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# Assessing the Cost-Effectiveness of Modernizing the KC-10 to Meet Global Air Traffic Management Mandates

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# Preface

The KC-10 "Extender" air refueling aircraft has been in operation with the U.S. Air Force for nearly 25 years without significant modernization. At the request of the Office of the Assistant Secretary of the Air Force for Acquisition, Global Reach Programs, the RAND Corporation is conducting a cost-effectiveness analysis of modernizing the KC-10 in the areas of avionics (communication, navigation, and surveillance capabilities, or CNS), night-vision imaging systems, command and control (specifically, data-link capability), additional multipoint refueling capability, defensive protection, and reliability and safety upgrades.

This work focuses on avionics upgrades to the KC-10 and was conducted as part of the larger KC-10 modernization cost-effectiveness project.

Impending avionics mandates for airspace access around the world will limit the KC-10, as currently configured, from the most fuel-efficient routings and altitudes. This monograph examines the cost and effectiveness of modernizing the KC-10 to meet these upcoming global air traffic mandates.

This research was sponsored by Maj Gen Randal D. Fullhart, director, Global Reach Programs, Office of the Assistant Secretary of the Air Force for Acquisition, Headquarters U.S. Air Force, and conducted within the Force Modernization and Employment Program of RAND Project AIR FORCE for a fiscal year (FY) 2008 project titled "KC-10 Modernization Roadmap."

## RAND Project AIR FORCE

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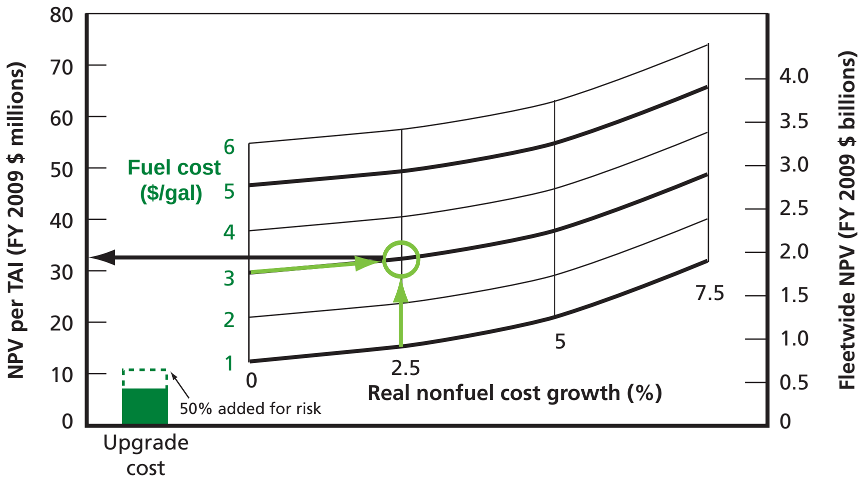
# Summary

The KC-10 "Extender" air refueling aircraft is approaching 25 years of service without undergoing significant avionics modernization. Without upgrades, the CNS capabilities of the KC-10 will not allow it to comply with various upcoming air traffic management (ATM) mandates around the world. Noncompliance with these mandates would prevent the KC-10 from flying the most fuel-efficient altitudes and routings in civil air traffic systems and cause delays both on the ground and in the air. (See pp. 5–17.)

A loss of access to optimal airspace and routings would increase operations costs and degrade the wartime effectiveness of the KC-10. For this study, we conducted a cost-effectiveness analysis to determine whether potential avionics modernization options are worthwhile. Our analysis shows that, overall, a KC-10 CNS/ATM upgrade would be cost-effective and result in net cost avoidance. That is, the projected net present value (NPV) of the operations cost avoidance from avionics modernization during the remaining life of the KC-10 fleet exceeds the upgrade cost of the modernization.

Most of the cost avoidance results from fuel savings and thus depends on the price of fuel. Figure S.1 shows the estimated average upgrade cost and future cost avoidance of a CNS/ATM upgrade to the KC-10 on a per-aircraft basis (left axis) and a fleetwide basis (right axis). On the left side of the figure, the green bar represents the estimated upgrade costs per aircraft. The right side of the figure shows the NPV cost avoidance based on the per-gallon cost of fuel and the real rate of cost growth of nonfuel items (primarily contractor logistics

**Figure S.1**
**CNS Upgrade Cost Versus Cost Avoidance Due to CNS Upgrade**



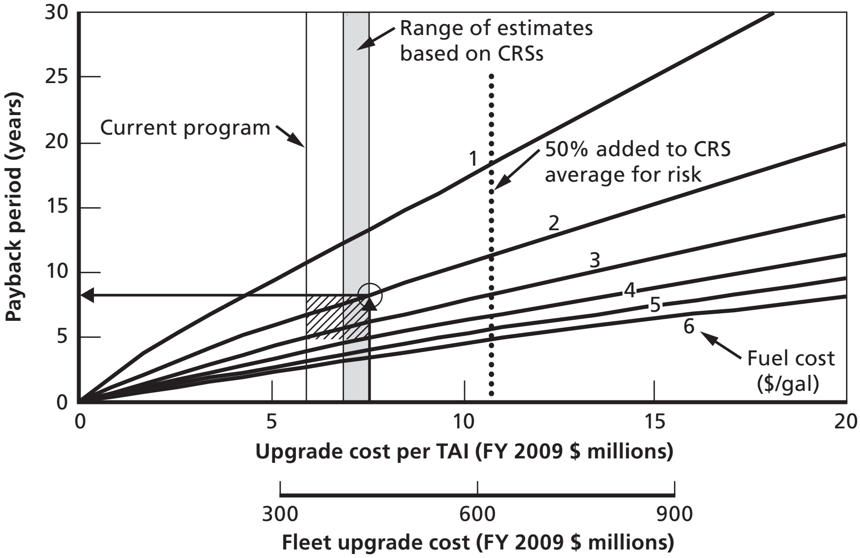

NOTE: TAI = total aircraft inventory.
RAND *MG901-S.1*

support and personnel costs).[1] The cost avoidance from modernization exceeds the upgrade cost over a wide range of assumptions, even in a worst-case scenario of a $1-per-gallon fuel cost and 0-percent real cost growth for nonfuel items. Furthermore, the savings from avoiding altitude restrictions alone (not counting the savings from avoiding delays) are still greater than the upgrade cost. (See pp. 26–32.)

Figure S.2 shows the payback period as a function of the upgrade cost and the cost of fuel per gallon. The payback period can be useful for understanding how soon an investment will be recouped on a nondiscounted basis. In the range of cost estimates for the upgrade, and assuming fuel costs between $2 and $4 per gallon, the payback period ranges from five to eight years. The payback would not begin until 2015, the year in which the first mandates are planned to take effect. (See pp. 32–34.)

[1] In the example in the figure, we assume a constant, real $3-per-gallon fuel cost and real cost growth of 2.5 percent. The intersection of these values (denoted by the green circle) relative to the left vertical axis is the NPV of the savings—$32 million in this example.

**Figure S.2**
**Payback Period from CNS Upgrade**




NOTE: CRS = concept refinement study.
**RAND** *MG901-S.2*

Without modernization, in addition to increased steady-state operations costs, wartime mission effectiveness would be degraded. Not all tanker wartime missions would be affected by the mandates. However, our assessment shows that the KC-10 would be less effective in deployment, air bridge, national reserve, and global strike missions. A noncompliant KC-10's effectiveness ranges from 93 percent to 100 percent of that of a compliant KC-10, depending on the mission. To maintain the existing level of wartime effectiveness (prior to upcoming mandates), the aircraft would have to be modernized or additional tanker aircraft would have to be procured. The costs of either pursuing the upgrade or purchasing additional tankers are comparable. (See pp. 35–44.)

There are additional benefits to modernizing the avionics of the KC-10 fleet that do not necessarily decrease cost or improve wartime effectiveness but nonetheless add to the flexibility of the fleet in meeting mission requirements. These benefits include additional access to airports for landing and continued access to established air refueling tracks. Additional navigation capability (required navigation performance, or RNP, of 0.15–0.3)[2] would allow access to more airports in poor weather. However, most of these airports currently lie in the continental United States (CONUS): Only 26 of the 228 potential newly accessible runways are located outside the CONUS. To best leverage this capability, it must be combined with the means to quickly produce the associated instrument approaches required at more airports. Without modernization, continued access to Hickam Air Force Base (AFB), Hawaii, could be an issue. Furthermore, the KC-10 would be excluded from 70 percent of existing air refueling tracks in the United States. The loss of access to these established refueling locations and altitudes would preclude a majority of military air refueling training. However, we found that, without modernization, complete exclusion of the KC-10 from European airspace would be unlikely. (See pp. 44–48.)

2 RNP 0.15–0.3 capability allows an aircraft to conduct instrument approaches to landing in poor visibility conditions without the use of ground-based navigational aids.

## Acknowledgments

We are grateful for the contributions of many individuals in the U.S. Air Force and the U.S. government. Maj Gen Randal D. Fullhart, director, Global Reach Programs, Office of the Assistant Secretary of the Air Force for Acquisition, sponsored this work; his predecessor, Maj Gen David S. "Scott" Gray, was the sponsor until November 2008. Both provided support and guidance during the study. Our action officers in Office of the Assistant Secretary of the Air Force for Acquisition, Mobility Division—Lt Col Brian Jonasen, Lt Col Eugene Croft, Allan Haenisch, and Tod Beatrice—consistently provided helpful input and guidance throughout our research. Finally, Lt Col Matt Bonavita at Air Force Materiel Command was instrumental in initiating this effort.

We benefited from the input, critical review, support, and coordination provided by our day-to-day action officer, John O'Neill, Air Mobility Command (AMC) Analysis, Assessments, and Lessons Learned (AMC/A9). We also thank Dave Merrill and Jim Donovan, AMC/A9, for their support, guidance, and feedback. We are particularly grateful to Alan McCoy for sharing the tanker "horseblanket" data. We also extend our appreciation to other AMC staff who provided data, information, and critical reviews of our work. We thank Lt Col James Craft, David Ziegler, and James Rummer at AMC Plans, Programs, and Requirements (AMC/A5Q) for their interest, corporate knowledge, and suggestions during this analysis. We received valuable input and participation from Lt Col Todd LaBille, AMC Comptroller

(AMC/A8), and Lt Col James Pena, AMC Air, Space, and Information Operations (AMC/A3).

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## Abbreviations

| | |
|---|---|
| ACARS | Aircraft Communications Addressing and Reporting System |
| ADS-B | automatic dependent surveillance–broadcast |
| ADS-C | automatic dependent surveillance–contract |
| AFB | Air Force base |
| AFTOC | Air Force Total Ownership Cost |
| AMC | Air Mobility Command |
| AMC/A3 | Air Mobility Command Air, Space, and Information Operations Directorate |
| AMC/A5Q | Air Mobility Command Plans, Programs, and Requirements Directorate |
| AMC/A8 | Air Mobility Command Comptroller |
| AMC/A9 | Air Mobility Command Analysis, Assessments, and Lessons Learned Directorate |
| AMP | aircraft modernization program |
| AoA | analysis of alternatives |
| ATC | air traffic control |
| ATM | air traffic management |

| | |
|---|---|
| ATN | Aeronautical Telecommunications Network |
| BRNAV | basic area navigation |
| CNS | communication, navigation, and surveillance |
| COCOM | combatant command |
| CONUS | continental United States |
| CPDLC | controller-pilot data-link communication |
| CRS | concept refinement study |
| CVR | cockpit voice recorder |
| DoD | U.S. Department of Defense |
| ELT | emergency locator transmitter |
| FAA | Federal Aviation Administration |
| FANS | Future Air Navigation System |
| FDR | flight data recorder |
| FL | flight level |
| FM | frequency modulation |
| FY | fiscal year |
| GDSS | Global Decision Support System |
| GLONASS | Global'naya Navigatsionnaya Sputnikovaya Sistema [Global Navigation Satellite System] |
| GPS | Global Positioning System |
| HF | high frequency |
| ICAO | International Civil Aviation Organization |
| LAAS | Local Area Augmentation System |
| LNAV | lateral navigation |

| | |
|---|---|
| LPV | localizer performance with vertical guidance |
| MLS | microwave landing system |
| Mode S | Mode-Select |
| NAS | National Airspace System |
| NPV | net present value |
| O&S | operation and support |
| OEP | Operational Evolution Partnership |
| OMB | Office of Management and Budget |
| OPLAN | operations plan |
| PAF | RAND Project AIR FORCE |
| PRNAV | precision area navigation |
| RNAV | area navigation |
| RNP | required navigation performance |
| RVSM | reduced vertical separation minimum |
| SAASM | Selective Availability/Anti-Spoofing Module |
| SATCOM | satellite communication |
| SPARC | Strategic Projection of Airspace Requirements and Certifications |
| TAI | total aircraft inventory |
| TAWS | terrain awareness warning system |
| TCAS | Traffic Alert and Collision Avoidance System |
| USAFRICOM | U.S. African Command |
| USCENTCOM | U.S. Central Command |
| USEUCOM | U.S. European Command |

| | |
|---|---|
| USNORTHCOM | U.S. Northern Command |
| USPACOM | U.S. Pacific Command |
| USSOUTHCOM | U.S. Southern Command |
| VDL | very-high-frequency data link |
| VHF | very high frequency |
| VNAV | vertical navigation |
| WAAS | Wide Area Augmentation System |

CHAPTER ONE

# Introduction

This work is part of a larger overall project investigating the costs and benefits of modernizing the KC-10 "Extender" air refueling aircraft. This monograph focuses on the costs and benefits of enhanced communication, navigation, and surveillance (CNS) capabilities to ensure compatibility with air traffic management (ATM) system modernization in many parts of the world. The analysis examines upgrades to avionics systems required to meet projected ATM capability mandates, which will allow the KC-10 to interoperate smoothly with civil air traffic control (ATC) systems worldwide.

This project's other modernization areas include compatibility with night-vision imaging systems, command and control (specifically, data-link capability), additional multipoint refueling capability, defensive protection, and reliability and safety upgrades. Future reports will present analyses from the other parts of this study, which the Air Force requested. During the research effort, it became apparent that the Air Force needed to budget for avionics upgrades to the KC-10 soon or risk not being able to modernize in time to meet global requirements. As a result, the Air Force requested that the CNS/ATM part of the overall study be prioritized and that a separate report be produced to document the results and inform the decision regarding modernizing KC-10 avionics to meet CNS/ATM mandates.

By CNS/ATM mandates, we specifically mean aircraft or crew capabilities that are legally mandated for airspace access and ATC services by national airspace authorities such as the Federal Aviation Administration (FAA) in the United States. Future CNS/ATM mandates seek to enable a more efficient flow of aircraft through the ATC system. This increased efficiency will stem from improvements in CNS capabilities that allow an increased number of aircraft to operate in a given volume of airspace without degrading existing levels of safety. In this monograph, we assess only the mandates that are required for airspace access.

Impacts of noncompliance with upcoming CNS/ATM mandates include exclusion from optimal altitudes, air traffic delays, inefficient routings, and restricted access to both busy airports and established air refueling tracks. The most fuel-efficient altitude for jet transport–category aircraft like the KC-10 is generally between 30,000 and 40,000 feet. Many countries and International Civil Aviation Organization (ICAO) regions are mandating advanced CNS capabilities to access these premium altitudes.

During the course of this study, we consulted with a range of experts in both the KC-10 and CNS/ATM communities.[1] Major sources of information on specific modernization options were the CRSs conducted by five industry teams in 2007 for the KC-10 AMP.

The Air Force owns and operates a fleet of 59 KC-10 aircraft based at McGuire AFB, New Jersey, and Travis AFB, California. The fleet was acquired in the mid-1980s and is approaching 25 years of service. It has not received a major avionics upgrade in its lifetime.

In this monograph, we assess the impact of noncompliance with these mandates in terms of the costs that the Air Force will incur to operate the KC-10 for the remainder of its service life, assumed here to be until 2045. If the KC-10 fleet is upgraded to meet the mandates, its flying-hour program and average fuel-burn rate will stay the same; if it is not upgraded, it will require more hours and more fuel per hour to accomplish the same missions. We calculate the increased costs that

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[1] We drew on a variety of sources, including data from the Electronic Systems Center's annual CNS/ATM conference; McGuire Air Force Base (AFB) Operations Group; William Hershey at MITRE Corporation; the Air Force Flight Standards Agency; the KC-10 System Program Office CNS/ATM program manager; a number of directorates at the Air Mobility Command (AMC); contractor KC-10 Aircraft Modernization Program (AMP) concept refinement studies (CRSs); the Aerial Refueling Systems Advisory Group; and historical KC-10 analyses.

would be incurred by a noncompliant fleet and compare them to the cost of upgrading the aircraft. As described later, the future cost avoidance due to compliance is much larger than the upgrade cost of meeting the mandates.

We also assess how the wartime effectiveness of the KC-10 would be affected by noncompliance. Our approach is consistent with that described in the Air Force guidance for analysis-of-alternatives (AoA) studies, which are similar in nature (AFMC, 2008). That document calls for an assessment of "peacetime" costs. In this monograph, we characterize the operations costs incurred by the fleet for the rest of its lifetime (at the 1996–2006 mission level) as "steady state" rather than peacetime, recognizing that current operations include much wartime activity.

The mandates will also increase efficiency in other areas. They do not necessarily decrease cost or improve wartime effectiveness, but they add to the flexibility of the fleet in meeting requirements. These benefits include additional access to airports for landing and continued access to established air refueling tracks, as discussed in more detail later.

The next chapter describes the CNS/ATM mandates and the KC-10 avionics upgrades needed for compliance. Chapter Three presents our analysis of the costs of CNS/ATM modernization and the resulting operations cost avoidance from compliance. Chapter Four presents wartime and steady-state operational benefits resulting from the avionics upgrade. The final chapter presents our conclusions. An appendix provides additional data and elaborates on our analysis of the relation between nonfuel costs and flying hours.

CHAPTER TWO

# CNS/ATM Mandates and KC-10 Upgrades Required for Compliance

## Equipage Mandates

Airspace modernization decisions affect a wide range of parties, from private pilots, airlines, and military aviation users to air traffic service providers and industry participants. These groups benefit from improved operational efficiency, increased safety levels, and lower acquisition and operating costs. As a result, they help drive changes in technical and operational standards by identifying needs and participating in working groups and committees. The result of this consensus-based process is a set of standards, such as minimum operational performance standards and ICAO's Standards and Recommended Practices. Standardization organizations responsible for producing these recommendations include the ICAO, European Organization for Civil Aviation, European Aviation Safety Agency/Joint Aviation Authorities, Radio Technical Commission for Aeronautics, and the FAA.

In addition, governmental agencies, such as the FAA, develop legal mandates and certification requirements to regulate the implementation of new CNS/ATM capabilities, often basing their mandates on the consensus-developed standards. National mandates and standards are usually disseminated through Aeronautical Information Publications, Federal Aviation Regulations, type certificates, and other sources. While each individual country is responsible for laws governing its airspace, regional organizations (such as ICAO and EUROCONTROL, Europe's air safety organization) often guide policy by issuing "specimen" aeronautical information publications. This process allows continuity and reduces the burden on users to meet numerous disparate requirements as they transit from the airspace of one country to another (Hershey, 2008).

For this study, the global airspace requirements were broken down broadly by ICAO region definitions. We assume that users not properly equipped to meet the mandates proposed for a given ICAO region will face some penalty or be denied some benefit of compliance, including denial from premium altitudes, increased delays resulting from suboptimal routing or spacing, and airspace exclusion. While military aircraft are sometimes granted waivers, it is assumed here that they will face the same penalties for noncompliance as civil aircraft. While some exemptions may still be granted in the future, the expected growth in air traffic may limit the ability of noncompliant aircraft to operate in certain regions without causing significant disruption. Additionally, the worldwide volume of civil traffic compared to U.S. military traffic places the U.S. military in a clear minority.

## CNS/ATM Overview

Implementation of global CNS/ATM mandates is expected over the next two decades. We categorized the mandates and standards into four major classes: communication, navigation, surveillance, and other.

Communication systems allow aircraft to communicate with ground-based air traffic controllers. Traditionally, this has been accomplished through line-of-sight very-high-frequency (VHF) radios and voice communication capabilities. Increasingly, ATC communications rely on data links and beyond-line-of-sight radios (for example, those using satellite communication, or SATCOM, capabilities) instead of voice messages over VHF radios. In busy airspace, communication throughput limitations have restricted the number of aircraft that can access the airspace and increased the time it takes to send and receive air traffic clearances. As a result, new communication capabilities have been mandated to increase communication capacity.

Navigation systems allow aircraft to adequately maintain a specified route of flight to a given destination. Historically, navigation in aviation beyond pilotage (using ground references) has been accomplished by using a variety of ground-based radio beacons. These systems provide some combination of bearing and distance information from which an aircraft can establish its position. Later advances in avionics allowed the aircraft to electronically query all ground-based navigation aids within range and automatically determine its position (as opposed to manually tuning in individual navigation aids to get bearing and distance information, or using information from multiple navigation aids to triangulate position). With the advent of global navigation satellite systems (e.g., the U.S. Global Positioning System, or GPS, and the Russian global navigation satellite system known as GLONASS), an additional source of position information was added, allowing the aircraft to globally determine its position with unparalleled accuracy independent of a ground-based network.

Recent and forthcoming navigation mandates require aircraft to determine position independent of ground-based navigation aids, with varying degrees of accuracy and integrity.

Surveillance systems allow air traffic controllers to independently track the location of individual aircraft. Historically, this was accomplished using ground-based radar. Next, aircraft were equipped with radar transponders that replied to radar interrogation with a unique identifying code and altitude. Recently, systems such as automatic dependent surveillance–broadcast (ADS-B) and Mode-Select (Mode S) have enabled aircraft to self-report surveillance information to ground-based ATC systems and to other aircraft for collision avoidance.

Increasingly accurate surveillance and navigation systems allow aircraft to fly closer together without reducing the margin of safety. This closer spacing allows for a greater throughput capacity, thus reducing congestion and delays.

Some benefits of airspace modernization can be attained only through combinations of CNS systems. For example, access to Future Air Navigation System (FANS)[1] airspace requires ADS-Contract (ADS-C), controller-pilot data-link communication (CPDLC), and the ability to automatically log in to each controlling agency as the aircraft enters its airspace (facilities notification). Currently,

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[1] In this monograph, we refer to the current system standard, FANS-1/A.

FANS-1/A capability is required for 30/30 separations in some oceanic regions, and it will also satisfy future European requirements for the Aeronautical Telecommunications Network (ATN)/CPDLC.

Other mandates levied for military necessity or safety reasons span navigation safety, instrument approach, and military navigation and surveillance categories.

Navigation safety mandates may include terrain avoidance systems or aircraft collision avoidance systems. While these systems are important and improve safety, they do not generally increase access to airspace.

Instrument approach capabilities allow pilots to fly without visual reference to the ground down to various altitudes for landing. They thus allow pilots to operate aircraft at lower altitudes during approaches before making the decision to continue for landing or "go around." These systems may allow landing in low-visibility conditions at airports that do not have other ground-based landing systems. However, instrument approach systems are not required for airspace access and generally allow increased airport access only in areas where there is poor aviation infrastructure. Large transport-category aircraft like the KC-10, which requires runways in excess of 7,000 feet, normally operate from larger airports that already have the ground-based navigation aids for landing in low-visibility conditions.

Military navigation and surveillance mandates may include specific systems that counter enemy jamming or eavesdropping efforts. Examples of these types of systems are Mode 5 and the Selective Availability/Anti-Spoofing Module (SAASM). Like the other capabilities in this class, they generally do not increase access to civil airspace. However, they do add military value and may be satisfied in conjunction with other mandates. For example, if a particular embedded GPS or inertial navigation system is placed in an aircraft to satisfy a given navigation requirement, a GPS receiver that has SAASM capability could also satisfy the SAASM military-mandated requirement.

We discuss KC-10 military and safety capabilities in terms of compliance with existing standards or requirements for various capabilities. However, these safety and military mandates are not needed for access to civil airspace and were not considered in this study's cost-effectiveness analysis.

## Specific Capabilities

This section briefly describes CNS/ATM capabilities according to the previously defined categories: communication, navigation, surveillance, and other.

### Communication

Current and projected CNS/ATM communication capabilities include the following:

- *8.33-kHz radios:* 8.33-kHz radios are VHF voice radios that divide each standard 25-kHz voice channel into three separate 8.33-kHz channels, allowing a larger number of overall frequencies for controller-pilot voice communications (ESC, 2008).
- *High-frequency (HF) voice systems:* HF radios for analog voice communication are capable of beyond-line-of-site communication.
- *HF data-link systems:* These systems operate via HF data radios to support air operations centers and, in the future, ATC applications. HF data-link systems have not been approved for oceanic tracks due to technical problems (ESC, 2008).
- *SATCOM:* SATCOM systems provide data, voice, and fax capabilities, allowing aircraft to communicate in oceanic and remote areas where line-of-site communication systems are not available (except the north and south poles). Military command-and-control and civil ATC SATCOM systems are generally incompatible with each other (ESC, 2008). Additional SATCOM capabilities currently in use are SATCOM data-link and SATCOM voice systems.
- *CPDLC:* CPDLC is a data communication application used for text-based communication between pilots and controllers to augment voice traffic. It is available in Europe using VHF data-link (VDL) Mode 2 and the ATN. FANS-1/A is an avionics pack-

age that provides CPDLC capability (plus ADS-C) in oceanic airspace using the Aircraft Communications Addressing and Reporting System (ACARS).
- *VDL Mode 2:* VDL 2 is a data-link-only service designed to digitize VHF and improve the speed (data rate) of the VHF link. VDL 2 will likely be used within the continental United States (CONUS) as an interim data-link solution for en route ATC functions (ESC, 2008).
- *VDL Mode 4:* VDL 4 was developed by Sweden for ADS-B. It has some level of approval in Europe but no projected future mandates (ESC, 2008).

### Navigation

Current and projected CNS/ATM navigation capabilities include the following:

- *Reduced vertical separation minimum (RVSM):* This guideline reduces the vertical separation between properly equipped aircraft to 1,000 feet in RVSM airspace, which is generally between the altitudes of 29,000 and 41,000 feet. RVSM adds new flight levels to reduce congestion in heavy traffic areas (ESC, 2008).
- *Frequency modulation (FM) immunity:* FM immunity ensures that navigation receivers are immune from interference from commercial FM radio broadcasts. It protects receipt of VHF omnidirectional range and Instrument Landing System signals (ESC, 2008).
- *Area navigation (RNAV)–X:* RNAV is a method of aircraft navigation along any desired flightpath. The specification implies an accuracy requirement that the lateral navigation error remain less than *x* nautical miles at least 95 percent of the flight time by the population of aircraft operating in the airspace, on the route, or in accordance with a given procedure (Meyer and Bradley, 2001).
- *Required navigation performance (RNP) X:* RNP prescribes the system performance necessary for operation in a specified airspace based on a given required accuracy (RNP value). The basic accuracy requirement for RNP X airspace is for the aircraft to remain

within *x* nautical miles of the cleared position for 95 percent of the time in RNP airspace. There is an additional containment requirement for RNP operations. According to ICAO, any potential deviation greater than twice the RNP value must be annunciated with a probability of missed detection less than $10^{-5}$ (Meyer and Bradley, 2001). Larger RNP or RNAV values are not necessarily satisfied by meeting the requirements for a smaller value. For example, an aircraft meeting RNP 0.3 requirements does not automatically satisfy RNP values for all accuracies greater than 0.3.[2] Each specification may have unique requirements depending on what phase of flight it is intended for and where it is being implemented.

- *RNP 12.6:* RNP 12.6 is the navigation performance required for North Atlantic Minimum Navigation Performance Specification airspace (ESC, 2008).
- *Basic area navigation (BRNAV):* BRNAV is a European requirement for RNAV that meets RNP 5 accuracy (ESC, 2008).

**Surveillance**

Current and projected CNS/ATM surveillance capabilities include the following:

- *Mode S:* The primary role of the Mode S transponder is to "selectively" respond to interrogations (as opposed to responding to all interrogations) from a sensor to provide airborne data information, including identification, equipage, and altitude. Enhanced Mode S additionally provides magnetic heading, indicated airspeed, Mach number, vertical rate, roll angle, track angle rate, true track angle, ground speed, and selected altitude (ESC, 2008).

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[2] According to the ICAO, "[W]hen an aircraft's capability meets the requirements of a more stringent RNP airspace, based on specific infrastructure, this capability might not meet the requirements of a less stringent RNP airspace (due to the lack of supporting infrastructure appropriate to its navigation equipment fit), e.g., RNP 1 [distance measurement equipment/distance measurement equipment–only] certified aircraft is not capable of operation in RNP 10 (oceanic) airspace" (Meyer and Bradley, 2001).

- *ADS-B:* The ADS-B surveillance function is based on position data computed by airborne equipment and sent to the ground system. ADS-B–equipped aircraft can regularly broadcast messages reporting the aircraft's position, velocity, and other information (ESC, 2008).
- *Traffic Alert and Collision Avoidance System (TCAS):* This system comprises a family of airborne devices that function independently of the ground-based ATC system and provide collision-avoidance protection (ESC, 2008).

### Other

Other capabilities that do not fall into the previously discussed categories of communication, navigation, or surveillance include the following:

- Navigation Safety
  - *Cockpit voice recorder (CVR):* This device records the flight crew's voices and other sounds inside the cockpit. In the event of an aircraft accident, it helps reconstruct the events leading to the accident. The device is one of the two "black boxes" often mentioned in news reports in the aftermath of aviation accidents (ESC, 2008).
  - *Emergency locator transmitter (ELT):* The ELT is a device contained in a crash-resistant box that emits a signal to aid in locating a downed aircraft (ESC, 2008).
  - *Terrain awareness and warning system (TAWS):* These systems warn pilots of terrain proximity to prevent flight into terrain or obstacles by comparing an aircraft's position information to a terrain database.
  - *Flight data recorder (FDR):* This device records many different operating conditions including flight time, altitude, airspeed, heading, aircraft attitude, engine parameters, control surface positions, and status of aircraft systems. The flight data recorder is one of the two "black boxes" often mentioned in news reports of aviation accidents (ESC, 2008).

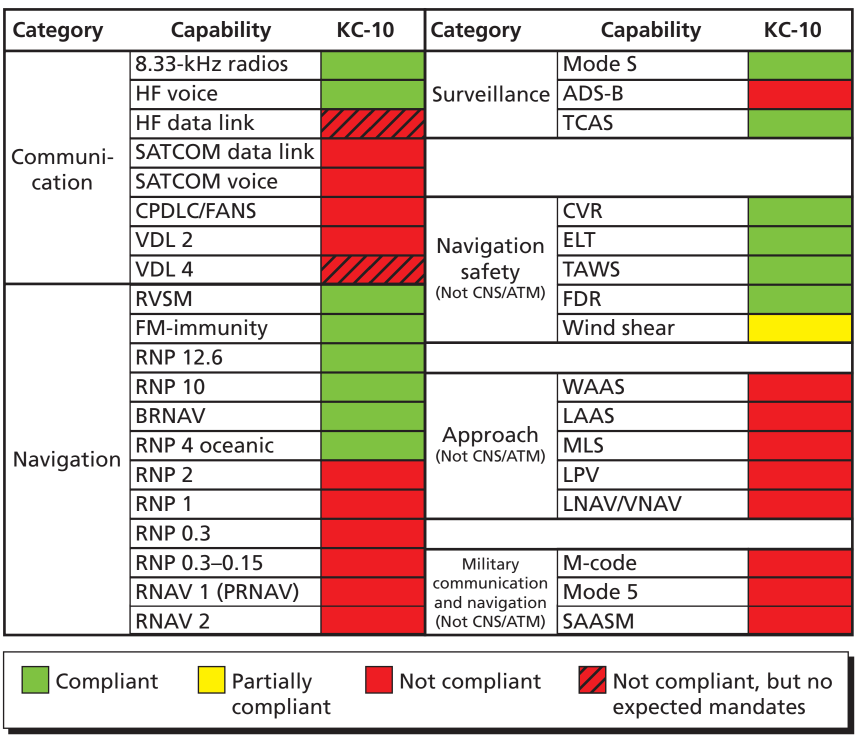
  - *Wind shear:* A reactive wind-shear system processes data from standard aircraft instruments to determine the presence of wind shear. A predictive windshear system uses aircraft weather radar to look forward and provide ten to 40 seconds of warning (ESC, 2008).
- Approach
  - *Wide Area Augmentation System (WAAS):* WAAS is an FAA-developed space-based augmentation system used to improve the accuracy, integrity, and availability of GPS (FAA, 2008a).
  - *Local Area Augmentation System (LAAS):* This FAA-developed ground-based augmentation system provides differential corrections to the GPS signal to enable precision landing operations. LAAS provides greater accuracy than WAAS.
  - *Microwave landing system (MLS):* This ground-based landing system was designed to replace the Instrument Landing System. It has largely fallen out of favor with the advent of RNP-based landing procedures and equipment.
  - *Localizer performance with vertical guidance (LPV):* These procedures identify WAAS vertical guidance approach minimums with electronic lateral and vertical guidance. The obstacle-clearance area is considerably smaller than the lateral and vertical navigation (LNAV/VNAV) protection, allowing lower minima in many cases (FAA, 2008a).
  - *LNAV/VNAV:* Guidance approach minimums for lateral and vertical navigation have been developed to accommodate an RNAV instrument approach with vertical guidance, but the lateral and vertical integrity limits are larger than with a precision approach or LPV (FAA, 2008a).
- Military
  - *M-code:* M-code is a military signal designed to further improve the antijamming and secure access of military GPS signals.
  - *Mode 5:* Mode 5 is a transponder mode mandated by the office of the Secretary of Defense to replace Mode 4. Mode 5 incorporates advanced encryption and additional functionality similar to ADS-B, including position and identification information.

– *SAASM:* This module allows the decryption of precise GPS signals and is the newest generation of security architecture for military GPS users.

## Current KC-10 CNS/ATM Capabilities

Figure 2.1 shows the current capabilities of the KC-10 with respect to existing and projected CNS/ATM capabilities and standards. The figure is divided into the areas of communication, navigation, surveillance, and other (navigation safety, approach, and military), as described in the previous section.

**Figure 2.1**
**Current Avionics Capabilities of the KC-10**




NOTE: PRNAV = precision area navigation.
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The KC-10 is already compliant with some CNS/ATM mandates (the green boxes in Figure 2.1). A red box indicates that the KC-10 is not currently compliant. Wind shear is the only capability for which the KC-10 is partially compliant: The KC-10 does have a reactive system to alert pilots of wind shear, but it does not yet have a more advanced predictive wind-shear alerting system. A red crosshatched box indicates that the KC-10 does not have the capability and that there are no mandates for the capability in the foreseeable future: HF data link is not approved for ATC communications (U.S. Air Force, undated), and the VDL 4 protocol is under development in Europe to potentially support time- and safety-critical applications, including ADS-B (ESC, 2008).

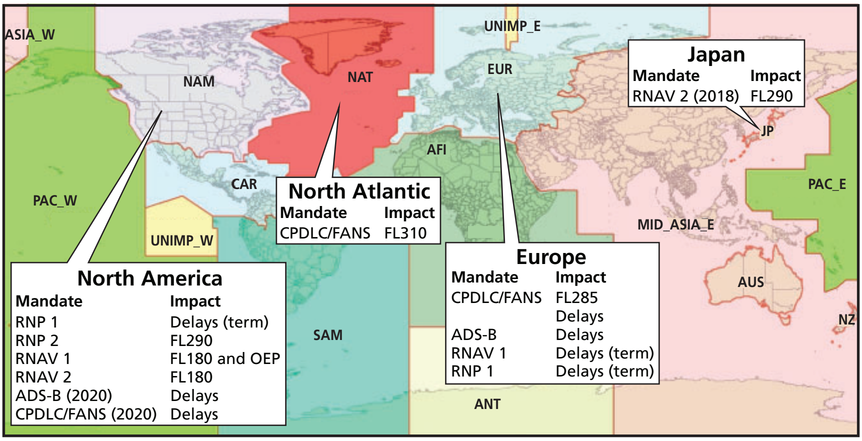
Some capabilities span more than one category—specifically, RNP 0.3 and RNP 0.3–0.15. These levels of navigational capability are generally needed to fly instrument approaches. However, the requirements to meet the mandates are qualitatively similar to RNP requirements in the navigation category. We address the impact of RNP 0.3–0.15 capability in Chapter Four.

## CNS/ATM Mandates

Aircraft that are noncompliant with mandates are subject to the restrictions or penalties established by individual national ATC authorities. Each country may establish unique equipage and certification requirements for airspace access as well as penalties for noncompliance with its mandates. Even though each country can regulate and enforce its own airspace access, countries typically coordinate regionally to facilitate air traffic operations.

An aircraft that is noncompliant with a given CNS/ATM mandate is generally restricted from the most congested altitudes (which are the most fuel-efficient) and/or subject to airborne delays. The practical effect of altitude restrictions is to limit the maximum altitude of a noncompliant aircraft. In Figure 2.2, these maximum altitudes are expressed in terms of flight levels (FLs), which equate to hundreds of feet above mean sea level. Thus, FL180 corresponds to approximately 18,000 feet above mean sea level. If the impact of noncompliance is

**Figure 2.2**
**Future CNS/ATM Mandates Affecting the KC-10**

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delays, then "delays" is shown in the "impact" column for each ICAO region in Figure 2.2. Sometimes, the impact involves access to and delays at busy U.S. airports (Operational Evolution Partnership, or OEP) or to airport terminal areas. The main source of information for mandate dates and noncompliance impacts is the Strategic Projection of Airspace Requirements and Certifications (SPARC) database maintained by CNS/ATM experts from the 853rd Electronic Systems Group at Hanscom AFB, Massachusetts.[3]

Figure 2.2 provides an overview of future CNS/ATM mandates that will affect the KC-10 if it is not modernized. This assembly of CNS/ATM mandates is unique to the KC-10 and shows only those capabilities that the K-10 lacks that also have future mandates. Mandates are shown grouped by ICAO region and are slated for implementation in 2015 unless otherwise noted. An abbreviated indication of the impact of noncompliance for each of the mandates is also provided.

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[3] SPARC is a software application prepared by the Air Force Electronic Systems Center's Global Air Traffic Systems Group. It displays global and regional maps based on CNS/ATM implementation schedules, displays Air Force platform CNS/ATM schedules, analyzes global civilian flight routes, and examines noncompliance impacts resulting from CNS/ATM implementations.

Many mandates take effect in 2015 and many of the analytical warfighting scenarios used to evaluate the impact of modernization on the wartime mission of the KC-10 are set in 2025. Relatively few additional CNS/ATM mandates come into effect between 2015 and 2025. The post-2015 mandates in North America are scheduled for 2020, and the RNAV proposal for Japanese airspace is scheduled for 2018.

## Modernizing the KC-10

In this analysis, we assess the costs and benefits of adding to the KC-10 all of the capabilities in the communication, navigation, and surveillance categories with which it is noncompliant (as shown in Figure 2.1). This would make the KC-10 compliant with all mandates currently expected (Figure 2.2).

A detailed engineering study to determine the installation process and procedure was beyond the scope of this study. However, avionics upgrades generally do not involve structural modifications to an airframe (with the exception of adding antennas). As a result, such an upgrade does not change the performance characteristics of the aircraft and essentially involves replacing one or more components with updated line-replaceable units. These units must then be integrated into the remaining systems on the aircraft (e.g., flight control actuators, flight control position sensors, remaining avionics, wiring, data buses, antennas). In this analysis, we allowed for an installation schedule provided by the Air Force, which showed the first two aircraft modified in 2011 and the rest of the fleet being modified through 2015, with an average fleet modification date in the third quarter of 2013.

CHAPTER THREE

# Expected Operations Cost Avoidance and Equipage Costs for KC-10 CNS/ATM Modernization

In this chapter, we examine the cost implications of noncompliance in steady-state operations with the mandates discussed in Chapter Two. Specifically, we evaluate the operation and support (O&S) cost increase (relative to a fully compliant aircraft) that would result from a noncompliant aircraft operating under the mandates. We calculate these costs starting in 2015, when the KC-10 would first become noncompliant, through 2045, the planned retirement date of the fleet. For 2018 and 2020, we incorporate the effects of the additional mandates coming into effect. We use two years of KC-10 operational flight-profile data to characterize KC-10 operations and the 11 years of data from the Air Force Total Ownership Cost (AFTOC) database to calculate the change in flying time and fuel usage. To estimate the costs of modernization, we draw from contractor-based estimates in conjunction with information provided by the KC-10 System Program Office. Comparing the estimated cost avoidance with the expense to modernize, we show KC-10 CNS/ATM modernization to be a cost-effective investment.

## Approach

This section provides an overview of our approach to modeling KC-10 operations and calculating the cost impact of noncompliance. To calculate the change in O&S costs, we first calculated the percentage changes in the amount of fuel consumed and the number of flying hours for a fleet of noncompliant aircraft. The two years of flight operational data were used to calculate these percentage changes. This data set was validated to be representative of KC-10 flying by experts at the AMC's Air, Space, and Information Operations (A3) and Logistics (A4) directorates. The percentage changes were then applied to the KC-10 fleet's average flying hours and fuel usage over the 11-year period from 1996 to 2006 (950 hours/total aircraft inventory [TAI]/year and 18,900 lb/hr). The cost of the additional flying hours and fuel was then calculated over the planned life cycle of the KC-10 fleet.

We then analyzed each of the nearly 20,000 flights in the flight-profile data to determine the distance traveled in each ICAO region. We modeled each flight using the KC-10 performance manual[1] and current operational practices to determine the amount of fuel used and the flight time for each flight. Fuel use and flight time were calculated under conditions of full compliance and noncompliance with all CNS/ATM mandates, presented in Figure 2.2. For the fully compliant condition, each flight operated at the most fuel-efficient altitudes and did not experience any delays. Noncompliant aircraft were subject to altitude restrictions and delays by ICAO region, as shown in Figure 2.2.

For example, suppose an aircraft flies from the United States to Germany. A noncompliant aircraft making this flight would be limited to FL180 for the North American portion of the flight. Over the North Atlantic, the noncompliant aircraft would be limited to a maximum of FL310. In the European ICAO region, the noncompliant aircraft is limited to FL285 and experiences delays. If this noncompliant aircraft's flight took place in 2020 or later, it would also experience delays in the North American region. A compliant aircraft making this same flight could fly the same route but would not be subject to any altitude restrictions or delays.

Both the distribution of flights by region and leg distance affect the overall increase in fuel and flight time of noncompliant aircraft. The regional distribution of a flight affects overall fuel use and flying time because the impacts of noncompliance differ by region, with North America being the most restrictive. The distance of each flight affects fuel use and flight time due to aircraft performance constraints based on

[1] All KC-10 performance calculations were based on U.S. Air Force (2005).

the average weight of the aircraft when it is in a specific ICAO region. For example, a very heavy aircraft departing from the East Coast of the United States and crossing the Atlantic may not be able to climb above FL310. For this flight, in the North Atlantic region, there would be no impact resulting from noncompliance because physics would limit the aircraft's performance before the CNS/ATM mandates would.

Altitude restrictions affect fuel use because jet transport aircraft, like the KC-10, generally burn more fuel per mile at lower altitudes. Altitude restrictions also increase the number of flying hours required to accomplish a given mission because the operational speeds of the KC-10 at lower altitudes are, on average, slower than speeds at higher altitudes.[2] In our analysis, the KC-10 carries out the same missions whether compliant or not—that is, it accomplishes the same training, deployment, and other operational tasks.

Delays also increase the amount of flight time. The mandates do not specify the length of delays that will result from noncompliance but simply note that noncompliant aircraft will be subject to them. In our modeling, we apply a representative flight delay of 14 minutes each time a noncompliant aircraft transits an ICAO region in which delay is a projected consequence of noncompliance. This number is the median air delay attributable to traffic volume, ATC, and other ATM factors (DOT, 2007), based on one year of U.S. domestic airline delays attributable to the National Airspace System (NAS).[3] Delays that all aircraft would experience regardless of compliance with airspace requirements (e.g., late aircraft arrival, security, extreme weather) have been removed, leaving only the delays attributable to heavy traffic volume, air traffic control, and so on.

Increases in fuel use increase costs based on the additional fuel burned. Increases in flight hours increase costs based on both the addi-

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[2] Based on KC-10 operational practice, in our analysis, the KC-10 flies at Mach 0.825 for normal cruise for flights capped at FL285 or higher. For flights capped at FL180, it flies at an indicated airspeed of 320 knots (kts). This equates to a true airspeed of 489 kts at FL285 and 412 kts at FL180.

[3] Data are from the Bureau of Transportation Statistics. Because the goal was to characterize the typical magnitude of a NAS delay when such a delay occurred, only flights that experienced NAS delays were included in the median calculation.

tional fuel burned during those flight hours and the additional nonfuel costs that are a function of flying hours. For the KC-10, these nonfuel costs are primarily contractor logistics support and personnel costs. In 2006, KC-10 nonfuel costs were $8,200 per flying hour in FY 2009 dollars, according to the AFTOC database. Regressions of nonfuel costs on flying hours and a time trend show that nonfuel costs are proportional to flying hours raised to the 0.26 power. This means that every 10-percent increase in flying hours leads to a 2.6-percent increase in nonfuel costs. The appendix presents additional detail on the statistical basis for the relationship between flying hours and nonfuel costs.

## KC-10 Steady-State Operations

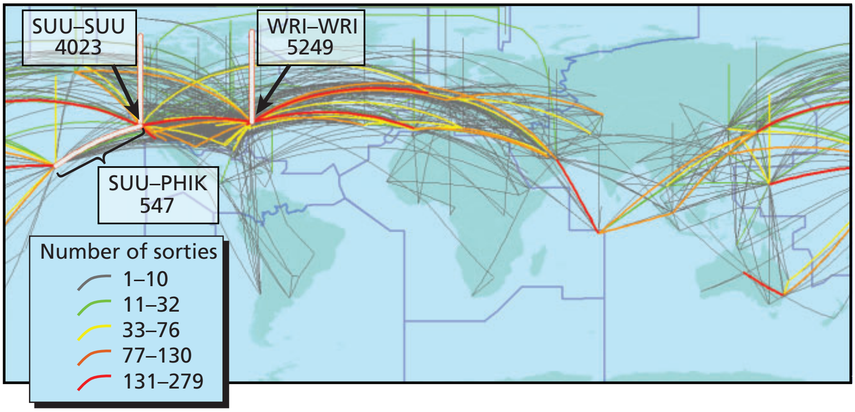
This section presents the character of KC-10 operations because O&S cost increases depend on the nature of KC-10 operations as well as the type and locations of the mandates. Figure 3.1 represents flights made by KC-10s over the two-year period (FY 2006–FY 2007). It is based on the Global Decision Support System (GDSS) database of the approximately 20,000 sorties performed by KC-10s during that time (Air Mobility Command, 2008).[4]

Each departure-arrival pair in the figure is shown connected by the great circle route between the two airports (which may not be the actual flight routing). Additionally, the pairs are color-coded by how often they occurred, as indicated in the legend. The two vertical lines on the East and West coasts of the United States represent the sorties that departed from either McGuire or Travis AFB and returned to the same base. These same-base sorties accounted for 46 percent of all sorties: 26 percent at McGuire and 20 percent at Travis. The third most frequent departure and arrival pair is between Travis AFB and Hickam AFB, Hawaii. These sorties account for nearly 3 percent of the total.

As can be seen in the figure, the majority of the flying occurred in North American airspace, with significant flying across the Atlantic,

[4] Air Mobility Command uses the GDSS to track airlift missions in real time and to keep a historical record of flying operations.

**Figure 3.1**
**Worldwide KC-10 Sorties, FYs 2006–2007**




NOTE: The figure shows unique 2006–2007 KC-10 departure-arrival pairs from GDSS. PHIK is the airport code for Hickam AFB, SUU is Travis AFB, and WRI is McGuire AFB.
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into the Middle East (the current area of responsibility), and across the Pacific.

We measured the impact of CNS/ATM noncompliance on fuel use and flight hours for each sortie in the operation pattern shown in Figure 3.1. Flights that had different arrival and departure bases were divided into the segments flown in each ICAO region. For missions that took off from and returned to the same base (which accounted for 46 percent of the total flying hours), the GDSS data set did not contain explicit information regarding flight details between takeoff and landing. To accurately model these missions, we developed representative missions incorporating additional data we obtained from the 305th Operations Support Squadron at McGuire AFB. From GDSS, we obtained the total number of same-base missions, individual sortie durations, and the split between operational and training missions. From the 305th Operations Support Squadron data, we characterized the nature of local training missions in terms of how much time was spent conducting refueling training compared to transiting between practice areas for both aerial refueling and takeoff and landing training.

The majority (about 75 percent) of the same-base missions were training missions. Of that 75 percent, there was nearly an even split between missions that visited either one or two refueling tracks. The distance between the departure base and any refueling track was modeled as 220 nautical miles (nm). The tanker spent one hour on each track on missions that visited two tracks and two hours on track for missions that visited only one track in our representative sorties. For these training missions, either 30 minutes (two-track missions) or one hour (one-track missions) was spent in the local traffic pattern conducting takeoff and landing training. The operational sorties were split into three ranges, short (500 nm), medium (750 nm), and long (1,000 nm). Figure 3.2 shows a representation of this same-base flying.

With this modeling of the same-base sorties, we then were able to estimate the impact of noncompliance for this significant portion of KC-10 operations.

## Impact of CNS/ATM Noncompliance on Fuel Use and Flying Hours

We now estimate the cost avoidance from modernizing the KC-10 to comply with the projected mandates. In Figure 3.3, we present the percentage increase in fuel use for a noncompliant fleet over a compliant

**Figure 3.2**
**Percentage Breakdown of Same-Base KC-10 Sorties**

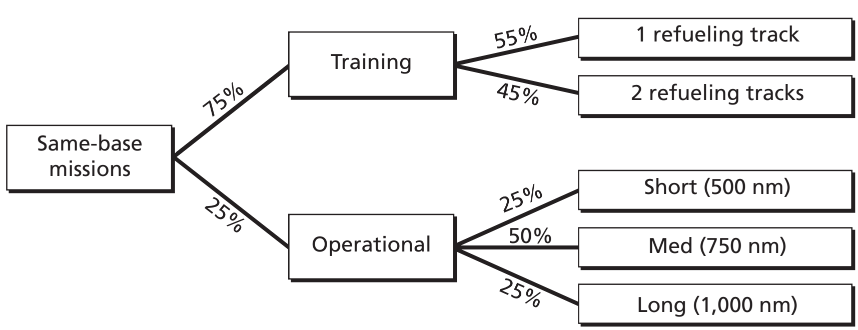


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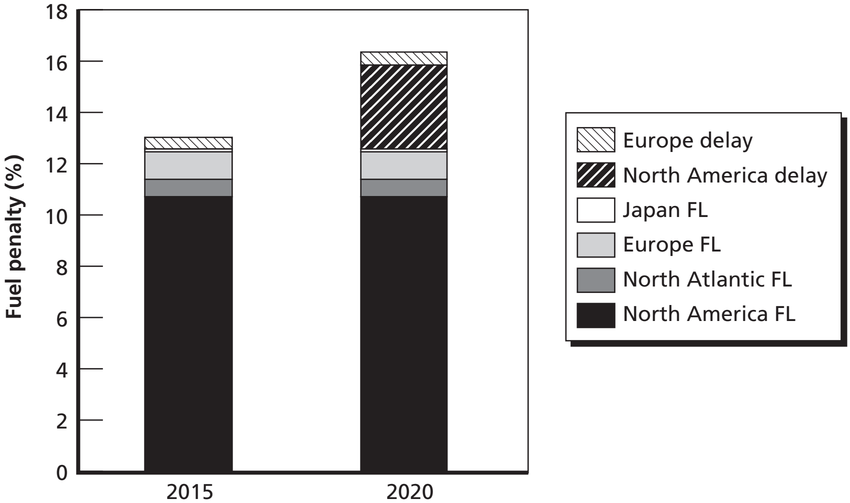
**Figure 3.3**
**Additional Fuel Use Due to Altitude Restrictions and Flight Delays**

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one. As described earlier in this chapter, a noncompliant fleet requires more fuel for two reasons. First, it cannot access optimal altitudes (i.e., altitudes at which fuel burn per mile is minimized). Second, it incurs delays in airspace access and operates at slower airspeeds at lower altitudes, both of which increase fuel use because of increased flying time. In Figure 3.3, fuel use increases that are the result of altitude restrictions and flight delays are shown separately by region. The portion of additional fuel use due to altitude restrictions is indicated by "FL" in the legend. The relative proportion of the increase in each region depends on both the severity of the restriction in that region and the level of KC-10 operations there.

The North American region contributes the greatest amount of additional fuel burn based on altitude restrictions because it has both the most severe altitude restriction (FL180) and the highest proportion of flying operations (see Figures 2.2 and 3.1). The altitude-based fuel penalty in 2015 and 2020 is the same, because there are no additional altitude restrictions imposed in the interim years. The crosshatched portions of the two bars show the effect attributable to flight delays in both

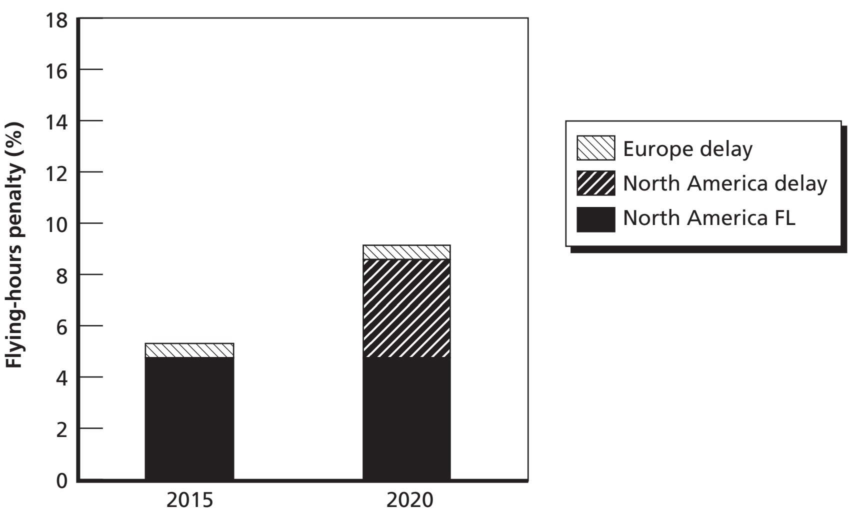
European and North American airspace. The more substantial increase occurs in 2020 in the North American region, which has highest percentage of KC-10 flying operations. There are no CNS/ATM mandates scheduled after 2020. The increases in fuel usage are 13.0 percent in 2015 and 16.3 percent in 2020.

Figure 3.4 depicts the increase in flying hours due to noncompliance. As in Figure 3.3, the increase is separated into the contributions attributable to altitude restrictions and delays, by region. Flight delays and flying at lower altitudes both lead to an increase in the annual flight hours required to carry out KC-10 missions. The percentage increases in flying hours are 5.0 percent in 2015 and 8.9 percent in 2020.

## Cost Avoidance from CNS/ATM Modernization

The increases in flight time and fuel usage shown in Figures 3.3 and 3.4 can be translated into monetary costs. In Figures 3.5 through 3.8, we present these costs in terms of net present value (NPV). Future years'

**Figure 3.4**
**Flying-Hour Penalty Due to Flight-Level Restrictions and Flight Delays**

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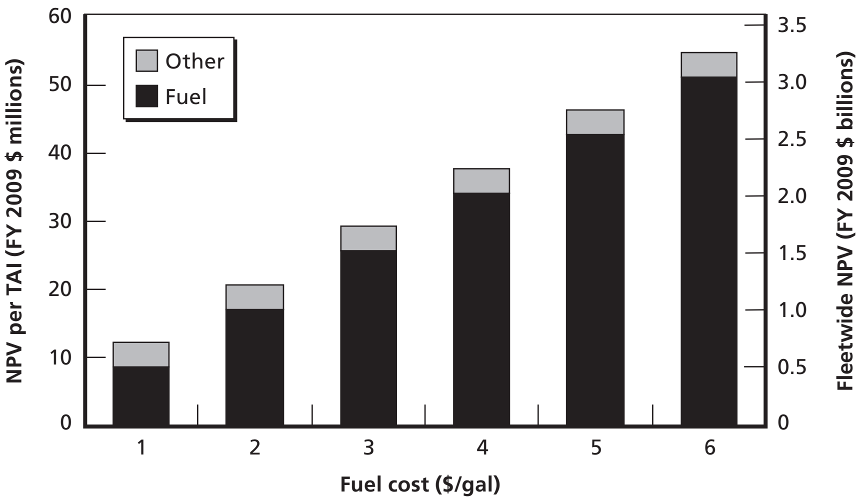
cost avoidance is discounted to account for the time-value of money.[5] Savings do not start until 2015, because that is the year in which the mandates are scheduled to come into effect. The calculation ends in 2045, the projected year of retirement of the KC-10 fleet. All costs are in base-year FY 2009 dollars, which account for inflation as forecast by the U.S. Department of Defense (DoD). If the real cost of nonfuel flying-hour-related items increases faster than the postulated inflation in DoD assumptions, the future cost avoidance from modernization would be greater. (FY 2009 dollars are used throughout this analysis.)

Figure 3.5 shows the cost avoidance should the KC-10 meet all CNS/ATM mandates, from both the fuel saved and the avoidance of

**Figure 3.5**
**Cost Avoidance Due to CNS Upgrade**




NOTE: The figure assumes 0-percent real nonfuel cost growth.
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5 NPV is the appropriate way to judge modernization investments based on true resource cost. A payment that is delayed can be invested productively until required, which lowers its effective cost by the amount of the return on investment. To this end, the Office of Management and Budget (OMB) directs this type of discounted analysis. We used the most recently available (December 2008) OMB-directed real long-term discount rate of 2.8 percent, which represents the "return on investment," in our analysis (OMB, 2008).

other flying-hour-related costs. The left vertical axis shows the NPV in millions of dollars saved per aircraft. The right vertical axis shows the NPV in billions of dollars for the fleet of 59 aircraft. NPV represents the sum of all cost avoidance for the KC-10 fleet between the years 2015 and 2045.

Most of the cost avoidance from CNS/ATM modernization results from fuel savings, with some additional savings from avoiding flying-hour-related personnel, contractor support, and other costs. It follows, then, that the dollar amount of the cost avoidance is closely tied to the cost of fuel. The black portion of each bar in Figure 3.5 represents the cost avoidance due to fuel costs alone. The smaller, gray portion of each bar represents the cost avoidance from nonfuel-related costs.

Figure 3.6 shows the same cost avoidance as Figure 3.5 but also includes results for 2.5-, 5-, and 7.5-percent real annual nonfuel cost growth.[6]

The Air Force recently released a standard cost of fuel for analytical calculations of $2.90 per gallon (AFI 65-503, 1994). This number is used to estimate costs for current operations and applies to budget years 2008 and 2009. Since there is no official long-term fuel cost forecast, this number is generally recognized as a reasonable base-case assumption for estimating costs in future operations. However, the cost of jet fuel recently neared $4 per gallon and historically has been closer to $2. Figure 3.6 shows the cost avoidance estimated at any combination of future jet fuel price and nonfuel flying-hour-related real cost growth.

## Cost to Upgrade the KC-10 to Be CNS/ATM Compliant

The KC-10 fleet must be modernized to meet the upcoming CNS/ATM mandates in order to realize the cost avoidance presented in Figure 3.6. The cost of the upgrade relative to the expected cost

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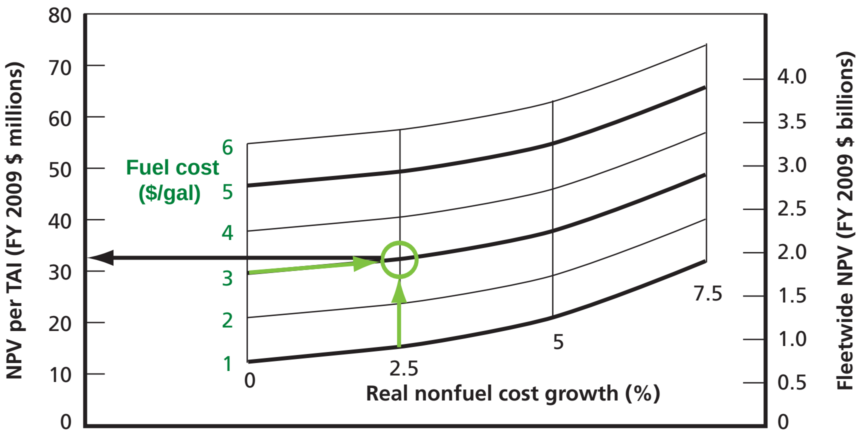
[6] In the example in the figure, we assume a constant, real $3-per-gallon fuel cost and real nonfuel cost growth of 2.5 percent. The intersection of these values (denoted by the green circle) relative to the left vertical axis is the NPV of the savings—$32 million in this example. In the regression analysis of the AFTOC data, the historical growth rate of the real cost of nonfuel flying-hour-related items was 5 percent per year.

**Figure 3.6**
**Cost Avoidance Due to CNS Upgrade at Alternative Levels of Annual, Real Nonfuel Cost Growth**

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avoidance determines whether the modernization is cost-effective based on steady-state operation costs alone; wartime effectiveness benefits are an additional factor and are considered later. To obtain an estimate of the modernization costs, we were given access to CRSs from five contractors on the broad modernization of the KC-10 under the KC-10 AMP program. Of the five studies, two had cost information at a level of detail sufficient to attribute costs to specific CNS upgrades. Cost estimates included both hardware and installation. The specific items are as follows:

- communication management
- Electronic Flight Instrumentation System
- Electronic Standby Instrumentation System
- flight management systems
- navigation sensors
- SATCOM
- VDL
- initial spares, training, data, and support equipment
- system development and demonstration.

Table 3.1 shows the cost estimates per aircraft. These cost estimates include a very similar set of components to those in the current program of record for KC-10 CNS/ATM modernization. The cost estimate for the current program is $5.9 million per TAI in FY 2009 dollars, so the contractor-based estimates are somewhat higher. Acknowledging the uncertainties in cost estimates and factors that are unknown until a specific configuration is established and the first aircraft modified, we show a 50-percent level of growth in upgrade cost overall in the figures.

## Cost-Effectiveness of Upgrading the KC-10 to Be CNS/ATM Compliant

Figure 3.7 illustrates both the estimated upgrade costs and future cost avoidance for a range of fuel costs and rates of real nonfuel cost growth. The upgrade cost shown in Figure 3.7 is the average of the two contractor-based estimates and, in all cases, is less then the NPV cost avoidance. The left set of bars, shaded red, shows the cost avoidance generated by avoiding altitude restrictions and flying at optimal altitudes. The blue bars show the cost avoidance from both flying at optimal altitudes and avoiding delays. The dashed extensions of each bar show the total cost avoidance should the real cost of nonfuel-related items grow at 2.5 and 5 percent, respectively.

**Table 3.1**
**Cost Estimates for KC-10 CNS/ATM Modernization**

| | KC-10 CNS/ATM Upgrade | |
|---|---|---|
| **Cost Estimate** | **Cost per TAI (FY 2009 $ millions)** | **Fleet Cost (FY 2009 $ millions)** |
| Cost estimate A | 7.5 | 443 |
| Cost estimate B | 6.9 | 407 |
| System Program Office estimate | 5.9 | 351 |

**Figure 3.7**
**CNS Upgrade Cost Versus Cost Avoidance Due to CNS Upgrade**

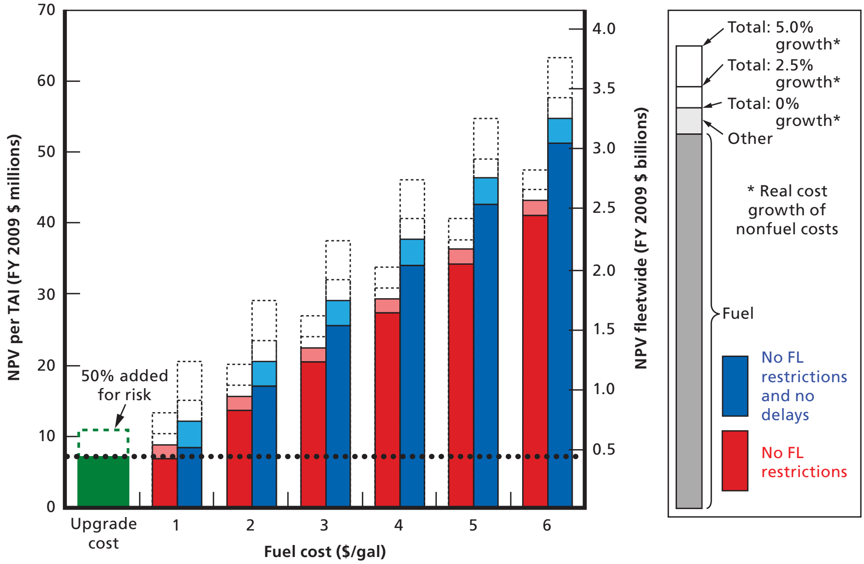


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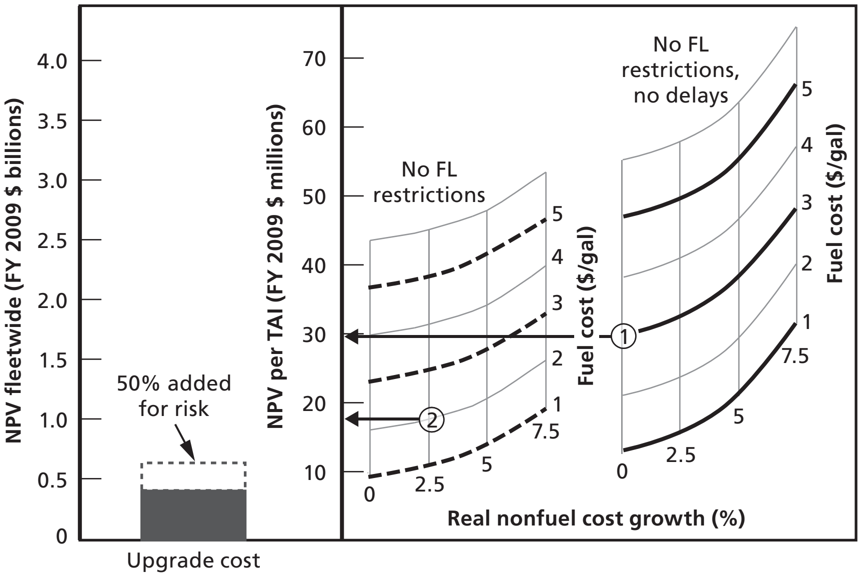
Figure 3.8 shows the estimated cost avoidance and upgrade cost in a different format, providing the cost avoidance over a range of fuel prices and real cost growth of nonfuel costs. On the left side of the figure, the green column is the average of the two contractor-based estimates of upgrade costs, as in Figure 3.7. Moving to the right, the two grids can be used to determine NPV cost avoidance based on the cost of fuel per gallon and real cost growth of nonfuel items. The left grid shows cost avoidance from avoiding altitude restrictions alone, and the right grid shows cost avoidance based on avoiding both altitude restrictions and delays.

For example, using cost avoidance from both FL restrictions and delays, we assume a $3-per-gallon fuel cost and 0-percent real cost growth, resulting in approximately $29 million in cost avoidance per aircraft. This $29 million is well above either of the cost estimates to acquire the CNS upgrades. Under these assumptions, there would be NPV savings to the Air Force unless the upgrade costs per aircraft exceeded $29 million. As another example, using only cost avoidance

**Figure 3.8**
**CNS Upgrade Cost Versus Cost Avoidance Due to CNS Upgrade (detail)**

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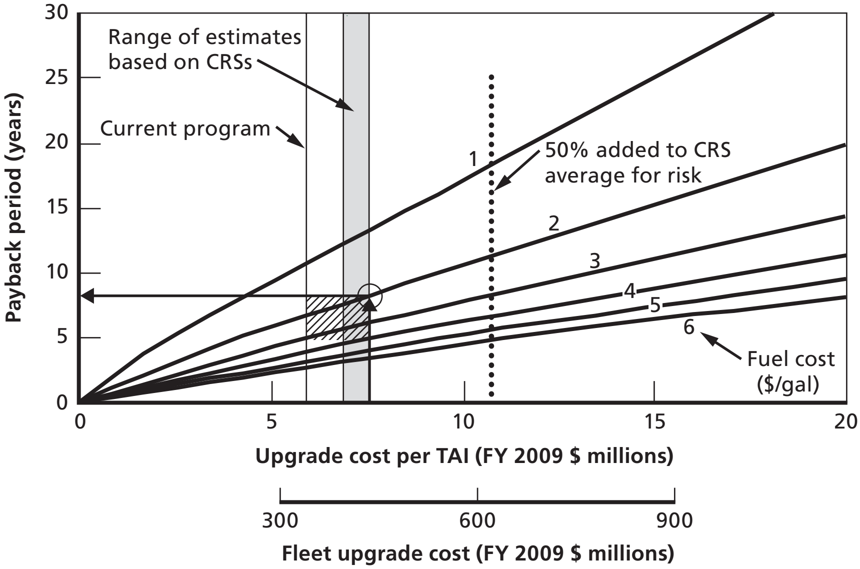
from circumventing altitude restrictions, we assume a $2-per-gallon fuel cost and 2.5-percent real cost growth, leading to approximately $17 million in cost avoidance. As noted earlier, in the regression analysis of the AFTOC KC-10 cost data, the historical rate of growth of the real cost of nonfuel flying-hour-related items was 5 percent per year. Figure 3.8 shows results for 0-, 2.5-, 5-, and 7.5-percent real annual growth.

Another informative indicator of the value of a modernization investment is its payback period. Payback period does not account for the time value of money. Figure 3.9 presents the payback period based on the upgrade cost per TAI and the price of fuel. The vertical lines represent the estimated cost of the current program and the two contractor-based estimates. In this figure, the real cost growth of nonfuel items is assumed to be 0 percent.

**Figure 3.9**
**Payback Period**

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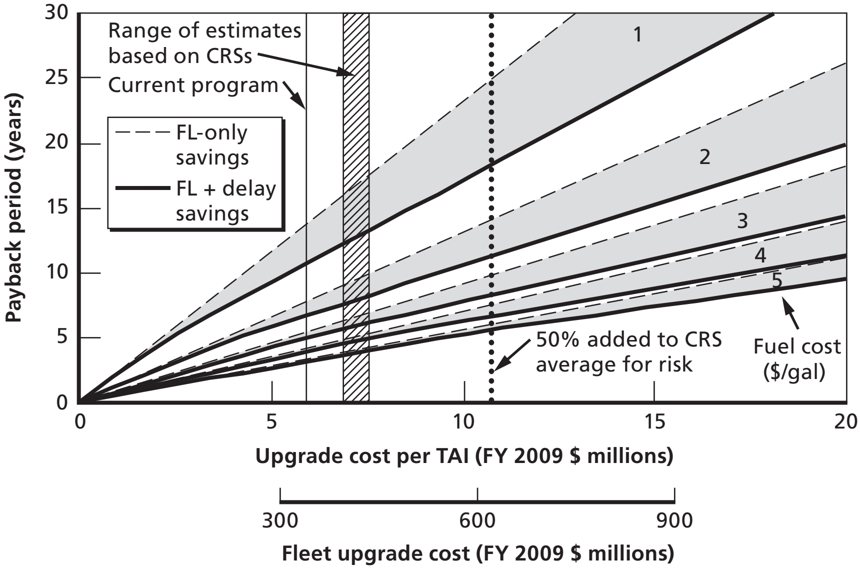
For example, with an upgrade cost per TAI of $7.5 million and a fuel cost of $2 per gallon, the payback period is approximately ten years. Note that cost avoidance would not start until 2015, and the figure assumes that the entire fleet is modernized prior to 2015.

Figure 3.10 shows the payback period using two different assumptions for cost avoidance. The bottom bound for each fuel cost, which is based on the cost avoidance of both circumventing altitude restrictions and avoiding delays, is the same as in Figure 3.9. The top bound for each fuel cost shows the payback period based only on the cost avoidance of circumventing altitude restrictions. Using the lesser amount of cost avoidance, the payback period is no more than two years longer in the range of estimated upgrade costs and fuel costs greater than $2 per gallon.

**Figure 3.10**
**Payback Period with Two Levels of Savings**

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## Observations

Our analysis of steady-state KC-10 operational costs with and without CNS/ATM modernization found that the NPV of the cost avoidance from the upgrade is substantially greater than the cost of the upgrade. This is true even in the conservative scenario of $1-per-gallon fuel costs and zero real cost growth of nonfuel items. We found that the payback period is about 15 years using these conservative assumptions. Less conservative assumptions result in a payback period of six to eight years.

CHAPTER FOUR

# Operational Benefits of CNS/ATM Modernization

In Chapter Three, we showed that the NPV cost avoidance from escaping the penalties of CNS/ATM noncompliance are greater than the costs to modernize the KC-10 to meet the CNS/ATM mandates. In this chapter, we address the wartime effectiveness implications of meeting global CNS/ATM mandates. We analyzed which types of wartime tanker operations are affected by not modernizing, and we present here the implications of noncompliance on tanker effectiveness. In addition, there are several benefits to modernizing that do not necessarily decrease cost or improve wartime effectiveness but that add to the flexibility of the fleet in meeting requirements. These benefits include increasing airport access and maintaining access to existing air refueling airspace.

## Warfighting Missions

To determine the warfighting impact of not modernizing the KC-10, we first determined which specific missions would be affected. This determination is based on consideration of the wartime scenario and judgment about whether ATM mandates would be enforced. There is no certainty about this future condition, so our assessments are based on judgment and experience. We have discussed these issues with many informed military and political experts, but the ultimate judgment is our own. We analyzed seven broad tanker missions. Three were not affected by CNS/ATM mandates—namely, homeland defense, Operations Plan (OPLAN) 8010 (Strategic Deterrence and Global Strike), and employment. The four missions affected by the mandates are deployment, air bridge, national reserve, and global strike. Each of these is discussed in more detail later in this chapter. Our analysis of these missions is based on in the information in the KC-X AoA,[1] the *Mobility Capabilities Study* (DoD and JCS, 2005), and tanker doctrine as found in Joint Publication 3-17 (JCS, 2002).

### Wartime Missions Not Affected by CNS/ATM Modernization

The CNS/ATM mandates do not have an impact on the wartime effectiveness of homeland defense, OPLAN 8010, and employment missions.

In terms of homeland defense, we considered a scenario similar to that in the United States after the terrorist attacks of September 11, 2001. In our scenario, fighter combat air patrols are in place over major U.S. cities and other critical locations. These patrols require air refueling support and a high fuel state to engage any potential adversaries. In this situation, civil ATC authorities would likely grant waivers to tanker aircraft that are noncompliant to ensure national security.

OPLAN 8010 refers to a large-scale nuclear strike mission. Given the gravity of conducting a massive nuclear strike against an enemy, compliance with CNS/ATM mandates will likely not be required.

For employment missions, CNS/ATM mandates would be waived if the noncompliant aircraft were flying combat sorties. If a country were willing to base U.S. military aircraft, it would likely waive CNS/ATM requirements to transit its airspace. For this same reason, we concluded that missions in Iraq and Afghanistan would not be affected by CNS/ATM mandates.[2]

The wartime tanker missions that would be affected by noncompliance with CNS/ATM mandates include deployment, air bridge, national reserve, and global strike. To model these wartime missions, we used mission descriptions from the KC-X AoA. To measure effec-

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1 By "KC-X AoA," here and throughout this monograph, we are referring specifically to the "Analysis of Alternatives (AoA) for KC-135 Recapitalization" study conducted by RAND in 2005 (see Kennedy et al., 2006).

2 Stillion, Orletsky, and Fitzmartin (2006) provide detailed descriptions of these missions.

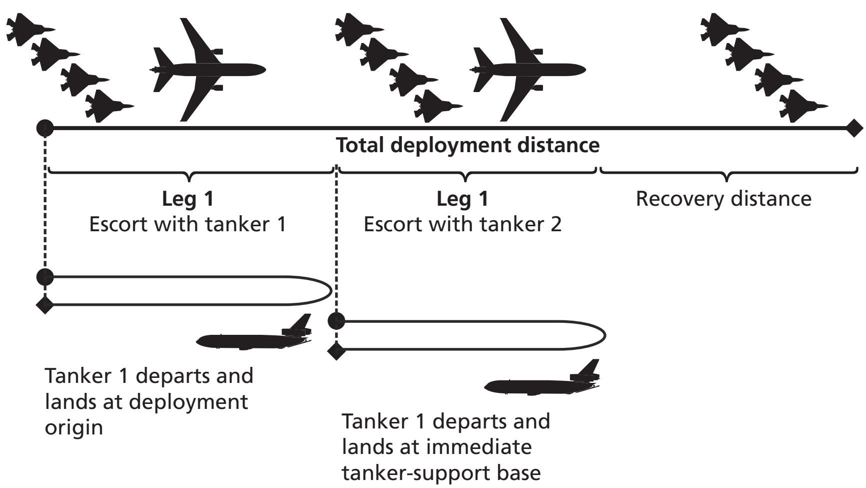
tiveness, we calculated the number of tankers required to conduct each mission under conditions of both compliance and noncompliance with CNS/ATM mandates. All wartime effectiveness assessments were conducted for the year 2025 and are based on the structure of the receiver fleet (that is, the aircraft being refueled), as projected for that year in the KC-X AoA.

**Deployment**

The tanker deployment mission entails refueling military aircraft deploying to a theater of operation over ranges that the receiver aircraft could not transit without aerial refueling. The mission is represented as a series of legs. Along each leg, one tanker aircraft accompanies the receiver aircraft package and then returns to the base from which it departed. The length of the individual legs is determined by the capability of the KC-10 under both compliant and noncompliant conditions. Figure 4.1 presents the deployment mission.

Included in this mission are four different types of deployment packages, representing the refueling demands of different types of

**Figure 4.1**
**Tanker Deployment Mission**

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aircraft. The packages are small fighters (e.g., F-16, unmanned combat air vehicle, AV-8), medium fighters (e.g., F-35), large fighters (e.g., F-15, F-22), and heavy aircraft (e.g., E-A, E-8, RC-135).

Figure 4.2 shows the deployment missions that we evaluated in this study. We model deployment missions flying to each of the five combatant commands (COCOMs) using the representative distances shown in the figure: from U.S. Northern Command (USNORTHCOM) to U.S. European Command (USEUCOM), U.S. Pacific Command (USPACOM), U.S. Central Command (USCENTCOM), U.S. Southern Command (USSOUTHCOM), and U.S. African Command (USAFRICOM). These missions transit more than one ICAO region, and the impact of noncompliance on overall effectiveness depends on how much of the mission is flown in each region.

### Global Strike, Air Bridge, and National Reserve Missions

Although global strike, air bridge, and national reserve missions vary in their overall military purpose and goals, they are very similar from the perspective of the tanker operations required to support them. In these missions, large aircraft receive a single substantial offload from the tanker to extend their range, rather than requiring a continuous escort as in the deployment mission. These missions are modeled with the tanker flying 1,000 nautical miles to meet the heavy receiver and then offloading at 5,500 pounds per minute, retaining enough fuel to return to its originating base with reserves. This scenario is shown in Figure 4.3. In our models, these missions take place wholly in a single ICAO region.

## Operational Impact of Noncompliance with Mandates

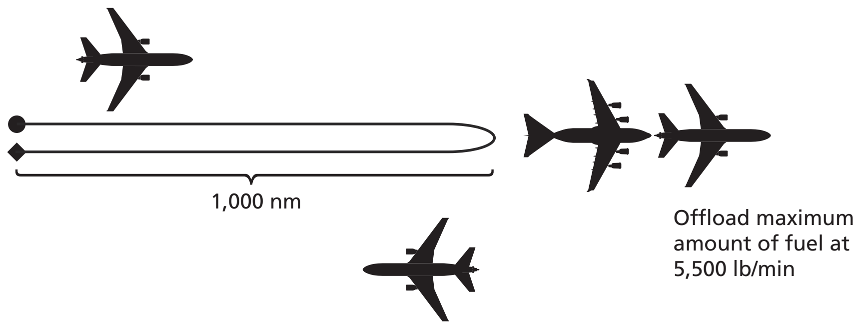
We now present our analysis of the impact of the KC-10's noncompliance with the mandates in terms of operational effectiveness. We begin with the deployment effectiveness decrement due to noncompliance in each ICAO region. This decrement relates to the number of tankers required to perform a mission and is the ratio of required compliant tankers to required noncompliant tankers. We then show the

**Figure 4.2**
**Deployment Distances to Each COCOM**


| COCOM | Distance (nm) |
|---|---|
| USEUCOM | 5,000 |
| USPACOM | 6,750 |
| USCENTCOM | 5,000 |
| USSOUTHCOM | 5,000 |
| USAFRICOM | 6,750 |

RAND *MG901-4.2*

**Figure 4.3**
**Global Strike, Air Bridge, and National Reserve Missions**




RAND *MG901-4.3*

effectiveness decrement for deployment missions to each of the five COCOMs, which depends on how much of each COCOM deployment is flown in each ICAO region (due to the unique mandates in each region as shown in Figure 2.2 in Chapter Two).

Figure 4.4 shows the deployment effectiveness of an unmodified KC-10 in 2025 relative to the effectiveness of a compliant KC-10. We present the information in this manner because a modernized KC-10 that meets all CNS/ATM mandates maintains the wartime effectiveness of the current fleet. That is, modernizing to meet CNS/ATM mandates maintains 100-percent effectiveness of the KC-10 fleet, while an effectiveness decrement will result for a noncompliant KC-10 operating under the new mandates. The region in which the KC-10 is most affected is North America, but most deployment missions require relatively little time in that region. In the Europe and North Atlantic regions, the KC-10 is affected to a lesser degree. In the other ICAO regions, the KC-10 is not affected.

Table 4.1 shows the effectiveness of an unmodified KC-10 relative to that of a compliant KC-10 in deploying from CONUS to each of the COCOMs. The effectiveness values range from 93 percent for deployments to USSOUTHCOM to 100 percent (i.e., no effectiveness decrement) for deployments to USPACOM.

**Figure 4.4**
**Deployment Effectiveness of an Unmodified KC-10 Relative to That of a Fully Compliant KC-10, by ICAO Region, 2025**

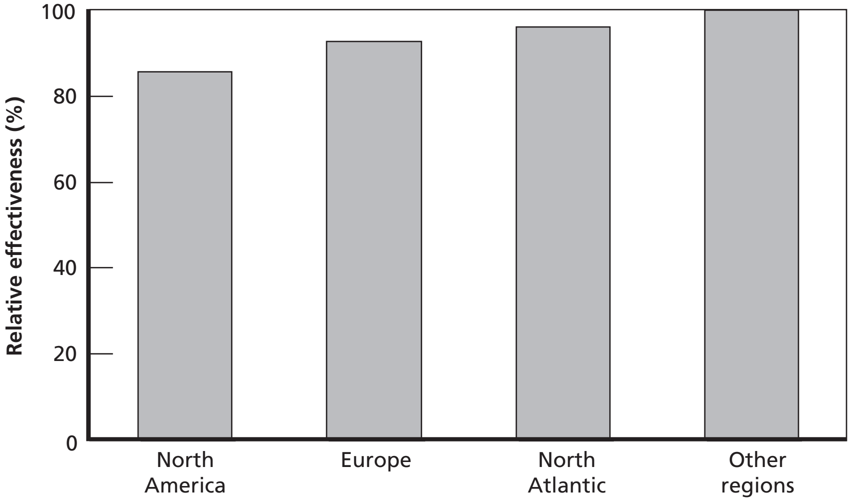



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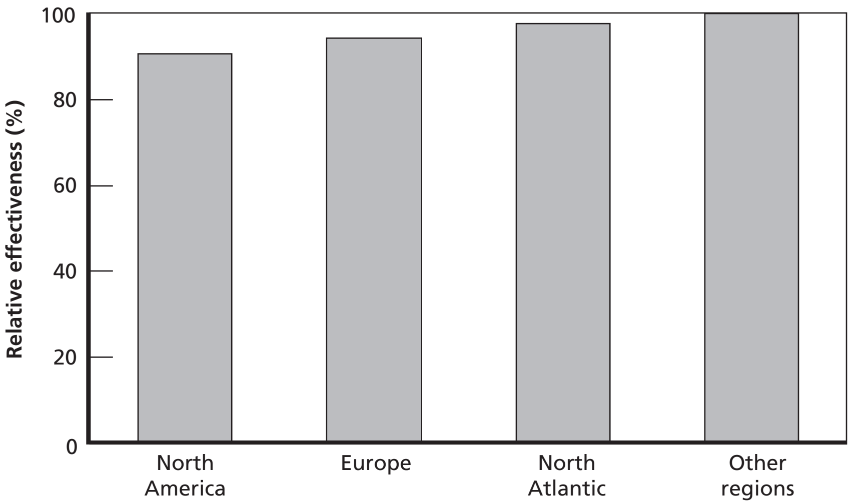
**Table 4.1**
**Combatant Commands, ICAO Regions, and Aggregate Deployment Effectiveness**

| COCOM | ICAO Regions Transited | Aggregate Effectiveness (%) |
|---|---|---|
| USEUCOM | North Atlantic, Europe | 95 |
| USPACOM | Pacific, Asia | 100 |
| USCENTCOM | North Atlantic, Europe, Asia | 95 |
| USSOUTHCOM | North America, Caribbean and South America | 93 |
| USAFRICOM | North Atlantic, Africa | 99 |

We now consider the other air refueling missions of global strike, air bridge, and national reserve operations. Figure 4.5 shows the effectiveness of these missions in each ICAO region. As stated earlier, we modeled these missions as taking place wholly within a given ICAO region. The average effectiveness across all ICAO regions for these

**Figure 4.5**
**Global Strike, Air Bridge, and National Reserve Mission Effectiveness of an Unmodified KC-10 Relative to That of a Fully Compliant KC-10, by ICAO Region, 2025**

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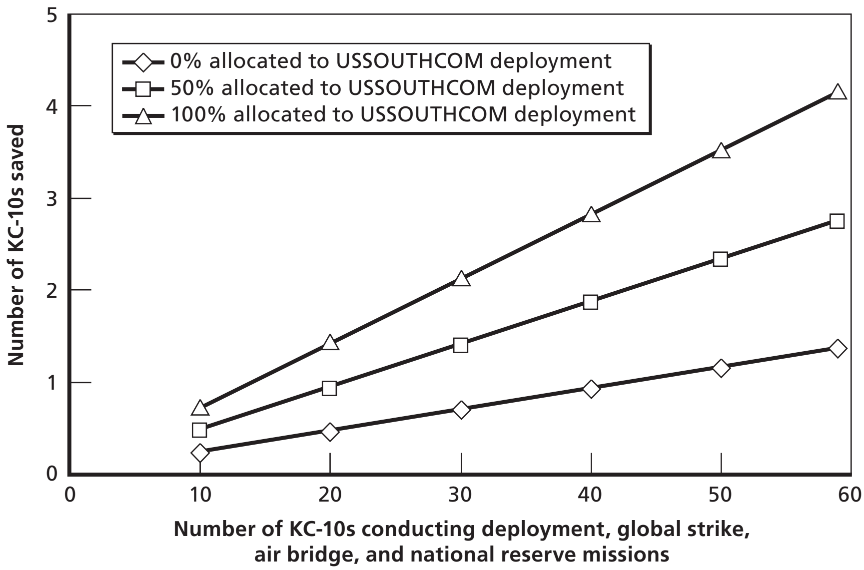
missions is 97.7 percent, and we use this average as the overall decrement for these missions, taking operations in each region as equally likely.

The decrement in wartime effectiveness can be related to the number of tankers required to meet the overall wartime requirement. Without the upgrade, a greater number of tankers would be required to carry out the same set of missions.

For example, assume that a particular set of missions requires 100 tankers before CNS/ATM mandates are in place and that, without CNS/ATM modernization, the tankers become 95-percent effective after the mandates take effect. Then, for that same set of missions, 106 tankers (100/0.95, rounded to next whole tanker) would be required instead of the original 100. Figure 4.6 presents a parametric evaluation of the number of KC-10s whose contribution to the wartime set of missions would be lost if modernization is not performed. To maintain the same wartime effectiveness, an equivalent number of additional tankers, KC-Xs, would have to be procured.

**Figure 4.6**
**Parametric Evaluation of Tankers Saved Relative to the Number Devoted to Different Missions**

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The horizontal axis in Figure 4.6 shows the number of tankers devoted to the missions on which the CNS/ATM mandates have an impact. Each line in the figure represents a different fraction of those aircraft devoted to the deployment mission,[3] as opposed to the global strike, air bridge, or national reserve missions. For example, say 40 KC-10s are devoted to deployment, global strike, air bridge, and national reserve missions, with half (20 KC-10s) flying deployment missions and the other half flying global strike, air bridge, and national reserve missions. In this case, the contribution of two KC-10s would be lost if the CNS/ATM upgrades were not performed. According to the analysis in the KC-X AoA, the monetary savings (NPV) of avoiding the acquisition and operation of an equivalent number of additional

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[3] In the figure, we use a USSOUTHCOM deployment mission, which is the mission with the greatest savings resulting from CNS/ATM modernization. The figure could be constructed with any of the deployment missions, however.

KC-X tankers would be $625 million in FY 2009 dollars, or $10.6 million per KC-10. This is comparable to the estimated KC-10 CNS/ATM modernization cost.

## Airport and Airspace Access

There are other issues and concerns that are important to consider with regard to tanker CNS/ATM modernization that do not necessarily decrease cost or improve wartime effectiveness but that add to the flexibility of the fleet in meeting requirements. These are (1) the amount of additional airport access provided by RNP 0.15–0.3, (2) the impact of being excluded from OEP airports, (3) the impact on accessing established air refueling tracks, and (4) the impact of potentially being excluded from European airspace. This section addresses each of these concerns in turn.

### Additional Airport Access Provided by RNP 0.15–0.3

An aircraft that has RNP 0.3 (or better) capability has the potential to land on runways that do not accommodate ground-based instrument approaches. This capability could allow the KC-10 to land at a greater number of airports that have a runway for which the only instrument approach is not built on ground-based navigational aids. For an airport to be newly accessible to the KC-10 because of RNP 0.15–0.3, it must both be able to accommodate the physical size of the KC-10 and have an RNP instrument approach that is surveyed and published. During the course of this work, we examined runways worldwide that were longer than 7,000 feet, the minimum required runway for KC-10 operations.[4] Our goal was to identify the number of additional runways (and their locations) that would become accessible to the modernized KC-10. In total, we examined 2,421 runways and found that 228 had only a GPS instrument approach, while 2,193 had at least one instrument approach other than GPS. Therefore, if the KC-10 had RNP 0.3

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[4] The minimum runway length for the KC-10, according to Air Force Policy (AFI 11-2KC-10, 2006) is 7,000 feet.

(or better) capability today, we could expect an additional 228 runways to be available for operations. Most of these sites, however, are located in CONUS. Figure 4.7 shows the geographic distribution of these 228 additional runways, and Figure 4.8 shows the actual location of each of the airports that have these runways. Of the 228 runways, 39 are outside CONUS at 26 different airports.

More important than the current number of additional runways and their locations where the KC-10 could conduct instrument approaches is the realization that, to best take advantage of this capability, there must be an accompanying ability to rapidly produce instrument approach procedures. Even more airports outside CONUS—beyond the 26 shown in Figure 4.8—could be accessible for an RNP 0.3–capable KC-10 if RNP 0.3 procedures were developed for those airports. Possible locations to exploit this capability would typically have poor aviation infrastructure that does not currently support the equipment for instrument approaches (i.e., in Africa). Although these sites would not require additional ground equipment, they would

**Figure 4.7**
**Geographic Distribution of Additional Runways Available to the KC-10 with RNP 0.3 Capability**

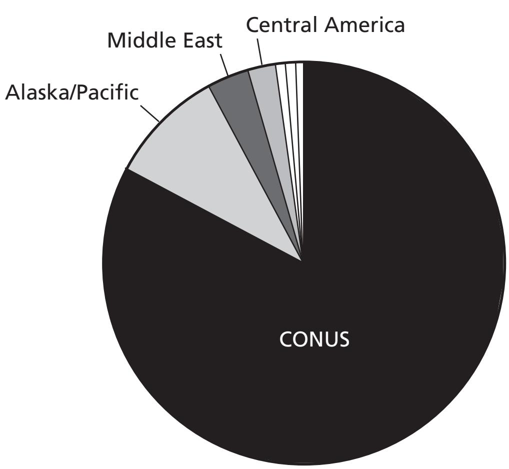


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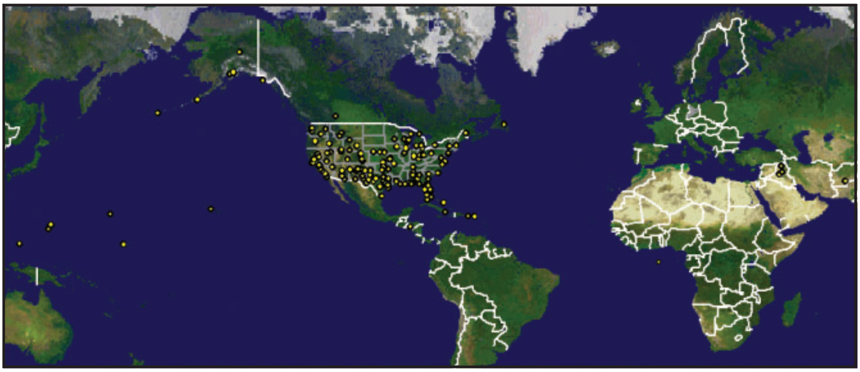
**Figure 4.8**
**Location of Additional Airports Available to the KC-10 with RNP 0.3 Capability**



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require that the RNP 0.3 instrument approach procedures be surveyed and constructed. The ability to rapidly develop these procedures is important and would allow greatest leverage of RNP 0.3 capability.

## Impact of Exclusion from OEP Airports

We now consider the impact of being excluded from OEP airports.[5] Mandates for RNAV 1 are proposed to operate at FAA OEP airports in 2015. The KC-10 infrequently transits OEP airports, with the exception of Honolulu International, which is a joint-use airport with Hickam AFB. Counting Honolulu, 4 percent of KC-10 sorties transit OEP airports. This percentage drops to less than 0.5 percent if Honolulu is not counted. As a result, the only major effect of these mandates on KC-10 operations would be at Hickam AFB.

## Impact on Access to Established Air Refueling Tracks

We now consider the impact of not modernizing KC-10 avionics' ability to access established air refueling tracks. As discussed earlier, by 2015, CNS/ATM upgrades will be required for operations above FL180

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5 As designated by the FAA and Congress, OEP airports are the 35 busiest airports in the United States.

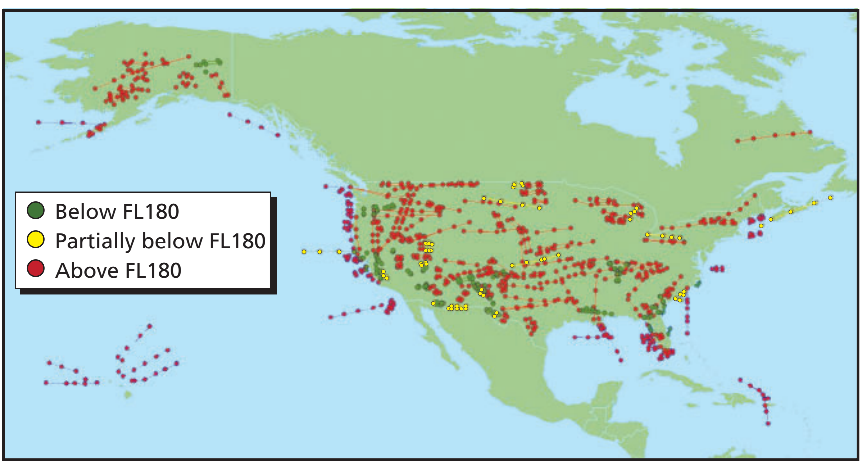
in the North American ICAO region. This would have a significant impact on the KC-10, since many of the established CONUS air refueling tracks are located above FL180. Figure 4.9 shows the locations of the refueling tracks and their altitudes compared to FL180. Seventy percent of all tracks are completely above FL180. The loss of access to these established refueling locations and altitudes would preclude a majority of military air refueling training missions.

Changing the altitude of an air refueling track currently requires coordination with the FAA (FAA, 2008b). However, should the military attempt to make several tracks lower than FL180, it might face resistance from the civil aviation community. As a result, trying to establish and use the same tracks at a lower altitude may prove difficult for the Air Force.

### Impact of Exclusion from European Airspace

An exclusion scenario is often discussed when the subject of noncompliance with CNS/ATM is raised. While it is a possibility, we do not judge it likely that an aircraft would be excluded entirely. Rather, noncompliant aircraft would be subject to altitude restrictions and delays,

**Figure 4.9**
**Location of Air Refueling Tracks Relative to FL180**

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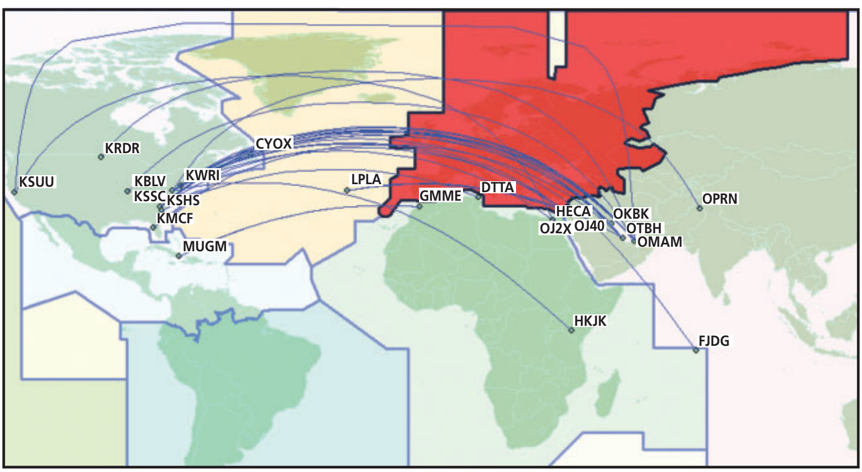
which is how we have modeled all the results to this point. However, to illustrate the impact of exclusions on KC-10 operations, we present the following analysis.

Twelve percent of KC-10 sorties originated or terminated in the European ICAO region. The KC-10 could not accomplish these sorties if it were excluded, so its missions would need to be carried out in another manner. There are two alternative possibilities. The first is to use the KC-10 to carry out the mission but to avoid a stop in Europe. The second is to use a different aircraft for the mission. Depending on the mission, neither of these potential workarounds may be available.

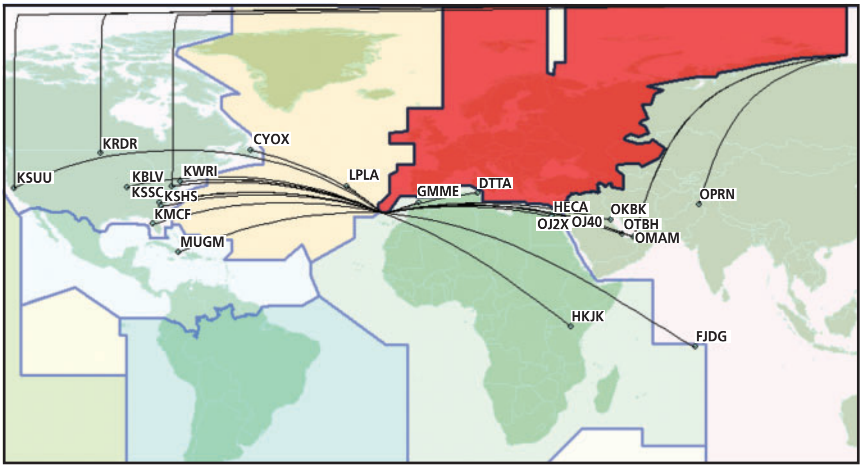
A much smaller number of sorties, 0.7 percent, transited Europe without taking off or landing in the European ICAO region. Figure 4.10 shows the departure and arrival pairs of those sorties connected by a great circle (which is not necessarily the actual flight path of the sortie). Figure 4.11 shows flight paths for these sorties if they were to fly around the European ICAO region.

**Figure 4.10**
**KC-10 Sorties That Transited Europe Without Taking Off or Landing in the European ICAO Region**




NOTE: Departure and arrival locations are identified by airport code.
RAND *MG901-4.10*

**Figure 4.11**
**Flight Paths for Sorties Flying Around the European ICAO Region**




NOTE: Departure and arrival locations are identified by airport code.
RAND *MG901-4.11*

For KC-10 operations overall, avoiding the European region would result in only a 0.2-percent increase in fuel usage and flight time from the baseline, as characterized by the operations depicted in Figure 3.1 in Chapter Three. The increase is small because these particular sorties account for a small percentage of overall KC-10 flights (0.7 percent). However, for these sorties alone, there is a significant increase in fuel and flight hours. For these routes, flying around the European ICAO region increases fuel usage by 9 percent and flying hours by 7.7 percent.

## Observations

This chapter showed that not modernizing KC-10 avionics to comply with CNS/ATM mandates would negatively affect both wartime and steady-state operations. If the KC-10 is not modernized, between one and three more tankers—depending on how KC-10s are allocated to warfighting operations—will be required to carry out the same wartime deployment, global strike, air bridge, and national reserve operations.

After CNS/ATM mandates take effect, fully compliant KC-10s will maintain the same level of effectiveness as the current fleet. In addition to maintaining wartime mission effectiveness, KC-10 modernization has other benefits, including increased airport access and continued access to established air refueling tracks. Finally, the unlikely prospect of complete exclusion from the European region would minimally affect overall fuel usage and flying hours, but it would make operations and planning more difficult because missions would have to be conducted with different routings or alternative aircraft.

CHAPTER FIVE

# Conclusions

Future CNS/ATM mandates will be implemented over the coming years to enhance the efficiency of ATC systems worldwide. This increased efficiency will allow an increased number of aircraft to operate in a given volume of airspace without degrading existing levels of safety, but the mandates will require improvements to the CNS capabilities of the KC-10 and other aircraft. The impacts of noncompliance with upcoming CNS/ATM mandates include exclusion from optimal altitudes, air traffic delays, inefficient routings, and restricted access to busy airports and established air refueling tracks.

The Air Force's fleet of KC-10 aircraft has not undergone a major avionics upgrade in its lifetime. The KC-10 is compliant with some CNS/ATM mandates, but it has deficiencies that will need correction if the aircraft is to be fully compliant in the future.

In our analysis, we showed that modernizing KC-10 avionics to comply with CNS/ATM mandates results in operation cost avoidance (in terms of NPV) that exceeds the cost of the upgrade. We showed that this result is robust across a wide range of fuel costs, operation cost growth rates, and costs of the modernization options. The payback period will likely be around ten years, with the cost avoidance starting in 2015, when the first mandates come into effect.

In addition, KC-10 CNS/ATM modernization will maintain the effectiveness of the KC-10 fleet in wartime operations. If modernization does not occur, wartime effectiveness will be degraded. Successful execution of wartime missions under CNS/ATM mandates without modernization would require more tankers than is the case today. The cost of the additional tankers is comparable to the KC-10 CNS/ATM modernization cost. Furthermore, KC-10 modernization would confer other benefits, including increased airport access and continued access to established air refueling tracks.

APPENDIX

# KC-10 Assumptions and Nonfuel Cost Estimation

## KC-10 Aircraft

Table A.1 shows the characteristics of the Air Force's current KC-10 fleet that figured into our analysis.

## Nonfuel Costs

Our analysis of the relation of nonfuel costs to flying hours is based on data in the AFTOC database from 1996 to 2006. The data are presented in both then-year and FY 2008 dollars, and we based our analysis on the FY 2008 data. These data are escalated to FY 2009

**Table A.1**
**KC-10 Characteristics**

| KC-10 Fleet Characteristic | Number/Amount |
|---|---|
| Number of aircraft | 59 |
| Primary aircraft authorized | 54 |
| Flying hours per year per aircraft | 953 |
| Average KC-10 fuel flow | 18,872 lb/hr<br>2,817 gal/hr |
| Operating weight | Same for modernized and nonmodernized aircraft |

SOURCE: Information on flying hours per aircraft and average KC-10 fuel flow come from the AFTOC database, 1996–2006.

by the budget authority deflators in the 2009 "Green Book" (Office of the Under Secretary of Defense [Comptroller], 2008). We used the "military pay" escalation rate (1.034) for personnel, and the "operations and maintenance" escalation rate (1.020) for the other categories. The appropriate weighted average is 1.025 (see Table A.2).

We divided nonfuel costs into personnel (AFTOC category 1.0), contractor logistic support (AFTOC category 5.0), other unit-level consumption (AFTOC category 2.0, less category 2.1.1, which is fuel), and other nonfuel costs (all others). For each of these categories, we estimated the following equation:

$$\ln(C) = a + b\ln(F) + ct,$$

where $C$ is cost; $F$ is the number of flying hours; $t$ is an index of time; and $a$, $b$, and $c$ are the coefficients.

The results of the regression analysis are presented in Table A.2, along with each category's share of total nonfuel costs.

Table A.2 also shows, in the last row, the results of a regression of all nonfuel costs on $F$ and $t$. The coefficients in this equation are the same as the weighted averages of the coefficients of the four nonfuel categories of personnel, contractor logistic support, other unit-level

**Table A.2**
**Results of Regression Analysis of Nonfuel Costs (t-statistics in parentheses)**

| Cost Category | Share | Coefficient on $F$ ($b$) | Coefficient on $t$ ($c$) |
|---|---|---|---|
| Personnel | 0.35 | 0.13<br>(3.0) | 0.032<br>(15.6) |
| Contractor logistic support | 0.57 | 0.31<br>(1.1) | 0.064<br>(5.0) |
| Other unit-level consumption | 0.05 | 0.67<br>(1.9) | 0.080<br>(4.7) |
| Other nonfuel | 0.03 | 0.40<br>(0.4) | 0.019<br>(0.4) |
| Total nonfuel | 1.00 | 0.26<br>(1.3) | 0.051<br>(5.3) |

consumption, and other nonfuel costs. For clarity of presentation, we use this overall regression to project how nonfuel costs change with flying hours and time. The *b* value of 0.26 implies that a 10-percent increase in flying hours leads to a 2.6-percent increase in nonfuel costs; the *c* value of 0.051 implies that nonfuel costs increased, on average, 5.1 percent per year more than inflation over the 1996–2006 period.

The t-statistic of 1.3 for the coefficient *b* implies that a zero value for the impact of flying hours on nonfuel costs cannot be statistically rejected at the 95-percent confidence level. For our base-case results, we used the 0.26 value, which is statistically the best estimate based on the data; we also show fuel cost savings only, which is the total savings if the number of flying hours has no impact on nonfuel costs. One reviewer of this monograph argued that, since Air Force staffing policy is based on a given wartime surge flying program, flying hours should have no impact on personnel costs. The historical data imply that the relation between personnel costs and flying hours is the strongest statistically (t-statistic = 3.0); however, the coefficient is relatively low (0.13). If this coefficient were constrained to zero, the overall coefficient would fall from 0.26 to 0.21, and this would not change the nature of our results.

The historical data also imply that nonfuel costs have risen about 5 percent per year more than inflation during the 1996–2006 period. To be conservative in our cost-saving estimates, our base case is that this phenomenon stops and that, in the future, nonfuel costs rise only at the overall rate of inflation. We include a 5-percent case as well.

By using this historical relation for projection, we are assuming that modernized aircraft have the same relation of nonfuel costs to flying hours as current KC-10s, or that the underlying reliability and maintainability factors do not change as a result of modernization.

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