that enables the execution of new operational concepts, increases performance, and manages costs. The options presented in this study are not the only set of solutions, but they do suggest that if the US Air Force makes hard choices across portfolios and is supported by Congress, it can overcome budgetary obstacles to significantly improve this decade and field a more resilient aerial refueling force.

INTRODUCTION

The aerial refueling enterprise is essential to the US ability to project power globally in defense of its interests. As the Joint Force adopts new concepts to enhance its lethality and gain decision advantage, aerial refueling is increasingly necessary to enable a more-distributed and dynamic force. However, with an aging inventory of tanker aircraft and stiff budgetary headwinds, it is an open question whether the US Air Force can field the aerial refueling force that the nation needs.

This study assessed the current and programmed US aerial refueling enterprise and found it would be unable to support US strategy and operational concepts against peer adversaries such as the PRC. However, the study also determined the US military could address these shortfalls and improve the operational resilience of its aerial refueling enterprise by adopting new concepts, capabilities, capacities, and posture.[5] In scoping its effort, this study analyzed the aerial refueling enterprise as an interdependent operational system that enables airpower and is comprised of three main elements:

- **Surface architecture:** the network of airfields, maintenance facilities, and bulk fuel storage and distribution facilities and systems necessary to enable tanker operations;
- **Command, control, and communications (C3):** the organizations and tools necessary to design and execute effective aerial refueling concepts and plans, and the communications capabilities to enable dynamic operations; and
- **Tanker Aircraft:** the family of aircraft capable of transferring fuel midair to other aircraft.

Photo: An Aircraft Maintenance Squadron crew chief marshals the KC-46A Pegasus on the flightline February 21, 2019, at McConnell Air Force Base Kan. (Alexi Myrick/US Air Force)

This report focuses on the contributions of the US Air Force aerial refueling fleet but accounts for the roles played by Navy and Marine Corps tanker aircraft and identifies opportunities for deepening cooperation with US allies and partners. Additionally, although the report assesses the anticipated performance of different aerial refueling architecture options by measuring the aggregate capacity of fuel delivered and the number of aerial refueling offload points that can be continuously supported, it does not assess the quantitative sufficiency of options to support national strategy and operational plans. Instead, it bases its capacity requirement on the 479 tankers stipulated by the 2018 MCRS.[6] The 479-tanker requirement of the MCRS captures the demands of the force in terms of offload capacity and distribution of tankers in the air.

This study describes the historical evolution of the aerial refueling force, highlighting relevant lessons for policymakers. It reviews the implications of changes in strategy, threats, and demands on the aerial refueling force before assessing the current and programmed force's expected performance in relevant scenarios. Informed by these assessments, it proposes new concepts and capabilities for a new aerial refueling architecture and concludes by offering options for evolving the force. Appendix A compares in greater detail the characteristics of three notional plans for the aerial refueling architecture.

CURRENT STATE AND EVOLUTION OF THE AERIAL REFUELING FORCE

The US Air Force currently fields a mixed aerial refueling force of 379 KC-135, 50 KC-10, and 47 KC-46A tankers. Tanker aircraft and their crews are drawn from the US Air Force's active and reserve components and the Air National Guard. Tankers are organized into squadrons of usually 12 aircraft and administrated by US Air Force Air Mobility Command (AMC), which is the Air Force Major Command responsible for logistics aircraft. As the Air Force component commander for US Transportation Command (USTRANSCOM), Air Mobility Command exercises operational control over all but two tanker squadrons.[7]

The US Marine Corps and US Air Force also possess C-130 aircraft variants capable of refueling tactical and tiltrotor aircraft and helicopters, and the US Navy's F/A-18E/F fighters can be equipped with a drogue and fuel tanks to "buddy tank" other aircraft. Tanking by these other aircraft serve a small but important role in supporting the employment of tactical aircraft.[8]

US Air Force tankers operate from a network of airfields and support facilities on US, allied, and partner territory, especially those locations with large fuel stores suitable for refueling tankers on the ground. These sites, in turn, rely on bulk fuel distribution capabilities such as pipelines, ports, tanker ships, and trucks to deliver fuel to storage tanks. When operating from

Photo: An F-15 Strike Eagle (L) prepares to be refueled by a KC-135 Stratotanker from the 340th Expeditionary Air Refueling Squadron December 29, 2003. (Suzanne M. Jenkins/US Air Force via Getty Images)

Figure 3: Constituent elements of a simplified aerial refueling enterprise effects chain

Source: Report authors

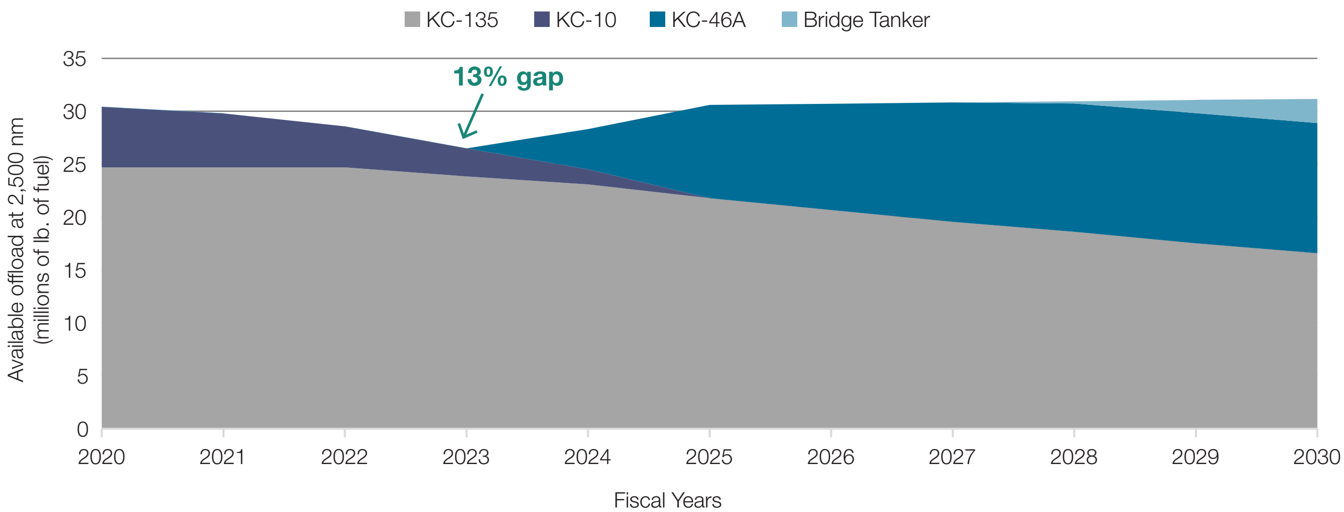
sites without existing bulk fuel storage or distribution capabilities (or if they have been damaged), DoD relies on expeditionary over-the-shore fuel delivery systems (such as the Offshore Petroleum Distribution System or the Amphibious Assault Bulk Fuel Delivery System); inland fuel delivery systems (such as the Inland Petroleum Distribution System); and expeditionary fuel storage bladders. Figure 3 presents constituent elements of a simplified aerial refueling enterprise.

The existing architecture effectively supports ongoing DoD operations. However, it faces major challenges that threaten to significantly degrade its capacity during peacetime competition, and even more so during a major conflict. Most prominently, the refueling fleet is aging and experienced multiple delays on its path to recapitalization. The average tanker today is 52 years old, and the KC-135 fleet is projected to reach an age of over 80 years if it is retired as planned during the late 2040s. Such a prolonged service life for a high-demand aircraft not only risks catastrophic failures that could ground large portions of the fleet, but also leads to very high O&S costs. For example, the KC-135R fleet has exhibited a 3% annual real growth in cost per flying hour.[9]

The US Air Force initially attempted to begin to recapitalize the tanker fleet in 2002. However, a corruption scandal derailed initial plans and led to a 2007 40-year plan in which the Air Force would procure three tranches of tankers, termed KC-X, KC-Y, and KC-Z.[10] Due to a competition protest, final award of KC-X aircraft did not take place until 2011, when the US Air Force selected Boeing to develop and deliver a planned 179 KC-46As.

Development and manufacturing delays on the KC-46A program further hindered the KC-X recapitalization program, and as of August 2021 the US Air Force has only received 47 air-

Figure 4: Planned fully operational US Air Force tanker fleet fuel offload capacity



The chart assesses fuel offload at 2,500 nm with one hour on station and two hours of reserve. The Bridge Tanker is modeled as KC-46A.

Source: Report authors.

craft, when in 2007 it had originally planned on receiving 143 KC-Xs by 2021. Furthermore, continued problems with the KC-46A's aerial refueling remote vision system and other systems mean that those aircraft that have been delivered may not be certified for full operations until 2024 or later, and there may be a shortfall in trained KC-46A crews until around 2027.[11]

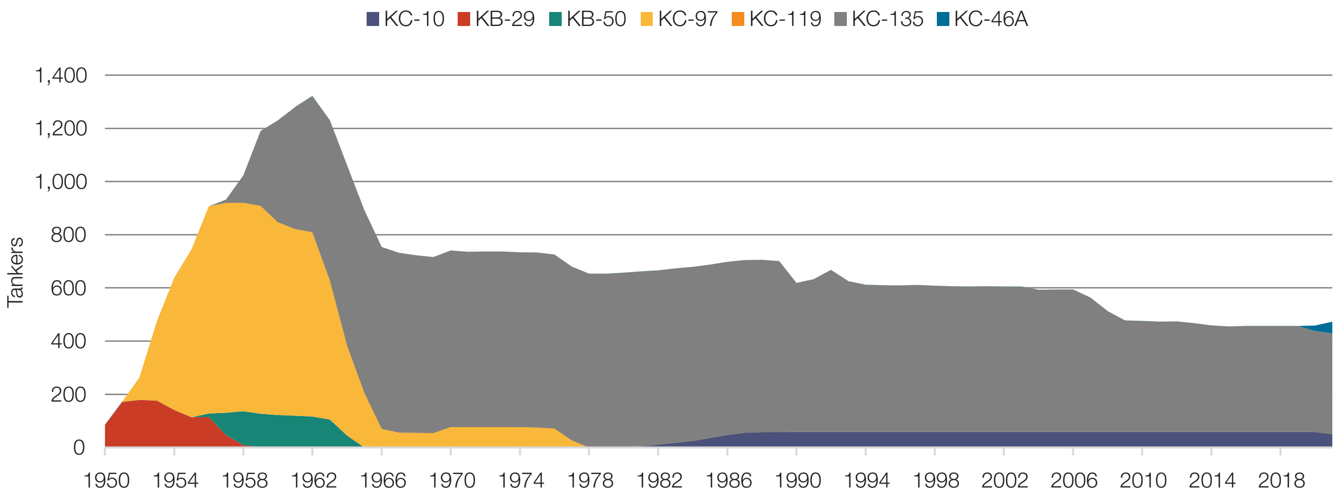
Simultaneously, in 2014 the US Air Force decided to retire the KC-10 tanker fleet (as well as some older KC-135s) early to save O&S costs, and in the FY 2021 National Defense Authorization Act (NDAA), Congress approved gradual retirement of the tankers by FY 2025.[12] As the Air Force retires KC-10s and KC-135s (especially before KC-46As are fully operational), it is on track to lose up to 13% of its fully operational refueling capacity over the next five years, as shown in Figure 4. To better understand how the US Air Force reached this point and draw lessons for the future, the following section briefly reviews the history of US aerial refueling.

A Short History of US Aerial Refueling

In 1923 the US Army Air Service conducted the first aerial refueling.[13] Over the next few decades, aerial refueling concepts and technologies evolved, and in 1948 General Carl Spaatz, the first Chief of Staff of the new US Air Force, made aerial refueling the highest priority of the service in order to unlock airpower's intercontinental potential. Rather than aircraft relying on slowly hopping across a network of airfields to deploy, aerial refueling offered the potential of establishing transoceanic "air bridges" that strategic bombers could use to swiftly deter the Soviet Union and attack it if necessary. Tactical and other aircraft could also use the air bridge to rapidly deploy as part of a response to Soviet aggression.

For its first tankers, the US Air Force used converted propeller-driven B-29 bombers, designated KB-29M. To keep up with the new faster, turbojet-powered B-47 bombers, the Air Force succeeded the KB-29M with purpose-built KC-97 tankers. Re-

Figure 5: Evolution of the US Air Force tanker fleet



Source: Report authors. Data are drawn from *US Air Force Statistical Digest* and *US Air Force Almanac*.

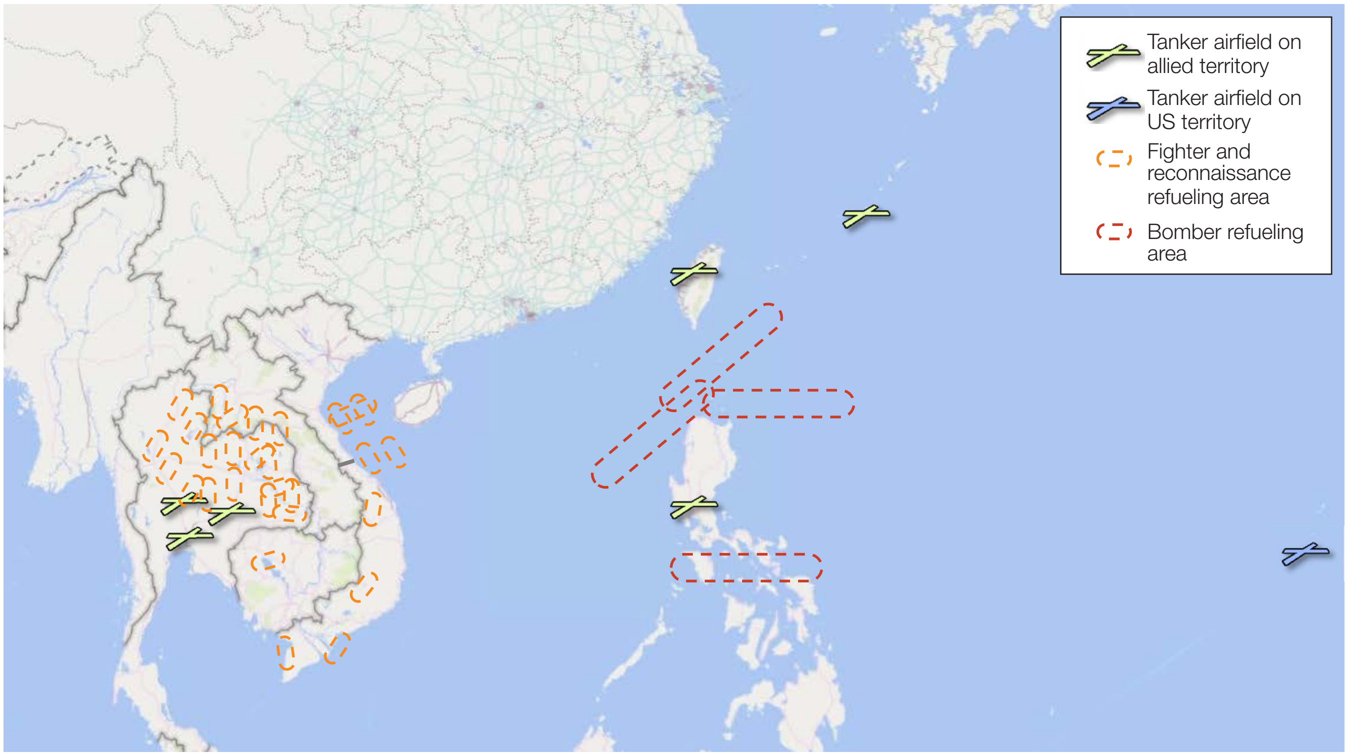
flective of the pace in which the US Air Force embraced aerial refueling, nearly 500 tankers were fielded a mere five years after General Spaatz prioritized aerial refueling, and as shown in Figure 5, the Air Force maintained a fleet of approximately 700 tankers throughout the Cold War.

Early aerial refueling relied on various technologies in which hoses were dragged behind the offloading aircraft to a receiving aircraft. The most advanced variant was the probe-and-drogue system, in which the receiving aircraft would insert a probe into the offloading aircraft's trailing drogue. Although this system would continue to evolve and is still in use today by NATO fighter aircraft, US Navy and Marine Corps fighters, and helicopter and tiltrotor aircraft, the US Air Force's evolving bomber fleet needed to more rapidly and reliably receive large quantities of fuel at higher speeds and in challenging weather. In response, by 1950 Boeing developed a "flying boom" design that involved the extension of a fixed boom from the offload aircraft into a receptacle on the receiving aircraft.[14] The flying boom technology was better suited for refueling large aircraft, such as Strategic Air Command bombers, and in 1950 it was incorporated into the KC-97 tanker and the subsequent KC-135 tanker that became the workhorse of the tanker fleet and continues to serve in that role today. The KC-135 is a version of the Boeing 707 airliner, and most tankers since 1950 have been derivatives of commercial aircraft.

Over time the KC-135 design evolved, and the current KC-135R and KC-135T tankers feature greater thrust (which aids takeoff from shorter runways), higher fuel efficiency, and greater fuel offload capacity than their KC-135 predecessors. To enable rapid transoceanic reinforcement of bases in Europe directly from the United States, during the 1970s, the US Air Force began to pursue a new tanker with greater offload capacity at range than the KC-135. The KC-10 was selected for this application in 1977.[15]

Aerial refueling tankers and receiver aircraft first conducted combat missions during the Korean War. However, the scope and scale of operations was limited, as relatively few of the tactical aircraft employed could receive fuel midair and the bulk of the US Air Force's heavy bomber force and tanker force was held in reserve for nuclear deterrence missions. During the Viet-

Figure 6: Tanker operations in the Vietnam War



Data are based on figures in George R. Fessler, Jr., *Aerial Refueling in Southeast Asia, 1964–1970*, US Headquarters Pacific Air Forces, CHECO Division, June 17, 1971, pp. 20, 25. Airfield icons in this and subsequent figures are based on the style of those in Mark Gunzinger, Carl Rehberg, Jacob Cohn, Timothy A. Walton, and Lukas Autenried, *An Air Force for an Era of Great Power Competition* (Washington, DC: Center for Strategic and Budgetary Assessments, 2019).

Source: Report authors.

nam War, however, aerial refueling became standard for both fighters and bombers. Tankers were employed from eight bases in Guam, Japan, the Philippines, the Republic of China (Taiwan), and Thailand. Figure 6 depicts tanker bases and aerial refueling control points and tracks. Tanker support allowed fighter and attack aircraft to carry heavier loads and allowed B-52 bombers to conduct strikes from Guam. As the war fluctuated in intensity, the number of tankers employed varied, but an average of 13% of the KC-135 fleet was committed to operations in Vietnam.[16]

Operations Desert Shield and Desert Storm in Iraq were the next major US operations that involved aerial refueling.[17] Nearly 100 tankers operating from airfields in France, Greece, Japan, Spain, Turkey, the United Kingdom, and the United States formed "air bridges" across the Atlantic and Pacific Oceans that allowed aircraft to rapidly deploy from US bases into the Middle East. A mix of airfield infrastructure challenges and initially fluctuating political positions of host nations limited the scale of air bridge operations and, in turn, the flow of aircraft to the Middle East.[18] Once in

Figure 7: Tanker operations in Operation Allied Force

Source: Report authors. Data are drawn from "Air Force Doctrine Publication 3-36: Air Mobility Operations, Air Refueling Operations," US Air Force, June 28, 2019, p. 57; William Knight and Christopher Bolkcom, *Air Force Air Refueling: The KC-X Aircraft Acquisition Program* (Washington, DC: US Congressional Research Service, 2008), p. 3; and John G. Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force* (Dayton, OH: US Air Force Institute of Technology, 2000), p. 3.

theater, a network of 11 airfields in British Indian Ocean Territory (Diego Garcia), Egypt, Oman, Saudi Arabia, Turkey, and the United Arab Emirates were used to support tanker operations. A total of 271 US Air Force tankers (or 44% of its tanker fleet) were employed, establishing and sustaining the air bridge and enabling combat and support missions in the theater.[19]

During the 1990s, tankers were called upon to provide an increasing level of aerial refueling support of ongoing operations, such as the maintenance of no-fly zones over Iraq and the deployment of more aircraft from the United States forward, as the US Air Force reduced its overseas presence and adopted a more expeditionary model. In 1999, Operation Allied Force, the NATO response to Yugoslav aggression in Kosovo, proved to be the next major test of tanker capacity. One hundred seventy-five tankers participated in the operation, establishing an air bridge across the Atlantic and offloading fuel in the theater.[20] Tankers in Europe were based out of 12 airfields in France, Germany, Greece, Hungary, Italy, Spain, Turkey, and the United Kingdom. Figure 7 depicts the operation's tanker bases and aerial refueling control points and tracks. Although the operation was successful, the combination of Operation Allied Force and other ongoing operations and deterrence commitments led to the simultaneous employment of 40% of the Air Force tanker fleet and 80% of tanker crews.[21]

In response to the terrorist attacks of September 11, 2001, the pace of tanker operations further increased. Tankers flew thousands of missions that enabled homeland defense air patrols as part of Operation Noble Eagle, and the US Air Force employed 80 tankers in Operation Enduring Freedom in Afghanistan.[22] In 2003 Operation Iraqi Freedom required another major tanker contribution, reaching a peak of 319 tankers to establish an air bridge and conduct operations in Iraq.[23] Operating from 15 airfields throughout Southwest Asia and Europe, 210 tankers (consisting of 185 US Air Force tankers and other US Marine Corps, Australian, and United Kingdom tankers, in addition to Navy tankers onboard aircraft carriers) directly supported Operation Iraqi Freedom in the theater, and another 95 tankers were tasked to support the deployment of aircraft.[24]

Even after Operation Iraqi Freedom was completed, tanker operations continued at a high rate, averaging 13,000 sorties per year in support of operations in Afghanistan and Iraq from 2004 to 2007.[25] At the same time, the US Air Force decided to retire 121 of its oldest KC-135 tankers (or 20% of its total tanker fleet) to forgo the costs necessary to modernize and sustain these aging aircraft into more modern variants, leaving it with a force of 473 tankers by 2011. That same year, US forces contributed to Operation Unified Protector (referred to as Operation Odyssey Dawn by the United States), the NATO operation to enforce United Nations Security Council resolutions concerning the Libyan Civil War. The operation took place amid a period in which tanker units were already heavily subscribed supporting ongoing operations in Afghanistan and Iraq; assisting with the relief of Japan following the March 2011 earthquake and tsunami (Operation Tomodachi); supporting a presidential visit to Latin America; and participating in contingencies, exercises, and routine deployments in every combatant command.[26] Other aircraft units were engaged in routine training and heavy maintenance.

With only 34 US Air Force tankers deployed to Operation Unified Protector (Odyssey Dawn), every taskable US Air Force tanker unit was engaged in ongoing operations, training, maintenance, or mandatory rest.[27] The stress was exacerbated by the lack of suitable airfields near Libya, which increased aircraft flight times and made nearly all aircraft reliant on aerial refueling. Large airborne surveillance aircraft required a dedicated tanker for each sortie.[28] Moreover, even though operations took place from developed Europe, many airfields lacked sufficient fuel stores or ramp space, or else were civil airports that were not made available for military flights.[29] Thus, tankers were forced to operate at relatively long distances of 1,000 to 1,100 nm, and the limited number of US tankers, complemented by 13 other NATO tankers, constrained the scope and tempo of air operations.

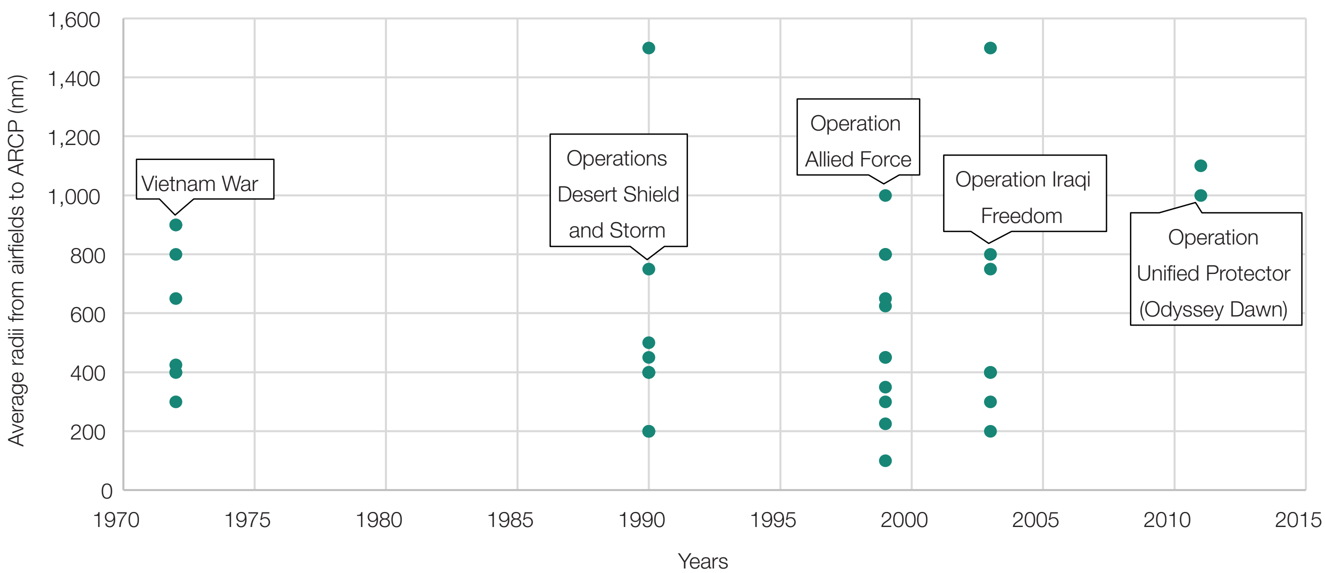
Lessons Learned from US Aerial Refueling

The history of US aerial refueling highlights four trends and dynamics that should inform the future force.

Access to and conditions of tanker airfields and airspace greatly impact refueling capacity.

Political access, operational infrastructure, receiver and tanker flight distances, and environmental factors at airfields shape the design of not only tanker plans, but the scale, tempo, and distribution of an entire air war. Political access to airfields has consistently been a limiting factor on tanker operations. During the Vietnam War, depending on the stage of the conflict, Thailand sought to limit the number of US aircraft (including tankers) at airfields or denied access to certain civil and military airfields that would have been convenient for US forces. During Operations Allied Force and Unified Protector, NATO countries limited tanker access to civil airports. During Operation Iraqi Freedom, Egypt, Saudi Arabia, and Turkey denied US forces

Figure 8: Average distance from tanker bases to air refueling control points



Source: Report authors. Data are drawn from John G. Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force*, (Dayton, OH: US Air Force Institute of Technology, 2000), pp. 39–40, 62; and T. Michael Moseley, "Operation Iraqi Freedom – By the Numbers," US Central Air Forces, 30 April, 2003, https://www.globalsecurity.org/military/library/report/2003/uscentaf_oif_report_30apr2003.pdf; Julia Denman, Walter Ochinko, Trisha Kurtz, Joy Labez, and Howard E. Kapp, *Operation Desert Storm: Aerial Refueling Operational Efficiency* (Washington, DC: US General Accounting Office, 1993), p. 5; Margaret Romero, *Algebra of Tankers* (Dayton, OH: Air Force Institute of Technology, 2006), p. 3; Karl P. Mueller, Gregory Alegi, Christian F. Anrig, Christopher S. Chivvis, Robert Egnell, Christina Goulter, Camille Grand, Deborah C. Kidwell, Richard O. Mayne, Bruce R. Nardulli, Robert C. Owen, Frederic Wehrey, Leila Mahnad, and Stephen M. Worman, *Precision and Purpose: Airpower in the Libyan Civil War* (Santa Monica, CA: RAND Corporation, 2015), p. 88; and "Air Force Pamphlet 10-1403: Air Mobility Planning Factors," US Air Force, October 24, 2018, p. 18.

the level of base access that was granted in Operations Desert Shield and Desert Storm, which disrupted Air Force tanker refueling operations in support of Navy carrier air wings flying from the Mediterranean. Overflight restrictions are another key access variable that has affected tanker operations, either by making support from some airfields impractical or by requiring circuitous flight paths that extend tanker flights and decrease available offload capacity.

Suitable infrastructure at potential tanker airfields is another factor affecting tanker offload capacity. Fully loaded tankers tend to require long airfields (8,000 or more feet in length), sufficient ramp space to park and maintain their aircraft, and access to large quantities of fuel that can be quickly delivered into the aircraft. The portion of airfields that meet all three of these criteria is limited—especially if there is political pressure to limit US presence at appropriate civilian airports. In response to the paucity of suitable sites, large-scale tanker operations have historically relied on a mix of military and civil airfields.

Access to airfields and airspace has, in turn, impacted the distances that receiver aircraft must operate to conduct operations. In general, air planners base fighter and other support aircraft forward in a theater, given their lower levels of endurance, whereas tanker aircraft are based farther back. Additionally, the US Air Force has historically operated heavy bombers from intermediate or rear area locations, which require considerable tanker support on long or complex missions.[30]

The basing of tankers at airfields far from operating areas lowers offload capacity for receiver aircraft and reduces tanker utilization rates. Even though large-scale tanker employments have been in operations in which the risk to tankers was low and the operating theater was compact, a range of political and operational infrastructure factors have led most tankers to be based relatively far from their air refueling control points (ARCPs), the locations where they deliver fuel to aircraft (shown in Figure 8).[31]

Long flight distances lower the average offloads available to receivers, as tankers must burn more fuel transiting to and from their aerial refueling points. At long distances, multiple tankers may be necessary to refuel heavy aircraft with high fuel requirements, such as bombers, cargo planes, and large C2 and intelligence, surveillance, and reconnaissance (ISR) aircraft. Over time, long flight distances also lower the availability rate of tankers, as tankers must spend more time transiting to and from ARCPs; additional tankers must be dedicated to support the same mission; maintenance demands accumulate; and crews require longer rest periods between flights. For example, in Operation Allied Force, when NATO had access to a relatively large number of airfields in European countries, planners initially sought a tanker utilization rate of 1.5 sorties per day.[32] However, as the war progressed and a significant portion of tankers needed to be based at distant airfields in Spain and the United Kingdom, the sortie rate ended up being less than one per day. Therefore, long flight distances negatively impact not only the amount of fuel available to accommodate receiver aircraft fuel onload requirements, but also the "booms in the air," or the number of tankers capable of refueling receiver aircraft.

The final major factor related to airfield access is weather. Hotter temperatures and wet or icy runways require aircraft to have more thrust or longer runways to safely take off and land. During the Vietnam War, for example, the combination of high temperatures, wet runways, and power-limited engines on early KC-135 models led tankers to only be capable of taking off with about three-quarters of their fuel capacity. Therefore, operational planners must account for not only airfield characteristics, but also the impacts of weather on operations at the airfields, such as forcing reductions in takeoff fuel capacity.

Overall, access to suitable airfields and airspace has likely been the greatest factor affecting how many tankers can be employed and, in turn, the scale, tempo, and distribution of air operations. As noted in historical assessments of air operations during all the case studies examined, tanker availability (strongly influenced by suitable airfield and airspace availability) was the primary limiting factor in generating additional combat missions, regardless of the size or intensity of the operation.[33] Future planners will need to carefully consider the impacts of access on potential plans, especially if access can be shaped by not only political, infrastructure, distance, and weather factors, but also the threat of adversary action.

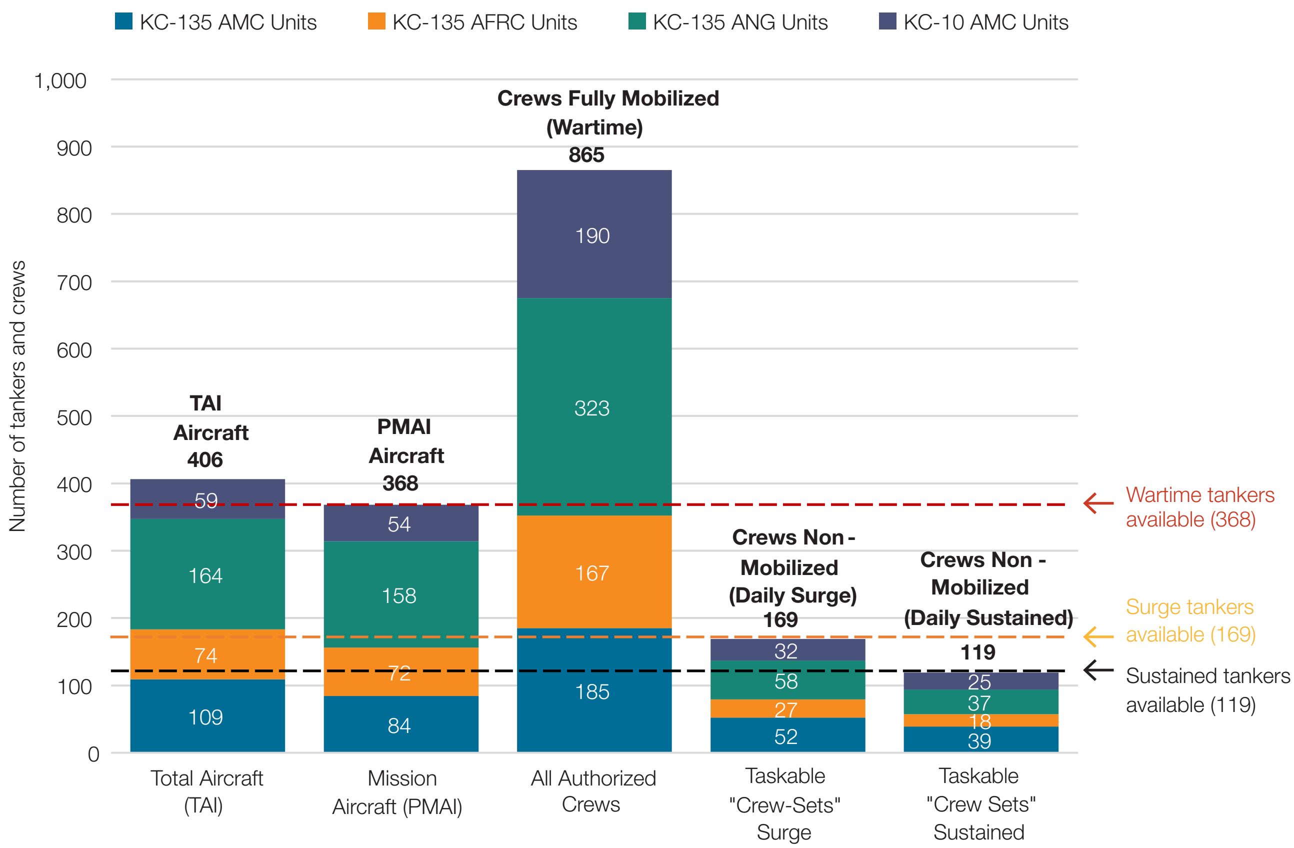
Tanker operations have been concentrated at few airfields.

The access and suitability factors described above often constrain tanker operations to a few airfields during an operation. In these historical case studies, more than half the tankers employed in theater were concentrated at three or fewer airfields. The high concentration of tanker operations at a few airfields creates vulnerabilities and results in a brittle refueling architecture, potentially degrading much of a theater's air operations.

The tanker fleet has operated at a higher than anticipated rate of employment.

During the Cold War, most of the tanker fleet was devoted to supporting nuclear deterrence missions. Therefore, only a moderate portion of the tanker fleet was available to support conventional operations, with 13% of the KC-135 fleet (and about 12% of the total US Air Force tanker fleet) employed in the Vietnam War, for instance. As DoD allocated fewer bombers and other aircraft to the nuclear deterrence mission after the Cold War, a larger portion of the fleet was made available to support conventional warfare missions, with approximately 44% of the tanker fleet employed in Operations Desert Shield and Desert Storm and 53% employed

Figure 9: Difference between wartime and peacetime taskable tails

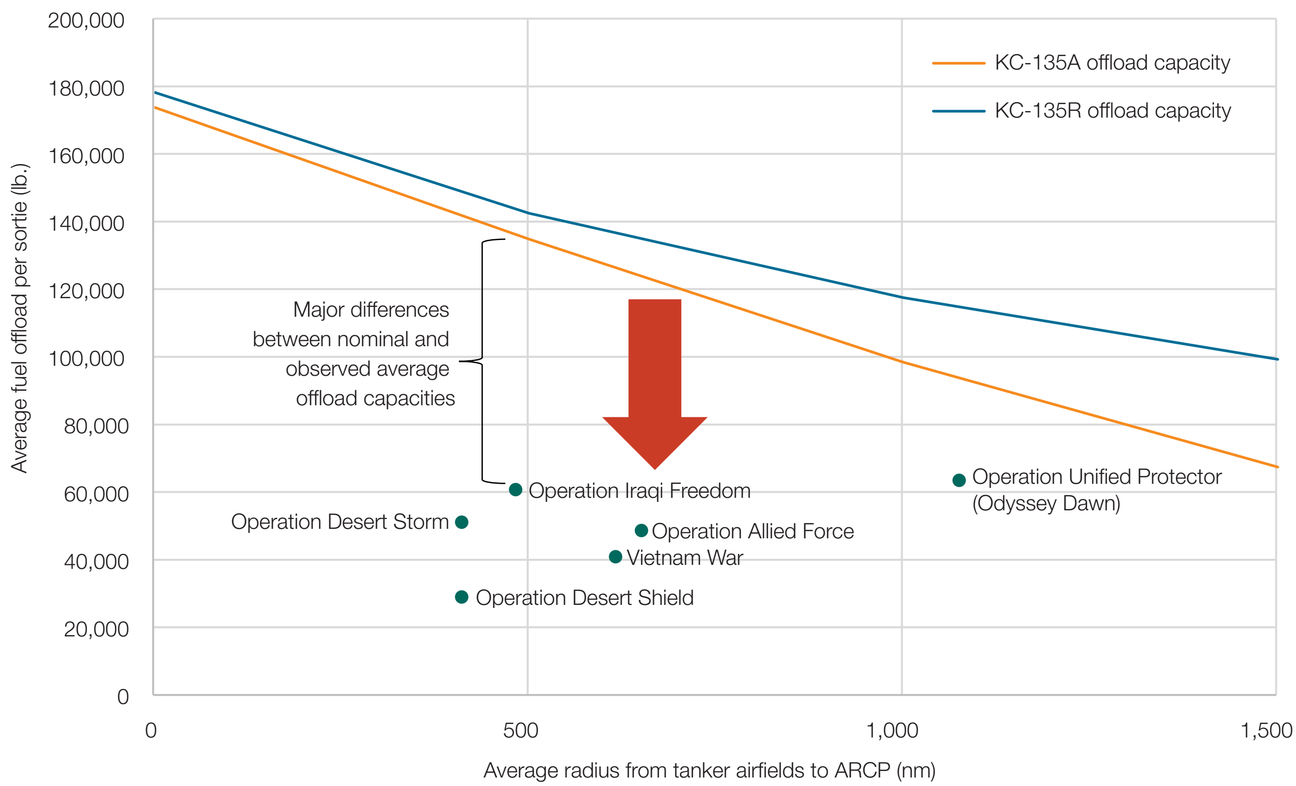


Source: Chart modified by report authors; original chart concept and data are drawn from Aaron A. Borszich, *Effects of KC-10 Divestment on Daily Competition Sortie Requirements* (Dayton, OH: Air Force Institute of Technology, 2020), p. 17.

in Operation Iraqi Freedom. Today, in addition to conflicts and ongoing needs for nuclear deterrence and homeland defense, DoD employs tankers for a growing number of peacetime deployments, exercises, and contingencies that tax the force's capacity.

The high utilization rate of the tanker fleet not only stresses tanker airframes, but also stresses personnel. About 56% of tanker units are resident in the Air Force Reserve Component (AFRC) and Air National Guard (ANG), rather than the active-duty force. This feature allows the Air Force to more economically maintain large numbers of aerial refueling personnel, and in the case of a major war, the Air Force could call upon all its AFRC and ANG personnel to increase the number of crews available for aircraft. Increased air and ground crew ratios can help units maintain higher aircraft utilization rates and helps provide an attrition reserve of personnel. However, this feature of the tanker fleet has the disadvantage that, during peacetime, it is impractical for the Air Force to fully utilize all tanker aircraft.[34] Figure 9 depicts the delta in FY 2019 between aircraft available to AMC and the number of crews, and helps to illustrate the concept of "taskable tails" developed by Aaron A. Borszich.[35] Even though in 2019 there were 368 aircraft in the Primary Mission Aerospace Inventory (PMAI),

Figure 10: Differences between nominal and observed average offload capacities



Source: Report authors; Data are drawn from George R. Fessler, Jr., *Aerial Refueling in Southeast Asia*, *1964–1970*, US Headquarters Pacific Air Forces, CHECO Division, June 17, 1971, p. 25; John G. Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force*, (Dayton, OH: US Air Force Institute of Technology, 2000), pp. 39–40, 62; T. Michael Moseley, "Operation Iraqi Freedom – By the Numbers," US Central Air Forces, 30 April, 2003, https://www.globalsecurity.org/military/library/report/2003/uscentaf_oif_report_30apr2003.pdf; Karl P. Mueller, Gregory Alegi, Christian F. Anrig, Christopher S. Chivvis, Robert Egnell, Christina Goulter, Camille Grand, Deborah C. Kidwell, Richard O. Mayne, Bruce R. Nardulli, Robert C. Owen, Frederic Wehrey, Leila Mahnad, and Stephen M. Worman, *Precision and Purpose: Airpower in the Libyan Civil War* (Santa Monica, CA: RAND Corporation, 2015), p. 78; "Air Force Pamphlet 10-1403: Air Mobility Planning Factors," US Air Force, October 24, 2018, p. 18; and "Air Force Doctrine Publication 3-36: Air Mobility Operations, Air Refueling Operations," US Air Force, June 28, 2019, p. 57. In the figure, KC-135A and KC-135R offload capacity each account for one hour on station. Moreover, the average radii from airfields to ARCP uses a weighted average that accounts for the number of aircraft based at each airfield during that operation.

and there were a total of 865 crews that could be generated in wartime, only 119 crews could be provided by active-duty AMC, AFRC, and ANG personnel on a sustained daily basis without mobilizing more personnel or restricting non-operational activities of active-duty personnel such as professional education or routine medical appointments. Therefore, the number of "taskable tails" is significantly less than the total number of aircraft available for flight operations. In peacetime, tanker capacity is generally limited by the available number of crews, while in a conflict tanker capacity would be limited by the number of available aircraft.

In the historical case studies that were reviewed, air planners requested that tankers be manned at 2.0 or more crews per tanker, which generally allows multiple sorties per aircraft per day. However, as a result of other mission demands and training requirements, the US Air Force would usually only provide 1.5-1.8

crews per aircraft, which, in turn, reduces sortie rates from distant tanker bases to one or fewer per day.[36] As observed in Operation Unified Protector, the high rates of employment of the force in steady-state operations created a situation in which it took a significant effort to generate sufficient personnel from the AFRC to meet the demand, and although many reserve personnel volunteered to deploy, by mid-July 2011 the force was running out of volunteers and was approaching an unsustainable daily surge rate that could have required formally mobilizing reservists.[37]

Tanker operations normally exhibit offload inefficiency.

Throughout its operations, the US Air Force has sought to maximize the efficiency of aerial refueling by increasing the proportion of tanker fuel delivered to receivers. Offload efficiency, or the percentage of a tanker's fuel that is delivered to aircraft, has generally increased as tankers adopted faster fuel transfer technologies, higher thrust and more fuel-efficient engines, and larger designs such as the KC-10. It has also improved through new planning techniques that seek to match the number and fuel needs of receivers with the capacity of refueling aircraft (increasing the receiver to tanker ratio) and improve the ability of offload and receiver aircraft to rapidly find each other and mate. Additionally, during conflicts the offload efficiency has generally increased as deployments requiring fuel-intensive air bridges decrease, operations stabilize, and unexpected demands diminish. For example, an initial offload efficiency of 58% in Operation Desert Shield gave way to one of 64% in Operation Desert Storm.[38]

Nonetheless, observed average tanker offloads during conflicts have been significantly less than nominal aircraft offload capacities. As depicted in Figure 10, a range of factors, including tankers needing to spend more time on station transferring fuel to receivers, shorter runways and weather conditions forcing tankers to take off with less than full loads, the need for reserve tankers, and other factors led to a significant difference between nominal and observed average offload capacities.[39] On some sorties, tankers returned to their airfields with fuel surpluses; in many cases, though, fuel was burned midair maintaining station or otherwise adapting to the friction of conflict. The implication for tanker design is that future aircraft should have sufficient fuel offload capacity to account for unanticipated inefficiency in the system, either caused by operational friction or adversary action.[40]

Summary of Insights

Throughout history, US planners consistently underestimated aerial refueling demands and overestimated the level of basing and overflight access that US forces would obtain to satisfy them. Future analyses should bring these factors to the forefront. Additionally, significant combat operations and steady-state peacetime demands required large offloads, numerous and distributed tankers, and enough surplus capacity in individual tankers and operational plans to adapt to changing political and military factors—a fact made more difficult as the tanker fleet has shrunk and aged. These challenges have been significant enough in an era in which tanking has largely taken place from sanctuaries on the ground and in the air. Learning lessons from the past, the US Air Force now needs to prepare for a future in which aerial refueling may be contested, and DoD needs the tanker force more than ever to enable new distributed and long-range operational concepts.

SHIFTS IN STRATEGY, THREATS, AND DEMANDS, WITH IMPLICATIONS FOR THE AERIAL REFUELING FORCE

President Joseph R. Biden, Jr.'s *Interim National Security Strategic Guidance* aims for a favorable distribution of power to deter and prevent adversaries from threatening US and allied interests.[41] It also calls for setting clear priorities within the US defense budget to advance US interests globally, and no capability area is more important to US power projection than logistics, including aerial refueling.[42]

The 1993 Bottom-Up Review prioritized logistics to maintain rapid US strategic mobility, even as it reduced overall force structure and forward-based presence.[43] Subsequent defense strategies repeatedly reiterated this priority. The 2018 National Defense Strategy (NDS) called for "resilient and agile logistics" capable of operating under "persistent multi-domain attack" as one of eight capability areas that need to be strengthened to prepare the United States for an era of renewed great-power competition.[44] Nearly four years later, though, the current logistics force, including the aerial refueling enterprise, is not prepared or postured to conduct such operations, and current US Air Force modernization plans do not adequately pursue the capabilities necessary to meet this goal.

Photo: Sailors stand near fighter jets on the deck of the Chinese People's Liberation Army (PLA) Navy aircraft carrier on April 23, 2019. (Mark Schiefelbein/AFP via Getty Images)

Relevant Threats to Logistics

The US aerial refueling enterprise has evolved since the Cold War to emphasize high-efficiency delivery from relative sanctuary on the ground and in the air. However, adversaries have developed the ability to disrupt aerial refueling operations and deny US forces the ability to project power or execute preferred CONOPS over a protracted conflict.

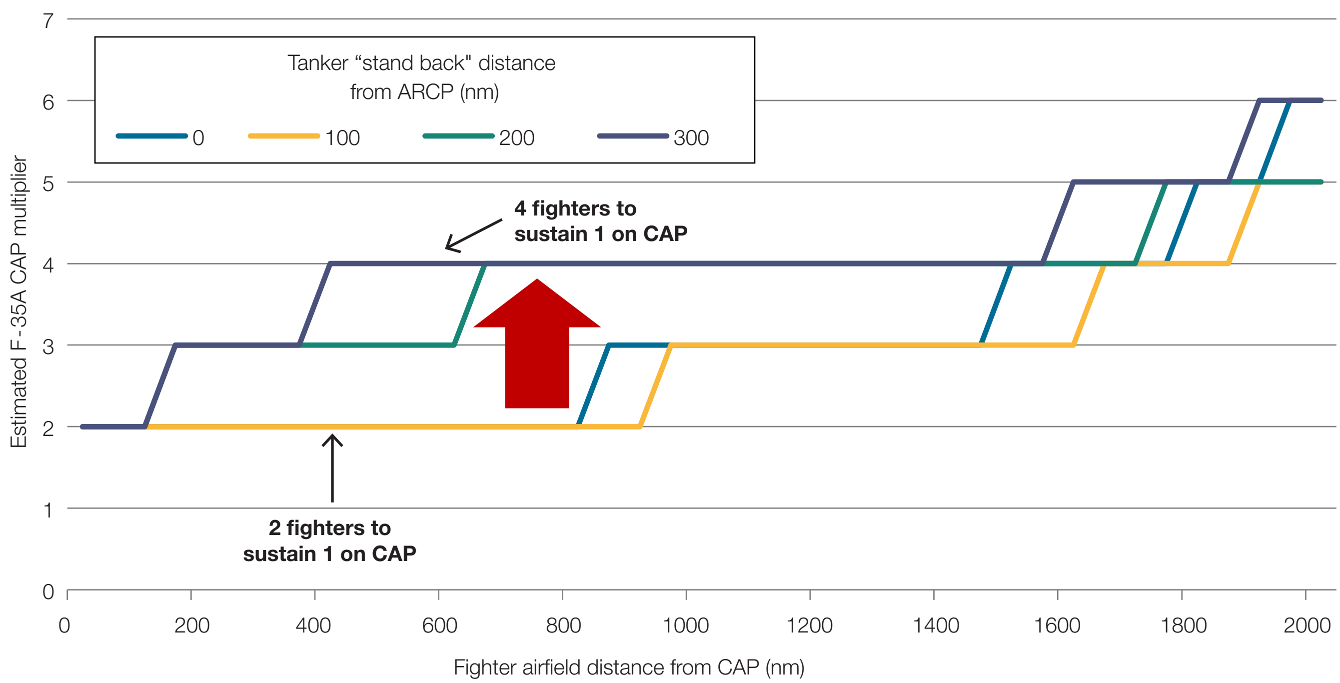
The greatest threats to aerial refueling are on the ground. Airfields can be attacked by different air and missile or special forces threats, damaging or destroying tanker aircraft; runways and ramp space; and airfield infrastructure, such as maintenance facilities, aircrew quarters, and fuel storage and distribution systems.[45] Airfields currently used by US Air Force tankers generally lack high-capacity air defenses, hardened shelters suitable for tankers, or other active or passive measures to defend against air and missile attacks. Other elements of the aerial refueling enterprise can also be attacked on the ground. Refineries and bulk fuel storage tanks and distribution systems can be destroyed, and the maritime tankers, pipelines, trains, or trucks necessary to deliver fuel to bulk storage at airfields or elsewhere can be attacked at loading or unloading points, such as ports or in transit.[46] These threats can exact high levels of attrition, damaging or destroying aircraft and maritime tankers, killing tanker crews, and destroying operational and maintenance infrastructure.

Threats on the ground can also impose what could be called virtual attrition. If planners disperse aircraft at airfields to complicate targeting or reduce target density, the number of aircraft that can be parked or serviced at those airfields (and, in turn, be employed in the air) declines.[47] If personnel at airfields are disrupted from their tasks by responding to attacks, then operational efficiencies drop.[48] If tankers are distributed among airfields without a commensurate increase in maintenance capacity, availability rates may decline, thus decreasing tankers in the air. Similarly, if tankers operate farther from threats to reduce the density of enemy attacks, then more tankers will spend longer periods in transit (and burning more fuel in transit) and fewer tankers can be sustained forward (and offload capacities decline).

Cyber and electromagnetic spectrum (EMS) threats can not only disrupt aerial refueling operations, but also exploit penetrations to understand US operational plans. These threats apply equally to US government and commercial assets. For example, if adversaries penetrated the cyber networks of commercial companies employed by the US government to deliver fuel using maritime tankers to ports servicing tanker airfields (or government networks), adversaries may better understand how US forces planned to operate and develop plans to counter them. General Darren W. McDew, former commander of US Transportation Command, testified in March 2018: “threats in the cyber domain pose the greatest threat to our decisive logistics advantage.”[49]

The aerial refueling enterprise also faces significant threats in the air. Intercept aircraft and surface-based air defenses can shoot down tankers. They and other air defenses can also detect aerial refueling operations, which not only poses a threat to tankers, but also provides cueing to adversaries that other aircraft (including low observable ones) may be operating in the area. As on the ground, these threats can impose not only real attrition, but also virtual attrition. By forcing tankers to operate farther from desired offload areas to reduce threats to tankers or cueing, supported aircraft must spend more time in transit and, in turn, have less range or time on station. Similarly, dedicating aircraft to protect tankers reduces the number of aircraft available for other missions and decreases the amount of fuel tankers have available to provide to other aircraft, as the escort aircraft themselves must be refueled. Figure 11 depicts how, as the tanker “stand back” distance from ARCPs increases in response to threats, the number of fighters necessary to maintain a combat air patrol (CAP) increases precipitously, imposing virtual attrition on the force as more fighters are necessary to conduct fewer tasks. Another type of virtual attrition relates to how, if tankers lack secure, low probability of detection/low

Figure 11: Ratio of fighters necessary to maintain a CAP in relation to fighter airfield and tanker “stand back” distances



As tanker “stand back” and fighter airfield distances increase, the number of fighters necessary to maintain a CAP increase. In the figure, fighters were modeled as F-35As and tankers as KC-46As.

Source: Report authors.

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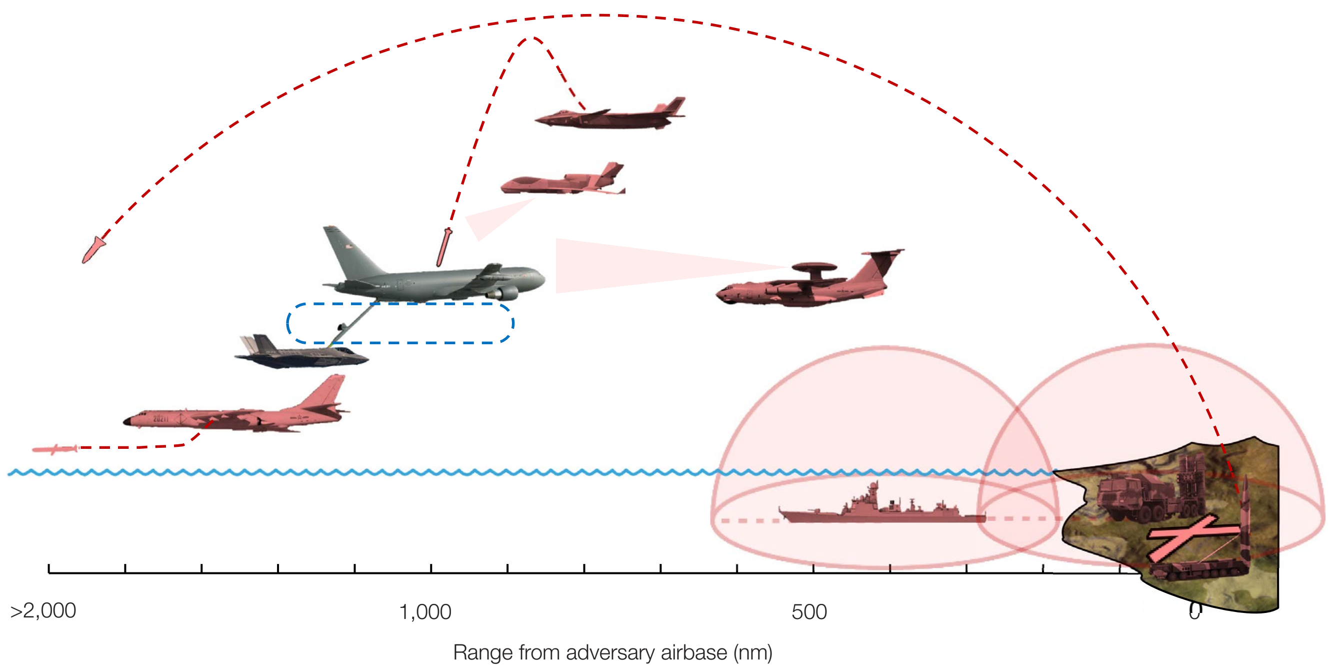
probability of intercept (LPD/LPI) communications datalinks necessary to avoid being located and targeted, their level of efficiency mating with receiver aircraft may diminish as they have difficulties finding each other or coordinating offloads under emissions controls.

A third class of threats to the aerial refueling enterprise relates to political and economic access. US aerial refueling operations rely on a network of airfields and other support infrastructure, much of which is located on allied or partner territory. If allies or partners restrict the use of airfields or other support infrastructure for tanker operations in response to coercion by adversaries or political disagreements, then the number of tankers (and, in turn, other aircraft) that can be employed in an operation would greatly diminish and US tankers would need to aggregate at a smaller number of airfields, which would be easier for an adversary to target and would impose less complexity on an adversary. Similarly, if support contractors declined to provide goods or services to US military forces due to political restrictions imposed by their parent governments or adversary coercion, then US tanker operations would suffer.

Another major challenge related to access involves tanker overflight. If countries restrict the ability of US tankers to overfly their airspace en route to operations (or restrict operations to narrow corridors of international airspace) due to their maintenance of

Figure 12: PLA air defense and strike capabilities



PLA air defenses can shoot down tankers or force them to operate at great standoff distances. PLA strike assets can target tanker airfields.

Source: Report authors.

a neutral status in a conflict, then it may make certain lines of approach impractical or force circuitous flights that greatly diminish available time on station or offload capacity. Additionally, even if countries do publicly or secretly allow US overflights, adversary exploitation of those countries' air defense networks may provide adversaries early warning of US tanker operations.

Among adversaries China poses the greatest threats to aerial refueling. It could exact high levels of real and virtual attrition that would greatly disrupt air operations. The Chinese Communist Party's People's Liberation Army (PLA) characterizes modern warfare as a confrontation between opposing operational systems and assesses that by paralyzing and destroying its operational system an enemy will "lose the will and ability to resist."[50] To defeat enemy operational systems, the PLA prioritizes achieving dominance in, and targeting of, enemy information flows. After information flows, degrading and exploiting the enemy's support system, including logistics support systems, is recognized as a top priority.[51]

Beyond doctrine, the PLA has fielded concrete capabilities that could target the US aerial refueling enterprise. The PLA can strike airfields located a great distance from Chinese territory, including Alaska and Australia, using aircraft and ground-launched weapons—even without conducting expeditionary operations from artificial features under its control or other countries' territory.[52] As the PLA fields more advanced aircraft, such as H-20 bombers and Y-20 tankers, it will likely be able to strike airfields at even greater distances and with greater stand-in attack capacity.[53] PLA strike capabilities are complemented by ship and submarine-launched weapons and paramilitary and special forces that could operate globally. The PLA and PRC intelligence agencies also have advanced cyber capabilities that they may use to degrade tanker operations or exploit information on the aerial refueling enterprise to counter US plans.

The PLA also has a variety of advanced air defense capabilities. The PLA has fielded a sophisticated overlapping network of passive and active sensors across domains that can detect high-signature aircraft, such as tankers, at a great distance from Chinese territory. As depicted in Figure 12, the PLA also has fielded surface-based air defenses on artificial features, ships, and ashore, and it has low observable, long-range aerial refuellable aircraft, such as the J-20, that could shoot down tankers or force them to operate at a great standoff distance.[54]

Lastly, the PRC may be able to leverage its growing comprehensive national power to constrain the US aerial refueling enterprise's level of political and economic access. The PRC may attempt to coerce countries into not allowing US tankers to operate from their territory, constrain tanker operations to only military bases (thus making them easier to target), or restrict tanker overflight access. Additionally, PRC intelligence agencies may target contractors to coerce them into not providing goods or services to US military forces.

Other countries also pose threats to aerial refueling. Russia has advanced strike, air defense, and cyber capabilities that it could use to degrade or exploit tanker operations, including by conducting strikes against tanker airfields in Alaska, Europe, and Hawaii. Although the scale of Russia's capabilities is not as great as China's, it would likely force more dispersed tanker laydowns and flight operations to be conducted at significant distances from areas of interest. Furthermore, Iran and North Korea also can strike nearby airfields used by US tankers, and tanker operations would need to account for air defenses in their territory. Lastly, as a sign of the increasingly contested nature of operations, the surface-to-air missiles of nonstate Houthi rebels in Yemen have posed threats to tanker operations that shaped the positioning of tanker tracks.[55] Overall, the aerial refueling enterprise is increasingly contested, and future tanker operations and force design will need to account for growing threats in the competition phase and conflict.

Growing Demands for Aerial Refueling

New US concepts and capabilities are increasing the demand for aerial refueling. Faced with challenges to its ability to counter adversary aggression, the US military has developed new operating concepts and capabilities that increase demand for aerial refueling. This section reviews US Air Force and other service operating concepts to identify their impact on aerial refueling.

In terms of operational concepts, all US military services are pursuing concepts with greater distribution across and within theaters. The US Air Force has developed a concept titled Agile Combat Employment that envisions utilizing air assets in a dynamic manner on the ground and in the air, enabled by disaggregated C2, to facilitate the targeting of enemy forces and complicate enemy targeting.[56] US Pacific Air Forces also developed a commensurate concept, Adaptive Basing, that aims to operate air assets from bases and airfields under differing levels of contestation.[57] These concepts recognize the need for air forces to account for adversary threats and respond by operating aircraft in a more dynamic manner among many airfields outside and within contested areas. Both responses require greater aerial refueling support—especially if tankers are based a great distance from desired fuel offload areas. The US Air Force concepts also pursue an improved ability to aggregate effects from a distributed laydown, which generally requires more aerial refueling support to provide aircraft with greater endurance to synchronize their operations. Lastly, the Air Force's shift to more expeditionary operations (rather than basing more aircraft forward) means that more aircraft would need to be deployed with tanker coronet support in a potential crisis.

Figure 13: MQ-25 test asset refuels a US Navy F/A-18 fighter

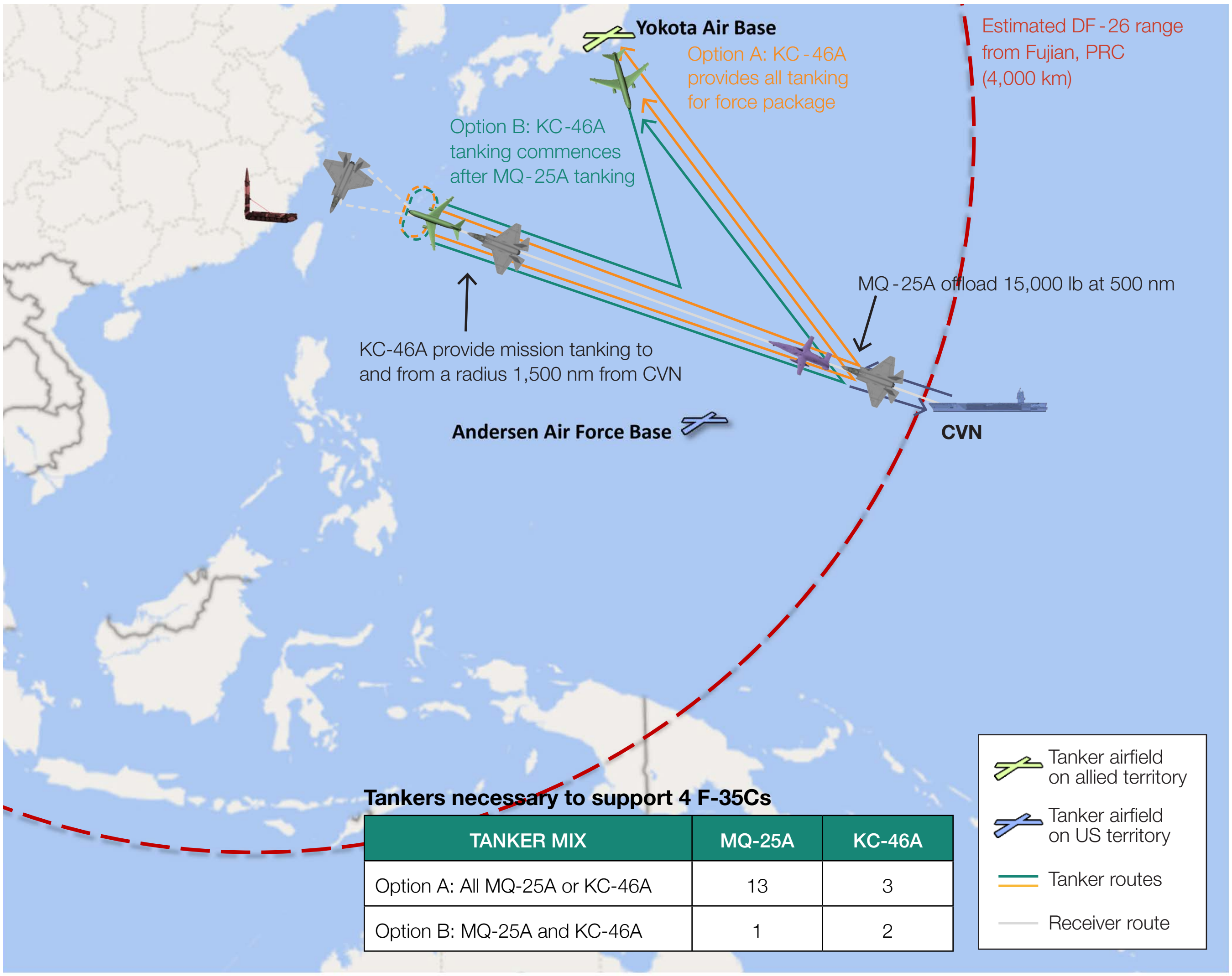
Source: Kevin Flynn, The Boeing Company.

Other military services have also adopted concepts that emphasize distribution. The US Navy's Distributed Maritime Operations (DMO) concept calls for operating the fleet leveraging the principles of "integration, distribution, and maneuver."[58] To complicate enemy targeting, US Navy carrier air wings (CVW) and land-based maritime patrol aircraft (MPA) may operate from greater range and in a more-distributed manner, which would likely require more US Air Force aerial refueling support. Moreover, the US Marine Corps' Expeditionary Advance Base Operations (EABO) concept calls for establishing a lethal and resilient "alternative forward force posture based on a more difficult to target, low-signature, and dispersed forward-basing infrastructure."[59] In line with EABO, tactical aircraft operating from aviation expeditionary advance bases may require aerial refueling support to increase their range or endurance, since fuel stores at austere airfields may be limited. Overall, service concepts that emphasize distribution on the ground and in the air and operating from greater range impose increased demands on the aerial refueling force.

Another class of demands on the aerial refueling force stems from changes in receiver aircraft force structure. Over the past three decades, the US Air Force and US Navy have increased their reliance on relatively short-range strike fighters, as compared to longer-range bombers or interceptors.[60] To effectively employ these assets, aerial refueling is required. This decade, the US Air Force plans to field the long-range B-21 bomber, but it is expected that the total size of the bomber force may remain relatively constant over the next decade as B-21s are introduced and B-1B bombers are retired.[61] Furthermore, the US Air Force is experimenting, or plans on experimenting, with different classes of risk-worthy or attritable aircraft, such as MQ-9 variants, the envisioned Next-Generation Multi-Role Unmanned Aerial System Family of Systems (Next-Gen Multi-Role UAS FoS), and the Low Cost Attritable Aircraft program.[62] Some of these aircraft may be aerial refueling capable. If the US Air Force would rely to a degree on these aircraft in place of fighters—especially for forward operations in highly contested environments, it may reduce aggregate aerial refueling demands, while posing a new class of demand for rapid refueling of numerous aircraft that have relatively small fuel capacities and may be distributed across a theater (in essence, more numerous, very small fighters). However, most US Air Force concepts envision these assets as providing additional mass that can be launched from contested areas and not supplanting fighter operations. Lastly, the US Air Force is developing a next-generation tactical aircraft, or family of systems, termed NGAD. If the US Air Force could shift to a force design that had a greater proportion of long endurance aircraft, such as B-21s, NGAD, and different classes of unmanned aircraft, it may reduce aerial refueling demands. However, absent commensurate conceptual changes, it will likely take a decade or more for the US Air Force to make a force structure shift that could greatly reshape aerial refueling demands.

The US Navy has fielded additional aircraft capable of being refueled midair, including the E-2D airborne early warning (AEW) aircraft and the P-8A MPA. To maximize their endurance, both classes of aircraft would benefit from aerial refueling. The Navy is also in the process of fielding a new

Figure 14: Comparison of future CVW offensive counter-air (OCA) capacity with and without US Air Force tanking



Tankers necessary to support 4 F-35Cs

TANKER MIX	MQ-25A	KC-46A
Option A: All MQ-25A or KC-46A	13	3
Option B: MQ-25A and KC-46A	1	2

Source: Report authors. Vignette depicts the minimum number of tankers required, inclusive of one recovery tanker for each option and exclusive of reserve tankers or tankers unavailable due to maintenance or other factors.

aerial refueling aircraft, the MQ-25A (shown in Figure 13). The Navy plans on acquiring a total of 72 MQ-25As to equip four MQ-25A per CVW. Each of the unmanned tankers will be capable of offloading approximately 15,000 pounds of fuel at 500 nm to aircraft with probe receivers (or enough to refuel two fighters).[63]

The addition of the MQ-25A to the CVW will increase the operating range of other carrier aircraft; however, the increased standoff distance that carriers and other ships may need to maintain from dangerous threats, such as land, sea, and air-launched cruise, ballistic, and hypersonic missiles, may offset the opportunities enabled by the MQ-25A. Moreover, the small number of MQ-25As currently planned for procurement may drive the Navy to operate MQ-25As as "recovery tankers" that provide fuel to aircraft in exigencies to help them recover aboard the carrier, rather than "mission tankers" that accompany aircraft on missions far from the carrier. As shown in Figure 14, for a future CVW to conduct even small operations with four F-35Cs, while keeping the carrier 4,000 km away (the reported strike distance of the DF-26 anti-ship ballistic missile) from land, it would either require far more MQ-25As than the four planned to be fielded on each carrier or significant US Air Force tanking support.[64] Additional MQ-25As—even if they came at the cost of fighters—could increase the strike capacity of the CVW. However, CVWs using a mix of supported aircraft similar to those of today will likely continue to be reliant on complementary US Air Force tanking. As with the US Air Force, the US Navy may field new CVW and land-based aircraft with greater endurance, such as a new carrier-based fighter termed F/A-XX, other variants of the MQ-25, or unmanned MPA; however, these force structure shifts will likely take time to impact aerial refueling demands. Overall, changes in threats, operating concepts, and force structure are levying increased demands on the aerial refueling force.

Scenarios for US Aerial Refueling

To assess ways to improve the US aerial refueling enterprise's capacity and resilience, this study examined relevant notional scenarios that highlight distinct operational needs. These scenarios serve to describe how aerial refueling forces would support operations and capture, at a general level, expectations regarding how forces might be employed in conflicts in support of US strategy.

This report uses a conflict with the PRC as its chief planning scenario. Conflict with the PRC could be instigated by Chinese aggression against Japan, the Philippines, the Republic of Korea, Taiwan, or other nations in the region. A conflict could also emerge from PRC efforts to control passage through international water or airspace. The act of aggression could vary geographically from being relatively small, such as a PRC invasion of a Japanese island in the Senkakus or a Philippine island in the South China Sea, to geographically expansive, such as an attempted invasion of the Japanese Sakishima Islands or Formosa itself. Independent of the initial cause of the conflict, a conflict with the PRC may geographically spread. Given the growing Chinese capacity for expeditionary operations and expanding military presence abroad, it is likely that US air forces would need to conduct operations not only across the Indo-Pacific, but elsewhere. Lastly, PRC acts of aggression could vary in their level of initial intensity, ranging from protracted gray zone operations to an air and maritime blockade to bombardment to an opposed landing. Similarly, a conflict's duration could involve quick, high-intensity conflict ("a short, sharp war") or could be prolonged at varying levels of intensity.[65]

Overall, scenarios involving the PRC feature US action to swiftly deny the aims of PRC aggression and reverse PRC gains, backed by the commitment to conduct a prolonged, global compellence campaign as necessary.[66] A conflict with the PRC—regardless of its geographic scale, warfighting intensity, or duration—would require high levels of aerial refueling support. If nearby bases are denied, long-range flights from distant airfields will require substantial refueling; however, if bases close to the conflict are undamaged and available, a larger number of aircraft would likely be employed, increasing refueling demands in aggregate. The aerial refueling enterprise would be stressed to support desired operations in a conflict against the PRC due to three primary factors: operational distances, threats, and refueling infrastructure constraints.

Operational Distances

The vast distances of the Indo-Pacific would increase the demand for tankers to support the deployment and employment of aircraft from bases in US states to the Western Pacific. Given the relatively short range of US fighter aircraft, even moving from airfields in central Japan to the Southwest Island Chain or Taiwan would require significant tanker support. The demand for tankers may further increase if, consistent with service concepts such ACE, EABO, and DMO, air forces conduct more-distributed operations in the air from more numerous airfields, many of which may not have bulk quantities of fuel. Conducting large-scale operations over vast distances would not only require numerous tankers that may exceed the capacity of the current force, but also would consume large amounts of fuel, which would require additional maritime tankers or other assets to deliver fuel to airfields.

Threats

Moreover, tanker forces would face major threats from the PRC. As previously discussed, the PRC is focused on defeating US support operational systems to render US forces incapable of operations. It could target the US aerial refueling enterprise on the ground and in the air in a variety of ways, at ever more extended distances from China, causing high levels of real and virtual attrition that seriously undermine the viability of US air operations. It could also coerce other countries into restricting or denying US forces access to airfields or airspace.

Refueling Infrastructure Constraints

Lastly, the paucity of suitable airfields, fuel stores, and bulk fuel distribution assets could constrain the scale and tempo of US operations. Through the United States' network of allies and partners, US forces could notionally operate from hundreds of airfields in the Indo-Pacific. Figure 15 depicts Indo-Pacific airfields in US or ally territory that could potentially support tanker operations. A critical assessment of that capacity, however, reveals that the number of airfields with sufficient runway length, ramp space, and fuel stores to support tanker operations is considerably more limited. It is also concentrated at major military or civil airfields, primarily located near the PRC and, in turn, potentially subject to higher density attacks. If the PRC coerced some US allies and partners to not allow tanker operations from their airfields, or if those countries restricted tanker operations to military airfields, then the number of airfields would fall further, not only restricting the number of tankers that could be employed but also concentrating them at fewer, easier-to-target locations.

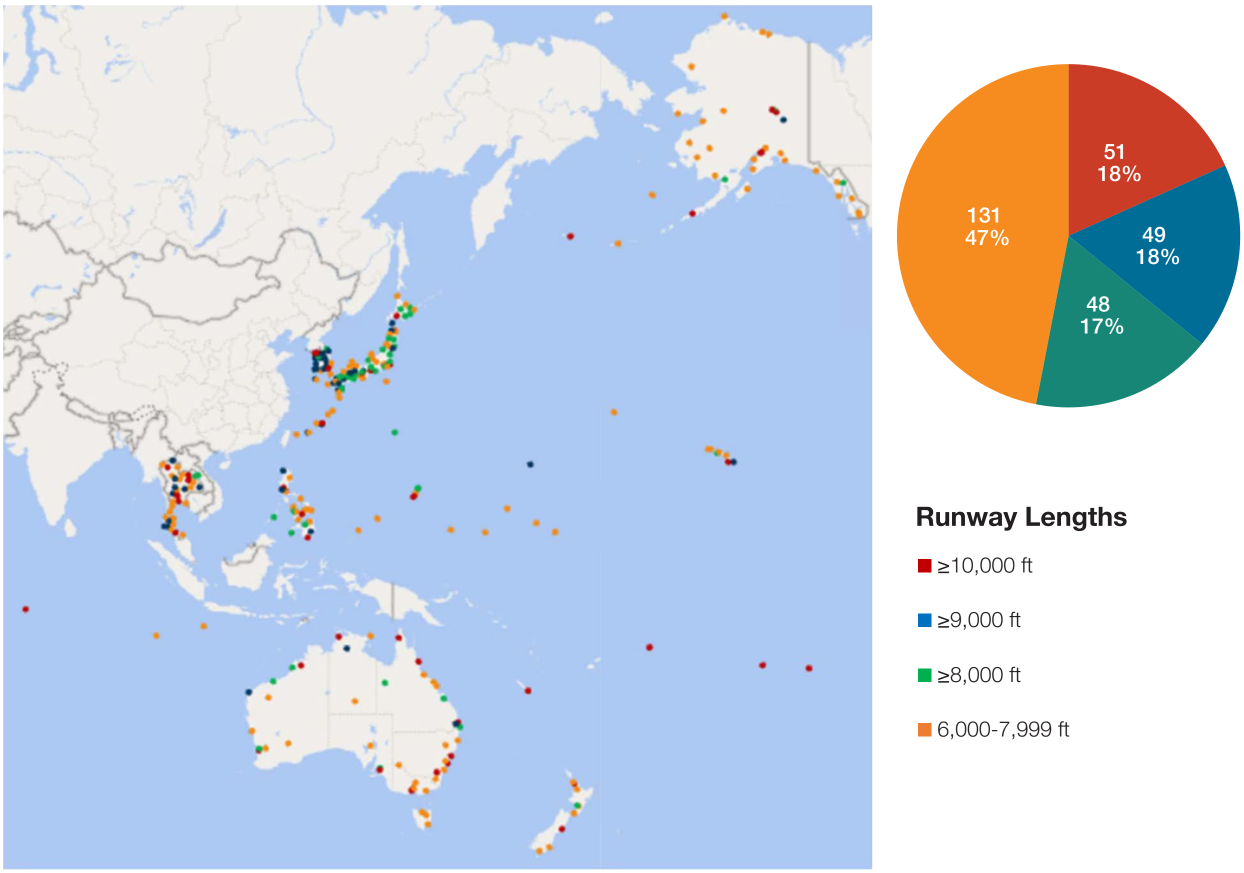
The US air mobility network in the Pacific also suffers another weakness. As shown in Figure 16, the deployment of aircraft largely takes place over two northern and central Pacific routes.

Both routes employ "en route" airfields to support air mobility airlift and tanker track activities, and the central route has a single point of failure in Guam.[67] If the PRC were to attack the en route airfields, it could significantly diminish the throughput of aircraft into the theater.

Another weakness in the US surface architecture relates to fuel stores and distribution. US military fuel stores are concentrated at large Defense Fuel Support Points (DFSPs), many of which are located within high-threat areas and are unhardened.[68] At US airfields and DFSPs, military construction projects over the past couple of decades have steadily replaced aging underground, hardened fuel stores with lower-cost aboveground storage tanks or lightly hardened cut-and-cover storage tanks, both of which are soft targets for PLA weapons.[69] DFSP fuel capacity is concentrated within the First and Second Island Chains, and fuel capacity is concentrated at a handful of large US military and joint airfields in the theater.

Apart from weaknesses in fuel stores, US forces lack resilience and capacity in fuel distribution infrastructure. Numerous airfields lack rapid repair and reconstitution equipment for pipelines or pumps that may be damaged in attacks and lack expeditionary systems for over-the-shore bulk fuel transfer systems needed to complement existing infrastructure under high-tempo operations or substitute for it if it has been damaged or destroyed. The United States also faces a major gap in the number of US-flag maritime tankers necessary to deliver fuel to airfields in contested environments. DoD only has access

Figure 15: Indo-Pacific airfields in US or ally territory that can support tanker operations



The figure includes airfields on US or ally territory in the Indo-Pacific with runways at least 100 ft wide.

Source: Report authors.

to two government-owned Military Sealift Command (MSC) tankers, five long-term MSC charters, and two tankers via the Maritime Security Program; these tankers would only address 10% of DoD's surge fuel transport requirement of 86 tankers, and given competing Navy and other service demands, the Air Force would likely be well short of required US-flag tankers.[70] Although some foreign flag tankers could likely be employed to deliver fuel in uncontested areas, US-flag tankers will be necessary to deliver fuel in contested or highly contested areas, such as to ports supporting high-value aerial refueling tanker bases.

Scenario Assessment

PRC

Overall, the US aerial refueling enterprise is ill-prepared for countering PRC aggression. Figure 17 depicts a tanker laydown in a notional contemporary conflict between the PRC and Japan. Tankers are employed from 11 US and allied airfields that have appropriate runway, ramp space, and fuel stores for KC-46A operations.[71] Assuming half of the airfields' ramp space was devoted to tankers, and that to maintain tactical dispersion a

Figure 16: US Pacific deployment routes

Source: Report authors, based on Figure 2.4 in Lostumbo et al., *Overseas Basing of US Military Forces: An Assessment of Relative Costs and Strategic Benefits* (Santa Monica, CA: RAND Corporation, 2013).

quarter of the available ramp space was used, then 60 KC-46A tankers or their equivalents could be employed in operations from the airfields. In total, the KC-46A or equivalent tankers would be able to offload approximately 4.5 million lb. of fuel per day at 2,500 nm, or they could sustain 2.3 ARCPs offloading 65,000 lb. per hour or 1.6 ARCPs offloading 100,000 lb. per hour at 2,500 nm. An ARCP offloading 65,000 lb. could continuously support six fighters, and an ARCP offloading 100,000 lb. could continuously support a large transport aircraft like the C-17, a bomber, or multiple medium-sized aircraft such as the P-8A.[72] The relatively small number of appropriate airfields would make it easy for the PRC to neutralize US tankers on the ground. Moreover, as ramp space and fuel are concentrated at the top airfields among the identified 11, if operations from the top three potential tanker airfields were denied, then the number of tankers that could be employed would drop by 55% and fuel

Figure 17: Laydown of potential airfields used by US tankers in a conflict with the PRC

Source: Report authors.

offload by 57%, assuming no degradation in capacity at the other airfields.[73]

The limited tanker offload capacity and ability to distribute bulk fuel may impose multiple dilemmas on planners. For example, along the northern deployment route, planners would be forced to choose between devoting tankers to deploy fighter and transport aircraft via air bridges or instead refuel bombers. In the Marianas, tanker capacity could be devoted to support US Air Force or US Navy aircraft patrols forward or bombers and transports entering the theater. And throughout the region, planners could generate more tanker capacity in the air by observing a ramp space dispersion ratio higher than 25%, but this would incur greater risk of more tankers being destroyed on the ground. Although prioritizing tanker support is not a new challenge for air planners, the theater's relatively few tanker airfields and long flight distances would limit friendly forces' lines of advance and make it easier for PRC air forces to avoid US forces or adequately prepare to intercept them. The brittleness of the US aerial refueling architecture on the ground and in the air would likely constrain the scale, tempo, and complexity of US and allied operations and lead to higher levels of tanker and receiver attrition, as aircraft would be more easily countered both on the ground and in the air, and they would suffer fuel exhaustion when tanker support was unavailable. Ultimately, it

Figure 18: Laydown of potential airfields used by NATO tankers in a conflict with Russia

Source: Report authors; tanker laydown is partially based on Gunzinger et al., *An Air Force for an Era of Great Power Competition*, p. 116. Dover Air Force Base is shown as a US origination point for air mobility operations to en route airfields, but it is not intended as a tanker airfield.

could cause the United States to be incapable of sustaining combat against the PRC in defense of US allies and partners.

Russia

A conflict with Russia could also stress the aerial refueling enterprise. As with China, multiple scenarios could impact the force, ranging from an expanded Ukraine crisis to a confrontation with Japan or the United States in the North Pacific to a large-scale invasion of a European state, such as one of the Baltic countries. Across these scenarios, Russian forces could pose different threats to aerial refueling forces.[74] In general, however, the scale of potential Russian attacks would likely be less than that possible by the PLA. Additionally, in the European theater, allied air defenses would provide forces with a defense in depth that would challenge Russian anti-air warfare operations and allow aerial refueling to take place closer to points of need, such as over Central Europe.

Allied forces could operate from over 200 developed military and civil airfields suitable for KC-46A or equivalent aircraft in NATO countries. Although a desire to reduce vulnerability from standoff attacks may force tankers to operate from longer distances (such as airfields in Western Europe), and political restrictions could limit the airfields and airspace available, likely available tanker airfield capacity in Europe is significantly greater than in US allied and partner countries in the Indo-Pacific.[75] In addition to the tankers necessary to employ forces, tankers would be needed to support the deployment of aircraft from bases in US states to Europe and the Pacific, but the Atlantic en route system has multiple route options that mitigate risks.[76]

Even if tankers were confined to 11 airfields in Europe relatively far from Russia (shown in Figure 18), and could only use 25% of the ramp space available in order to maintain tactical dispersion or provide space for other military or civil aircraft at those locations, it would be possible to operate 96 KC-46As or equivalents, offloading 60 percent more fuel than possible in the aforementioned Indo-Pacific case study. In aggregate, the number of tankers needed would be significant, and the capacity of tankers (in addition to preferred munitions stocks) would likely be the primary limiting factor on the scale of air operations. However, the operational design for the employment of tankers in a conflict with Russia is likely sound.

Assessment of Other Missions

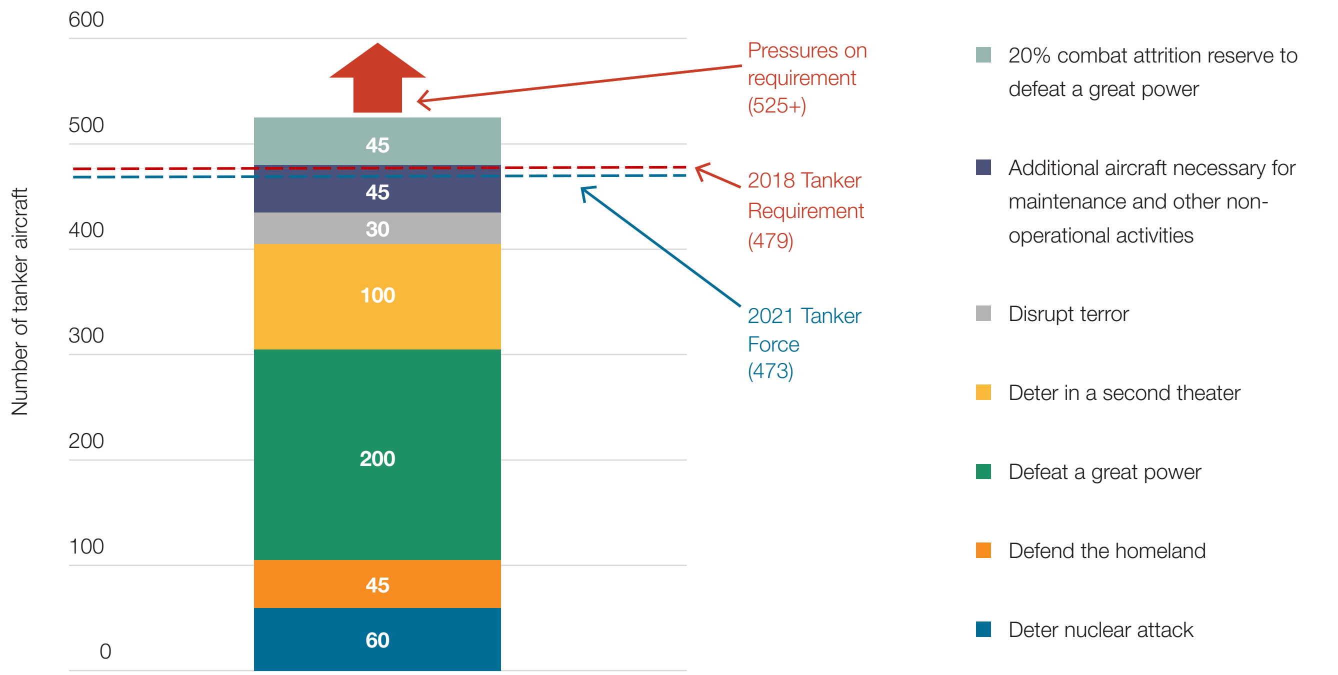
In any potential conflict with China or Russia, tankers would be called upon to support other missions. Tankers support the nuclear deterrence and continuity of government missions by refueling bombers and airborne command, control, and communications aircraft. Tankers also refuel airborne early warning and control (AEW&C) and fighter aircraft that guard US airspace against incursions by other countries and defend critical assets, including against the threat of aircraft hijacked by terrorists. As Russia has fielded longer-range cruise missiles that can be fired at Canadian and US targets from over the Arctic or Russian territory, it has driven demand for more defensive coverage from AEW&C and fighter aircraft, and, in turn, tanker support.[77] As the PLA fields longer-range missiles and low observable bombers such as the H-20, it, too, may impose new demands on the US aerial refueling force's support to homeland defense. Estimates of the number of tankers required to support the homeland defense and strategic deterrence/continuity of government mission range from around 105 to over 122.[78]

Lastly, the tanker fleet provides support to three other classes of missions. The first class is missions to counter violent extremist organizations and conduct other operations. Operations in Afghanistan, Iraq, Syria, and elsewhere have required a considerable number of tankers, as do routine presidential overseas missions.[79] As observed during Operation Unified Protector in 2011, the tanker fleet has been operating at such a high level supporting steady-state operations that it has lost much of its capacity to surge using the peacetime force. The second class of missions entails providing support for the routine and surged deployment of aircraft. The regular deployment of aircraft abroad normally requires considerable tanker support to drag fighters and other aircraft in coronet missions across the Atlantic or Pacific. Similarly, missions in which Bomber Task Forces conduct long-range and dynamic flights from US bases to areas abroad tend to require considerable tanker support. The third class of missions involves tankers necessary to support the training of receiver aircraft and the training of tanker crews. Collectively, aerial refueling demand in the competition phase is high, leading the Commander of USTRANSCOM to assert in 2018: "Day-to-day, high levels of air refueling fleet utilization are approaching a point that challenges the total force to sustain current levels of support."[80]

In planning scenarios against regional adversaries, previous studies have consistently estimated a need for at least 200 tankers, and another 100 or more to support homeland defense and sustain strategic deterrence.[81] Consistent with the 2018 NDS's wartime construct, the 2018 MCRS called for a fully mobilized Joint Force to be "shaped, sized, postured, and readied to simultaneously deter nuclear attack, defend the homeland, defeat a great power, deter in a second theater, and disrupt terror," and it identified a requirement of 479 tankers.[82] As shown in Figure 19, the aggregate demand for tankers in a conflict may exceed the capacity of the current tanker fleet—even without accounting for major combat attrition to the force. If the requirement to "defeat a great power" such as China or Russia were greater than the 200 tankers previously estimated as necessary to defeat a regional adversary, then the potential gap between requirements and existing force structure could be even greater.[83]

Analysis of potential conflict scenarios involving the aerial refueling fleet reveals major challenges to the force that call into question

Figure 19: Representative tanker wartime requirements



Source: Report authors; Deter nuclear attack and defend the homeland estimates are drawn from Mark Gunzinger, Carl Rehberg, Jacob Cohn, Timothy A. Walton, and Lukas Autenried, *An Air Force for an Era of Great Power Competition* (Washington, DC: Center for Strategic and Budgetary Assessments, 2019), p. 135. Defeat a great power is based on the defeat a regional adversary estimate drawn from Gregory D. Knepper, *Access Assured: Addressing Air Power Reach, Persistence and Fueling Limitations for Contested and Permissive Air Operations* (Washington, DC: Brookings Institute, 2014), p. 15. The requirement to defeat a great power is likely much higher than the requirement to defeat a regional adversary. The deter in a second theater estimate is assumed to require half as many aircraft as the defeat a great power requirement. The disrupt terror requirement is assumed to require 30 tankers. The number of additional aircraft necessary for maintenance and other nonoperational activities was estimated based on the ratio of PMAI and TAI aircraft in USTRANSCOM's FY 2019 fleet. Aaron A. Borszich, *Effects of KC-10 Divestment on Daily Competition Sortie Requirements* (Dayton, OH: Air Force Institute of Technology, 2020), p. 17. An additional category was added by applying a 20% attrition reserve to those aircraft estimated as necessary to defeat a great power.

the validity of planning assumptions that informed previous mobility studies and, in turn, the size and composition of the tanker enterprise. Tanker basing may be distant and globally contested (rather than proximate and secure); supported operations may be highly distributed and dynamic across and within theaters (rather than geographically localized and steady-state); rapid deployments may be needed to credibly deter or counter aggression (rather than counting on a gradual buildup of forces); tanker forces may incur significant attrition on the ground and in the air (rather than uncontested or lightly contested operations); assets supporting tanker operations, such as fuel stores and maritime tankers, may be politically contested or militarily attacked (rather than assuming assured bulk supplies and infrastructure); and conflicts may become protracted with varying levels of intensity or escalation (rather than short campaigns).[84] These new assumptions should inform DoD studies such as the MCRS, as well as service and Joint planning for the future force.[85]

Overall, changes in the threat environment and Joint concepts and forces are shaping demands on the aerial refueling enterprise. Without a capable and appropriately sized aerial refueling force, many of the operational concepts envisioned by the US Air Force and the other Services cannot be fully executed. Moreover, given the strains on the tanker fleet in the competition phase, it will be increasingly difficult for the force to sustainably generate the aerial refueling support necessary for US air forces to deter adversary aggression. To prevail in future conflicts, the Air Force should embrace new concepts and properly resource the requisite aerial refueling capabilities, capacity, and posture that is appropriate for the nation. In short, the nation needs a new aerial refueling architecture.

PROPOSED CHANGES TO THE FUTURE AERIAL REFUELING ARCHITECTURE

Aerial refueling will play an increasingly important role in US defense strategy. Air forces will need to operate from longer ranges, using tanker support to promptly deploy to deter or defeat aggression and reduce risks to some aircraft from basing near adversaries. Additionally, air forces based near and far will require greater endurance provided by tankers to orchestrate more complex, distributed operations and maximize flexibility in the air. As regional basing becomes more militarily and politically contested, the demand for aerial refueling will become more acute.

The United States should adapt its aging aerial refueling architecture to address these Joint Force demands and changes in the threat environment. Fielding an effective aerial refueling force capable of deterring and defeating adversary aggression will require the adoption of a holistic approach to force design and employment that assesses not only tankers, but also other elements of the refueling portfolio. By improving concepts, capabilities, capacity, and posture, an effective force will be resilient in the face of adversary action and support a lethal and dynamic force. It will feature enhanced survivability across domains, flexibility in terms of the operations it can support within and across theaters, and resilience in terms of its provision of reliable support that enables the execution of higher tempo, larger scale, or more complex air operations. Given competing fiscal demands, DoD will need to select options that, in concert,

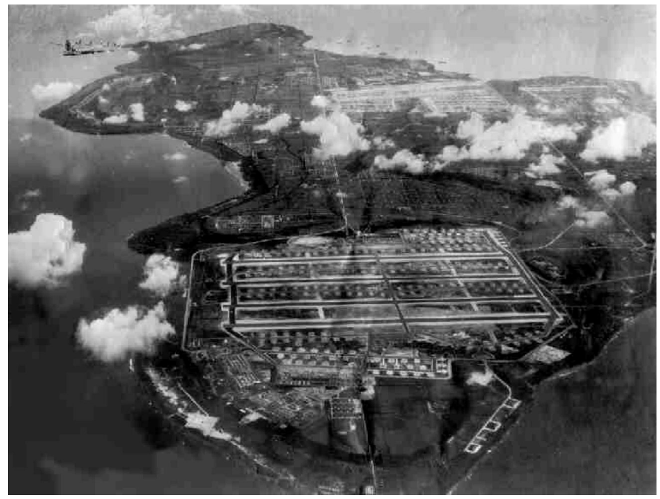
Photo: A US Air Force Rockwell B-1B Lancer and a Boeing KC-135 Stratotanker sit on the tarmac at Andersen Air Force base on August 17, 2017 in Yigo, Guam. (Justin Sullivan/Getty Images) maximize operational performance, while minimizing operational risk and total ownership costs.

To do so, this chapter proposes changes to help address gaps and secure opportunities in the current and future US aerial refueling architecture. It is informed by the previous chapter's scenario assessments and is organized into sections on changes to the aerial refueling surface architecture, aerial refueling C3, the aerial refueling fleet, and other aircraft concepts and capabilities.

Changes to the Aerial Refueling Surface Architecture

The biggest changes to the aerial refueling architecture are needed on the ground. Absent reform, the aerial refueling fleet may be confined in a conflict with China to about a dozen airfields where US forces would have political access and sufficient runway, ramp space, and fuel stores. Such a force could only support relatively few aircraft in the air and would be vulnerable to attack. Similar airfield and fuel challenges could be faced in a potential conflict with Russia—albeit to a lesser degree—or other scenarios, as was observed during the 2011 NATO operations in Libya.

Figure 20: Aerial view of Tinian in 1945



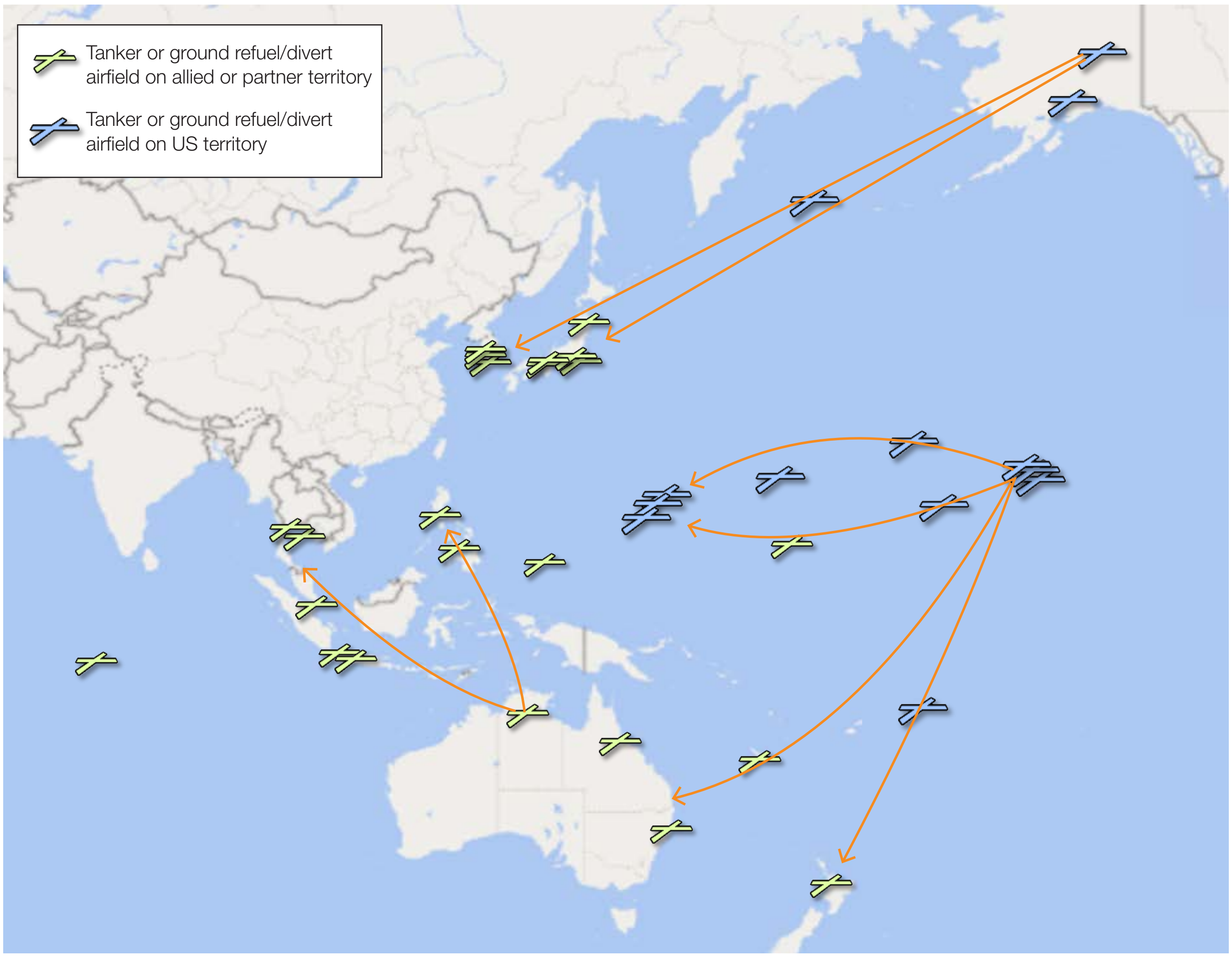
Upon completion in 1945, Tinian North Field (shown in the foreground) was the largest airfield in the world, operating 265 B-29 bombers. DoD plans may underutilize the old airfield by converting it to a mortar training range.

Source: US Air Force Historical Research Agency.

Instead, DoD could evolve the currently brittle posture to a more-distributed one that enables resilient, dynamic air operations. A more effective posture would leverage clusters of military and civil airfields on US and allied and partner territory at varying distances from desired fuel offload areas, consistent with Agile Combat Employment. At forward airfields, tanker operations could be distributed among numerous military and civil airports, especially those with ample ramp space, which would enable tankers to tactically disperse to drive up adversary salvo sizes or challenge their targeting. For example, by gaining access to civil airfields in Japan and the Republic of Korea, US forces could considerably increase tanker capacity and complicate Chinese targeting. In some cases, these forward airfields could be used for extended operations, while in others they could serve as "drop-in" locations for tankers to load fuel and take off. At intermediate distances from threats, DoD should focus on increasing the number of airfields and ramp space suitable for tankers. For example, in the Marianas, DoD could expand its modest plans for a Tinian Tanker Divert Site with a capacity for 12 tankers by repairing the island's existing northern airfields and adding resilient fuel stores and distribution capabilities.[86] And at great distances, DoD should focus on maximizing flexibility in terms of the ability to use different US and allied airfields to support deployments.

A mix of airfields at different distances is important to provide flexibility and mitigate threats, as airfields within and across clusters can mutually support each other and dynamically shift available offload capacity. Additionally, assured access to forward and intermediate airfields is essential to generating relevant levels of tanker offload capacity. For example, it takes more than five times as many KC-46As operating 3,000 nm away

Figure 21: Notional laydown of potential Indo-Pacific airfields supporting redundant deployment and employment paths



Source: Report authors.

from their ARCPs to match the capacity that can be delivered by KC-46As operating a third as far away, at 1,000 nm. Consequently, absent major changes to the Joint Force's fleet of receiver aircraft, a force solely employed from great distances supported by tankers launched from far away would not generate an operationally relevant level of mass.[87] As PLA threats become more pronounced in sophistication and scale, even distant bases in states such as Alaska and Hawaii or the continental United States will come under the threat of considerable attack; consequently, the response should not be to withdraw to fight from range but rather to develop a resilient force posture that fights from varying ranges.

Furthermore, DoD requires access to multiple, redundant paths to deploy and employ aircraft. Current single points of failure and limitations in capacity mean that if a tanker airfield node supporting a deployment path is suppressed or destroyed, the force will lose or severely limit its ability to maneuver from that axis. In response, as depicted in Figure 21, in the Pacific, DoD should expand its access to airfields along its northern and central routes (the latter in essence rebuilding the World War II "Royal Road"), such as by increasing airfield distribution and capacity on US territory in the Marianas, Wake Island, and Midway Island, and doing the same with Compact of Free Association allies and other partners.[88] For the northern route, DoD could enhance the robustness of existing airfields and add access to new airfields in Japan and Korea and boost the capacity and resilience of airfields in Alaska, including select airfields in the Aleutians. DoD could also develop access to a complementary southern route, leveraging Pacific allies and partners and US territory on American Samoa that would support flights to Australia, New Zealand, or French territory if the central routes were heavily suppressed, and which would enable operations to and through the Philippines, Indonesia, Singapore, and Thailand.

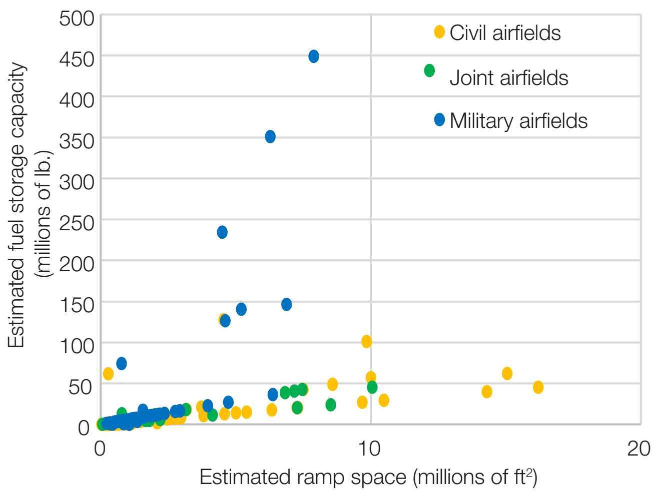
Access to additional airfields and ramp space along these routes would not only allow tankers to efficiently deploy more aircraft, but also would allow some aircraft to self-deploy by hopping across multiple airfields without using tankers, or by using less tanker support as there would be locations for aircraft to divert to in cases of emergencies. Lastly, some long-range aircraft, such as bombers, could operate directly from these airfields or use them as part of a shuttle bombing concept in which they would be rapidly refueled at an intermediate airfield.[89]

To enact this shift, DoD will need to enhance its posture on US territory and better cooperate with allies and partners. Among allies, the biggest challenge may be overcoming political restrictions that keep US aircraft concentrated at a small number of military airfields and limit access to numerous civil airfields. On US territory, DoD will need to commit to allocate necessary resources and adopt faster regulatory and budgetary approaches to conduct new military construction (MILCON) or repair of existing runways and ramp space.

Similar principles could be adopted, where appropriate, in other theaters. Aerial refueling forces will need access to airfields across theaters to provide an ability to counter an increasingly global PRC posture and support other operations. In particular, DoD should retain access to key deployment hubs in other regions, even as it enhances posture in the Indo-Pacific. For example, DoD should continue to cooperate with Portugal to conduct operations from Lajes Air Base in the Azores, which provides a critical central route for trans-Atlantic deployments from the United States to Europe or Africa (in case the northern route is interrupted) and supports the employment of aircraft directly from the airfield.[90]

Another class of necessary changes relate to bulk fuel storage at and around airfields. Tanker operations require large quantities of fuel. For example, a small detachment of 18 tankers operating from the planned Tinian Divert Site would require about half a million barrels of fuel per month, or more than twice as much as the capacity of the fuel tanks planned for construction.[91] Moreover, fuel is not evenly distributed across the theater, as an estimated 99% of fuel at US or allied airfields in the Indo-Pacific is concentrated at major airbases or airports or minor airbases. Additionally, there are relatively few airfields that have both large fuel stores and a great deal of ramp space necessary for deploying numerous tankers and exercising tactical dispersion (as shown in Figure 22). The concentration of fuel stores makes dispersing tankers to smaller civil or military airfields that rely on modest periodic or just-in-time deliveries of fuel problematic, as the dispersal airfields would not have enough fuel to provide tankers, and tankers would crowd out other aircraft with shorter ranges that could operate from those forward sites. Instead, smaller forward airfields should likely be reserved for use by fighter, ISR, or small transport aircraft.

Figure 22: Estimated Indo-Pacific airfield fuel storage capacity and ramp space



Relatively few airfields in the Indo-Pacific have large amounts of fuel and ramp space.

Source: Report authors, inspired by an unpublished 2016 chart by Timothy A. Walton and Ryan Boone.

Figure 23: US-flag tug and barge deliver fuel over the shore in Alaska

Source: Crowley Maritime Corporation.

The US Air Force and broader Joint Force does, however, need to improve its bulk fuel storage posture. It can do so in two ways. First, it can increase capacity at airfields that can be used by tankers—especially those where US forces are likely to have assured political access and face moderate threat levels. Second, it can construct hardened fuel stores to replace aging tanks or install new ones. Hardened underground fuel stores would provide DoD with assured fuel stocks. The construction of environmentally compliant hardened underground fuel stores—even though costly—would allow DoD to continue to have assured stocks, where needed, by increasing the necessary sophistication of adversary attacks. Where appropriate, DoD could build or contract complementary cut-and-cover tanks or aboveground storage tanks; however, a renewed emphasis on great power competition should be accompanied by a renewed recognition that hardened fuel stores are needed.

As numerous Cold War–era hardened underground fuel stores reach the end of their service lives, they should be replaced with new hardened underground fuel stores or renovated to provide equivalent or better protection. Airfields requiring new bulk fuel stores can leverage a complementary mix of fuel stores, including hardened underground fuel stores.

The third class of necessary changes to the aerial refueling architecture consists of bulk fuel distribution. Although secure fuel storage is vital, the likely scale of large operations against major adversaries such as China or Russia mean that it is unlikely the fuel stocks at airfields or DFSPs will suffice for protracted operations, and the high cost of hardened fuel stores means that it would be challenging to build enough fuel stores for very-long-duration operations. Additionally, fuel may not be sited at desired locations for distributed operations. Consequently, DoD should field capabilities needed to transfer fuel in bulk.

Chief among these are maritime tankers that deliver fuel from refineries or DFSPs to ports supporting airfields. Funding additional US-flag tanker slots in the authorized Tanker Security Fleet could increase the likelihood that airfields and, in turn, aerial refueling tankers will have sufficient fuel. Equally important are systems that transfer fuel from tankers or other delivery systems to airfields in an expeditionary manner, such as tugs and barges with pumps (shown in Figure 23), the Offshore Petroleum Distribution System, the Amphibious Assault Bulk Fuel Delivery System, and the Inland Petroleum Distribution System.[92] Over-the-shore fuel transfer systems are critical to allow fuel from tankers to reach airfields if port or supporting pipeline infrastructure is damaged or if air operations are taking place from austere airfields without access to developed ports.

Another approach to expeditionary fuel distribution involves transporting fuel on cargo aircraft. As the US Air Force has matured the Agile Combat Employment and Adaptive Basing concepts, it has experimented with using other mobility aircraft, such as C-17s and C-130s, to transport fuel to airfields and transferring that fuel on the ground to receiver aircraft (as shown in Figure 24).[93] The US Marine Corps has also experimented with using its C-130 and MV-22 fleets to refuel aircraft on the ground.[94] These valuable capabilities enhance the operational flexibility of air forces by creating opportunities to refuel, rearm, and resupply aircraft in an integrated manner from austere locations.

Figure 24: An F-22 fighter refuels from a fuel bladder carried by a C-130J transport

Source: Michael S. Murphy, US Air Force.

However, planners should be wary of substituting bulk fuel distribution capabilities with mobility aircraft. Transport aircraft are optimized to carry dry cargo and personnel and are not good fits for transporting bulk quantities of fuel. The C-17 is the largest mobility aircraft that would likely be used for such a mission, and it could offload around 90,000 lb. of fuel, which is less than half of the capacity of a KC-46A.[95] A C-17 could refuel six F-35As on the ground, and a C-130 could refuel slightly less than three. More importantly, transport aircraft will likely be in high demand supporting inter- and intra-theater mobility and other missions, such as transporting air and missile defense systems, munitions, other cargo, and personnel to distributed airfields. There will be important cases in which transport aircraft can distribute fuel on the ground to either supplement aerial refueling capacity or provide fuel in unique locations that will impose complexity on adversaries. However, the opportunity costs of using transport aircraft suggests operational designs should focus on transport aircraft performing other functions and instead field the necessary architecture of surface-base distribution systems, such as maritime tankers and barges, over-the-shore and inland fuel delivery systems, and trucks.

In addition to changes in their surface infrastructure and assets, tanker operations will require counter-ISR systems and air and missile defenses that many US tanker airfields may lack.[96] Counter-ISR capabilities could include passive measures, such as low-cost shelters to conceal aircraft from observation and to provide protection from elements or higher-cost, hardened shelters to drive adversaries to employ unitary warheads, as well as active measures such as decoys and counter-ISR jammers or weapons.[97] Tanker airfields should also be protected by active air and missile defenses capable of detecting and defeating threats such as aircraft and munitions, as well as being protected by US Air Force, other service, or ally or partner force protection units.

Overall, DoD will need to prioritize investments in its surface architecture—especially in the Indo-Pacific—for its aircraft to operate effectively. As stated by Senators Jim Inhofe and Jack Reed, the Chairman and Ranking Member of the Senate Armed Services Committee, regarding their proposed Pacific Deterrence Initiative: "Investments in theater missile defense, expeditionary airfield and port infrastructure, fuel and munitions storage, and other areas will be key to America's future force posture in the Indo-Pacific."[98]

Changes to Aerial Refueling C3

The US Air Force has embraced different automated planning tools for the air mobility force, including tankers. In 2016, the Defense Innovation Unit led development of Jigsaw, a tool that digitized and streamlined daily aerial refueling planning for air operations centers (AOCs) from a previous manual tool (shown in Figure 25), and in 2019 Air Force Operational Energy launched Magellan, a program that optimizes how the US Air Force allocates mobility aircraft for missions over extended time periods.[99] Both programs have been fielded and iteratively improved through agile software development processes, saving DoD millions of dollars in fuel and reducing the number of tankers and crews necessary to support operations.[100] These programs, and future iterations, can play an important role in better optimizing tanker capabilities with missions.[101] For example, 87% of KC-10 competition phase nonoperational and non-training sorties flown during the last decade were supporting missions that a single KC-46A (or possibly KC-135) could have performed.[102] Better platform-mission alignment in the future can help reduce operating costs.

New air operations tools should not only improve efficiency, but also improve effectiveness. Automated C2 and mission planning tools could receive human commands and use automated or artificial intelligence (AI)–enabled machines to develop and execute numerous and diverse courses of action featuring sophisticated, high-tempo and scale, distributed operations that would maximize options available to commanders.[103] These software decision support systems could also allow commanders to complement the greater scale and pace of decision-making with deception techniques such as distribution, feints and probes, and counter-ISR systems and approaches that would anticipate and better adapt to enemy threats, in turn imposing complexity on adversaries and mitigating risks.

If the software decision support tools were capable of edge processing and instantiations were distributed at different echelons across a theater (including at tanker airfields and tankers themselves), local units could execute advanced coordinated or integrated operations, even if communications with higher echelons were degraded or higher commands in AOCs were destroyed. These tools would not only support the operations of existing manned tankers, but also support the operations of future unmanned tankers conducting dynamic operations with little or no human control. Prototype tools aligned with this vision have been developed by the Defense Advanced Research Projects Agency (DARPA)'s Strategic Technology Office as part of the Mosaic Warfare portfolio, and these low-cost, high-impact decision support tools could be fielded by the US Air Force this decade as it matures its Advanced Battle Management System (ABMS) efforts.[104]

Another class of changes to C3 consists of changes to tanker communications and situational awareness capabilities. Tankers should adopt advanced radios, the ability to employ tactical datalinks, and situation displays. Such systems would allow tankers to receive and communicate orders using the previously discussed advanced C2 and planning tools. If tanker and receiver aircraft used advanced LDP/LPI datalinks, it could also improve the survivability of tankers by reducing their threat of geolocation and, in turn, engagement.[105] The use of new C2 and spectrum management tools would also allow tankers to reduce the level of communications needed from tankers and for commanders to be able to understand their status and dynamically plan operations.

Tankers could also play a role as communications relays and edge processing nodes.[106] In this concept, tankers would re-

Figure 25: The whiteboard on which US Central Command tanker refueling operations were planned before fielding of the Jigsaw tool

Source: US Air Force.

ceive information from forward operating aircraft or other assets (or even sense the environment using their own passive RF or other sensors), directly process it or use gateway translators if necessary, and retransmit it to other assets. This would not be a new mission for the tanker force, as airborne radio relay missions were flown by specially configured KC-135s during the Vietnam War.[107]

As modern tankers are equipped with communications systems and would be operating in the vicinity of other aircraft, they could support this mission in certain situations, and the US Air Force is acquiring a limited number of communications pods for the KC-46A that will connect the aircraft with different data links.[108] However, the Air Force should still plan for dedicated airborne communications relay assets to complement satellite communications for two primary reasons. First, communications relays will be needed for contested or highly contested areas where tankers will not operate, given enemy threats, and second, if tankers transmit with nondirectional datalinks at the high power levels necessary to overcome jamming or communicate with receivers at a distance, they will be susceptible to geolocation and attack. Consequently, tanker transmitters of opportunity could become targets of opportunity to adversaries. In light of potential attrition, relay systems that would be employed during a conflict should be unmanned to reduce risk to human operations and low-cost in order to ensure they can be acquired in sufficient numbers to overcome losses and enable rapid reconstitution if destroyed.

Changes to the Aerial Refueling Tanker Fleet

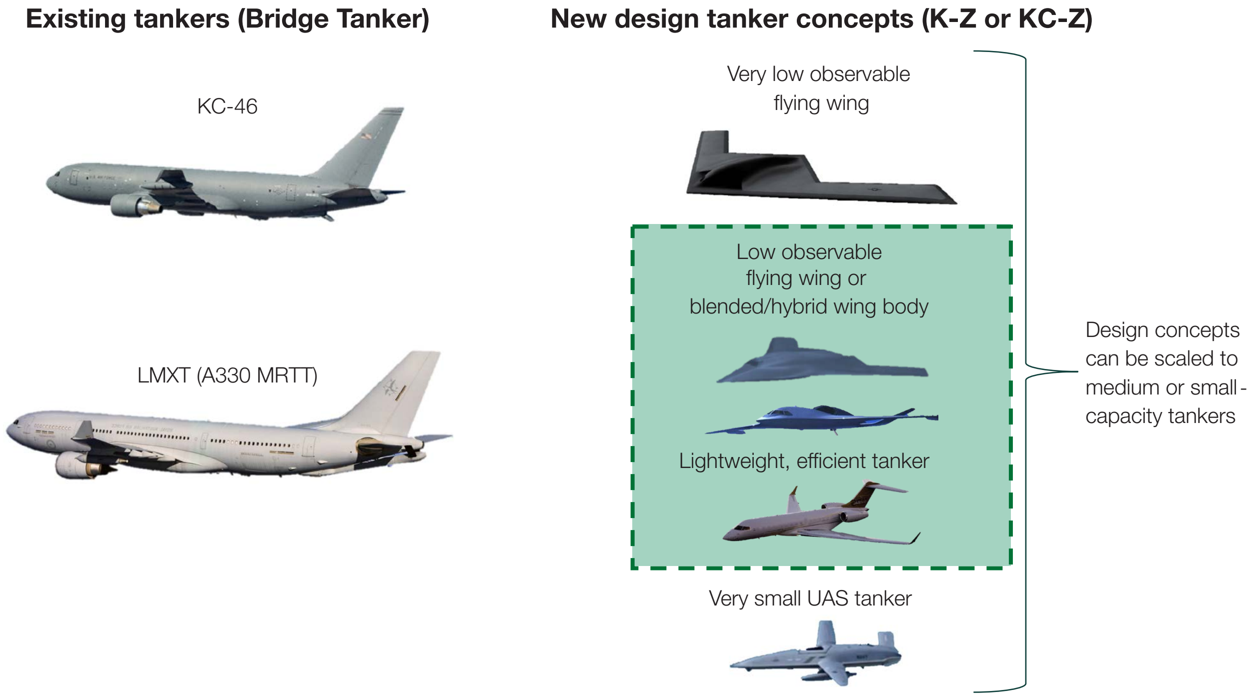
The current aerial refueling tanker fleet has served the nation well, supporting high-tempo operations around the world in mostly uncontested environments. However, it is steadily aging and becoming increasingly expensive to operate and sustain. Adversaries also threaten its utility, as tankers are vulnerable on the ground and lack sufficient defenses in the air to protect themselves inside contested areas.

This study refrains from generating a new tanker inventory requirement and instead proposes solutions for providing a fleet of 479 tankers, as determined by the 2018 MCRS study, and comparable in fuel offload performance metrics. However, to support a lethal and dynamic force that gains decision advantage, the US Air Force's tanker fleet composition should evolve, and the force should embrace new concepts of employment.

Through the KC-X program, the Air Force is recapitalizing a portion of its aerial refueling fleet with 179 KC-46A *Pegasus* tankers. As that program ends, the Air Force plans on procuring additional non-developmental aircraft through a "Bridge Tanker" program before developing and fielding a new tanker, referred to as K-Z. This section compares candidate aircraft and operating concepts that could be fielded in the coming decades through the lens of desired capacity, capability, and cost attributes for the tanker fleet.

Additional KC-46As are an option for the Bridge Tanker program. The KC-46A tanker is a medium-to-large design that is derivative of the commercial Boeing 767, with the ability to off-

Figure 26: Tanker options to complement the KC-46A



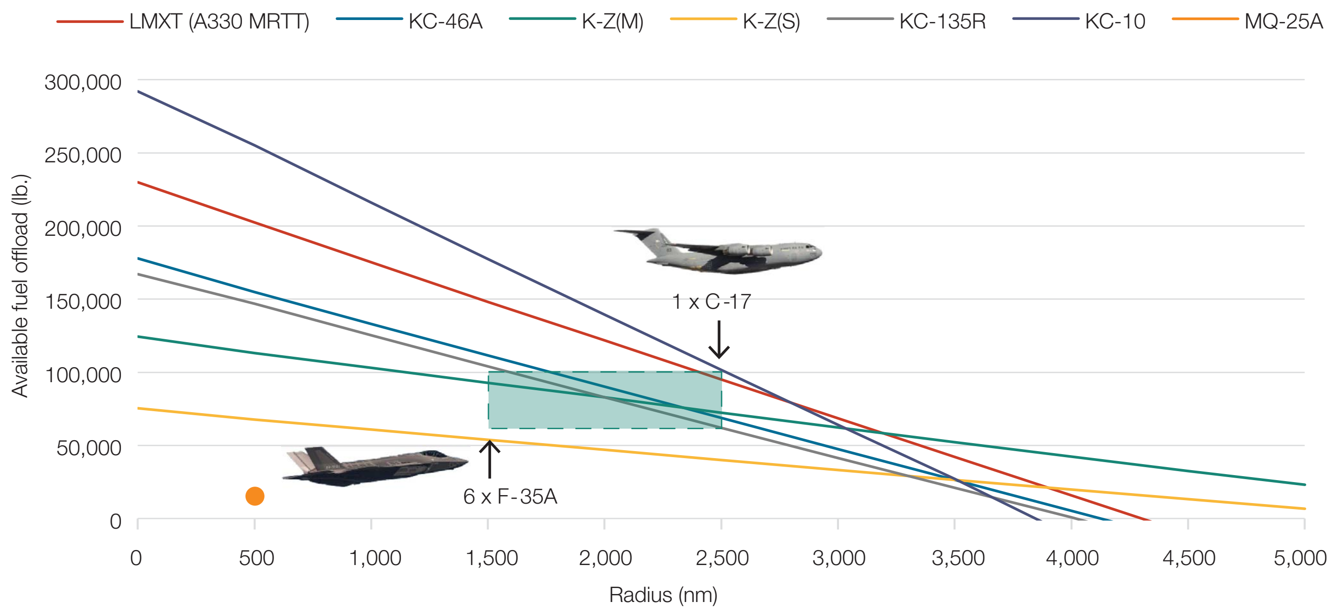
CHARACTERISTICS	LMXT (A330 MRTT)	KC-46A	K-Z(MEDIUM)	K-Z(SMALL)	KC-135R	KC-10
Empty weight (lb.)	265,055	204,000	95,000	70,000	122,500	250,000
Fuel capacity (lb.)	268,445	211,000	140,000	85,000	202,000	356,000
Fuel fraction	0.50	0.51	0.60	0.55	0.62	0.58
Required C-17 Parking Spots	1.29	0.88	0.47	0.54	0.60	1.02
Estimated RDT&E (FY 2022 $B)	0.276	0	6.9	4.6	N/A	N/A
Estimated APUC (FY 2022 $m)	225	191	111	65	N/A	N/A

Source: Report authors. Of note, although the KC-10 can load 356,000 lb. of fuel, its maximum takeoff weight is 590,000 lb., which allows the loading of 340,000 lb. of fuel on the ground.

load fuel through a boom and two attachable underwing drogue pods, carry dry cargo, and transport aeromedical patients and other passengers.[109] Although many of its capabilities are similar to the KC-135 that it is replacing, it features greater fuel efficiency and thrust, an enhanced communications suite, radar warning receivers, a Large Aircraft Infrared Counter-Measures (LAIRCM) system, and hardening to guard against electromagnetic pulses.[110] The KC-46A has an Average Procurement Unit Cost (APUC) of about $191 million.

The second non-developmental tanker option is a variant of the Airbus A330 MRTT.[111] Lockheed has partnered with Airbus to offer the US Air Force a version of the A330 MRTT that has been modified to incorporate an additional 25,000 lb. of fuel

Figure 27: Single tanker fuel offload capacity



This and subsequent charts assume flights to and from an ARCP, one hour on station, and two hours of reserve. This study's assessments generally followed procedures delineated in "Air Force Pamphlet 10-1403: Air Mobility Planning Factors," US Air Force, October 24, 2018. Note that fuel offload data at various ranges is not publicly available for the MQ-25A.

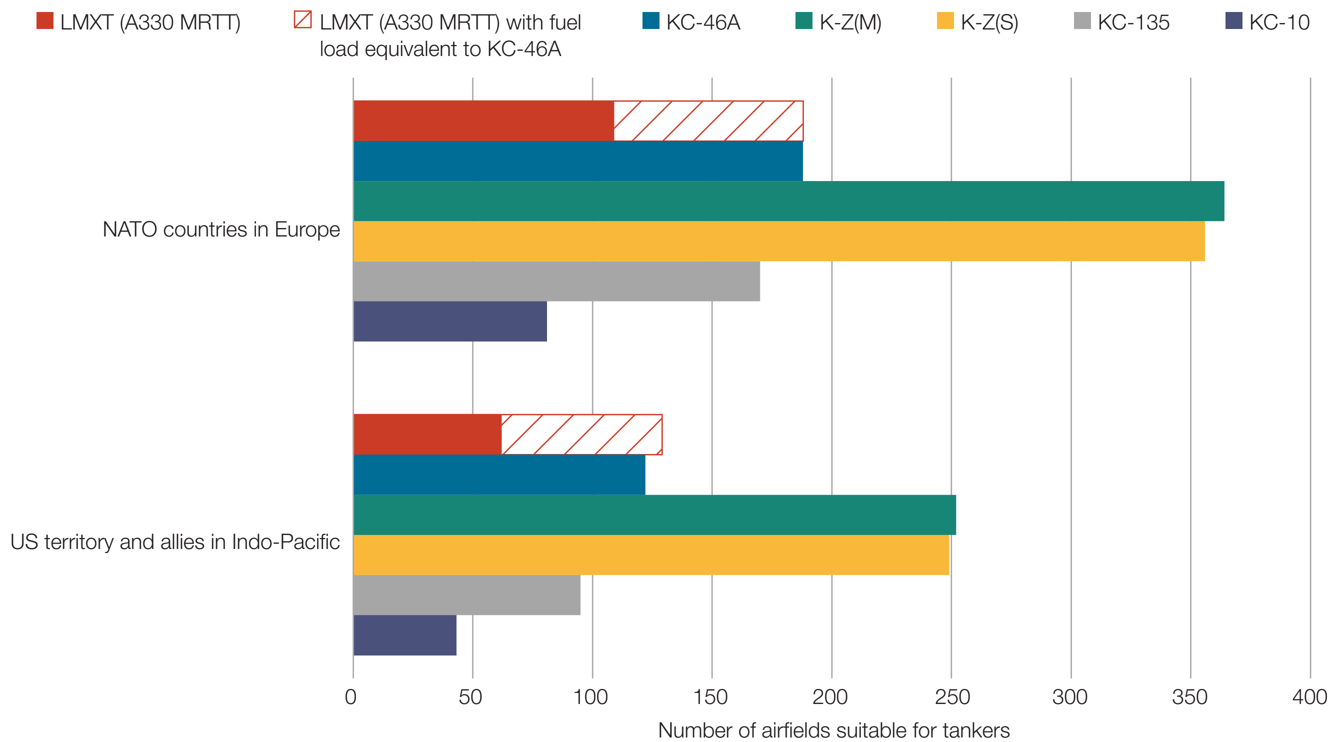
Source: Report authors.

capacity as the LMXT. The LMXT is a large tanker with similar characteristics to the KC-46A, but greater capacity in terms of fuel, aeromedical patients, and other passengers. The LMXT is expected to have an APUC of $225 million or less.

To succeed the Bridge Tanker program and sustain a fleet of 479 tankers as the remaining KC-135s are retired, the US Air Force may buy additional KC-46A or LMXT tankers or develop and procure a new tanker design. Concepts for the new aircraft have varied from very small, unmanned tankers that would receive fuel from legacy tankers to very large tankers capable of offloading large quantities of fuel from long ranges.[112] Some concepts for the tanker have envisioned low signature designs that would support aerial refueling of low observable aircraft in contested areas.[113] Lastly, the aircraft could be a dedicated tanker (and thus termed K-Z) or it could also have capacity for dry cargo (and receive the title of KC-Z). Figure 26 depicts tanker options to complement the KC-46A and compares them with current KC-135R and KC-10 tankers.

This study concludes that a medium-sized dedicated tanker, referred to as K-Z(M), would be a promising option to follow the Bridge Tanker. Using lightweight materials and forgoing structures necessary for the carriage of dry cargo, it could be a lightweight tanker design that could carry approximately 140,000 lb. of fuel. By using high-efficiency engines or an aerodynamically efficient

Figure 28: Number of airfields suitable for fully loaded tankers in NATO countries in Europe and US territory and allies in the Indo-Pacific



Smaller and lighter tankers could operate from more airfields. Of note, K-Z(M) is assumed to be capable of operating from more runways than K-Z(S) due to the incorporation of more robust, heavier landing gear. Additionally, LMXT can operate from an equal or greater number of airfields as KC-46A when carrying an equivalent fuel load. By loading less fuel than their full capacities, KC-46A and other tankers could operate from more airfields than those estimated in the chart.

Source: Report authors.

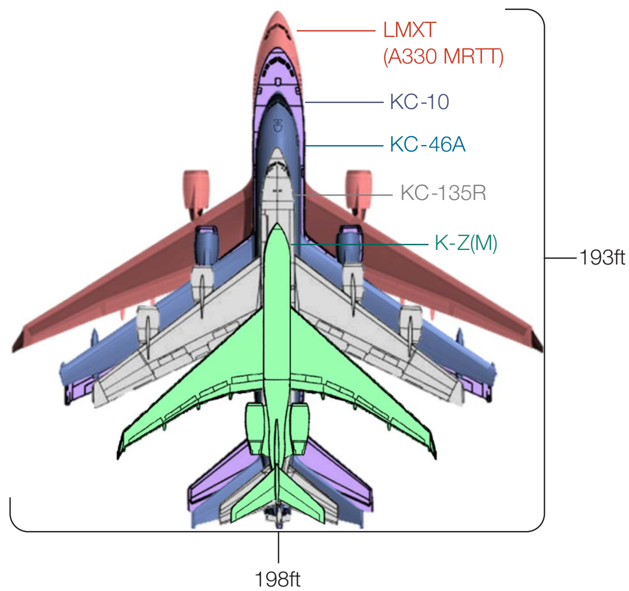
shape (e.g., wing-body-tail, blended/hybrid wing body, or flying wing), it could have long range and endurance.[114] Its smaller size compared to other tankers would allow more K-Z(M)s to fit in an airfield compared to larger tankers. The K-Z(M) could incorporate a reduction in size, shaping best practices, and robust soft-kill and hard-kill countermeasures to enhance its survivability, all at a moderate development and acquisition cost.[115] Its APUC of about $110 million would allow more tankers to be acquired for a given budget than larger tankers, even though it incorporates defensive systems.[116] The US Air Force should aim for the aircraft to be unmanned and should develop appropriate levels of automation for it to be so. However, the performance attributes of this study's aircraft conservatively assume space and weight for a two-man crew, in which one person would manage the aircraft while the other rested. Eliminating manning from the design could further reduce weight and cost or increase fuel capacity.

In comparing options, this report presents a small, dedicated unmanned tanker, K-Z(S), as an alternative to the K-Z(M) and other aircraft. The K-Z(S) could carry approximately 85,000 lb. of fuel, and using a lightweight wing-body-tail design and high bypass ratio engines, it could have very high fuel efficiency and endurance.[117] Its use of wide wings would slightly increase its requisite ramp space compared to the K-Z(M) design. Apart from radar warning receivers, LAIRCM, and communications datalinks, it would not have passive or active defensive measures. At $65 million, its APUC would be slightly more than a third of the cost of a KC-46A. The following sections evaluate the capacity, capability, and cost of Bridge Tanker and K-Z options.

Tanker Fuel Offload Capacity

The amount of fuel tankers can offload impacts their ability to support important missions during likely operational scenarios. Tanker offload capacity is impacted by numerous factors. Fuel load and fuel consumption rate shape the quantity of fuel that can be provided to receiver aircraft at different ranges, or the endurance of the tankers once on station. Figure 27 depicts the available offload of tanker options at different operating radii. Of the available new tanker options, the LMXT provides the most fuel capacity at most ranges, with the LMXT offloading at 2,500 nm approximately the same capacity as KC-10 that are being retired. The K-Z(M) and K-Z(S) options provide less fuel than larger tankers at shorter ranges; however, their high fuel efficiency allows them to provide comparable or superior offload capacity to larger tankers at very long ranges (or alternatively, very long endurance missions). Figure 27 also depicts potential offload demands for a single C-17 and six F-35As to represent refueling demands for a single large aircraft and multiple small aircraft.[118] Future tanker designs should be capable of providing operationally relevant quantities of fuel to a mix of aircraft. The LMXT and KC-46A are each capable of refueling a C-17 at approximately 1,750 and 2,500 nm radii, respectively; in contrast, the K-Z(M) concept is well-sized to refuel a flight of six F-35As out to 3,000 nm (or alternatively one P-8A). The smaller K-Z(S) could provide slightly less than this amount at 1,500 nm or less, while the very small MQ-25A being fielded by the US Navy can only provide approximately 15,000 lb. of fuel offload at 500 nm, enough to refuel two fighters.

Figure 29: Relative size of tanker options

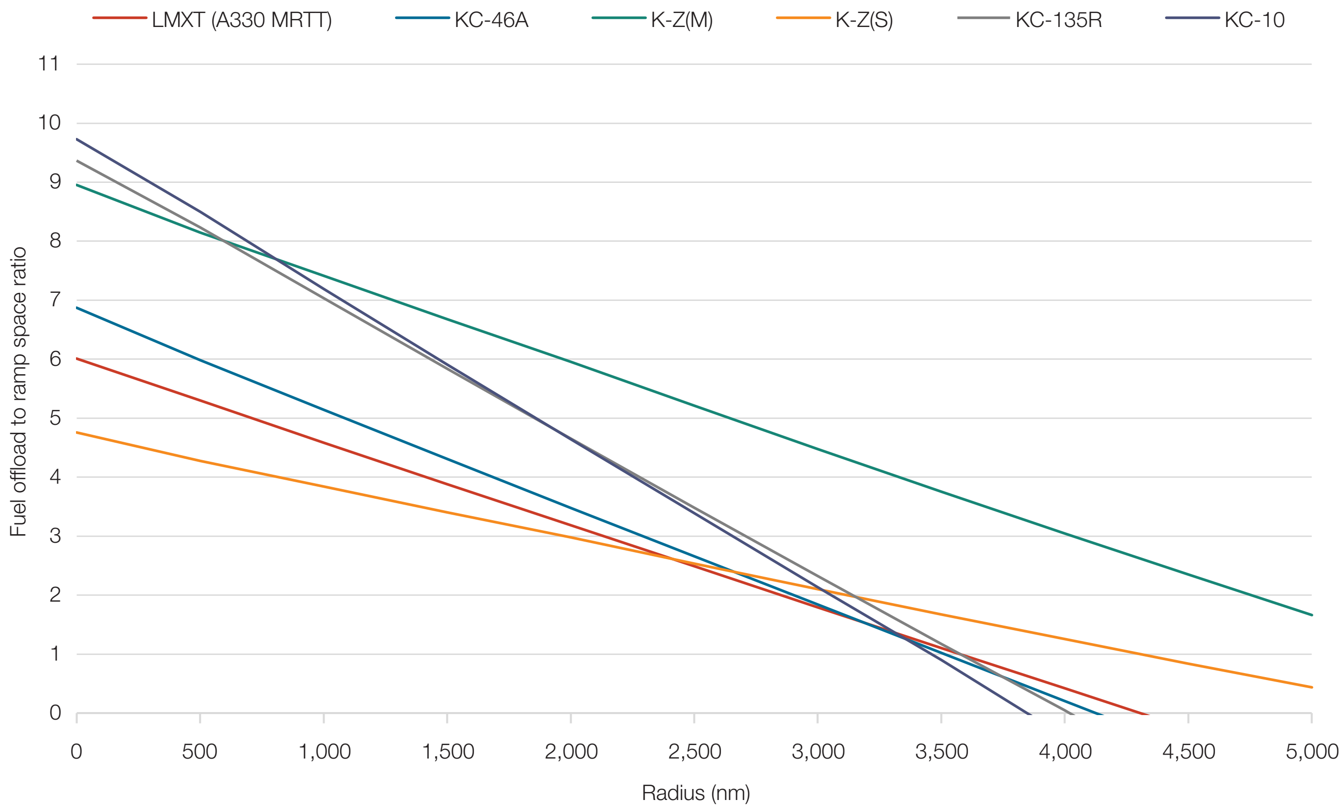


Source: Report authors.

Additionally, the thrust, weight, and gear structure of tankers affect the length and firmness of necessary airfields and, in turn, the locations where tankers can operate. Access to more airfields (provided the airfields have fuel) can enhance operational resilience. Figure 28 shows how the lighter-weight K-Z(M) and K-Z(S) concepts, by being able to operate from runways 6,000 ft or greater and with less-firm surfaces, could operate from more airfields when fully loaded than existing tanker designs.[119]

Access to more airfields is an operational benefit. However, perception of this advantage should be tempered by an understanding of available ramp space and fuel stores at airfields. For example, on US and allied territory in the Indo-Pacific, the K-Z(M) design could access twice as many airfields as the KC-46A, but it is only able to access 18% more ramp space, since

Figure 30: Tanker fuel offload to ramp space ratio

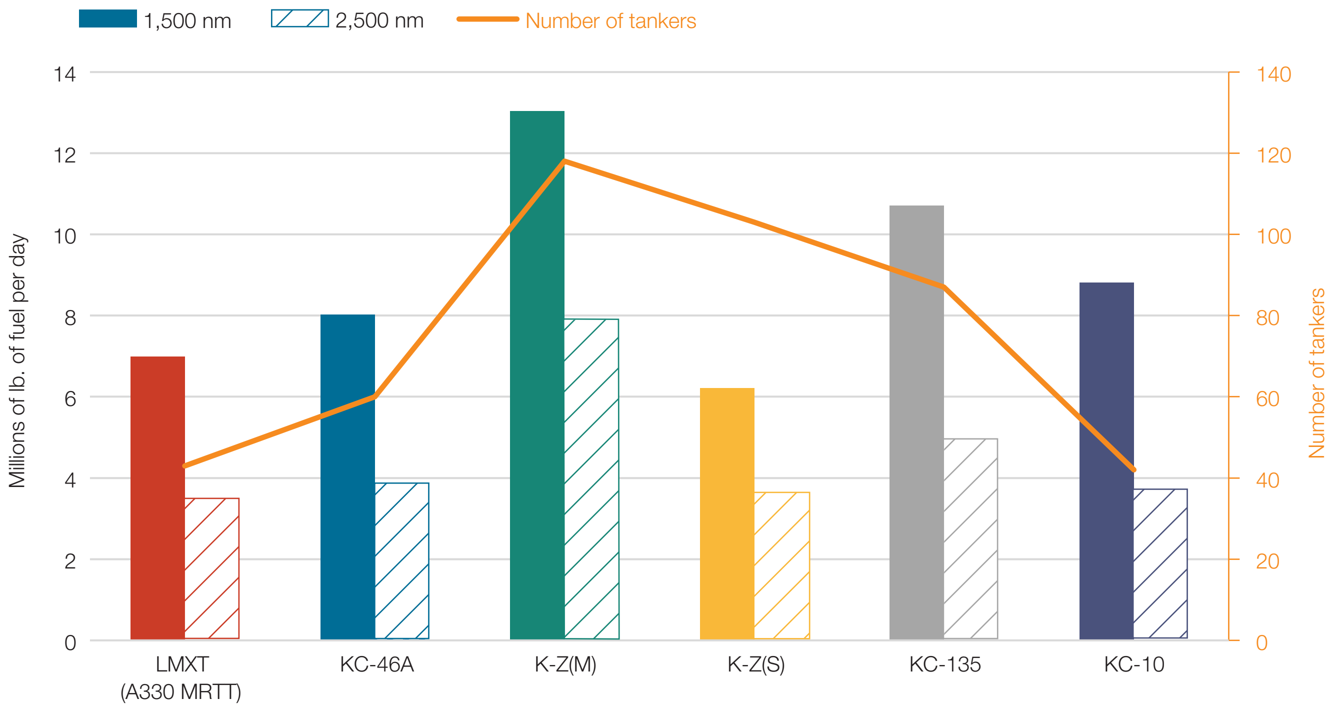


Source: Report authors.

approximately 93% of ramp space in the theater is located at major airbases or airports or minor airbases. Consequently, there is likely a promising middle space in which K-Z designs can operate from shorter runways (such as 6,000 ft or greater) and surfaces with less firmness than larger aircraft; however, the expense and weight of higher-thrust engines required to allow tankers to operate from very short runways may not be worth the effort, as there may be insufficient fuel and ramp space at those locations to support operations.[120] An exception to this observation is adding features to tankers to enable operation from runways that have been repaired after attacks, such as incorporating robust landing gear and positioning engines in locations that are less likely to ingest foreign object debris.

Lastly, the area of each individual tanker impacts the number of tankers that can operate from airfields. Figure 29 depicts the respective size of each tanker, with the size of the K-Z(M) notionally represented with a version of the Bombardier Global 6000 that has been modified with larger wings.[121] More of the smaller aircraft can fit on contiguous airfield apron space than larger aircraft.[122] A valuable metric for measuring the impact of size on tanker offload capacity is the ratio of a tanker's fuel offload at different ranges compared to the amount of ramp space it takes up (shown in Figure 30). Higher ratios indicate greater offload per square foot of ramp space, and as ramp space will likely be at a premium in contested environments, this metric should significantly inform tanker fleet evaluations. In this metric, the

Figure 31: Estimated tanker offload capacity from 11 Indo-Pacific airfields



Source: Report authors.

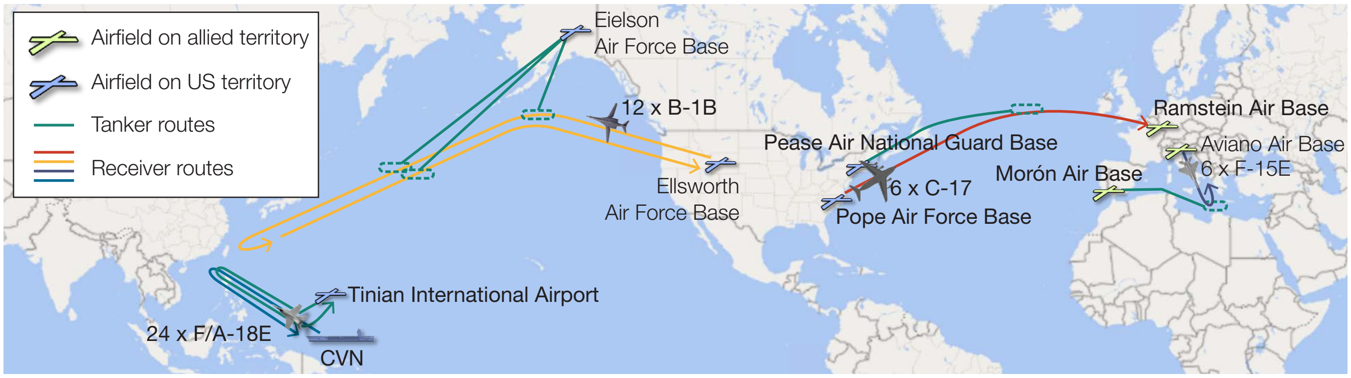
current KC-10 and KC-135 tankers and the proposed K-Z(M) design generally outperform alternatives.

Assessing Offload Capacity and Mission Vignette Performance

Figure 31 assesses the fuel offload per day that can be provided by different tanker types, if operating from the 11 Indo-Pacific airfields previously identified in Figure 17. Fleets of K-Z(M)s or KC-135s, with their superior fuel offload to ramp space ratios, could outperform aircraft with lower fuel offload to ramp space ratios, such as the LMXT, KC-46A, or K-Z(S).[123] Counterintuitively, a fleet of the smaller but higher fuel fraction and more fuel-efficient K-Z(M) design that can access all 11 airfields would exceed the aggregate offload capacity of large tankers, such as the LMXT or KC-10, although it would require far more K-Z(M) aircraft.[124]

Another important way to examine tanker capacity is by using mission vignettes. Vignettes can serve to illustrate operational considerations in ways that may not be evident from offload capacity metrics. Figure 32 depicts four notional vignettes representative of missions in which tankers provide coronet and escort tanking support for fighter, transport, and bomber aircraft. Overall, significantly fewer LMXTs are required than KC-46As or K-Z aircraft to accomplish the same missions; although, as the LMXT is larger, more ramp space is usually needed to support the same number of receiver aircraft. The ability to employ fewer tankers to accomplish missions promotes simplicity and economy of force in operational plans, and the need to operate a quarter to a third fewer LMXTs than KC-46As has a major benefit. Another interesting observation is that K-Z(M) aircraft can support some

Figure 32: Mission vignettes involving aerial refueling support



Support from Eielson to 12 Ellsworth B-1Bs striking targets in Taiwan Strait

	LMXT (A330 MRTT)	KC-46A	K-Z(M)	K-Z(S)	KC-135	KC-10
Tankers required	23	32	30	55	36	22
Tanker ramp space required (millions of ft^2)	4.30	4.05	2.04	4.30	3.14	3.23
Tanker procurement cost (billions)	$5.18	$6.12	$3.32	$3.59	N/A	N/A

Support from Tinian to 24 carrier-launched F/A-18Es conducting OCA sweep through Luzon Strait

	LMXT (A330 MRTT)	KC-46A	K-Z(M)	K-Z(S)	KC-135	KC-10
Tankers required	6	8	10	17	9	5
Tanker ramp space required (millions of ft^2)	1.12	1.01	0.68	1.32	0.78	0.73
Tanker procurement cost (billions)	$1.35	$1.53	$1.11	$1.11	N/A	N/A

Support from Morón to 6 Aviano F-15Es striking targets in Libya

	LMXT (A330 MRTT)	KC-46A	K-Z(M)	K-Z(S)	KC-135	KC-10
Tankers required	2	2	2	4	2	1
Tanker ramp space required (millions of ft^2)	0.37	0.25	0.14	0.31	0.17	0.15
Tanker procurement cost (billions)	$0.45	$0.38	$0.22	$0.26	N/A	N/A

Support from Pease to 6 Pope C-17s transporting forces to Ramstein

	LMXT (A330 MRTT)	KC-46A	K-Z(M)	K-Z(S)	KC-135	KC-10
Tankers required	3	4	5	8	5	3
Tanker ramp space required (millions of ft^2)	0.56	0.51	0.34	0.62	0.44	0.44
Tanker procurement cost (billions)	$0.68	$0.77	$0.55	$0.52	N/A	N/A

Source: Report authors. Vignettes depict the minimum number of tankers required, exclusive of reserve tankers or tankers unavailable due to maintenance or other factors. Additionally, tankers used in the first outbound ARCP of the B-1B vignette are assumed to also refuel returning B-1Bs. If this were not possible, 20-30% more tankers would be necessary.

Figure 33: Mission vignettes with fixed ramp space

Support from Eielson to Pope C-17s transporting forces to Andersen

	LMXT (A330 MRTT)	KC-46A	K-Z(M)	K-Z(S)	KC-135	KC-10
C-17s supported	9	9	13	6	13	14
Tankers required	9	13	25	20	18	11
Ratio of C-17s to tankers	1	0.69	0.52	0.3	0.72	1.27
Tanker procurement cost (billions)	$2.03	$2.49	$2.77	$1.3	N/A	N/A

Support from Hickam to Hickam-based F-22s transiting to Andersen

	LMXT (A330 MRTT)	KC-46A	K-Z(M)	K-Z(S)	KC-135	KC-10
F-22s supported	26	28	46	25	39	41
Tankers required	13	19	37	33	29	17
Ratio of F-22s to tankers	2	1.47	1.24	0.76	1.24	2.41
Tanker procurement cost (billions)	$2.93	$3.64	$4.09	$2.15	N/A	N/A

Source: Report authors.

long-range missions, such as the escort tanking mission near Libya or even the deployment of C-17s to Germany, while requiring significantly less ramp space and procurement cost than LMXT or KC-46A options.

Whereas Figure 32 shows tankers required for vignettes irrespective of ramp space, Figure 33 presents two other mission vignettes, in which ramp space at Hickam Air Force Base and Eielson Air Force Base is fixed, and alternately calculates how many receiver aircraft could be supported. The LMXT's ratio of receivers-to-tankers is better than all other aircraft except the retiring KC-10, demonstrating how the LMXT could efficiently support large offloads to large aircraft such as the C-17 and long-range fighter transits. In the case of the F-22 coronet, the additional two F-22s that can be supported by the KC-46A over the LMXT likely does not warrant the use of an additional six tankers.

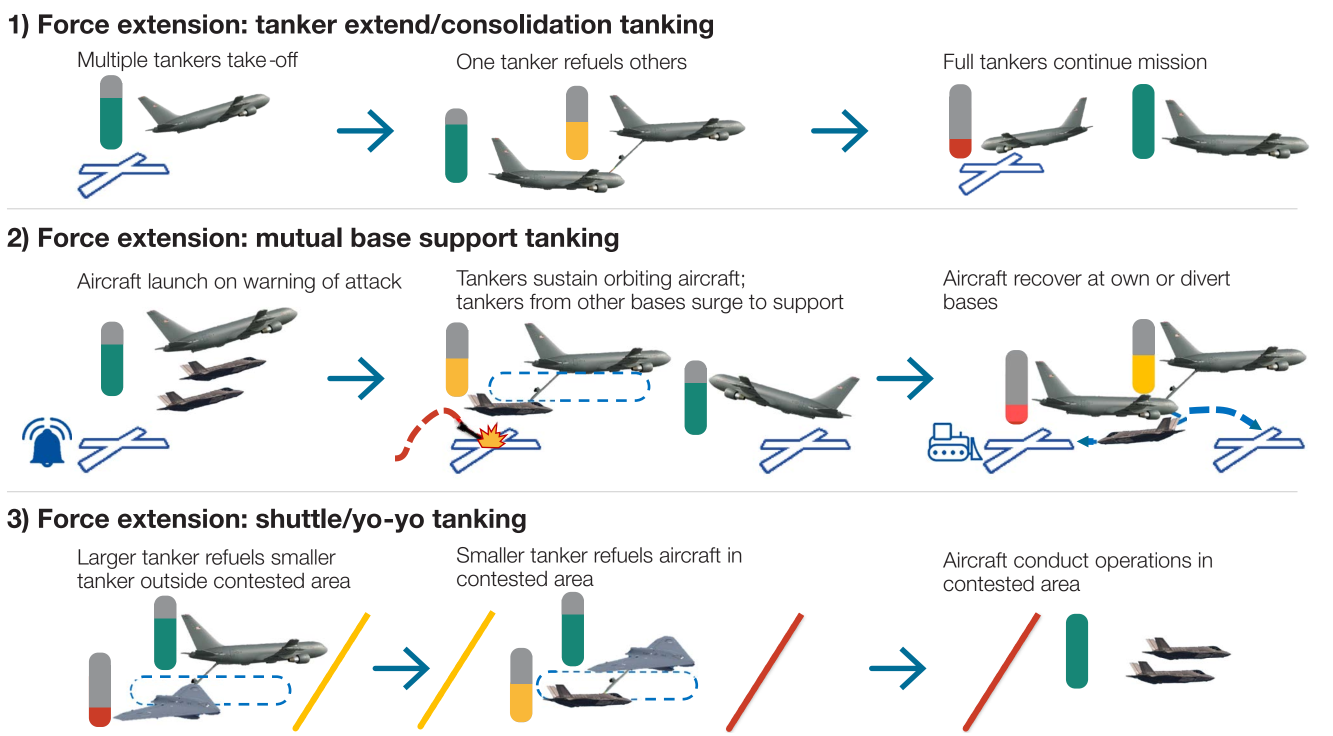
Role of Force Extension

Force extension, or using tankers to refuel other tankers, is an approach to improve the endurance and range of a refueling fleet.[125] The impact of force extension on K-Z design was considered as part of the study. Figure 34 depicts three employment concepts involving force extension to extend the range of tankers on long-range missions or consolidate fuel toward the end of a tanker's mission, to reinforce tanker and receiver aircraft when bases come under attack, and to have a standoff tanker refuel a smaller stand-in tanker that enters a contested area (and may shuttle or yo-yo back and forth refueling from larger tankers).

Force extension concepts should be incorporated into operational planning, and the enhanced use of automated planning tools will aid commanders in developing more-sophisticated plans that leverage force extension and other approaches to impose complexity on adversaries and make friendly forces more resilient. However, analysis of force extension concepts reveals that, in most cases, multistage deliveries of fuel are less efficient than single-stage deliveries, as shown in Figure 35. This insight applies across aircraft type mixes and most ARCP ranges. Force extension of K-Z(M) or K-Z(S) aircraft by a KC-46A or LMXT is more efficient than individual tanking by the KC-46A or LMXT; however, individual tanking by the K-Z(M) is more efficient than pairing up with larger tankers.

Moreover, many conceptual plans that rely on a mix of large and small tanker combinations (with smaller tankers based forward

Figure 34: Force extension refueling concepts



Source: Report authors.

Figure 35: Comparison of the efficiency of force extension and non-force extension sorties

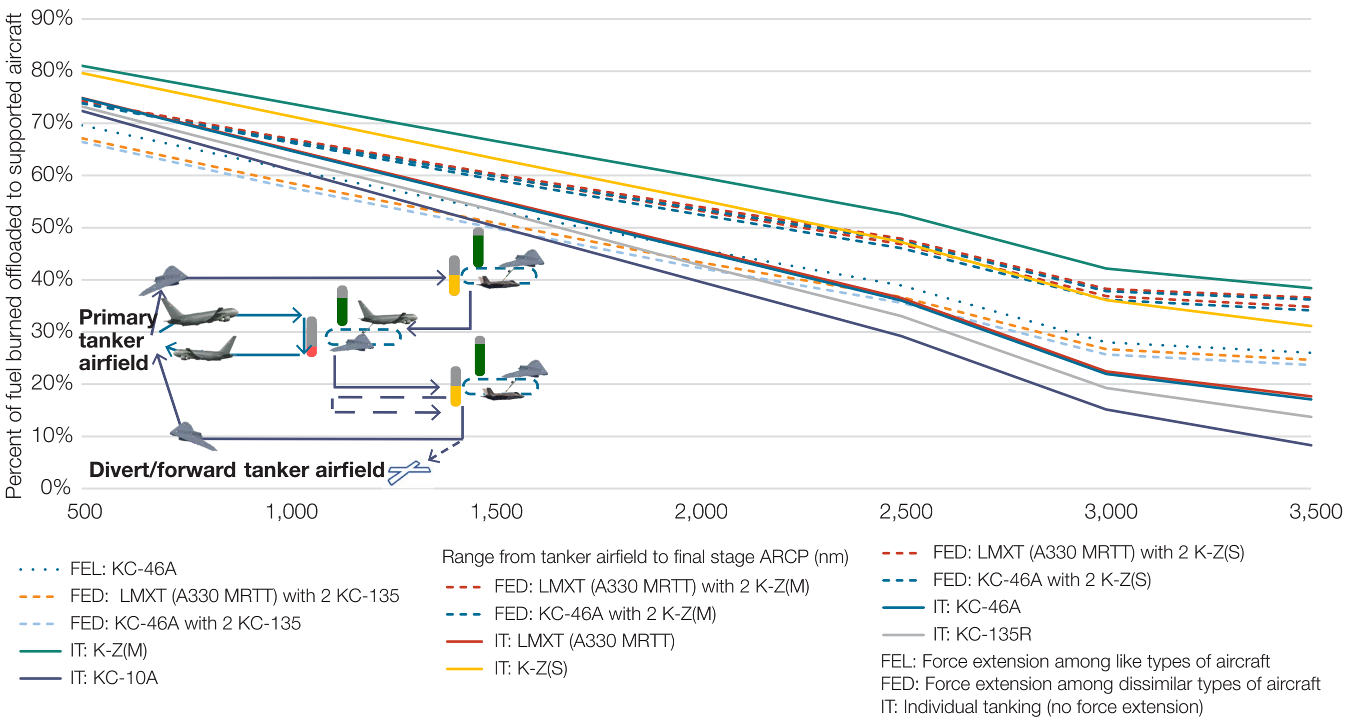


Chart shows the efficiency of refueling operations at different ranges. Higher percentages indicate greater efficiency. Inset graphic depicts a force extension operation between dissimilar aircraft. In the chart's inset figure, the shuttle tanker offloads fuel to a receiver aircraft, then refuels from another tanker and performs another offload to a receiver aircraft. It can continue shuttling back and forth from another tanker, or it can return to its original airfield or another divert or forward tanker airfield. The quantitative assessment in the chart assumes that the shuttle tanker(s) receive fuel once from the other tanker at a distance of two-thirds of the final ARCP radius, before returning to the primary tanker airfield.

Source: Report authors.

and larger ones based farther back) tend to allocate a larger portion of tankers to supporting aerial refueling rather than directly supporting receiver aircraft, which imposes operational complexity and reduces the flexibility of friendly forces. Basing multiple tanker types at a single airfield devotes more space to maintenance and other activities than comparable uniform tanker laydowns.

Overall, these dynamics suggest future tanker planning should employ force extension when appropriate and future tanker designs should incorporate universal receiver capability. However, future tankers should not be optimized to conduct force extension, for instance by being small or very small designs that would perfectly align their relatively small onload capacities with the offload capacities of larger tankers such as KC-46A or LMXT. Such a design would over-optimize a tanker for a narrow concept of employment, deny operational flexibility to the force, and could end up becoming a logistics tax rather than a logistics benefit. Additionally, as observed in historical operations, average tanker offloads are consistently less than tanker capacities. This difference can largely be attributed to the need for tankers to remain on station burning fuel and redundancy designed into operational plans to enhance resilience. Even with new C2 tools to improve offload efficiency, it is likely spare capacity will be needed on tankers, and small and very small tankers would lack necessary spare capacity. Future K-Z designs should be capable of providing fuel to aircraft at operationally relevant ranges on their own.

Implications for Tanker Designs

In summary, future tanker fleet design should account for not only the characteristics of individual tankers, but also their performance as force packages and at the theater level. This analysis finds that, in terms of the choice between the KC-46A and the LMXT for the Bridge Tanker program, the LMXT has greater fuel capacity, which confers more offload capacity and endurance at range. In particular, the LMXT excels at providing large offloads at long ranges. In most mission vignettes when ramp space is not a limiting factor, the LMXT can support receiver aircraft with significantly fewer tankers than the KC-46A. When ramp space limitations are accounted for, groups of KC-46As can offload more fuel than groups of LMXT, but they require a third to one-half more KC-46A tankers than LMXT tankers to do so (and a commensurate increase in associated ground and air personnel).

In terms of K-Z designs, a medium-size, lightweight, and fuel-efficient tanker appears to be a promising concept. The K-Z(M) could operate from more airfields, and its high fuel offload to ramp space ratio means that fleets of K-Z(M)s could potentially provide more fuel at range than larger tankers, such as the KC-46A and LMXT. The K-Z(M) could leverage force extension when appropriate, but would not be beholden to it. It would also have sufficient spare offload capacity at anticipated distances to adjust to operational demands, such as by remaining on station longer.[126] In short, the analysis suggests that bigger is not always better in terms of providing fuel capacity, and medium capacity is a promising area for K-Z designs.

Smaller tanker concepts, such as the presented K-Z(S) or very small tankers based on the MQ-25A, are not good fits for US Air Force capacity requirements. They are unable to support likely formations of fighter aircraft or small numbers of large aircraft at range or with sufficient endurance. Additionally, their need to employ force extension would impose operational complexity on friendly forces and tie up larger tankers to perform inefficient multistage transfers.

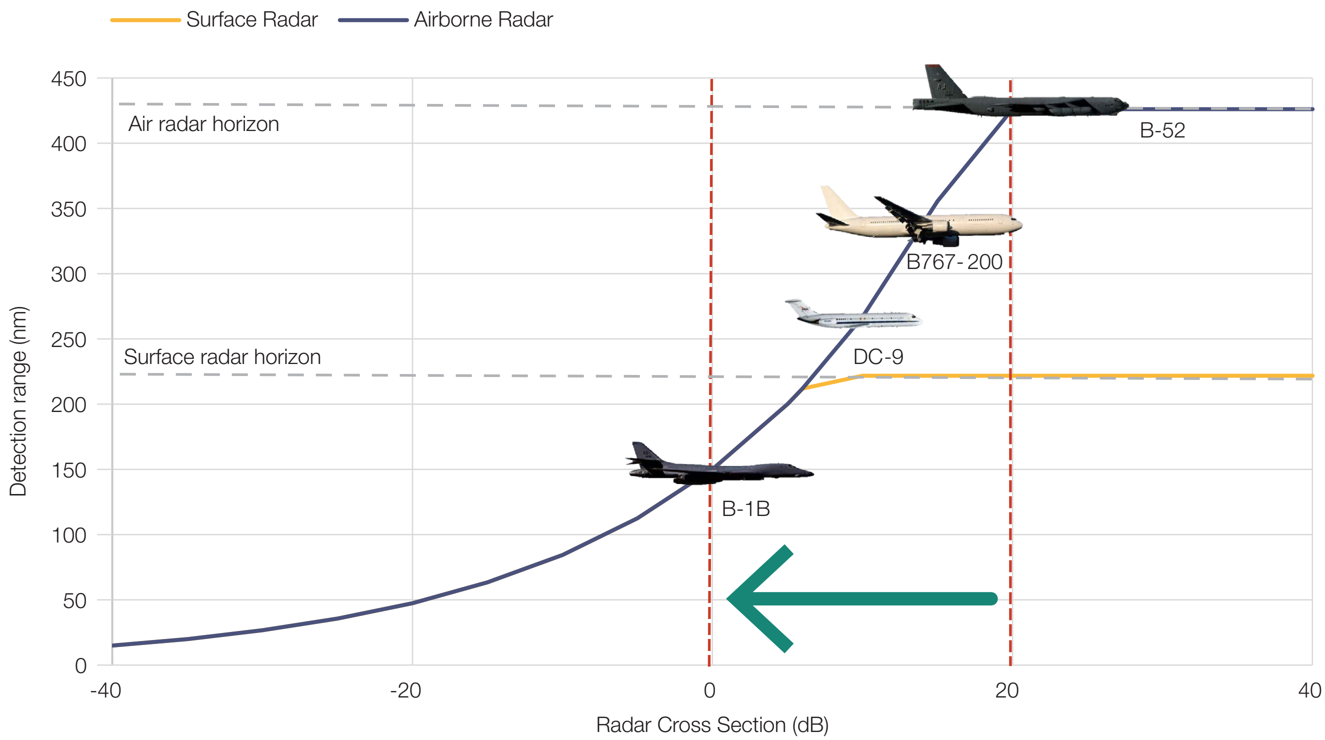
Tanker Capability

The future tanker force will need to adopt improved capabilities to enable it to support contested operations. Apart from the aforementioned C3 systems, chief among necessary capabilities are features that support enhanced survivability on the ground and in the air.[127] Without improved survivability, tankers will either be pushed back to ranges in which supported operations will no longer be viable, or threats to tankers will decrease the reliability of tanker support and, in turn, force commanders into adopting smaller-scale or simpler operations that will be easier for adversaries to counter.

On the ground, the presented K-Z designs could operate from more numerous airfields compared to current tankers, which, if coupled with other counter-ISR and air and missile defense measures, could improve survivability. Furthermore, smaller tanker designs would more easily fit inside shelters that could shield aircraft from observation and provide some protection against air and missile attacks.

In the air, future tankers should increase their survivability with two aims: reducing tanker standoff distances from threats to increase the reach or endurance of receiver aircraft and reducing anticipated attrition. Some analysts have proposed the development of very low observable tankers that could refuel receiver aircraft in contested environments. Such an aircraft could reduce the ability of adversaries to find low observable bombers or fighters via tanking operations, and it would allow receiver aircraft to receive fuel closer to their operating areas.[128] Very low

Figure 36: Simple estimation of radar detection range of aircraft



Source: Report authors. The curves depicted in the chart use estimates derived from the radar range equation, in which radar detection range is proportional to the ¼ power of RCS in m^2. The detection range of an airborne radar against a 10 dB fighter-sized target is estimated to be 470 km. Zhao Lei, "PLA Deploys Advanced Jets to Boost Electronic Capability," *China Daily*, September 4, 2015, www.chinadaily.com.cn/world/2015victoryanniv/201509/04/content_21787298.htm. The detection range of a surface radar against a target with an RCS of 4 m^2 is estimated to be 390 km. "S-400," Wikipedia, https://en.wikipedia.org/wiki/S-400_missile_system. Surface radars are operating at a height of 50 ft; airborne radars are operating at a height of 30,000 ft; and the presented aircraft are operating at a height of 30,000 ft. RCS estimates for the B767-200 and DC-9 are drawn from Roger Wehr, "Aircraft Scatter Update," W3SZ, 2017, https://w3sz.com/NEW_W3SZ_AircraftScatter_NEWS_Slides_2017.pdf. RCS estimates of 1 m^2 and 100 m^2 for the B-1B and B-52, respectively, are drawn from the second table in "Radar Cross Section," Global Security, www.globalsecurity.org/military/world/stealth-aircraft-rcs.htm.

observable features would also enhance the survivability of the tankers themselves.

However, a very low observable tanker that had sufficient fuel capacity would likely be challenging to develop. Moreover, as aircraft would mate to refuel, it may be challenging to prevent an increase in signatures, as radar reflections from interactions between the tanker and the receiver aircraft could be returned to adversary receivers. Lastly, the aircraft's potentially high development costs (possibly around $16 billion in RDT&E) and procurement costs (an APUC of around $265 million) would be challenging to fund amidst competing US Air Force and other budget priorities and may result in a much smaller tanker fleet or else foreclose other necessary investments in the aerial refueling enterprise, such as in the surface architecture.[129]

Rather than pursuing a very low observable tanker, US Air Force tanker survivability investments should focus on low-cost, high-impact options that reduce signatures and boost defenses. To reduce signatures, the K-Z tanker should employ low-cost measures such as its smaller size and shaping. As

Figure 37: Impact of tanker options on operational performance and costs

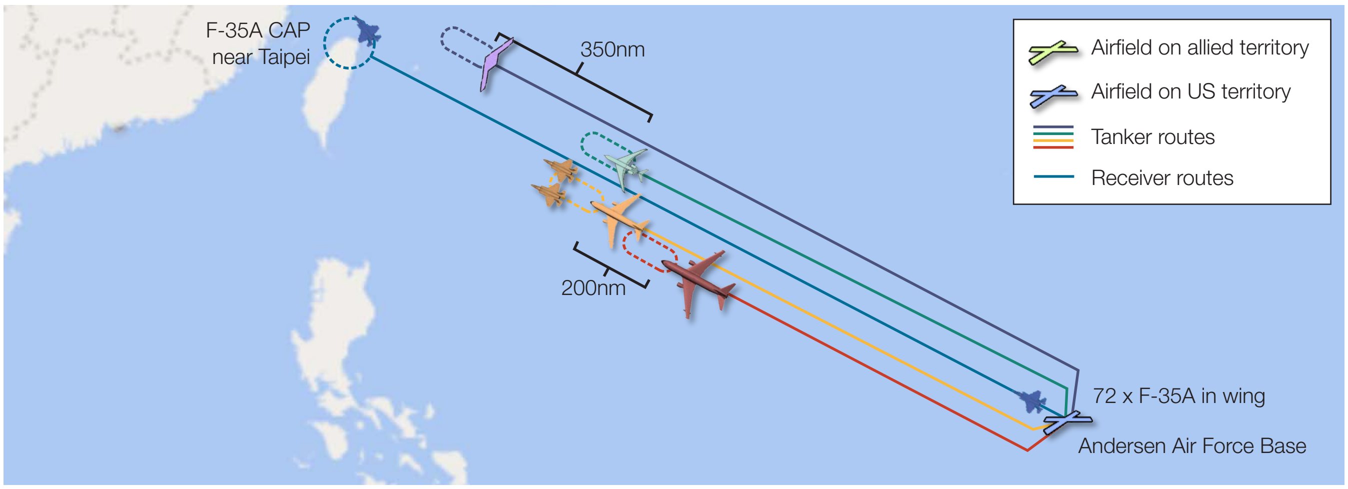


Figure is not drawn precisely to scale. Aerial refueling would take place not only at the depicted ARCPs, but also along the flight path.

Tanker options

	DISTANCE FROM ARCP TO CAP (NM)	F-35As ON CAP	TANKERS REQUIRED	PROCUREMENT COST OF TANKERS (BILLIONS)
KC-46A standing off	700	4	23	$4.4
KC-46A with 2 F-35A escorts	500	6	20	$3.8
Stand-in K-Z(M)	500	12	26	$2.9
Very low observable K-Z(M)	150	16	32	$8.5

Source: Report authors.

represented crudely in Figure 36, the estimated radar detection range of aircraft generally drops as aircraft become smaller or adopt radar cross section (RCS) control measures.[130] A DC-9 aircraft, which is roughly similar in size to the K-Z(M) concept, has an estimated detection range approximately 50 nm less than the B767-200 upon which the KC-46A is based. If the K-Z(M) aircraft adopted other signature control measures, such as those found in the late 1970s/early 1980s-era B-1B, the detection range could possibly drop further—even if the tanker were relatively non-stealthy in modern terms.

A 100 nm reduction in detection range compared to the KC-46A may reduce a tanker's standoff distance by the same amount. Although seemingly modest, such a change could significantly increase the availability of receiver aircraft and diminish adversary virtual attrition. For example, if a tanker could offload fuel to a CAP of F-35As flying 500 nm from their airfields at 200 nm from the CAP rather than 300 nm, it could reduce, from four to three, the number of F-35As required to maintain one constantly on station. In essence, the 100 nm increased stand-in distance could be worth an equivalent F-35A (that costs approximately $90 million) or more.

The bulk of survivability enhancements should be focused on measures to boost defenses. On some current and programmed tankers (such as some KC-135s and KC-46As), tankers could be equipped with C3 upgrades, soft-kill countermeasures such as defensive electronic attack jammers, and hard-kill countermeasures such as miniature anti-missile missiles, high-powered microwave weapons, or lasers. The same systems could also be applied to KC-46A or LMXT Bridge Tankers and K-Z tankers. These investments would have similar payoffs in terms of the benefits of reducing standoff distances through passive signature reduction.

Figure 38: Airbus' Automatic Air-to-Air Refueling system on an A330 MRTT refueling a Portuguese Air Force F-16

Source: Airbus.

Using a tactical vignette, Figure 37 depicts the impact of more survivable tankers.[131] Overall, the option of a stand-in K-Z(M)—even if it is only capable of offloading fuel at the same distance as an escorted KC-46A—would provide a major operational benefit in increasing fighters on station and would cost less to procure.[132] Moreover, the additional operational benefits of a very low observable K-Z(M) would likely not be worth its cost.

Automation and Refueling Systems

Another class of necessary capability improvements for the tanker fleet involve automation. Greater automation of aerial refueling functions, such as the operation of booms, could reduce tanker crew workloads or crew sizes, or allow previous tanker boom operators to perform other functions, such as airborne battle management. Airbus has demonstrated automated refueling of large and small aircraft on its A330 MRTT (as shown in Figure 38) and plans to certify it for use in 2022.[133] Boeing and the US Air Force have expressed interest in the Remote Vision System 2.0 program, setting the stage for future automated aerial refueling capability, if the US Air Force exercises an option to fund development of the technology.[134] Future technologies could also automate a receiver aircraft's process of mating with a tanker, which could improve the speed and success rate of transfers, especially when pilots are tired on long duration sorties or injured.

To effectively operate in contested environments, unmanned tankers will need to be capable of devising and executing operations in response to preplanned and dynamic tasking and conducting aerial refueling of manned and unmanned receivers with little or no emissions. Unmanned tankers could conduct lengthy missions without flight crew fatigue, and likely at higher utilization rates than manned aircraft. When appropriate, unmanned tankers could refuel from other tankers in the air and stay airborne for days, maximizing operational flexibility for commanders by providing persistent fuel nodes that could be dynamically repositioned. Additionally, as personnel would not inhabit the aircraft, planners could take greater operational risks with the aircraft. Lastly, the lack of personnel on the aircraft could allow aircraft designs to forgo human requirements and, in turn, save costs and weight.[135] Additional cost savings could be gained by eliminating flight crew, although some will still be needed for ground-based command and control or staff functions. Other savings could be achieved by reducing the number of training flight hours necessary to maintain squadrons' flight proficiency. Personnel reductions in necessary flight crew could also be reinvested to expand the number of ground support personnel, which could allow tankers to operate from more numerous locations in contested scenarios or at a higher tempo.[136]

The last class of capability improvements relates to aerial refueling boom and drogue modernization. Current booms and drogues are largely based on 1950s-era technology. Booms allow for higher rate fuel transfers and greater stability, but they generate a significant RCS, restrict tanker designs, and limit the transfer of fuel to one aircraft at a time. In contrast, pairs of drogues can be mounted on wings to enable two fighter-sized aircraft to refuel simultaneously, but drogues transfer fuel at lower rates, have a smaller operating envelope, and are more difficult to control in challenging weather.

In addition to greater automation of fuel transfers, future tankers could adopt new boom/drogue designs that increase the speed of fuel transfers and allow a single system to refuel probe and receptacle receivers.[137] For example, a new fuel transfer concept could employ a boom/drogue hybrid that would feature the extension of a large, semi-rigid hose that would be connected to a remora-like device that would automatically mate with probe-equipped and receptacle-equipped aircraft.[138] Coupled with automated flight controls on the tanker aircraft, such a system could accelerate the process of engaging with, and disengaging from, receiver aircraft. As the remora systems could be equipped on both aircraft wings, it could also allow tankers to offload fuel to two receiver-equipped aircraft simultaneously (instead of only one on current booms), which would reduce the time aircraft spend cycling to receive fuel and increase fleet efficiency.[139] The hybrid system would facilitate US Air Force tankers easily offloading fuel to both probe and receiver-equipped aircraft.[140] A final benefit is that the design may have a reduced RCS compared to traditional boom designs.

Tanker Costs

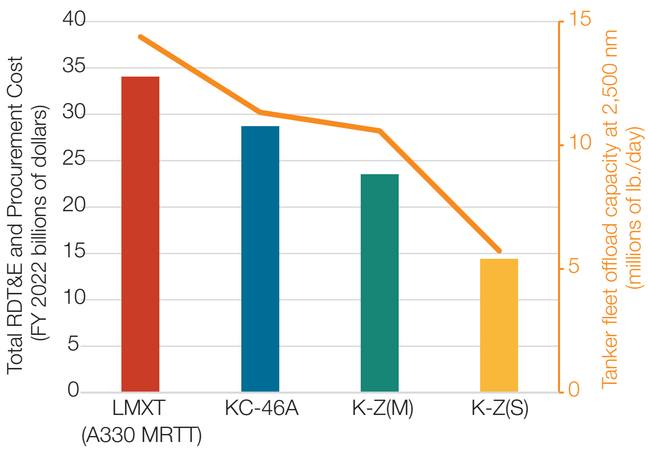
The US Air Force will need to contain tanker RDT&E, procurement, and O&S costs to successfully recapitalize its required fleet of 479 tankers and generate funding for other necessary improvements to the aerial refueling surface architecture and C3. Within the tanker aircraft portfolio, keeping RDT&E and procurement costs low is essential to ensure that the tanker fleet can buy aircraft at a sufficient rate to at least gradually replace the current force, if not drive down its age (and O&S costs) over time. Assuming 40-year service lives, as planned for the KC-46A, the US Air Force would need to procure at least 12 tankers per year, assuming no losses or reserves, to maintain a force of 479 tankers. If shorter, 30-year service lives were assumed, 16 tankers would need to be procured annually.

The high RDT&E costs of new aircraft may serve as a deterrent to launching a K-Z program. However, if desired performance parameters are carefully selected, RDT&E costs can be kept to a reasonable level. For example, this study conservatively assumes RDT&E costs for the K-Z(M) and K-Z(S) concept designs of $6.9 and $4.6 billion, respectively (three and two times the estimated RDT&E costs of the MQ-25A tanker, which will be aircraft carrier-qualified). These costs would be significantly less than the possibly $16 billion or so required to develop a very low observable tanker. Similarly, aircraft procurement costs should be kept low. This study conservatively assumes that a K-Z(S) with an APUC of $65 million has a cost per pound equivalent to the KC-46A, and a K-Z(M) with an APUC of $111 million has a cost per pound 25% more than the KC-46A.[141]

The US Air Force has expressed interest in acquiring 140-160 Bridge Tankers.[142] The procurement of 150 Bridge Tankers and 150 K-Z tankers would complement 179 KC-46A and result in a total fleet of 479 tankers. Figure 39 depicts the estimated RDT&E and procurement costs to field fleets of 150 tankers, and the daily offload capacity they could provide at an operating radius of 2,500 nm. In terms of Bridge Tanker options, selection of LMXT would provide 27% more offload capacity than the KC-46A at a 21% higher cost. For the remaining 150 tankers, a force of K-Z(M)s would cost less than continuing KC-46A production and provide only slightly less offload capacity, which could be offset by its ability to operate deeper into contested environments.

Viewed another way, if the US Air Force continues funding tanker development and procurement in the amount it spent

Figure 39: Cost to field and fuel offload capacity gained from 150 tankers



Source: Report authors.

in FY 2022, it could spend $23.8 billion on new tanker RDT&E and procurement over a decade. This amount could buy 104 LMXTs, 124 KC-46As, 152 K-Z(M)s, or 294 K-Z(S)s. A stand-in, but not very low-observable, K-Z(M) would therefore be a tanker design that could help the Air Force meet the 479 aircraft requirement.

The current tanker fleet is challenged by rising O&S costs that threaten to compel force structure cuts to generate savings. For example, from FY 2011 through FY 2018, the maintenance costs of KC-135 tankers steadily rose approximately 6% per year, even though the mission capable rates, aircraft availability rates, and size of the fleet dropped.[143] For the US Air Force to field a large fleet of tankers capable of conducting operations in competition and conflict, it will need to lower the force's O&S costs and consider total lifecycle costs in the acquisition of tankers. In the near term, improved optimization of tanker scheduling and routing, the implementation of predictive maintenance technologies and techniques, and new approaches to leverage commonality with commercial parts in acquisition can significantly lower operations and maintenance costs.[144]

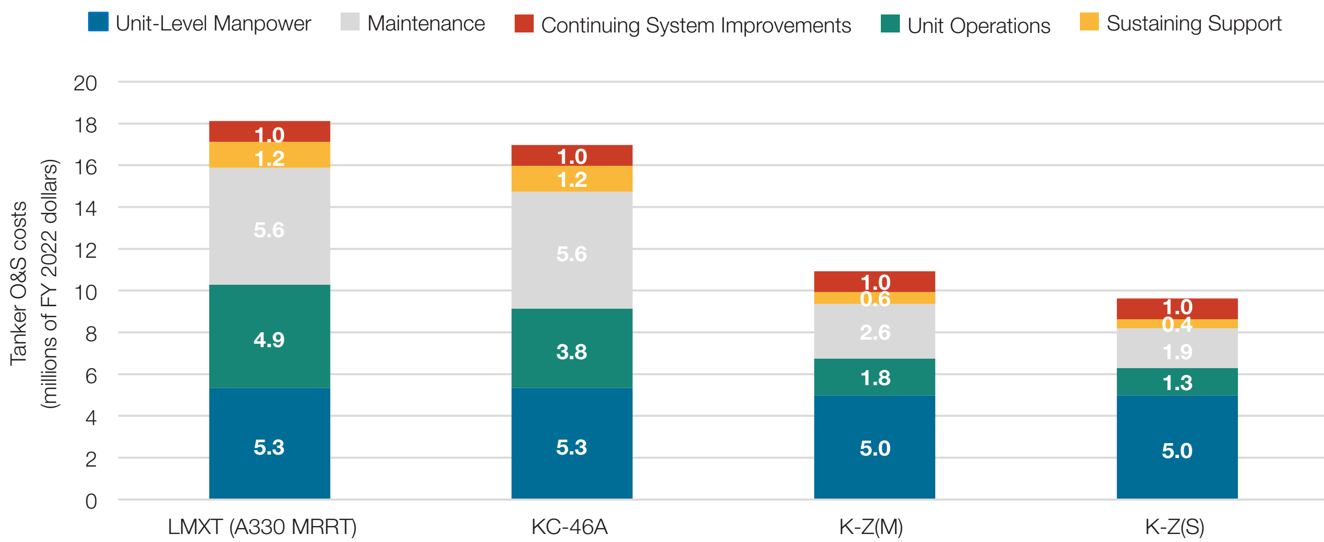
New aircraft, however, will be necessary to arrest the steady rise in O&S costs as the current tanker fleet continues to age. Comparing potential tanker O&S costs in Figure 40, LMXT and KC-46A costs are likely similar, with the LMXT estimated to cost approximately $1.1 million more per year to operate than the KC-46A, as it is a larger, heavier aircraft that burns more fuel per hour.[145] The O&S costs of K-Z aircraft could be significantly lower than those of current tankers. If the aircraft were unmanned and required little human control, reductions in a squadron's flight crew requirements could modestly reduce unit-level manpower costs.[146] More importantly, unit operations, maintenance, and sustaining support costs would be lower on the smaller, more fuel-efficient aircraft.[147] In total, K-Z(M) and K-Z(S) could have O&S costs more than a third less than the KC-46A. Further changes in K-Z unit operations, such as reducing tanker training flights, as the aircraft could be unmanned, would further reduce O&S costs.

By incorporating K-Z tankers into the fleet, the US Air Force could achieve considerable O&S savings that could be redirected toward other priorities. Additionally, the differences in current and proposed K-Z tanker offload capacities and O&S costs suggests an opportunity for specialization. For example, up to 85% of non-operational and non-training sorties performed by KC-10s involve small offloads that could likely be conducted by a K-Z(M) tanker more economically.[148] Through specialization and the use of improved mission planning and C3 tools, K-Z(M) could focus on smaller offloads, while larger tankers such as the KC-135, KC-46, or LMXT would fly less frequently and focus on larger offload missions.

Insights Regarding Bridge Tanker and K-Z Choices

The US Air Force needs to develop a more resilient aerial refueling architecture through new concepts of employment and by evolving the tanker fleet with the Bridge Tanker and K-Z. Reviewing desired attributes in the areas of capacity, capability, and cost reveals insights regarding the types of aircraft that should be selected.

Figure 40: Estimated tanker annual O&S costs



Source: Report authors.

In terms of the Bridge Tanker competition, the LMXT provides more fuel capacity than the KC-46A and could perform many missions—especially those involving long-distance, high-capacity offloads to large aircraft or long coronets—with fewer tankers than the KC-46A. If its employment is optimized to focus on missions where its capacity can reduce the number of tankers needed, the LMXT's advantages could allow it to support missions with fewer sorties than KC-46As during peacetime (thus reducing operating costs) and grant the Joint Force greater fuel offload and endurance in crises or conflicts.

However, some of the LMXT's advantages are partially offset by its characteristics. Although it provides 38% more fuel than the KC-46A at 2,500 nm, it is 47% larger.[149] The LMXT's fuel offload to ramp space ratio is mostly lower than the KC-46A's. Accordingly, even though the individual performance of each LMXT is significant, LMXTs generally take up more ramp space than KC-46As to accomplish the same mission, albeit with fewer tankers. Conversely, the lower offload capacity of each KC-46A requires more tankers and associated ground and air personnel to accomplish the same mission. Lastly, the KC-46A can operate from shorter, less firm airfields than the LMXT when both aircraft are fully loaded. The LMXT, though, can use its thrust advantage to operate from the same or shorter airfields than the KC-46A when it is carrying an equivalent load of fuel to the KC-46A.

In terms of capabilities, the survivability of KC-46As and LMXTs against threats are comparable. A significant exception may be that the rigorously tested electromagnetic pulse (EMP) protection characteristics of the KC-46A may allow it to better support nuclear deterrence and continuity of government missions, although the LMXT's greater fuel capacity may allow it to perform these missions with fewer aircraft.[150] Both aircraft have comparable boom and drogue technologies, the exception being the LMXT's boom is more mature than the KC-46A's, and Airbus has developed and tested an automated aerial refueling system for its boom operation that improves the efficiency of boom refueling.

In terms of cost, the KC-46A's procurement and O&S costs are estimated to be 16% and 6% less expensive, respectively, than the LMXT, as a result of it being a smaller, more fuel-efficient aircraft.[151] Aircraft procurement costs may affect the rate at which new aircraft can be procured to replace aging tankers.

The KC-46A and LMXT each have notable advantages and disadvantages. In crisis or conflict scenarios in which ramp space at airfields is limited and contiguous, groups of KC-46As could potentially provide more capacity, albeit with more tankers. In the competition phase, the KC-46A also provides an aircraft that is less expensive to procure and operate. However, in situations in which tanker employment is limited more by the number of tankers that can be deployed rather than ramp space constraints, the LMXT provides more fuel offload capacity and could accomplish the same missions with fewer tankers, which promotes operational simplicity and economy of force. Moreover, the LMXT's higher offload capacity at long ranges makes it better suited to refuel from distant airfields large aircraft such as bombers or drag smaller aircraft such as fighters. In selecting a future Bridge Tanker, the US Air Force will need to assess how ramp space and aircraft limitations may shape future operations and carefully analyze performance of aircraft options across a range of missions and scenarios.

For K-Z, the US Air Force should prioritize development of a highly efficient tanker with a medium fuel capacity. To maximize efficiency, the tanker should forgo carriage of dry cargo or other non-refueling missions. It should eschew small or very small designs that could not effectively support anticipated force packages of small or large aircraft and that would be dependent on support from larger tankers. It should also avoid very large, costly tankers that would not effectively fit on available airfields and, because of their lower fuel efficiency, deliver less fuel at range than alternatives.

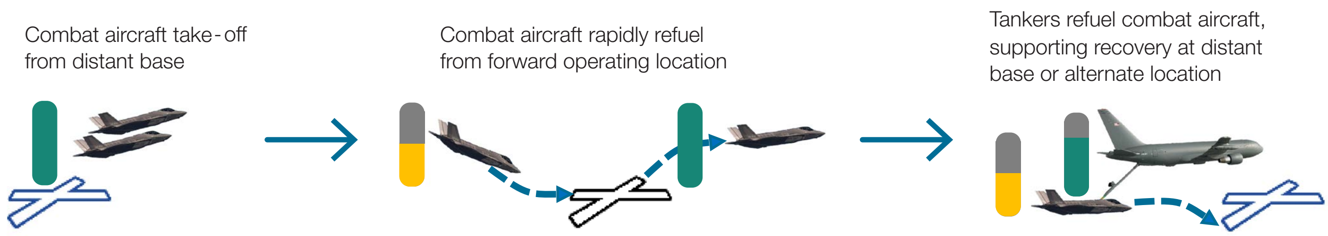
Furthermore, the US Air Force should take a balanced approach to survivability that makes some improvements in reducing tanker signatures but focuses on incorporating soft-kill and hard-kill defenses to enable a moderate stand-in capability. Consequently, the US Air Force should avoid very low observable tanker designs that would be expensive to develop and procure. With necessary investments in automation, the K-Z could be an unmanned aircraft, or, at the very least, an aircraft in which a human operator would predominantly play a C2 rather than pilot role. By balancing capacity and capability attributes, the development, procurement, and O&S costs of the aircraft could be kept at a manageable level that would be achievable within the US Air Force's anticipated budget. Overall, the US Air Force has viable options in the near term for the Bridge Tanker program and can mature necessary technologies this decade for the K-Z program.

Changes to Non-tanker Aircraft

Some of the most consequential improvements to the logistical supportability of the Joint Force may come from outside the aerial refueling enterprise. New concepts and capabilities can reduce tanker demands and make other aircraft more efficient and logistically independent.

New concepts of operation and employment can help reduce aerial refueling demands and contribute to creating a more lethal and dynamic force. The use of shuttle missions (pictured in Figure 41) would have a larger proportion of a mission's receiver aircraft fuel be delivered on the ground rather than in the air. Fighter, ISR, and other aircraft could take off from a distant base, rapidly refuel with their engines on from forward operating locations, continue conducting their missions, and aerial refuel on the way back to their original base or to another base. This approach would allow receiver aircraft to use fuel stocks at dispersed airfields forward and would shift tankers from the primary providers of fuel to ones that supported the second stage of a mission or stepped in to recover receivers if their intended forward operating locations were unavailable. Such a shift would allow a greater proportion of tankers in theater to focus on other missions.

Figure 41: Tanker-supported shuttle missions



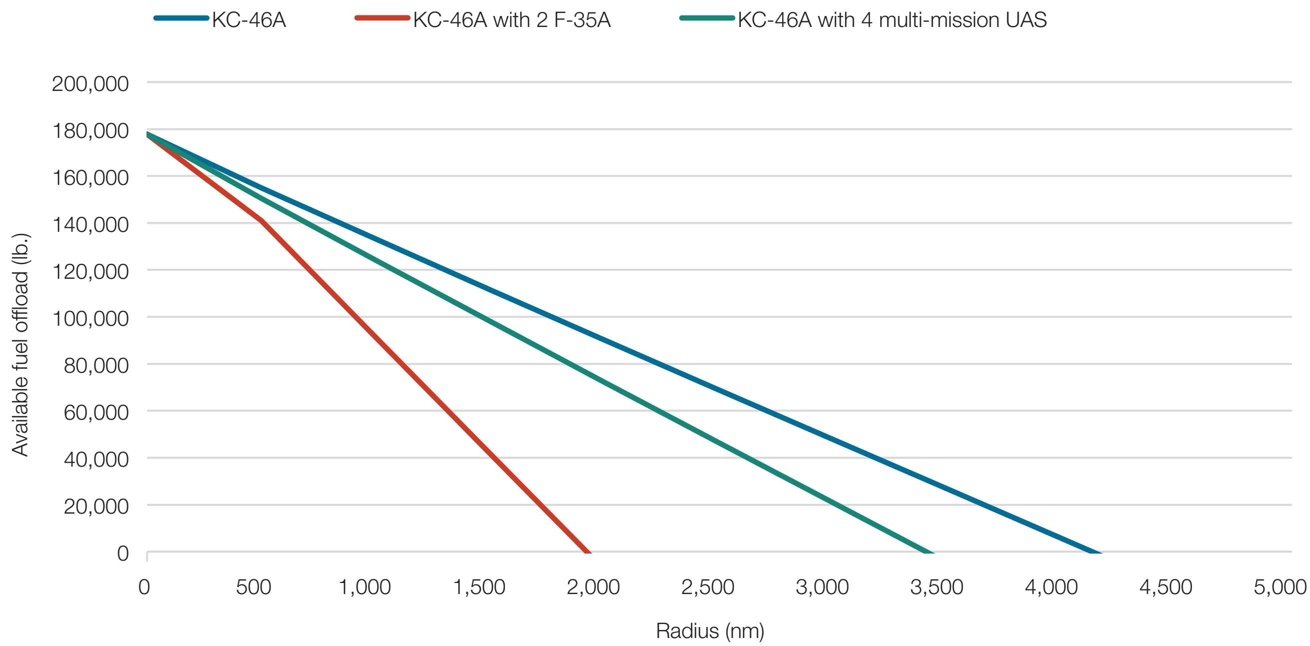
Source: Report authors.

Figure 42: Concept artwork of the General Atomics Defender unmanned aircraft refueling from and protecting a tanker

Source: General Atomics Aeronautical Systems.

The survivability of tankers could be improved by assigning them DCA escorts, which may allow tankers to operate closer to adversary areas. Next-Gen Multi-Role UAS, such as the Defender concept shown in Figure 42, could protect tankers and other high-value aircraft using a fuel-efficient UAS, which would leave tankers more fuel for other receivers.[152] As shown in Figure 43, even if twice as many UAS, such as the Defender rather than the F-35A, are needed to protect a KC-46A, the KC-46A

Figure 43: Fuel-efficient UAS escorts would greatly increase a tanker's available fuel



Source: Report authors.

tanker could have approximately 80,000 more pounds of fuel to offload to other aircraft at around 2,000 nm.

As aircraft are designed or modified, new technologies could help reduce aerial refueling demands. Simple technologies, such as wider plumbing on fighter-class aircraft, would allow them to receive fuel from tankers at the higher rates used by transport and bomber aircraft.[153] Hybrid electric propulsion is another class of technology that is rapidly maturing for use in aircraft and could significantly increase fuel efficiency on new designs, as well as aid in the generation of electric power for use in directed energy weapons. Moreover, the US Air Force has funded research and development of new engine technologies that could enhance the thrust and fuel efficiency of not only new aircraft such as NGAD, but also existing ones such as the F-35.[154] It also plans to re-engine the B-52 fleet with fuel-efficient commercial engines that could increase endurance and decrease aerial refueling demands.[155]

Each of these and other potential concepts and capabilities should be rigorously examined for their costs and benefits. On the whole, however, changes to non-tanker aircraft will be essential to reduce tanker demands, increase operational flexibility, and lower lifecycle costs. To field an operationally effective and fiscally sustainable force, the US Air Force will need to meter its tanker demand, as well as reshape its supply.

Summary

Without significant changes to the US Air Force aerial refueling architecture, DoD risks fielding air forces unable to conduct complex, distributed operations at scale. Rising O&S costs and dropping readiness rates could sap the tanker fleet of its force structure or leave it unable to support the desired number of peacetime operations. During conflict, adversaries may be emboldened to exploit vulnerabilities in both the brittle aerial refueling architecture and US operational plans more broadly. As the strength of the

US aerial refueling architecture becomes a weakness, US military forces may be incapable of deterring or defeating aggression.

Using new operating concepts, the proposed mix of improvements in the aerial refueling surface architecture, C3 capabilities, tankers, and other aircraft could yield a resilient enterprise that would improve the Joint Force's ability to support US national and operational strategies. The aforementioned concepts and capabilities either exist or leverage technologies that could be matured this decade and cost-effectively incorporated onto tankers and other aerial refueling systems by the early 2030s. The next chapter presents a plan to evolve the aerial refueling architecture into that future vision.

FIELDING THE FUTURE FORCE

The US Air Force can transition to a resilient aerial refueling enterprise with enhanced survivability, optionality, and assuredness. However, to overcome "increasing budget pressures based on growing costs of sustainment for current and aging force structure, continuous combat operations, and long-deferred modernization," the US Air Force will need to heed Chief of Staff of the Air Force General Charles Brown's call to "accelerate change or lose."[156]

Air Force leaders will need to act quickly to recapitalize the aerial refueling fleet, because competing demands on funding will only grow worse over time. Due to delays developing and incorporating KC-46As into the fleet, the US Air Force may need to retain aging KC-135s into the 2040s to maintain a fleet of 479 or more tankers. The aging KC-135 fleet's rising O&S costs will likely reduce funding available for tanker RDT&E and procurement. Costs for the B-21, Ground Based Strategic Deterrent (GBSD), and NGAD programs are also expected to rise in the latter half of the 2020s and could crowd out resources for procuring a Bridge Tanker or developing K-Z aircraft.[157] And continued growth in military personnel costs is expected to further reduce DoD's purchasing power, and rising national debt and entitlement costs are expected to limit future federal discretionary spending, including on defense.

Further delaying aerial refueling modernization by deferring the Bridge Tanker or K-Z programs would incur major operational risks that could reduce the US military's ability to deter aggression. Additionally, delay would only aggravate the problem of rising O&S costs and compound the size of the procurement

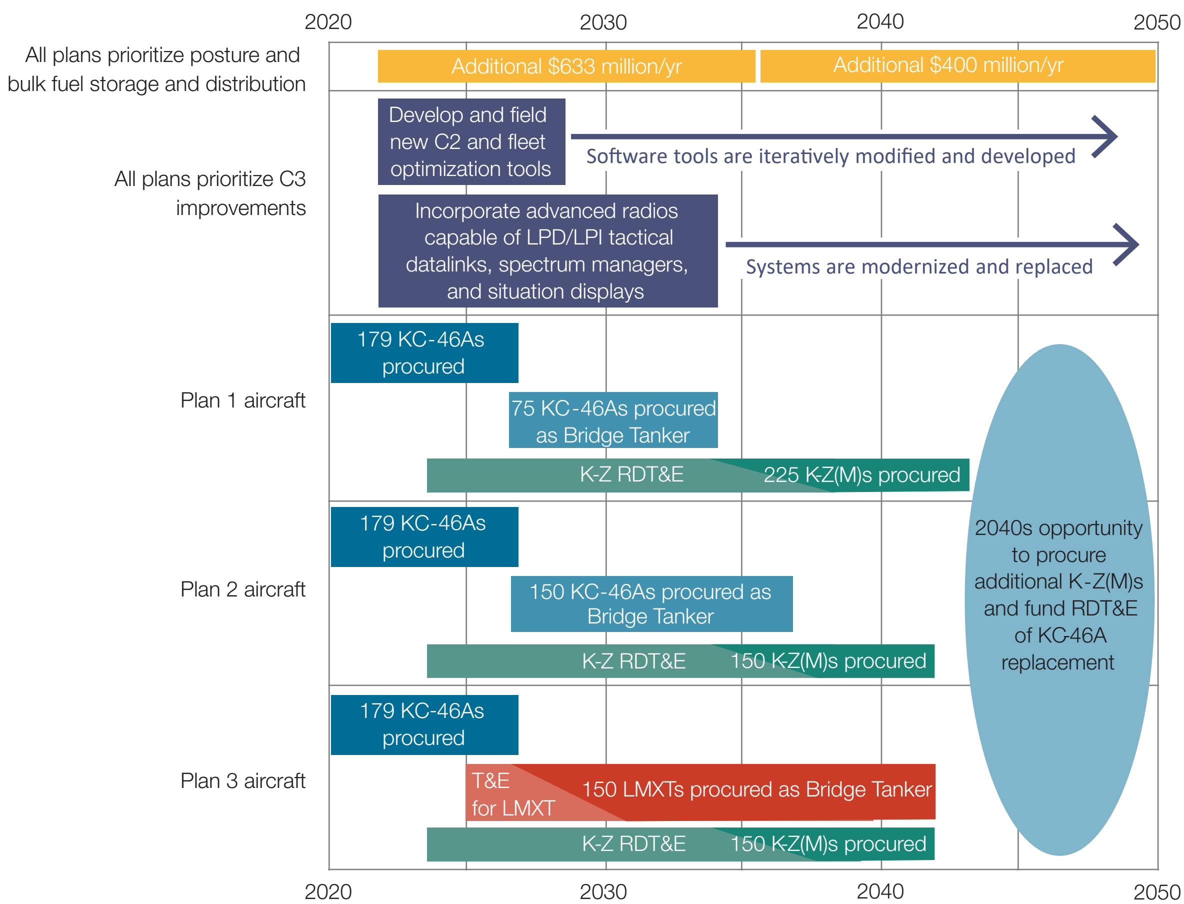
Photo: A KC 135R tanker drops its nozzle to refuel the E-4B NOAC while flying from Andrews Air Force Base, Maryland to Tunisia, on July 29, 2012. (Mark Wilson/Getty Images) bow wave that would then be needed in the 2030s to replace aging aircraft.[158] Instead, the US Air Force should implement a plan that maximizes operational performance in the near to mid-term within anticipated fiscal constraints.

Options for the Aerial Refueling Force

The US Air Force can take a holistic approach to force design that appropriately funds elements of the entire aerial refueling architecture. To evaluate potential procurement options, this study developed notional plans (summarized in Figure 44 and further described in Appendix A) that illustrate the choices available to DoD.

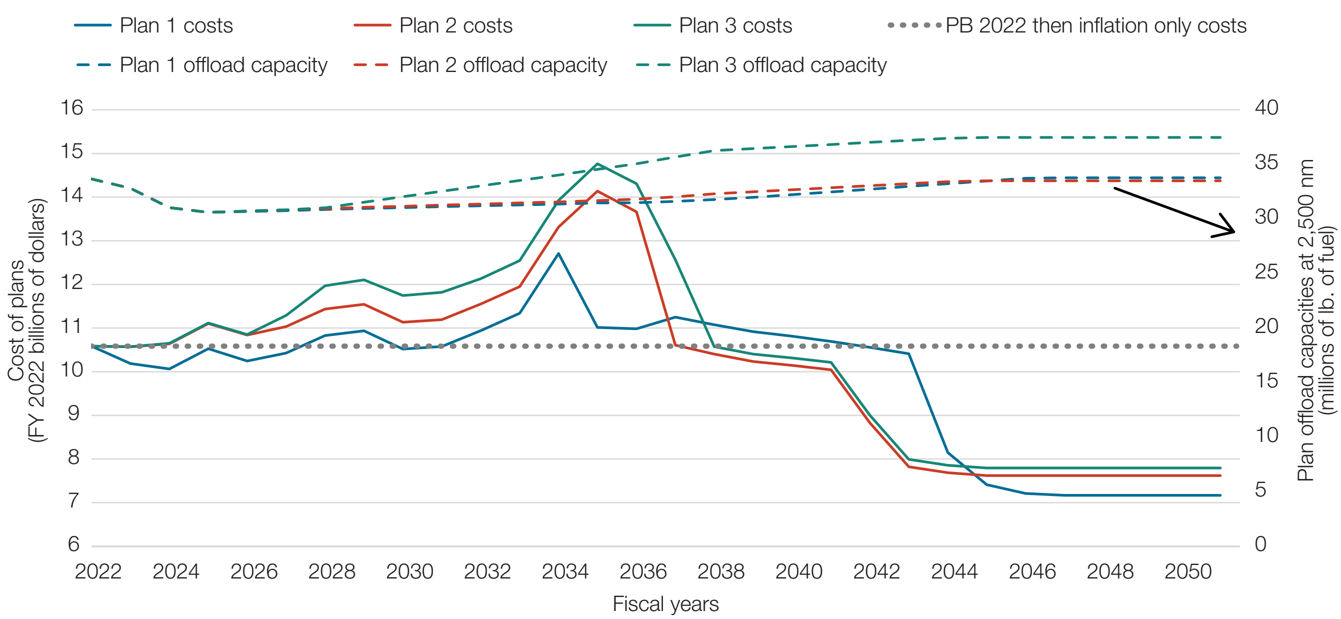
All three plans prioritize funding investments in Indo-Pacific posture and bulk fuel distribution and C3 improvements. In terms of aircraft, the three plans maintain 479 tankers in the fleet from FY 2025 onward, assume that KC-10s are retired by FY 2025, and advance the development of K-Z(M) during the 2020s, resulting in the delivery of the first K-Z(M)s by FY 2035. The three plans differ in their approach to the Bridge Tanker, with the first

Figure 44: Summary of aerial refueling architecture plans



Source: Report authors.

Figure 45: Cost and fleet fuel offload capacity of plans by year



Source: Report authors. Plan costs include estimated tanker aircraft RDT&E, procurement, and O&S costs and additional posture and fuel distribution costs.

buying 75 additional KC-46As, the second 150 KC-46As, and the third 150 LMXTs. Figure 45 depicts total plan costs (in terms of aircraft RDT&E, procurement, and O&S costs and additional posture and fuel distribution investments) and fleet fuel offload capacity at 2,500 nm.

Funding for surface architecture assets such as airfield ramp space, bulk fuel storage, maritime tankers, and fuel over-the-shore delivery systems generally falls under US Air Force military construction or outside of the Air Force budget altogether, and it is frequently under-resourced. To fund necessary investments in the surface architecture, the US Air Force should prioritize these investments upfront, rather than treating them as an afterthought that may possibly be funded depending on competing budget priorities. Starting with the FY 2022 budget, the three plans allocate an average $633 million per year toward posture and bulk fuel distribution investments, in addition to DoD's programmed and planned investments. After the first decade, an average $400 million more per year is spent. The proposed airfield and fuel storage investments listed in Table 1 are sized to support eight groups of 12 KC-46A tankers operating at a high rate and costed using Tinian's expensive Area Construction Cost Index.[159] Construction could be concentrated at one or a few locations, or more widely spread out throughout the Indo-Pacific.

By funding necessary posture and bulk fuel distribution investments, the US Air Force could generate more employable tanker capacity, more tanker offload capacity, more ARCPs to enable distribution and tempo, and more resilient fuel stores. Figure 46 depicts differences in effective capacity between the estimated programmed DoD force and the same force leveraging the enhanced surface architecture proposed by Hudson, with both approaches using KC-46A equivalents.[160] The proposed invest-

Table 1: Posture and bulk fuel distribution investments for FY 2022–2031

INVESTMENTS	TOTAL COST (FY 2022 MILLIONS OF DOLLARS)
8 x 1.6 million ft^2 tanker parking aprons	$767
4 x 9,000 ft runways with parallel taxiways	$388
4 x 220,000 bbl sets of aboveground storage tanks	$437
4 x 220,000 bbl sets of cut-and-cover storage tanks	$1,032
4 x 220,000 bbl sets of hardened underground storage tanks	$1,755
4 x Inland Petroleum Distribution Systems	$94
4 x Offshore Bulk Fuel Transfer Systems	$280
4 x Single Point Mooring Systems	$60
15 x Tanker Security Fleet slots funded for a decade	$1,500
TOTAL	**$6,333**

Source: Report authors.

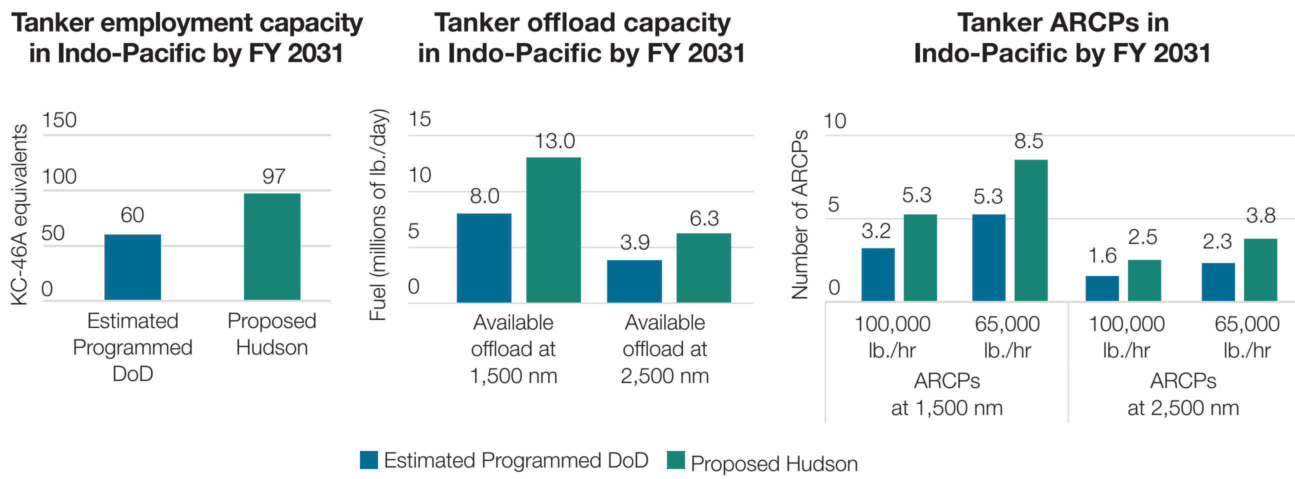
ments would support 63% more tankers in the Indo-Pacific as DoD's programmed force (or alternatively allow greater tanker dispersion) and could approximately double tanker capacity by 2041. This major difference suggests that investments in the surface architecture can greatly impact the capacity, distribution, and optionality of the force in a cost-effective manner.

Funding for these investments could be drawn from additional resources, other elements of the US Air Force budget, or if necessary, by reducing the procurement rate of KC-46A or Bridge Tankers. Even if it comes at the expense of aircraft, improved surface architecture has the net effect of improving the tanker fleet's effective offload capacity. Conversely, given surface architecture deficiencies, additional aircraft investments without improving the surface architecture will yield little marginal benefits apart from creating a larger attrition reserve. Moreover, the Bridge Tanker and K-Z programs are unlikely to deliver aircraft in mass until the early to latter half of the 2030s, respectively. Consequently, near-term investments into the surface architecture, C3, and tanker survivability are the highest value approaches to boost tanker capacity and capability in the 2020s.

In terms of aircraft, as the US Air Force evaluates the KC-46A and LMXT for the Bridge Tanker program, it will need to assess how operational demands and threats will shape aerial refueling demands. Basing may be heavily contested, thus placing a premium on ramp space and requiring a significant portion of tanker sorties to be generated from distant airfields. Given the coming gap in high-capacity, long-range offload tankers generated by the retirement of the KC-10, the US Air Force will need to consider whether the Bridge Tanker should aim to fill that void, cognizant of the fact that the Bridge Tanker will not enter the force in numbers until the 2030s. The Bridge Tanker will also need self-defense measures to enable it to refuel aircraft at the edge of contested areas and may need EMP hardening.

All three plans deliver more offload capacity and can sustain more aerial refueling points than the current force. The plan that acquires LMXT confers 11% more offload capacity at 2,500 nm than the alternative plans and would provide slightly more points that deliver 65,000 lb. and 100,000 lb. of fuel per hour at 2,500 nm, but it would require 8-16% more ramp space. Beyond the nominal performance of the force, however, as shown in Figure 46,

Figure 46: Cost and fleet fuel offload capacity of plans by year



Proposed surface architecture investments would increase effective tanker capacity in the Indo-Pacific by 63% within a decade and approximately double it by 2041. Alternatively, greater airfield capacity could enable a higher degree of tanker dispersion. Please see the section "Shifts in Strategy, Threats, and Demands with Implications for the Aerial Refueling Force: Scenario Assessment," for an explanation of the chart's methodology.

Source: Report authors.

all three plans' investment in the necessary surface architecture would greatly increase their effective capacity in the Indo-Pacific.

Procurement and lifecycle costs will also play an important role in the selection and procurement profile of the Bridge Tanker. If the aerial refueling enterprise is faced with flat budgets, it may need to lower the procurement rate of the Bridge Tanker to make available sufficient funding to also appropriately resource surface architecture improvements, C3 and tanker self-defense capabilities, and K-Z RDT&E. After contract award in FY 2023 or FY 2024, the first Bridge Tankers could be delivered by FY 2028 or FY 2029. Informed by its assessment of the relative demand for high-capacity offload provided by the Bridge Tanker or stand-in tanking capability provided by the potential K-Z program, the US Air Force can set the number of Bridge Tankers procured at a low number (such as 75), a medium number (such as 150), or a high number (such as 200).

To ensure the Bridge Tanker paves the way for K-Z, the US Air Force will need to start K-Z research and development in the 2020s. After initial US Air Force studies and requests for information in FY 2022 and 2023, K-Z research and development could start in FY 2024 and last until FY 2031. Robust research and development funding in this period would allow the maturation of necessary automation technologies, the development of new boom/drogue and self-defense systems applicable to K-Z, KC-46, and KC-135 tankers, and the funding of multiple aerospace contractors to conduct preliminary and then detailed design and prototyping work.

After this methodical approach of technology maturation, design, and prototyping to buy down risk, a single contractor could receive a production award in FY 2032 and could deliver the first two aircraft in FY 2035, with two more aircraft in FY 2036, before gradually scaling up from FY 2037 to FY 2040 to deliver 18-24 K-Z(M)s per year. If the technology necessary to provide the K-Z(M)'s desired performance parameters did not require as much research and development funding or time as conservatively estimated, acquisition of K-Z(M) could take place sooner. By acquiring K-Z(M)s at rates of 18-24 tankers per year, the three plans retire aging KC-135s sooner than anticipated by the US Air Force, which reduces fleet O&S expenditures, and frees up funding for procurement of K-Z(M) or continued improvements to the surface architecture.

In terms of total RDT&E, procurement, O&S, and surface architecture costs, the first plan mostly stays within the funding levels established in the President's Fiscal Year 2022 budget proposal, adjusted for inflation, over the next 30 years—even though (like the other two plans) it spends $14 billion on additional posture and bulk fuel distribution investments. The plans acquiring 150 KC-46A or LMXT Bridge Tankers would cost $7.5 and $17.6 billion more than the first plan, respectively.

A final class of other aircraft considerations involve commercial tanking and international cooperation. The US Navy currently employs commercial KC-135 and KDC-10 tankers operated by Omega Tankers in support of training, testing and evaluation, and coronet fighter movements.[161] Boom-equipped commercial tankers could perform these and other non-combat missions for the US Air Force, and a larger national fleet of government and commercial tankers could help meet the high demand for aerial refueling. For example, of the 6,174 sorties that US Air Force Major Commands requested aerial refueling support to meet training objectives, only half received it.[162]

Directed by Congress in the FY 2020 NDAA, the US Air Force is now evaluating the potential roles and costs of commercial aerial refueling. As KC-10s are retired, one potential option is to lease the tankers to commercial operators, who could carefully extend their lives by employing the tankers on a limited set of missions, such as domestic training and exercises or coronet flights. This approach could not only preserve a core set of KC-10 operators, but also may allow the US Air Force to focus its tanker fleet on preparing for contested operations. Previous analyses of commercial tanking, such as the KC-X Analysis of Alternatives, concluded: "There is no compelling reason for the Air Force to outsource aerial refueling […] commercial sources of aerial refueling would only be *cost-competitive* with organic refueling if their air refueling assets were employed in the commercial market on a part-time basis while the Air Force's are not."[163] Air Mobility Command's ongoing analysis will critically evaluate whether commercial aerial refueling could complement US Air Force tanking in a manner that would not detract O&S funds from the government tanking fleet, perhaps by providing aerial refueling services to not only the US government, but also allied and partner nations.

In terms of international cooperation, the United States should work to deepen international cooperation in terms of ground and overflight access for aerial refueling and other operations. Access to more locations, such as civil airports, would greatly increase tanker capacity in theater and complicate adversary targeting. Current political limitations on tanker access restrict the scale and scope of allied aerial refueling operations in potential conflicts. Accordingly, the US government should collaborate with allies and partners to diversify the range of access to military and civil airfields in countries where the United States already has access (such as Australia, Japan, the Republic of Korea, and the Philippines); deepen the level of access in countries farther from the PRC that could play a critical role (such as Compact of Free Association states, France, India, Indonesia, and New Zealand); and dedicate continued effort to maintain appropriate levels of access and infrastructure at key nodes across the globe that enable intercontinental power projection (such as Lajes Air Base, Portugal). Another crucial area for deepening cooperation is approving the technical compatibility of different tanker-receiver pairs, so that US tankers can refuel the widest range of allied aircraft and vice versa.

The KC-46A and Bridge Tanker programs also provide opportunities to deepen aerial refueling cooperation. The KC-46A is being adopted by Israel and Japan, and other countries are considering it for their fleets.[164] Sixty-one of the alternative A330 MRTT have been ordered by eight countries and organizations.[165] Commonality in aircraft types facilitates cooperation and could allow US forces to use allied maintenance facilities and vice versa.

The deliberate approach proposed for the K-Z program also provides a prime opportunity for cooperation with allies and partners. The K-Z(M) would have an offload capacity well aligned with supporting formations of fighter aircraft or small numbers of large aircraft commonly found in allies and partners.[166] As the K-Z(M) would not rely on exquisite low observable technology, it could be more easily exported. Its low procurement and O&S costs would make it an attractive buy for numerous countries that either do not have an aerial refueling capability or would like to complement or replace existing widebody tankers with less expensive ones.

Charting a Course

The US Air Force's aerial refueling architecture is inadequate to support US strategy and operational concepts, especially against China. The architecture is vulnerable on the ground and in the air and lacks the necessary C3 tools and survivability to support US Air Force and Joint concepts. Deficiencies in the architecture's posture and bulk fuel storage and distribution limit the effective employment of the aerial refueling fleet's full capacity and make the force vulnerable and predictable. The tanker fleet has been repeatedly cut to minimize costs, yet delays in recapitalization have resulted in an aging, increasingly expensive to operate fleet that is strained to its maximum capacity during normal competition phase operations and whose fuel offload capacity is dropping as KC-10s are retired. These challenges frustrate the US ability to sustainably implement at scale new operational concepts that leverage distributed, dynamic operations to gain decision advantage. As China assesses the US air operations operational system, the traditional US strength of aerial refueling could be viewed as a critical weakness that could be exploited and cause the United States to be incapable of sustaining combat against the PRC in defense of US allies and partners.

In response, this study recommends that the US Air Force take a holistic approach to aerial refueling force design that enables the execution of new operational concepts, increases operational performance, and manages costs. The recommendations presented in this study offer a practical approach for fielding a fleet of 479 or more effective tankers. They are derived from the assumptions made by the authors regarding future operating threats and demands and system performance parameters and costs. As the US Air Force considers opportunities, it will need to conduct its own assessments of these areas.

It is clear, however, that there are technically viable and fiscally achievable alternatives to field a resilient aerial refueling architecture. To change, the US Air Force will need to not only embrace new operating concepts, but also commit itself to decisive cross-portfolio trades that appropriately accelerate and fund high-impact investments across the entire aerial refueling enterprise and will generate a resilient aerial refueling force.

APPENDIX A: POTENTIAL PLANS

This study developed and analyzed various 30-year aerial refueling plans. Three potential plans are summarized below to highlight their advantages and disadvantages. All plans maintain 479 tankers in the fleet from FY 2025 onward and assumed that KC-10s are retired by FY 2025.[167]

Plan 1: Truncated Bridge Tanker

Starting with the FY 2022 budget, an average $633 million per year could be allocated toward Indo-Pacific posture and bulk fuel distribution investments, in addition to programmed and planned investments. After a decade, an average $400 million more per year could be spent.

In terms of aircraft, this plan procures 75 additional KC-46s through the Bridge Tanker program, resulting in a fleet of 254 KC-46s. The annual KC-46A procurement rate is kept at a stable 12 tankers per year (rather than oscillating some years to 14 or 15 tankers) from FY 2023 until completion of procurement in FY 2034. By reducing the KC-46A buy rate and keeping a squadron of KC-135s in the force for another decade, the US Air Force can fund investments into the surface architecture and other areas such as C3 and tanker defenses.

The lower KC-46A procurement rate in the 2020s also frees up funds to accelerate the K-Z program. After initial US Air Force studies and requests for information in FY 2022 and 2023, K-Z research and development would start in FY 2024 and last until FY 2031. Robust research and development funding in this period would allow the maturation of necessary automation technologies, the development of new boom/drogue and self-defense systems applicable to K-Z, KC-46, and KC-135 tankers, and the funding of multiple aerospace contractors to conduct preliminary and then detailed design and prototyping work. After this methodical approach of technology maturation, design, and prototyping to buy down risk, a single contractor would receive a production award in FY 2032 and would deliver the first two aircraft in FY 2035 and two more aircraft in FY 2036, before gradually scaling up from FY 2037 to FY 2040 to deliver 24 K-Z(M)s per year, for a total force of 225 K-Z(M)s.[168] If the technology necessary to provide the K-Z(M)'s desired performance parameters did not require as much research and development funding or time as conservatively estimated, acquisition of K-Z(M) could take place sooner.

Plan 2: Buy KC-46A Bridge Tanker

The second plan could make the same investments in posture and bulk fuel distribution as the first plan. In terms of the Bridge Tanker, it procures 150 more KC-46As (for a total fleet of 329 KC-46As) at a rate of mostly 15 per year. This approach would entail few programmatic risks and would increase tanker commonality throughout the fleet. Like the first plan, it would start K-Z research and development in FY 2024 and would procure 150 K-Z(M)s at a rate of largely 18 per year (instead of the 24 in Plan 1).

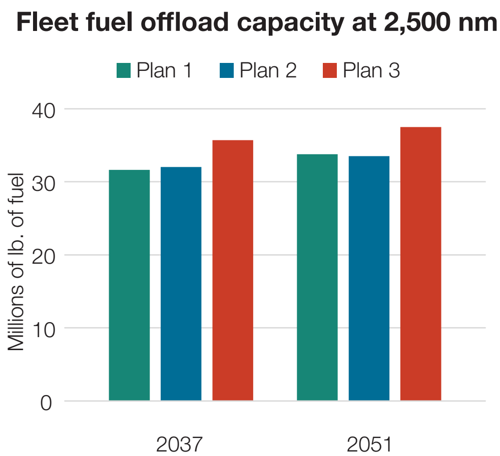
Plan 3: Buy LMXT Bridge Tanker

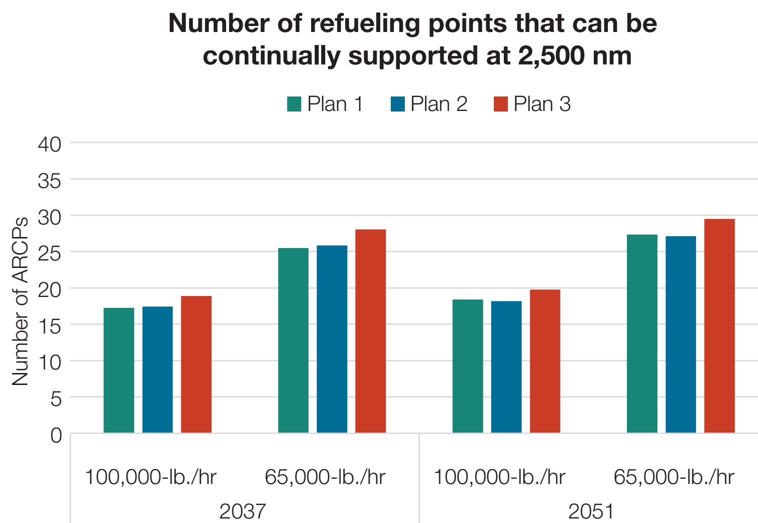
The third plan would make the same investments as Plan 2 in posture and bulk fuel distribution and K-Z(M) development and procurement. However, it would procure 150 LMXTs at a rate of mostly 15 per year for the Bridge Tanker program. If the US Air Force did not levy significant new requirements on the LMXT, such as additional EMP hardening, its development, testing, and evaluation costs would be limited, and the first tankers could be delivered by FY 2029.[169] As the larger, higher-capacity LMXT is more expensive than the KC-46A, if necessary, procurement could take place at a lower rate of 12-13 aircraft per year.

Comparing plans

Plan 3 that incorporates LMXTs provides the most offload capacity. As shown in Figure 47, it would provide a nominal offload capacity at 2,500 nm 11-12% greater than the alternative plans and would provide 8-10% more points that deliver 65,000 lb. and 100,000 lb. of fuel per hour at 2,500 nm (a good measure for booms in the air for fighters and transports/bombers, respectively), but it would require 8-16% more ramp space.

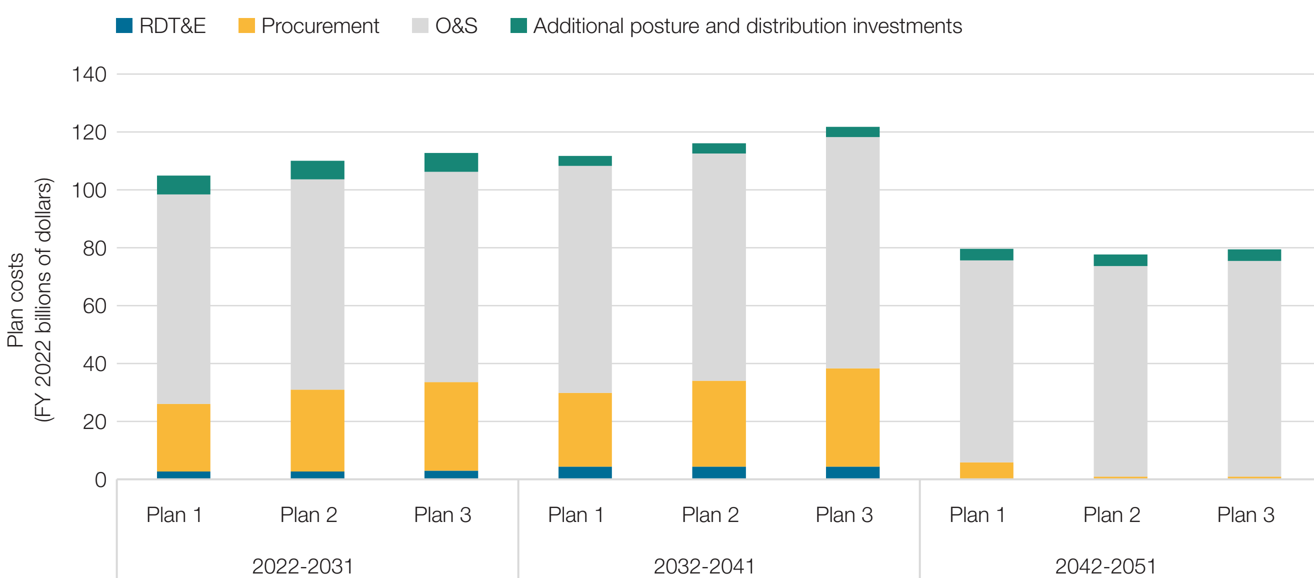
Figure 47: Fuel offload provided and ramp space required for plans





Source: Report authors.

Figure 48: Plan costs by decade



Source: Report authors.

None of the plans prevent a 2020s drop in nominal offload capacity as KC-10s are retired, since Bridge Tankers and K-Z(M)s would not reach the force in mass until the early 2030s and late 2030s, respectively. However, if all three plans made the proposed investments in posture and bulk fuel distribution, employable tanker capacity in the Indo-Pacific could increase by 63% within a decade and approximately double by 2041.

In terms of total RDT&E, procurement, O&S, and surface architecture costs over the next 30 years, Plan 1 mostly stays within the funding levels established in the President's Fiscal Year 2022 budget proposal, adjusted for inflation, over the next 30 years—even though (like the other two plans) it spends $14 billion on additional posture and bulk fuel distribution investments. Plans 2 and 3 would cost $7.5 and $17.6 billion more than the first plan, respectively. Plan 1's costs would peak in FY 2034, the first and final year of K-Z(M) and KC-46A procurement, respectively. Plan 2 and 3's costs would crest from FY 2034-2037, when Bridge Tanker and K-Z(M) procurement would take place concurrently. Figure 48 depicts plan costs by decade.

By the early 2040s, the effects of replacing most KC-135s with new K-Z(M)s in all three plans would be manifest in lower fleet O&S costs. KC-135s are fully retired by FY 2047 in Plan 1 and FY 2044 in Plans 2 and 3. Additionally, the K-Z(M)'s estimated service life of 30 years (rather than the 40 years of existing tankers such as the KC-46A) would support redirecting costs from aircraft sustainment to innovative RDT&E and procurement. The anticipated reduction of total costs during the 2040s would be an opportunity to procure additional K-Z(M)s to support additional demand or create a larger attrition reserve, or to conduct RDT&E of a KC-46A replacement that could be procured in the early 2050s, which would keep tanker fleet age and O&S costs low.

ENDNOTES

1 This figure is exclusive of US Air Force C-130 tanker variants.

2 Stephen R. Lyons, "Statement of the Commander of US Transportation Command Before the Senate Armed Services Committee on the State of the Command", US Transportation Command, February 25, 2020, p. 5.

3 Timothy A. Walton, Ryan Boone, and Harrison Schramm, *Sustaining the Fight: Resilient Maritime Logistics for a New Era* (Washington, DC: Center for Strategic and Budgetary Assessments, 2019), p. 2.

4 "Mobility Capabilities and Requirements Study (MCRS) 2018: Executive Summary," US Transportation Command, February 8, 2019.

5 The study employs the following definition of operational resilience developed by RAND: "Operational resilience: The capacity of a force to withstand attack, adapt, and generate sufficient power to achieve campaign objectives in the face of continued, adaptive enemy action." Jeff Hagen, Forrest E. Morgan, Jacob L. Heim, and Matthew Carroll, *The Foundations of Operational Resilience* (Santa Monica, CA: RAND Corporation, 2016), p. 68.

6 "Mobility Capabilities and Requirements Study (MCRS) 2018: Executive Summary."

7 Two of the total 39 KC-10 and KC-135 tanker squadrons are assigned to the United States Indo-Pacific Command (USINDOPACOM) and the United States European Command (USEUCOM) and are based at Kadena Air Base, Japan, and Royal Air Force Base Mildenhall, United Kingdom.

8 For example, during Operation Iraqi Freedom, US Navy and Marine Corps tankers provided less than 5% of the total fuel offloaded by tankers. Defense Science Board*, Task Force Report on Aerial Refueling Requirements*, US Department of Defense, May 2004, p. iii.

9 David Trunkey, "Operating Costs and Aging of Air Force Aircraft," US Congressional Budget Office, January 23, 2019, slide 18, https://www.cbo.gov/publication/54926.

10 William Knight and Christopher Bolkcom, *Air Force Air Refueling: The KC-X Aircraft Acquisition Program* (Washington, DC: US Congressional Research Service, 2008), p. 17.

11 Lyons, "Statement of the Commander of US Transportation Command," p. 5.

12 Christopher R. MacDonald, *Next Generation Tanker: Optimizing Air Refueling Capabilities in 2030 with a Divested KC-10 Fleet* (Dayton, OH: Air Force Institute of Technology, 2015), p. 12; and William M. (Mac) Thornberry, "National Defense Authorization Act for Fiscal Year 2021: Conference Report to Accompany H.R. 6395," US House of Representatives, December 2020, pp. 72–73.

13 Erin Lasley, "Refueling through the Century," US Air Mobility Command, 2018, https://www.amc.af.mil/About-Us/AMC-History/View/Article/1475424/refueling-through-the-century/.

14 Lasley, "Refueling through the Century."

15 The demand for the KC-10 was also significantly informed by Operation Nickel Grass, in which cargo and aircraft were delivered to Israel during the 1973 Yom Kippur War using Lajes Air Base, Portugal, as an en route airfield. Given basing and overflight restrictions by most European and all Arab nations that forced US Air Force aircraft to take circuitous flight paths and limited effective KC-135 offload capacity, extensive aerial support was necessary. Even then, C-5 and C-141 cargo aircraft were required to make refueling stops at Lajes, which increased delivery times. The KC-10 was envisioned as better capable of supporting long-range, high offload missions in the future than KC-135s. "Global En Route Strategy White Paper," US Air Mobility Command, 2008, p. 12, http://www.au.af.mil/awc/africom/documents/GlobalEnRouteStrategy.pdf; and Margaret Romero, *Algebra of Tankers* (Dayton, OH: Air Force Institute of Technology, 2006), p. 5.

16 John G. Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force*, (Dayton, OH: US Air Force Institute of Technology, 2000), p. 3.

17 Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force* p. 3.

18 Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force*, p. 35.

19 Julia Denman, Walter Ochinko, Trisha Kurtz, Joy Labez, and Howard E. Kapp, *Operation Desert Storm: Aerial Refueling Operational Efficiency* (Washington, DC: US General Accounting Office, 1993), p. 5.

20 Knight and Bolkcom, *Air Force Air Refueling*, p. 3.

21 Rebecca Grant and Loren Thompson, *Modernizing the Aerial Refueling Fleet* (Arlington, VA: Lexington Institute, 2006), p. 2.

22 Knight and Bolkcom, *Air Force Air Refueling*, p. 3.

23 Knight and Bolkcom, *Air Force Air Refueling*, p. 14.

24 James E. Dittus, *The KC-135 with a Multi-Point Refueling System: Increased Capability with Unknown Costs* (Dayton, OH: Air Force Institute of Technology, 2003), p. 7; Stephen Uyehata, *Global Vigilance, Reach, and Power? Made Possible only with a Robust Tanker Capability* (Newport, RI: US Naval War College, 2005), p. 8; and Defense Science Board, *Task Force Report on Aerial Refueling Requirements*, p. 27.

25 Knight and Bolkcom, *Air Force Air Refueling*, p. 3.

26 Karl P. Mueller, Gregory Alegi, Christian F. Anrig, Christopher S. Chivvis, Robert Egnell, Christina Goulter, Camille Grand, Deborah C. Kidwell, Richard O. Mayne, Bruce R. Nardulli, Robert C. Owen, Frederic Wehrey, Leila Mahnad, and Stephen M. Worman, *Precision and Purpose: Airpower in the Libyan Civil War* (Santa Monica, CA: RAND Corporation, 2015), p. 78.

27 Ian Brezinski, "Lesson from Libya: NATO Alliance Remains Rel-

evant," *National Defense Magazine*, November 1, 2011, https://www.nationaldefensemagazine.org/articles/2011/11/1/2011november-lesson-from-libya-nato-alliance-remains-relevant; Mueller et al., *Precision and Purpose*, p. 78; and John A. Tirpak, "Lessons From Libya," *Air Force Magazine*, December 1, 2011, https://www.airforcemag.com/article/1211libya/.

28 Jason R. Greenleaf, "The Air War in Libya," *Air and Space Power Journal*, March-April 2013, p. 32.

29 Mueller et al., *Precision and Purpose*, pp. 89–90.

30 For example, the employment of two B-52 bombers to bomb targets in Iraq from Guam on a highly circuitous flight path during Operation Desert Strike in 1996 required the support of 29 tankers, which equated to 14.5 tankers per bomber. Dittus, *The KC-135 with a Multi-Point Refueling System*, p. 6. As an alternative case study of how bombers can require relatively limited tanker support, in 2020 two B-1B bombers flew roundtrip from Ellsworth Air Force Base, South Dakota, to Orland, Norway, with the support of only two tankers. "Ellsworth AFB B-1s Integrate with Allies, Partners in Nordic Region," US Air Force, May 21, 2021, https://www.af.mil/News/Article-Display/Article/2194060/ellsworth-afb-b-1s-integrate-with-allies-partners-in-nordic-region/. Furthermore, forward basing bombers can greatly reduce tanker demands.

31 An ARCP is a "planned geographic point over which the receiver aircraft arrive in the observation/astern position stabilized behind the assigned tanker." Hiram C. Williamson, *Fueling the Fight: Optimizing Air Refueling Procedures for the KC-135* (Maxwell, AL: Air Command and Staff College, 2018), p. 4. Unless explicitly noted, this report treats ARCPs as interchangeable with tracks and other methods of meeting receiver aircraft.

32 Romero, *Algebra of Tankers*, p. 3; and Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force*, p. 49.

33 Payne, *A Comparative Study of KC-135 Operations in Vietnam, Desert Storm, and Allied Force*, p. 41; Dittus, *The KC-135 with a Multi-Point Refueling System*, p. 7; and Mueller et al., *Precision and Purpose*, pp. 89–90.

34 Directly tasking the ANG or AFRC requires a US Code Title 10 mobilization, so most of their participation in USTRANSCOM missions is voluntary. Additionally, as ANG and AFRC crews often have civilian careers outside of the military, there is a limit to the frequency and duration that crews can be tasked to perform missions outside of war without affecting retention efforts in the force. To help overcome these challenges, the US Air Force is shifting to a Total Force Integration organization in which active duty and reserve aircrew will share the same facilities, and aircraft owned by the two commands will be collocated at the same base. Aaron A. Borszich, *Effects of KC-10 Divestment on Daily Competition Sortie Requirements* (Dayton, OH: Air Force Institute of Technology, 2020), p. 18.

35 Borszich, *Effects of KC-10 Divestment on Daily Competition Sortie Requirements*, p. 17.

36 Mueller et al., *Precision and Purpose*, p. 90.

37 Mueller et al., *Precision and Purpose*, p. 90.

38 Denman et al., *Operation Desert Storm*, p. 6.

39 Reserve tankers include "reliability tankers," or tankers that provide an airborne alert capability; ground alert tankers ready to launch and support receivers, including aircraft that may be sortied from an airfield under attack; and a spare tanker designated to perform a mission if another tanker is unable to do so. Romero, *Algebra of Tankers*, p. 10.

40 Aerial refueling operations in scenarios against the PRC would likely require more extensive reliability or reserve tankers than recent or contemporary operations, as the threats to tankers would likely be higher, operations would deviate from plans more frequently due to adversary action, and there would be fewer divert airfields where aircraft could recover if tanking were not successful. These factors suggest aggregate fuel offload efficiency may decline in a future conflict because of the need for individual tankers and networks of tankers that retain more spare capacity.

41 Joseph R. Biden, Jr., "Interim National Security Strategic Guidance," The White House, March 3, 2021, p. 9.

42 Biden, Jr., "Interim National Security Strategic Guidance," p. 14.

43 Les Aspin, *Report on the Bottom-Up Review* (Washington, DC: Office of the Secretary of Defense, 1993).

44 Department of Defense, *Summary of the 2018 National Defense Strategy of the United States of America: Sharpening the American Military's Competitive Edge* (Washington, DC: DoD, 2018), p. 7.

45 Miranda Priebe, Alan J. Vick, Jacob L. Heim, and Meagan L. Smith, *Distributed Operations in a Contested Environment: Implications for USAF Force Presentation* (Santa Monica, CA: RAND Corporation, 2019), p. ix.

46 The higher-flashpoint JP-5 aviation fuel used in naval aircraft that operate on ships is produced by fewer refineries and stored in fewer locations, which creates greater challenges in distributing it to tankers and receiver aircraft.

47 If aircraft are dispersed at airfields to reduce their density and to force adversaries to target more aimpoints, available ramp space diminishes. In 2021, Lt. Gen. Clint Hinote, the US Air Force's deputy chief of staff for strategy, integration, and requirements, stated that in a 2020 wargame the US Air Force "never filled up any airfield more than 50%." Valerie Insinna, "A US Air Force War Game Shows What the Service Needs to Hold Off—or Win against— China in 2030," *Defense News*, April 12, 2021, https://www.defensenews.com/training-sim/2021/04/12/a-us-air-force-war-game-shows-what-the-service-needs-to-hold-off-or-win-against-china-in-2030/.

48 Priebe et al., *Distributed Operations in a Contested Environment*, p. ix.

49 Darren W. McDew, "Statement Before the House Armed Services Committee, Readiness Subcommittee and the Seapower and Projection Forces Subcommittee," US House of Representatives, March 8, 2018, p. 18.

50 Jeff Engstrom, *Systems Confrontation and System Destruction Warfare* (Santa Monica, CA: RAND Corporation, 2018), pp. i and x.

51 In support of defeating enemy logistics support systems, the PLA has developed the operational guidance theory of Active Strategic Counterattacks on Exterior Lines that describes approaches, including degrading and exploiting logistics and information, to defeat an enemy operating on exterior lines, that is, the United States. Anton Lee Wishik II, "An Anti-Access Approximation: The PLA's Active Strategic Counterattacks on Exterior Lines," *China Security* 19 (2011): 37.

52 Philip S. Davidson, "Statement Before the Senate Armed Services Committee on US Indo-Pacific Command Posture," US Senate, February 12, 2019.

53 Lu Xuanzhan, "China's Y-20 Tanker Variant Spotted Conducting Aerial Refueling for J-20 Fighter Jet," *Global Times*, November 17, 2020. The PLA also employs drogue-equipped H-6U tankers on missions, such as refueling H-6K bombers and J-8D fighter-bombers. Zhang Tao, "H-6U Aerial Refueling Tanker Improves PLA Air Force's Long-range Raid Capability," *China Military Online*, September 8, 2015, english.chinamil.com.cn/news-channels/china-military-news/2015-09/08/content_6671974.htm.

54 John Stillion, *Trends in Air-to-Air Combat: Implications for Future Air Superiority* (Washington, DC: CSBA, 2015), p. 49.

55 Oriana Pawlyk, "Saudi Coalition Down '1 to 2' Tankers of Fuel Daily After US Ends Refueling Mission," *Military.com*, November 21, 2018, https://www.military.com/dodbuzz/2018/11/21/saudi-coalition-down-1-2-tankers-fuel-daily-after-us-ends-refueling-mission.html.

56 Scott D. Adamson and Shane Praiswater, "With Air Bases at Risk, Agile Combat Employment Must Mature," *Defense News*, November 12, 2020, https://www.defensenews.com/opinion/commentary/2020/11/12/air-bases-are-at-risk-without-the-agile-combat-employment-approach/.

57 Priebe et al., *Distributed Operations in a Contested Environment*, pp. viii–ix; and Matthew L. Collins, *Beyond Tanker Adaptive Basing: Alternative Options to Improve United States Indo-Pacific Command's Air Refueling Readiness Posture and Extend Operational Reach* (Newport, RI: US Naval War College, 2019), p. 7.

58 "CNO Visits Navy Warfare Development Command," Navy Warfare Development Command, April 13, 2017, www.navy.mil/submit/display.asp?story_id=99893.

59 Art Corbett, "Expeditionary Advanced Base Operations (EABO) Handbook: Considerations for Force Development and Employment," US Marine Corps Warfighting Lab, June 1, 2018, p. 5, https://mca-marines.org/wp-content/uploads/Expeditionary-Advanced-Base-Operations-EABO-handbook-1.1.pdf.

60 The proportion of short-range fighters in the US Marine Corps aircraft inventory has remained relatively constant.

61 "Air Force Outlines Future of Bomber Force," US Air Force, February 12, 2018, https://www.af.mil/News/Article-Display/Article/1438634/air-force-outlines-future-of-bomber-force/.

62 Thomas Newdick, "Reaper Drone Replacement Requirements Now Include Air-To-Air Combat Capability," *The Warzone*, March 9, 2021, https://www.thedrive.com/the-war-zone/39677/mq-9-reaper-replacement-requirements-now-include-air-to-air-capability-in-contested-airspace.

63 Sam LaGrone, "Navy Releases Final MQ-25 Stingray RFP; General Atomics Bid Revealed," *USNI News*, October 10, 2017, https://news.usni.org/2017/10/10/navy-releases-final-mq-25-stingray-rfp-general-atomics-bid-revealed.

64 "Military and Security Developments Involving the People's Republic of China 2019," US Department of Defense Office of the Secretary of Defense, 2019, p. 45. Additional tankers would be necessary given availability rates.

65 "Navy Official: China Training for 'Short Sharp War' with Japan," *USNI News*, February 18, 2014, https://news.usni.org/2014/02/18/navy-official-china-training-short-sharp-war-japan.

66 Timothy A. Walton, "Securing the Third Offset Strategy: Priorities for the Next Secretary of Defense," *Joint Force Quarterly* 82 (Third Quarter 2016): 8–9.

67 The northern route has the benefit of being significantly shorter, but it is most adversely affected by severe winter weather. The southern route is longer and has a single point of failure in Guam, but generally has better weather. In addition, all en route locations on the southern route are on US territory. Michael J. Lostumbo, Michael J. McNerney, Eric Peltz, Derek Eaton, David R. Frelinger, Victoria A. Greenfield, John Halliday, Patrick Mills, Bruce R. Nardulli, Stacie L. Pettyjohn, Jerry M. Sollinger, and Stephen M. Worman, *Overseas Basing of U.S. Military Forces: An Assessment of Relative Costs and Strategic Benefits* (Santa Monica, CA: RAND, 2013), pp. 44–47; and Stacie L. Pettyjohn and Alan J. Vick, *The Posture Triangle: A New Framework for U.S. Air Force Global Presence* (Santa Monica, CA, RAND Corporation: 2013), pp. 30–33.

68 Christopher Goulait, "Fuel Rebalance," US Defense Logistics Agency, November 10, 2015, https://www.dla.mil/AboutDLA/News/NewsArticleView/Article/630725/fuel-rebalance/.

69 "FY 2020 Military Construction, Defense-Wide," US Defense Logistics Agency, p. 33, https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2020/budget_justification/pdfs/07_Military_Construction/7-Defense_Logistics_Agency.pdf.

70 Walton, Boone, and Schramm, *Sustaining the Fight*, pp. 77–84.

71 For another assessment of sites in the Indo-Pacific that could potentially be used to support aerial refueling, please see: Mark Gunzinger, Carl Rehberg, Jacob Cohn, Timothy A. Walton, and Lukas Autenried, *An Air Force for an Era of Great Power Com-*

petition (Washington, DC: Center for Strategic and Budgetary Assessments, 2019), p. 113.

72 Unless otherwise noted, charts in this report assess offload capacity with one hour on station and two hours of reserve. The capacity to refuel six F-35As enables the tanker(s) to either refuel six F-35As or spend more than an hour loitering and then refuel fewer fighters, such as four F-35As.

73 This estimate ranks airfields by ramp space. If ranked by estimated fuel stores, the elimination of the top three airfields would cause an even greater drop of 74% in available fuel capacity at tanker airfields.

74 The Russian Federation's fielding of advanced conventional threats to aerial refueling aircraft on the ground and in the air poses similar threats to ones anticipated by Douglas Cole in 1989. Douglas Cole, *The Need for a Tactical Aerial Refueling Platform* (Maxwell Air Force Base, AL: Air War College, 1989).

75 Whether Sweden or Finland would grant NATO forces overflight rights or access to basing is an example of an airspace assumption that could greatly alter the vectors that NATO forces could operate from and impact aerial refueling demands. Robert Dalsjö, Christofer Berglund, and Michael Jonsson, *Bursting the Bubble, Russian A2/AD in the Baltic Sea Region: Capabilities, Countermeasures, and Implications* (Stockholm, Sweden: Swedish Defence Research Agency, March 2019), p. 64.

76 Aircraft flying trans-Atlantically from the United States can take the northern route through RAF Stations Mildenhall or Fairford in the United Kingdom, or, if necessary, fly directly to Spangdahlem or Ramstein in Germany. Taking the central route, they can stop in Morón Air Base or Naval Station Rota in Spain or Lajes Air Base, Portugal. A southern route can use Ascension Island, United Kingdom, as an en route airfield.

77 Brian W. Everstine, "NORAD: Advanced Cruise Missile Threat Requires Better Awareness," *Air Force Magazine*, March 16, 2021.

78 Gunzinger et al., *An Air Force for an Era of Great Power Competition*, p. 135; and Defense Science Board*, Task Force Report on Aerial Refueling Requirements*, p. 28.

79 The US Air Force's current VC-25A "Air Force One" aircraft are capable of aerial refueling. The replacement VC-25Bs are not planned to have an aerial refueling capability. Joseph Trevithick, "New Air Force One Jets To Have 1,200 Nautical Miles Less Range Than Originally Required," *The War Zone*, June 20, 2019, https://www.thedrive.com/the-war-zone/28443/new-air-force-one-jets-to-have-1200-nautical-miles-less-range-than-originally-required. Nonetheless, the future presidential support and continuity of government mission will still require extensive aerial refueling to support other specialized aircraft that support this mission, such as E-4B and E-6B aircraft, as well as C-17 transports that move presidential cargo.

80 McDew, "Statement Before the House Armed Services Committee, Readiness Subcommittee and the Seapower and Projection Forces Subcommittee."

81 Defeat a regional adversary estimate is drawn from Gregory D. Knepper, *Access Assured: Addressing Air Power Reach, Persistence and Fueling Limitations for Contested and Permissive Air Operations* (Washington, DC: Brookings Institute, 2014), p. 15. The Defense Science Board found that homeland defense could require "up to 122 KC-135 equivalent tankers ... depending on the number of patrol aircraft aloft." Defense Science Board*, Task Force Report on Aerial Refueling Requirements*, p. 28.

82 "Mobility Capabilities and Requirements Study (MCRS) 2018: Executive Summary," US Transportation Command, p. 1. For comparison, MCRS 2016 concluded that a fleet of 567 KC-10s and KC-135Rs and 79 KC-130s (or 20% larger than the available force) were necessary to meet demands in the most stressing case. MacDonald, *Next Generation Tanker*, p. 14.

83 For comparison, in *An Air Force for an Era of Great Power Competition*, the authors concluded that a conflict against the PRC would require the support of 280 tankers, and a conflict against Russia would require the support of 183 tankers. Gunzinger et al., *An Air Force for an Era of Great Power Competition*, p. 120.

84 Walton, Boone, and Schramm, *Sustaining the Fight*, pp. 29–32.

85 Courtney Albion, "Mobility Capability Study Delayed from January to Mid-spring," *Inside Defense*, October 27, 2020, https://insidedefense.com/insider/mobility-capability-study-delayed-january-mid-spring.

86 "Tinian Divert Infrastructure Improvements," US Department of the Air Force, http://pacafdivertmarianaseis.com/.

87 For a review of arguments that tankers "should be operated from bases out of the range of China's conventional ballistic missiles," please see Robert C. Owen, *Basing Strategies for Air Refueling Forces in Antiaccess/Area-Denial Environments* (Dayton, OH: Air Force Research Institute, 2015), pp. 3–4.

88 For information on the "Royal Road," please see Edward S. Miller, *War Plan Orange: The U.S. Strategy to Defeat Japan, 1897-1945* (Annapolis, MD: Naval Institute Press, 1991).

89 The US Air Force's bomber fleet has started to conduct training flights flying from Hawaii and Wake Island that experiment with this concept. Danielle Quilla, "First Hawaii Deployment Proves B-2 Strategic Flexibility to Ensure Free, Open Indo-Pacific," October 4, 2018, https://www.af.mil/News/Article-Display/Article/1654080/first-hawaii-deployment-proves-b-2-strategic-flexibility-to-ensure-free-open-in/.

90 Heather Salazar, "B-2 Spirit Integrates with NATO Ally at Lajes Field," US Air Force, March 25, 2021, https://www.af.mil/News/Article-Display/Article/2547730/b-2-spirit-integrates-with-nato-ally-at-lajes-field/.

91 This sentence estimates the fuel burned by a detachment of 18 tankers offloading their maximum amount of fuel at 1,500 nm, continuously. It includes fuel offloaded to receivers and burned by the tankers. Eighteen tankers could operate from the site, but a maximum of 12 could be sustained on the ground.

For information on the Tinian Divert Site construction project, please see: “Military Construction Program FY 2021 Budget Estimates,” US Department of the Air Force, February 2020, pp. 69–86, https://www.saffm.hq.af.mil/Portals/84/documents/FY21/MILCON_/FY21%20Air%20Force%20MILCON_1.pdf?ver=2020-02-10-091213-253.

92 For example, an amphibious assault bulk fuel system could link a maritime tanker with the tactical airfield fuel dispensing system to fuel tankers at airfields that required fuel. “Tactical Airfield Fuel Dispensing System (TAFDS),” US Marine Corps Systems Command, http://www.marcorsyscom.marines.mil/Portals/105/pdmeps/docs/FUEL/B0675.pdf; and “Amphibious Assault Fuel System (AAFS),” US Marine Corps Systems Command, http://www.marcorsyscom.marines.mil/Portals/105/pdmeps/docs/FUEL/B0685.pdf.

93 Charles Q. Brown, Jr., Bradley D. Spacy, and Charles G. Glover III, “Untethered Operations: Rapid Mobility and Forward Basing Are Keys to Airpower’s Success in the Antiaccess/Area-Denial Environment,” *Air and Space Power Journal*, May-June 2015, p. 20.

94 The MV-22 Osprey can carry about 12,000 pounds of fuel. David Vergun, “Aerial Refueling Adds Lethality to DOD Aviation,” US Department of Defense, February 21, 2020, https://www.defense.gov/Explore/Features/Story/Article/2089889/aerial-refueling-adds-lethality-to-dod-aviation.

95 The C-17 could offload fuel using either an R-11 Refueling Vehicle or an Aerial Bulk Fuel Delivery System, both of which could be internally transported. Kelley J. Stewart, “C-130J Refuels F-22s Using Aerial Bulk Fuel Delivery System,” Hill Air Force Base, December 3, 2020, https://www.hill.af.mil/News/Article-Display/Article/2434192/c-130j-refuels-f-22s-using-aerial-bulk-fuel-delivery-system/.

96 John Stillion, “Fighting Under Missile Attack,” *Air Force Magazine*, August 1, 2009, https://www.airforcemag.com/article/0809fighting/.

97 Low-cost shelters for tankers could not only conceal aircraft, but also reduce corrosion rates. Defense Science Board, *Report on Aerial Refueling Requirements*, pp. v–vi. For a discussion of large shelters that could protect tanker aircraft, please see: Stillion, “Fighting Under Missile Attack,” and Owen, *Basing Strategies for Air Refueling Forces in Antiaccess/Area-Denial Environments*, p. 5.

98 Jim Inhofe and Jack Reed, “The Pacific Deterrence Initiative—Peace through Strength in the Indo-Pacific,” *War on the Rocks*, May 28, 2020, https://warontherocks.com/2020/05/the-pacific-deterrence-initiative-peace-through-strength-in-the-indo-pacific/.

99 Corrie Poland, “The Air Force Is Becoming More Agile—One Project at a Time,” US Air Force Operational Energy, April 24, 2019, https://www.safie.hq.af.mil/News/Article-Display/Article/1823169/the-air-force-is-becoming-more-agile-one-project-at-a-time/.

100 Other aerial refueling tools that have been developed include the Air Refueling Control Model, Theatre Battle Management Core System, Tanker Assignment Tool, Tanker Employment Tool, and the Air Refueling Control Model. Borszich, *Effects of KC-10 Divestment on Daily Competition Sortie Requirements*, p. 15.

101 Lara Seligman, “Refueling over Afghanistan? There’s an App for That,” *Aviation Week & Space Technology*, November 30, 2017.

102 Data are drawn from Borszich, *Effects of KC-10 Divestment on Daily Competition Sortie Requirements*, p. 35. Borszich analyzed data from 2011 to 2019.

103 Bryan Clark, Dan Patt, and Timothy A. Walton, *Implementing Decision-Centric Warfare: Elevating Command and Control to Gain an Optionality Advantage* (Washington, DC: Hudson Institute, 2021), p. 7.

104 Examples of relevant DARPA programs include Resilient Synchronized Planning and Assessment for the Contested Environment (RSPACE), Adapting Cross-Domain Kill Chains (ACK), and Complex Adaptive System Composition And Design Environment (CASCADE). DARPA, “Resilient Synchronized Planning and Assessment for the Contested Environment (RSPACE),” DARPA.mil, https://www.darpa.mil/program/resilient-synchronized-planning-and-assessment-for-the-contested-environment; DARPA, “Adapting Cross-Domain Kill Chains (ACK),” DARPA.mil, https://www.darpa.mil/program/adapting-cross-domain-kill-webs; and DARPA, “Complex Adaptive System Composition And Design Environment (CASCADE),” DARPA.mil, https://www.darpa.mil/program/complex-adaptive-system-composition-and-design-environment.

105 Andrew Eversden, “Air Force’s Air Mobility Command Successfully Tests New Tactical Data Link,” *C4ISRNet*, July 2, 2020, https://www.c4isrnet.com/c2-comms/2020/07/02/air-forces-air-mobility-command-successfully-tests-new-tactical-data-link/.

106 For discussion of recent trials involving these capabilities, please see Thomas Newdick, “KC-135 Tanker Tested with Loyal Wingman Drone,” *The Warzone*, April 12, 2021, https://www.thedrive.com/the-war-zone/40136/kc-135-tanker-tested-with-loyal-wingman-drone-as-part-of-major-defensive-upgrade.

107 Fessler, *Aerial Refueling in Southeast Asia*, p. 25.

108 Theresa Hitchens, “First ABMS Buy: KC-46 Pods to Link F-22, F-35,” Breaking Defense, June 25, 2021, https://breakingdefense.com/2021/06/first-abms-buy-kc-46-pods-to-link-f-22-f-35/.

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110 Rachel Cohen, “Boeing: KC-46 Tanker Can Survive EMP Blast,” *Inside Defense*, July 28, 2017.

111 “A330 MRTT,” Airbus, https://www.airbus.com/defence/a330mrtt.html.

112 Andrew K. Petry, *Effectiveness Based Design of a Tactical Tanker Aircraft* (Dayton, OH: Air Force Institute of Technology, 2016), p. iv; and Gunzinger et al., *An Air Force for an Era of Great Power Competition*, pp. 168–169.

113 Joseph Trevithick, “Lockheed Martin Is Crafting New Stealth and Drone Tanker Concepts for the USAF,” *The War Zone*, September 20, 2018, https://www.thedrive.com/the-war-zone/23723/lockheed-martin-is-crafting-new-stealth-and-drone-tanker-concepts-for-the-usaf.

114 The ability of tankers to transport dry cargo and personnel enables the efficient use of limited ramp space for dual purposes and provides additional cargo and personnel capacity to the air mobility fleet. However, the addition of cargo bay volume imposes a significant weight and drag penalty to tanker designs. This study concludes that, through specialization in the force, large KC-46A or LMXT tankers could support the transport of dry cargo and personnel, while the K-Z would fully focus on aerial refueling.

115 Previous analyses, such as the KC-X Analysis of Alternatives, concluded that new-design tankers were not cost-effective with commercial-derivative tankers, as the effectiveness of a specialized design did not offset their higher research and development costs and higher production costs. Michael Kennedy, Laura H. Baldwin, Michael Boito, Katherine M. Calef, James S. Chow, Joan Cornuet, Mel Eisman, Chris Fitzmartin, Jean R. Gebman, Elham Ghashghai, Jeff Hagen, Thomas Hamilton, Gregory G. Hildebrandt, Yool Kim, Robert S. Leonard, Rosalind Lewis, Elvira Loredo, Daniel M. Norton, David T. Orletsky, Harold Scott Perdue, Raymond A. Pyles, Timothy L. Ramey, Charles Robert Roll, Jr., William Stanley, John Stillion, Fred Timson, and John Tonkinson, *Analysis of Alternatives (AoA) for KC-135 Recapitalization: Executive Summary* (Santa Monica, CA: RAND Corporation, 2006), p. 1. This Hudson study concludes that a new, dedicated-tanker K-Z design could be cost-effective in terms of RDT&E and production costs and in terms of total lifecycle costs.

116 This cost estimate assumes a cost per pound of $1,164.28 on a 95,000-pound empty weight aircraft. The K-Z(M)’s cost per pound is 25% more than the KC-46A’s cost per pound of $931.42. The additional cost per pound stems from the incorporation of robust defensive countermeasures, automation systems, and platform shaping.

117 For comparison, the turboprop KC-130J has a fuel capacity with external tanks of 61,364 lb. When an additional internal fuselage fuel tank is added, the KC-130J can have a maximum fuel capacity of 85,756 lb., which is approximately equal in capacity to the K-Z(S) concept. “KC-130J Tanker,” Lockheed Martin, https://www.lockheedmartin.com/en-us/products/c130/kc-130j-tanker.html.

118 Receiver aircraft are assumed to onload 60% of their fuel capacities.

119 Airfield suitability was derived using airfield lengths, widths, Aircraft Classification Number/Pavement Classification Number (PCN) calculations, and recorded operations by the aircraft type. LMXT and KC-46A performance characteristics were derived from consultations with the contractors and from Airbus and Boeing aircraft characteristics manuals. KC-135 and KC-10 characteristics were drawn from *Air Force Pamphlet 10-1403* and the United Kingdom Ministry of Defence *Guide to Airfield Pavement Design and Evaluation*. K-Z(M) and K-Z(S) performance (using B720B and B737-200C aircraft as surrogates) was also derived from the *Guide to Airfield Pavement Design and Evaluation*. Runways with widths of at least 100 ft were deemed acceptable. Compared to the K-Z(S), the K-Z(M) uses a more robust, heavier landing gear design to enhance performance on lower PCN airfields or rough surfaces.

120 For reference, the KC-130J and A400M can operate at full gross weight from sea-level runways of 4,000 to 5,000 ft in length. Moreover, they can be towed across and taxi or park on unpaved surfaces equivalent to saturated clay soils. Owen, *Basing Strategies for Air Refueling Forces in Anti-access/Area-Denial Environments*, p. 10.

121 “Global 6000,” Bombardier, https://businessaircraft.bombardier.com/sites/default/files/2020-11/Global6000_SN%209695.pdf.

122 As apron space at some airfields is noncontiguously divided into areas sized for current tankers, further analysis should critically examine whether smaller designs could leverage their size to fit more tankers at an airfield, especially when aircraft are tactically dispersed.

123 This assessment takes the available ramp space at the 11 airfields and divides it in half to account for other aircraft needing to operate from the same airfields. Of the available ramp space, tankers on the ground only use a quarter of it in order to maintain tactical dispersion. After accounting for aircraft suitability to operate from the airfields based on runway length and firmness when tankers are operating at full loads, all aircraft deliver their maximum offloads at 1,500 nm and 2,500, remaining an hour on station and retaining two hours of reserves in the air. The model accounts for a 70% operational availability for all tankers and the time it takes to turn and launch tankers on the ground. The ability of the K-Z(M) to access all 11 airfields also contributes to its higher performance.

124 Fuel fraction is the percentage of an aircraft’s gross weight that is fuel.

125 Petry, *Effectiveness Based Design of a Tactical Tanker Aircraft*, p. 71.

126 For example, thanks to its fuel capacity and efficiency, at 1,500 nm the K-Z(M) would have sufficient spare offload capacity that it could remain on station for more than two additional hours and still have enough fuel to refuel six F-35As in a one-hour period and maintain two hours of fuel reserve.

127 Tankers’ ability to receive prompt early warning of enemy threats greatly impacts their survivability.

128 Michael Kennedy et al., *Analysis of Alternatives (AoA) for KC-135 Recapitalization: Executive Summary*, p. 13.

129 Development costs are based on consultations with aerospace contractors. Procurement costs assume an aircraft cost per pound thrice that of the KC-46A in a 95,000 lb. empty weight aircraft, which is the same weight as the proposed K-Z(M) design.

130 Shaping generally plays a larger role than size in affecting RCS levels. Size plays a large role in infrared signatures.

131 The figure assesses the performance of a wing of 72 F-35As deployed to Guam providing a continuous CAP over Taipei, Taiwan, with different types of tanking support. If KC-46A tankers supporting the F-35A were forced to stand back 800 nm from the PRC to avoid sweeps by PLA fighters such as the J-20, then only 4 of the 72 fighters could be continually maintained on station with the support of 23 tankers. Escorted KC-46As could operate slightly closer to the fighter CAPs, increasing by two the F-35As at the CAP and slightly reducing tanking demands. The use of K-Z(M) tankers capable of standing-in 200 nm through a mix of modest signature reduction and softkill and hardkill defensive systems would triple the number of F-35As that could be maintained on station and have a tanker procurement cost of $1.5 billion less compared to KC-46As operating from standoff. Additionally, even though the stand-in K-Z(M) tankers would be operating at the same distance as KC-46As with 2 F-35A escorts each, the ability to operate without escorts would double the number of F-35As that could operate forward. Lastly, the use of a very low observable K-Z(M) capable of offloading fuel 150 nm from the CAP would provide a 33% increase in F-35As on station compared to the stand-in K-Z(M), yet would require more tankers and would cost an additional $5.6 billion.

132 The escorted KC-46A is also problematic for other reasons. First, the two escorting F-35As would consume a considerable amount of fuel that could not be offloaded to the supported CAP (see Figure 43). Second, the escorting F-35As would be drawn from the wing's F-35As, thus reducing the combat potential at the supported CAP. Third, two F-35As may face challenges mounting a robust, multi-axial defense, in part because their sensors would face challenges comprehensively covering all quadrants at the same time while maintaining a sufficient standoff distance from KC-46A to allow the KC-46A to retrograde upon detection of enemy forces to stay outside the weapon engagement zones of super-cruising fighters armed with long-range AAMs, but also because large enemy sweep packages could likely defeat the outnumbered F-35As. As tankers are unlikely to be fast enough to outrun incoming attacks even with a moderate standoff, this insight suggests that tankers should have onboard defenses to increase the salvo size that enemy fighters would need to fire to overcome their defenses, and that tanker losses are to be expected. In response, operational refueling designs should be resilient, such as by having redundant tankers capable of stepping into tanker slots to support receiver aircraft when primary tankers are damaged or destroyed. Additionally, new DCA approaches that leverage long endurance unmanned aircraft should be pursued.

133 David Szondy, "Airbus Achieves First Large-aircraft Autonomous Aerial Refueling," *New Atlas*, July 15, 2019, https://newatlas.com/airbus-raaf-large-aircraft-refueling/55463/; and Didier Plantecoste, "A330 MRTT Briefing," Airbus, November 6, 2019.

134 Valerie Insinna, "Boeing's KC-46 Tanker Now Has a Pathway for Autonomous Aerial Refueling," *Defense News*, April 8, 2020, https://www.defensenews.com/air/2020/04/08/boeings-kc-46-tanker-now-has-a-pathway-for-autonomous-aerial-refueling/.

135 The weight associated with a crew member, cockpit, and ejection seat on a fighter-sized aircraft is approximately 1,000 lb. Additional weight savings could be generated by removing all associated human interfaces. Knepper, *Access Assured*, p. 20. In total, these weights could sum up to a few thousand pounds in a tanker, which would be significant but not extraordinary for an envisioned K-Z(M) 95,000 lb. empty weight aircraft with a base fuel capacity of 140,000 lb. A greater benefit could be the enhanced reliability of the unmanned aircraft by having fewer human-associated subsystems that could fail.

136 The US Air Force is suffering from a significant shortage in experienced tanker maintenance personnel, which would likely impede efforts to distribute tanker basing. Collins, *Beyond Tanker Adaptive Basing*, p. 10.

137 Trevithick, "Lockheed Martin Is Crafting New Stealth and Drone Tanker Concepts for the USAF."

138 This would include receiver aircraft with relatively low amounts of thrust, such as future UAS.

139 The addition of a modern, high throughput multi-point refueling system that could support different receiver types and aircraft could increase theater-wide refueling efficiency by 10-18%, both by accelerating refueling and by reducing the need for redundant aircraft to provide booms or drogues if the primary aircraft's single boom or drogue were not working properly. Dittus, *The KC-135 with a Multi-Point Refueling System*, pp. ix, 3. A final benefit is that new refueling technologies could possibly be more easily integrated onto a wider variety of aircraft, including commercial airliners.

140 For an example of a hybrid boom/drogue, please see Joshua M. Kusnitz, "Aerial Refueling System and Method," Boeing Company, Patent Number US 9.227,735 B2, January 5, 2016.

141 The K-Z(M) costs 25% more in terms of cost per pound than the KC-46A, with half of its cost difference stemming from advanced shaping and other signature management best practices and the other half devoted to C3 and defensive systems costing $11 million for each aircraft.

142 "Bridge Tanker (KC-Y)", US Air Force Mobility Command, July 19, 2021, https://sam.gov/opp/73fc3aa842c04fbc9f7d-1542f51e3e48/view.

143 Diana Maurer, *Aircraft Mission Capable Rates Generally Did Not Meet Goals and Cost of Sustaining Selected Weapon Systems Varied Widely* (Washington, DC: US Government Accountability Office, 2020), p. 43. Moreover, the KC-135R's cost per flying hour has exhibited a 3% annual real growth. Trunkey, "Operating Costs and Aging of Air Force Aircraft."

144 From FY 2011–2019, in only three years did KC-10 and KC-135 fleets meet their annual mission capable rate goals. New approaches are needed to boost the readiness and availability of the tanker fleet. Maurer, *Aircraft Mission Capable Rates Generally Did Not Meet Goals and Cost of Sustaining Selected Weapon Systems Varied Widely*, p. 41. The Defense Logistics Agency has

adopted a new approach to use Federal Aviation Administration–certified parts on KC-46A tankers. Cathy Hopkins, "DLA Aviation Parts Support Ensures Tankers Available for Aerial Refueling Mission," US Defense Logistics Agency, May 6, 2019, https://www.dla.mil/AboutDLA/News/NewsArticleView/Article/1834397/dla-aviation-parts-support-ensures-tankers-available-for-aerial-refueling-missi/.

145 The LMXT has an empty weight 30% heavier than the KC-46A, and it burns approximately 21% more fuel per hour than the KC-46A. The LMXT Unit Operations cost is estimated to be 30% more than the KC-46A. This estimate is consistent with the proportional O&S cost difference between the KC-10 and KC-135.

146 There are 1,070 personnel in a 12-tanker KC-46A squadron. This assessment recognizes that there are 3 crews per aircraft and 3 persons per crew, and assumes that two-thirds of aircraft flying crew slots on unmanned or optionally manned K-Z aircraft could be eliminated. The remaining third of flying crew personnel would be responsible for C2 of the aircraft (either on the ground or onboard the aircraft in the air if the aircraft were optionally manned) and staff work. In total, a K-Z squadron could have about 998 personnel, perhaps fewer if there is less maintenance required for smaller aircraft compared to the KC-46A. In total, a K-Z squadron is conservatively estimated to require 93% as many personnel as a KC-46A squadron.

147 The K-Z(M) and K-Z(S) weigh 46% and 34% of the operating empty weight of the KC-46A, respectively, and their average fuel burns are estimated to be 40% and 36% of the KC-46A, respectively.

148 Analysis of the 2011 to 2019 data from Borszich, *Effects of KC-10 Divestment on Daily Competition Sortie Requirements*, p. 35. The K-Z(M)'s ability to meet the requirements of missions requiring small offloads has not been parametrically modeled as done by Borszich in comparing KC-10 and KC-46A missions.

149 In contrast, the KC-10 is only 16% larger than the KC-46A but provides 48% more fuel at 2,500 nm.

150 For example, E-4B Advanced Airborne Command Post aircraft normally require the onload of approximately 150,000 lb. of fuel (or 40% of their fuel capacity). Two KC-10s normally conduct this mission, one providing offload and the other serving as an alternate. If the onload took place at a radius for the tanker of 1,000 nm or more, then two KC-46As may be required to provide the fuel offload and one or two additional tankers to serve as alternates. One LMXT could provide the entire 150,000 lb. of offload at 1,000 nm, and another LMXT could serve as an alternate.

151 If the LMXT were employed in a manner that reduced the number of sorties necessary compared to the KC-46A, then it could be more cost-effective. For a review of cost arguments favoring the KC-46 and A330 MRTT during the previous KC-X competition, please see: Alexandre Vautravers, "Fighting for Oil in the Skies? The Case of the KC-X Programme," *Journal of Transatlantic Studies* 13, no. 3 (2015): 282.

152 The application of UAS to support the DCA mission would also free up manned fighters for other missions. Another benefit of unmanned escorts is that the protected tanker could retrograde upon detection of enemy forces and allow the escorts to incur a higher risk of fuel exhaustion than would be possible with manned escorts. In some cases, the tanker may need to hold its position to support other receiver aircraft. However, by adopting new C2 tools that could dynamically reposition tankers, it may be possible to have one tanker retrograde while a reserve tanker is surged forward to meet receivers once the threat has diminished or been eliminated and before the receiver aircraft suffer fuel exhaustion.

153 Fighters can receive fuel at rates of around 2,000 lb. per minute or less, while large aircraft can do so at around 8,000 lb. per minute. Faster fighter onload rates would decrease the amount of time each individual aircraft needs to spend on a boom or drogue and, in turn, allow more aircraft to receive aerial refueling and for tankers to spend less time in this sensitive condition in which they are more susceptible to attack. Grant and Thompson, *Modernizing the Aerial Refueling Fleet*, p. 10.

154 "Future Initiatives," U.S. Air Force, https://www.safie.hq.af.mil/OpEnergy/Future-Initiatives/.

155 Valerie Insinna, "'Too Early to Say' When B-52 Engine Contract will Be Awarded," *Defense News*, February 25, 2021, https://www.defensenews.com/smr/air-force-priorities/2021/02/25/to-early-to-say-when-b-52-engine-contract-will-be-awarded-air-force-general-says/. The program may also be valuable for counteracting the additional drag caused by B-52s operating with external missiles. A 1985 US Congressional Budget Office study asserted that the use of external cruise missiles on B-52 bombers increased average tanker requirements by 34% for each bomber affected. Bonita J. Dombey, "Modernizing the Aerial Tanker Fleet: Prospects for Capacity, Timing, and Cost," Congressional Budget Office, September 1985, p. 6.

156 Charles Q. Brown Jr., "Accelerate Change or Lose," US Air Force, August 2020, p. 3, www.af.mil/Portals/1/documents/csaf/CSAF_22/CSAF_22_Strategic_Approach_Accelerate_Change_or_Lose_31_Aug_2020.pdf.

157 Mackenzie Eaglen and Hallie Coyne, *The 2020s Tri-Service Modernization Crunch* (Washington, DC: American Enterprise Institute, 2021), pp. 46–53.

158 The 2030s would also feature major US Air Force recapitalization programs that would restrict available budgets, such as B-21, NGAD, and GBSD procurement and potential RDT&E for a C-130 or C-17 replacement.

159 Each 1.6 million ft^2 parking apron is sized to support a squadron of 12 KC-46As and includes hydrant piping and related components to support 12 fuel valve pits. Each set of fuel storage tanks with a capacity of 220,000 bbl consists of one 100,000 bbl tank and two 60,000 bbl tanks. 220,000 bbl is greater than the fuel burned by 12 KC-46As providing 100,000 lb./hr offload at 1,500 nm over 14 days (205,585 bbl). Military construction costs are estimated from US Air Force FY 2021 budget estimates. ("Military Construction Program FY 2021 Budget Estimates", US Department of the Air Force.) Military construction costs are estimated using Tinian's Area Construction Cost Index of 2.64.

For comparison Eielson Air Force Base, Alaska has one of 2.37; Tindal, Australia one of 1.55; and Manchester, Washington one of 1.11. Bulk fuel distribution system costs are drawn from Walton, Boone, and Schramm, *Sustaining the Fight*, pp. 81-84.

160 These charts assume the restrictive laydown depicted in Figure 17 and that the proposed ramp space would be devoted to tankers.

161 Joseph Trevithick, "Retired Singaporean KC-135R Tankers Look Set To Join U.S. Private Aerial Refueling Market", *The War Zone*, September 29, 2020, https://www.thedrive.com/the-war-zone/36795/retired-singaporean-kc-135r-tankers-look-set-to-join-u-s-private-aerial-refueling-market.

162 Barbara Barrett, *Fiscal Year 2020 National Defense Authorization Act Report to Congress on Contractor-Operated Aerial Refueling Aircraft*, US Air Force, April 22, 2020, pp. 10-11.

163 Michael Kennedy, et al., *Analysis of Alternatives (AoA) for KC-135 Recapitalization: Executive Summary*, p. 13.

164 Mike Yeo, "UAE issues formal request to buy KC-46A tanker, says Boeing", *Defense News*, May 31, 2019, https://www.defensenews.com/global/mideast-africa/2019/05/31/uae-issues-formal-request-to-buy-kc-46a-tanker-says-boeing/.)

165 "A330 MRTT", Airbus, https://www.airbus.com/defence/a330m-rtt.html.

166 In 2006, Israel Aerospace Industries and Gulfstream partnered to develop a conceptual tactical tanker based on the G550 business jet capable of carrying 55,000 lb. of fuel. (Petry, *Effectiveness Based Design of a Tactical Tanker Aircraft*, p. 25.)

167 If the number of Total Aircraft Inventory tankers necessary to meet the MCRS tanker requirement were higher than 479, the three plans presented would need to incorporate additional tankers. Furthermore, the planned retirement of the KC-10 will cause a significant near-term reduction in aerial refueling capacity. Given the decision in the FY 2021 NDAA to allow the start of KC-10 retirements, this study assumed the retirements will continue. The US Air Force, USTRANSCOM, and Congress will need to carefully assess tanker capacity during this transitional period and if necessary take steps to retain KC-10 capacity. (*William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021: Conference Report to Accompany H.R. 6395*, pp. 72-73.)

168 Although the production of 24 K-Z(M)s per year is significant, in terms of aircraft pounds produced, it weighs approximately 25% less than the 15 KC-46As that have been manufactured by Boeing some years.

169 This study estimated an RDT&E cost for the LMXT of $275 million, which is equivalent in FY 2022 dollars to the cost of RDT&E expenditures for the non-developmental C-27J acquired by DoD in 2007. (Michael J. Sullivan, *Defense Acquisitions: Assessments of Selected Weapon Programs* (Washington, DC: US Government Accountability Office, March 2008), pp. 99-100.) If the LMXT needed modifications to meet the same EMP hardening or other requirements on the KC-46A, its RDT&E costs would likely increase. Incorporating EMP protection to a new aircraft adds less than 1% to the present value of its lifecycle costs but adding it to used aircraft raises costs by 10%. (Kennedy, et al., *Analysis of Alternatives (AoA) for KC-135 Recapitalization: Executive Summary*, p. 12.)

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