SUSTAINABILITY OF THE TF33 ENGINE

A CASE TO RE-ENGINE THE E-3 AWACS

GRADUATE RESEARCH PROJECT

Sean T. Stephens, Captain, USAF

AFIT-ENS-MS-20-J-053

DEPARTMENT OF THE AIR FORCE
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Wright-Patterson Air Force Base, Ohio

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Abstract

The JT3D jet engine developed by Pratt & Whitney in 1950s or TF33 as it is designated in the U.S. Airforce, was a top of the line jet engine used widely in the airline industry as well as in multiple military aircraft for over fifty years. Much of the TF33 core was derived from the J-57 engine developed in 1940s. Since the 1940s and 1950s, jet engine technologies have advanced significantly with modern engines fielding improved fuel efficiency, reduction of carbon emissions and noise pollution, and increased major maintenance inspection intervals. The airline industry completely retired the once great JT3D engine from its fleets as early as the mid-1990s. The Air Force, on the other hand, still maintains thousands of these engines on critical platforms like the E-3 AWACS and B-52 Stratofortress, whose decaying engines are experiencing reduced supportability and sustainability ultimately causing reductions to aircraft availability and mission capability. Several studies were conducted in the 1990s and early 2000s proposing the re-engining of TF33 powered aircraft. This study will take an extensive look at past studies on re-engining of TF33 powered aircraft, the current re-engine program for the B-52, and an analysis of engine removal and replacement data for the E-3 AWACS fleet on Tinker Air Force Base from 2007 to 2019 in a case for re-engining or retiring the E-3 platform.

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Introduction

All engines require continual maintenance to operate, but ultimately have finite life spans. Component removal and maintenance inspection intervals are developed to sustain aircraft over decades and to forecast scheduled maintenance requirements for components and major inspections at depot maintenance facilities. Depot level maintenance on aging and worn components is essential to sustaining aircraft long term; however, components' time in depot or overhaul is time not spent on aircraft flying missions for national defense. To minimize impact to mission, maintenance must maximize scheduled inspection and component time change intervals without creating increased unscheduled maintenance discrepancies. The balance between sustaining and using aircraft engines must be exceptionally well scheduled as sustainable power plants are critical to maintaining safety of flight, and engine changes at non-scheduled intervals cause significant disruption to mission with high logistics and maintenance costs. Due to a multitude of factors and despite maintenance managers' best efforts, many engines are replaced well before their scheduled interval. This research will analyze TF33 engine removal and replacement data for the United States Air Force E-3 Airborne Warning and Control System (AWACS) platform to highlight the sustainability and future viability of the power plant. After an extensive review of past studies on TF33 powered aircraft, this study will analyze the TF33 dataset and offer a recommendation on the future of the TF33 with regards to the E-3 AWACS.

Background

The E-3 Sentry airborne warning and control system, or AWACS, was fielded in March of 1977 (af.mil/About-Us/Fact-Sheets, 2012). For 43 years the AWACS has continued to deploy across the world in support of war and humanitarian operations, ever evolving with improving technologies. Despite all the systems that have changed over the years, the AWACS propulsions system has maintained a Pratt Whitney TF33-100A since its inception (af.mil/About-Us/Fact-Sheets, 2012). The AWACS is one of the last platforms to still use this engine and the only platform to use its sub-model which has several non-recurring engineering and acquisitions costs specific to the E-3 (National Research Council, 2017). Designated the JT3D in commercial use, the TF33 began production in 1960 and powered the Boeing 707 and McDonnell Douglas DC-8 as well as numerous military aircraft since 1970 to today (Davis, 2017). Many military aircraft powered by the TF33 have been examined for re-engining through nine studies since 1984, and all aircraft studied were re-engined except the E-3, E-8, and B-52, and the B-52 is now undergoing re-engining. (National Research Council, 2007). Though all commercial aircraft have been re-fit with newer engines, there are still 1,100 TF33s in the Air Force inventory that power the E-3, B-52H, E-8, WC-135, and OC-135 fleets, almost half as many of the 2,300 that were available in 2007 (Davis, 2017). There are still 31 AWACS currently in the USAF inventory with four engines per aircraft, totaling 124 TF33 engines on aircraft at any given time. Since 1962, Tinker’s Propulsion Maintenance Group has repaired and overhauled over 14,448 TF33s (Davis, 2017). Insinna (2017) states “The clock is counting down for the Air Force to make a decision as age, obsolescence and diminishing sources for spare parts could make current engines unsustainable as early as 2030.”

Motivation

With the growing age of the TF33 engine and the ongoing operations for the aircraft it continues to power, it is becoming clearer that this engine cannot keep up with its airframes. Many of the fleets that once used the TF33 engine have already been re-engined, and it is well past time for the remaining airframes to follow suit (National Research Council, 2007). Several studies have been conducted for the re-engining of the E-3. However, they all have concluded that the reduced engine maintenance and fuel costs do not outweigh the utilization rate or service life of the platform (National Research Council, 2007). This recommendation was made under the assumption that a new AWACS platform would be available in the next decade or two. It is now 2020 and there is still no replacement in sight for the E-3. Therefore, the TF33 is still very much in use and the need to understand its ability to operate and predict its potential for failure is at an all-time high. Another important factor is that the depot costs to overhaul the TF33 has experienced a significant increase from $257,000 in FY96 to $1.25 million per engine in FY06 (National Research Council, 2007). The cost to overhaul the TF33 today is approximately $1.7 million (Kalin, 2019). Even adjusting for inflation, these cost increases to overhaul the TF33 is significant.

Figure 1: TF33 Overhaul Cost

FY	Then Year Cost	2020 cost with inflation
1996	$257,000	$429,394
2006	$1,250,000	$1,626,140
2019	$1,700,000	$1,747,047

(Source: https://data.bls.gov/cgi-bin/cpicalc.pl)

The current TF33 scheduled time to overhaul is every 6,000 flight hours; however, engine changes for the Tinker E-3 fleet from 2007-2019 indicates an average of 2,753.5 hours… less than half of the current scheduled time to overhaul. This means the $1.7 overhaul is occurring twice as often as it should for this fleet of engines. This study will elaborate on the variables that most significantly impact the TF33 from meeting its 6,000-hour requirement and conclude with a recommendation.

Purpose Statement

This research will examine past studies and recent articles on the E-3, TF33 powered aircraft, and the recent decision by the U.S. Air Force to re-engine the B-52. Adding to this current body of knowledge, this research will thoroughly examine engine change data from 2007 to the present and extrapolate trends and conclusions that can be used to further a case to re-engine or replace the E-3 fleet.

Research Questions

What is the current state of the TF33 on the U.S. E-3 AWACS? How sustainable is the TF33 and what is it costing the Air Force to continue to operate this engine? Does it make sense to re-engine the E-3?

Research Hypotheses

Hypothesis 1: Engines with higher total operating hours will be more likely to fail before the overhaul interval.

Hypothesis 2: The majority of engine defects causing the need for engine changes are non-preventable.

Hypothesis 3: The cost of unscheduled and off-location engine changes justifies re-engine and would pay back re-engine within a decade

Scope

The literature review section will cover the E-3 in general as well as the TF33 as part of the JT3D engine family and look at wide use across the airline industry as well as U.S. and allied military aircraft. The literature review will also examine proceedings regarding the re-engine of the B-52 and re-engine studies done on TF33 powered aircraft over the past three decades. The novel information in this research is engine removal data compiled along with charts, graphs and tables generated by the author. This data is only applicable to the TF33 sub model used on the USAF E-3 AWACS fleet maintained at Tinker Air Force Base. Foreign and NATO AWACS, and other U.S. fleets that use the TF33 were not examined and this study should not be correlated to those fleets directly.

Assumptions

Multiple assumptions were made to alleviate research and data collection constraints, but must be highlighted as they could have an impact on this research. This research assumed that all previous overhauls were of the same type and caliber, however there may have been different levels of overhaul and specific repairs for each engine. It was assumed that all engine usage is created equal, and location of missions and potential deployments were not factored in. Several of the engine changes were annotated at Al Dhafra Air Base, UAE. This extreme location may factor into increased or decreased sustainability. Some aircraft may also have flown into tropical zones regularly, whereas others stayed in temperate zones, some may have been closer to the ocean or farther away creating other issues. These varying geographies are not considered in this research as the data was not readily available to account for.

Literature Review

Many studies have been conducted on re-engining TF33 powered aircraft, highlighting various concerns; however, this research is assumed to be the first analysis which takes an in-depth examination of engine change data in regard to re-engining a platform. Before elaborating on the methodology, charts and trends of this research, it is necessary to lay out the foundations on which this research stands. Studies have been conducted on re-engining TF33 platforms since the 1980s; furthermore, operators, maintainers, congressmen, and anyone who thinks they have a say in the matter have been discussing re-engining the E-3 AWACS for almost three decades. It is imperative before diving into the engine change data that these reports, articles, and discussions are given due tribute here.

The preponderance of this research is on the TF33 power plant rather than the E-3 airframe, however, it is valuable to provide background on the E-3 and its characteristics. Approximately 68 E-3A/B/C/D/F and 8 KE-3A aircraft based on the Boeing 707 airframe were produced, with a final production completed in 1991 (Forecastinternational, 2007). At time of production a single E-3A for the Air Force cost approximately $111.9 million in FY83 (Forecastinternational, 2007). A modern 40/45 upgraded E-3 is estimated at about $500 million in FY18. The TF33 was used for the E-3A, E-3B, and E-3C models and the CFM56-2 engine was used for the E-3A, E-3D, and E-3F (Forecastinternational, 2007).

Figure 2: E-3A Design Features

E-3A Design Features		
Dimensions/Weight/Performance	Metric	U.S
Length	44.15 m	144.83 ft
Height overall	12.73 m	41.75 ft
Wingspan	44.42 m	145.75 ft
Max TOW	151,955 kg	335,000 lb
Max speed	800+ kmph	434+ kt
Aircraft Ceiling	10,670+ m	35,000 ft
Range	9,250+ km	5,000+ nm

(Forecastinternational, 2007)

Figure 3: E-3 Variant Engine Specs

Propulsion			
Airframe	Qty	Engine	Notes
E-3A/B/C	4	P&W TF33-PW-100/100A	Two-spool turbofans rated 93.4 kN (21,000 lbst) each. The -100A is the most recent production variant. Powers USAF & NATO E-3s
E-3A/D/F	4	CFM56-2	Twin-shaft high-bypass turbofans rated 106.8 kN (24,000 lbst) each. Powers Saudi Arabia, France, and U.K. E-3s.

(Forecastinternational, 2007)

The E-3 provides the means to “detect, identify, track, and intercept airborne threats…manage both tactical and defensive fighter forces…identify and control friendly aircraft in the same airspace” (Forecastinternational, 2007). The AWACS is predominately used as a combat command and control center with Air Battle Managers on board that can identify enemy and control friendly assets in a given battlespace. The original proposals for the aircraft were submitted in the 1960s by Boeing and McDonnell Douglas, with Boeing winning the bid in July 1970 (Forecastinternational, 2007). The 30-ft. Rotodome which houses an APY-1/2 S-band type surveillance pulse Doppler radar and IFF/TADIL C array was designed by Keystone Engineering (Forecastinternational, 2007). The computer systems and software which translate the signals coming from the radar for the Air Battle Managers have changed several times since the original 1970 model, with the Air Force fleet currently wielding 30/35 and 40/45 model AWACS. The configurations changes of the E-3 from the original E-3A to the E-3B, and the various block modification upgrades have changed HF/UHF radios, added and removed computers and hard drives, such as upgrading to modern solid state, and improved display consoles, as well as numerous other systems on the AWACS. The surveillance equipment, displays, computers and antennas make up the “weapon system” of the AWACS. It follows then that the weapon system has been upgraded several times over the past half century as technology has improved and computers and radar systems become more efficient and more capable. “The first block 25 upgrade began in 1984, taking 10 USAF E-3As to the E-3C configuration” (Forecastinternational, 2007). The next major upgrade was the block 30/35 which began rollout in 1992, this modification added Electronic Support measures and new Global Positioning Systems equipment, as well as several improved communications systems

(Forecastinternational, 2007). Another significant improvement for the AWACS was the Radar System Improvement Program in the early 2000s which enabled the E-3 radar to "track smaller targets such as cruise missiles". The 40/45 upgrade consists of "new mission computing hardware and software, improved operator console displays and controls, and upgraded radar equipment…upgraded communications and navigation systems and enhanced electronic support measures" (Forecastinternational, 2007). Approximately two thirds of the Air Force fleet have been upgraded to the newest Block 40/45 model with the final third to be completed this decade. Although jet engines have improved over the past 50 years, with new engines being more fuel efficient, more powerful, as well as more environmentally conscious, the power plant of the E-3 has never been upgraded.

Figure 4: E-3 Development/Modification Timeline

E-3 Timetable		
Month	Year	Major Development
	1967	Initial Studies begun
July	1970	Boeing Selected as Prime Contractor
Feb	1972	First E-3/AWACS Airframe Test Flight
Jan	1973	Full-Scale development authorized
Early	1975	Production Authorized
Late	1976	Airworthiness testing completed
Mar	1977	First production aircraft delivered to USAF
Dec	1978	NATO members agreed to procure 18 E-3As
	1980	Block 20 Major Upgrade begins

Jan	1982	First of 18 NATO aircraft delivered
	1984	Block 25 Major Upgrade begins
Apr	1985	NATO order completed
	1986-87	Saudi E-KE-3A deliveries
	1987	Block 30/35 Major Upgrade begins
July	1989	Roll-out of first UK E-3D Sentry
	1991	Boeing closes 707 Line
	1992	E-3 deliveries to UK & France completed
Late	2001	USAF Block 30/35 upgrade complete
April	2005	USAF Radar System Improvement Program Complete
July	2006	Initial Test flight for Block 40/45 Major Upgrade
	2017	US Fleet DRAGON Modification Begins

(Forecastinternational, 2007)

Much of this paper speaks to the waning capabilities of the TF33 today, but that is not to take away from the impressive characteristics of the engine for its time. Developed in the 1950s, the first engine run was in 1958 and first flight on a B-45 Tornado test aircraft in 1959 (encyclopedia, n.d.). Over 8,000 JT3D engines were produced between 1959 and 1985 predominately for Boeing 707, Douglas DC-8s and a host of military aircraft (encyclopedia, n.d.). The engine was so versatile that a significant number of variants were designed to meet both the private sector and Air Force's unique needs.

Figure 5: JT3D Sub-Model Variation Specs

P&W Designation	Air Force Designation	Thrust	Notes
JT3D-1	N/A	17,000 lbf	Civil version, (water Injection Optional
JT3D-2	TF33-P-3	17,000 lbf	
JT3D-3	N/A	18,000 lbf	Water Injection Optional
JT3D-3A	TF33-P-5	18,000 lbf	
JT3D-3B	N/A	18,000 lbf	
JT3D-5A	TF33-P-7	18,000 lbf	Water Injection Optional
JT3D-8A	TF33-P-7	18,000 lbf	Water Injection Optional
JT3D-7	N/A	19,000 lbf	
JT3D-15	N/A	22,500 lbf	For unbuilt 707-820
N/A	TF33-P-3	17,000 lbf	For B-52H Stratofortress
N/A	TF33-P-5	18,000 lbf	For KC-135 Stratotanker
N/A	TF33-P-7	21,000 lbf	For C-141 Starlifter
N/A	TF33-P-11	16,000 lbf	For Martin RB-57F Canberra

(encyclopedia, n.d.)

To aid in understanding the timing for re-engining the E-3 it behooves this research to look at the B-52, which is currently in the process of re-engining its TF33 variant. When the private sector stopped using the TF33 in the 1990s, supportability in terms of spare parts and continued manufacturing of engines was drastically reduced. To ensure nuclear deterrence and conventional firepower of the Air Forces bomber forces it has recently been decided that the B-52 will remain in operation through the 2050s and beyond (Tegler, 2019). The Air Force finally decided to install new commercial jet engines on the B-52 fleet that will continue to have greater private sector supportability as well as enhanced operating capabilities thereby decreasing fuel consumption, and increasing range of the platform as well as enhancing its maintenance and economic feasibility (Tegler, 2019). One of the reasons the B-52 held out on re-engining for so long, despite studies since the early 1990s recommending either a sunset of the platform or new engines, was the ability to pull TF33 spare parts and new engines off other retired platforms out of the boneyard such as the KC-135 and C-141 (Tegler, 2019). The Air Force has already estimated that the TF33 will be unsustainable by 2030 which coupled with the desire to keep flying the jet until 2050 was the final push that drove the re-engine of the B-52.

The Tinker AWACS fleet is currently modifying all of its aircraft to the new 40/45 model as well as the glass cockpit DRAGON mod. The E-3 is clearly not going anywhere and may well fly until 2050 as well, yet there are no plans to re-engine it. The re-engine of the B-52 does not come without some stipulation to the engine makers. As the Air Force rolls out Commercial Engine Replacement Program (CERP), three requirements must be met: fuel efficiency be improved by 20-40 percent without any operational detriment; engines have the same 17,000 pound-thrust class; no change to current minimum control airspeed while maintaining the current combat ceiling and takeoff performance (Tegler, 2019). The new engines must also "be compatible with current B-52 electrical, hydraulic, pneumatic and fuel systems" and "external weapons carriage should be unaffected" (Tegler, 2019). The budget to re-engine the B-52s is set at $1.56 billion. A re-engine of the E-3 would likely be less as there are half as many aircraft, and half as many engines per aircraft compared to the B-52. Ballparking the cost to re-engine the E-3 fleet based solely on number of engines, which would be around $0.5 billion, equal to the price of a single E-3; however, as is often the case, this number may rise by the time the job is done (Tegler, 2019). The B-52 had four formal proposals and twice as many studies dating back to the 1970s before it finally decided to re-engine (Tegler, 2019). This study is at least the fourth of its kind for the AWACS since the 1990s, ideally it wouldn't take another 20 years and a completely unsupportable TF33 enterprise before the re-engine for the E-3 arrives. The private sector has been clamoring and offering up engines with current candidates such as the Rolls-Royce BR725 and Pratt & Whitney PW815 (Tegler, 2019). New engines would also bring the platform into the digital age, as modern commercial jet engines are electronically controlled. A new interface between engine controllers and the airframe and cockpit will need to be developed. The old dials and gauges that have been in the flight deck for decades will be replaced with LCD Displays indicating engine parameters, and the throttle station's old cable type connection will have to be replaced (Tegler, 2019).

The re-engine for the B-52 is not only the talk of Air Force, but of the DoD at large. The 2019 defense bill allocated a significant sum of money specifically for the B-52 program; however, the payback is expected in a mere 10 years' time (Tirpak, 2019). A similar return on investment could be expected for the E-3 if the Air Force decided to re-engine that platform. The previous recommendations were always turned down with the Air Force stating service life of the AWACS did not support re-engine. The E-3 program office should take heed of the B-52 re-engine and use the extensive research their program office has generated to save money and increase capability of the E-3. With the current modifications of the AWACS, it will easily be around for at least another 10 years if not more, so re-engining not just the B-52 but all TF33 fleets would be maintenance and mission enhancing as well as economically sensible. To re-engine the B-52, the industry will be conducting computer simulations to decide which companies' engine is the best fit (Tirpak, 2019). If the E-3 came on board now, they could also run these simulations for the AWACS while the technology is fresh, and the contractors and airmen are well versed in the software. These simulations will compare "engines for fuel efficiency, maintenance requirements, and performance under a wide variety of conditions" (Tirpak, 2019). The normal acquisition time from setting requirements to proceeding with production is usually 10 years, but with the new digital simulations the time is expected to drop to 6.5 years according to Air Force Acquisition Chief, Dr. William Roper (Tirpak, 2019). That timeline coupled with the projected sustainability of the TF33 set at 2030 means the trigger for AWACS needs to be pulled no later than 2023. According to the Air Force's "Bomber Vector" plan from 2018, the forecasted savings of re-engining the B-52 is set at $10 billion, with these savings coming from fuel, depot and field maintenance costs. Air Force Magazine states that the new mean time between overhauls for some of the potential candidate engines is around 30,000 hours as compared to the TF33's 6,000 hours (Tirpak, 2019). This could mean that E-3 engine changes and overhaul would happen approximately five times less often. In the data observed in this study, there were 302 engine changes from 2007 - 2019. Assuming the E-3 continues to fly for another 12 years, and the rate of engine change stays approximately the same, five times less than 302 is roughly 60. Not accounting for prep time or off-station logistics requirements, the standard maintenance time to change an engine is 24 hours. So if the E-3 was to have a new engine that could fly five times longer between overhauls, that would be the difference between 7,248 hours

(302 days) or 1,440 hours (60 days) across 12 years. That's 242 days of E-3 aircraft availability back to the warfighter. With the current cost of an engine overhaul at $1.7 million, a re-engine would also be the difference in overhaul costs; 302 engine overhauls = $513.4 million or 60 engine overhauls = $102 million, a $400 million dollar savings. This is the tip of the iceberg. It takes much longer than 24 hours to change an engine, because many of the engine changes are not done at home station on a scheduled basis. Ultimately, re-engining would dramatically reduce maintenance costs and increase aircraft availability. Pratt & Whitney, GE Aviation and Rolls-Royce are all touting their wares as the perfect fit for the B-52 re-engine. The BR725 from Rolls Royce offers increased fuel efficiency, increased range, and a staggering 95% reduction of carbon emissions; it is already a part of the military supply system as it powers the RQ-4A Global Hawk and the E-11 BACN (Tirpak, 2019). All of this research being done by Air Force Acquisitions and private industry could be generalized to the E-3; its results should not be wasted for another 10 years while the TF33 becomes more unsustainable. The engine the B-52 program decides upon may end up being different than the one the E-3 program would choose. Even if that were the case, it would befit the Air Force to re-engine both platforms at the same time, while the work and research on the best engine replacement candidate is being done now.

Figure 6: B-52 re-engine candidates: how the engines compare (Tirpak, 2019)

The B-52 re-engine will not happen overnight. Although the program has finally been greenlit, only two test aircraft are expected to have their engines replaced by 2022 with 74 more sets being acquired from 2026 to 2034 (Insinna, 2017). If this kind of timetable can be expected for the E-3; the re-engine would not be expected until 2039, almost a decade after the TF33 is expected to be completely unsustainable.

GE claims they are the clear choice as they have re-engined several platforms for the Air Force in the past. GE re-engined the KC-135 from the TF33 to the CFM56, the C-5M from the TF39 to CF6-80C2, and the U-2S from the J75 to the F118 (GE Aviation). On top of this, GE has supplied and supported the Engines for the B-2, B-1, B-58, B-47, B-36, and B-45. Their steadfast support has been ongoing since 1948 and they're not shy to talk about it. The two engines they are putting forth as valid candidates for the B-52 are the CF34-10 and Passport. (GE Aviation, 2019) With GE having re-engined several fleets to the CFM-56 and other E-3 variants already having the CFM56 and tech data to support, it may make the most sense to re-engine the US E-3 fleet with the CFM56.

Figure 7: CF34-10 & Passport Specs (GE Aviation, 2019)

CF34-10

GE's most reliable engine operating day in and day out under the harshest duty of the commercial world—regional aviation

Born as a scaled and improved version of the legendary CFM56* engine, the CF34-10 family is a proven stalwart of commercial aviation

- At eight flights per day, it tackles the toughest duty in commercial aviation with 1/3 more cycles per day than narrowbodies
- 2.5 million flights/cycles in last 12 months alone
- Fully mature with over 28 million (CF34-10) flight hours and over 157 million CF34 family flight hours
- 99.97% proven dispatch reliability
- Averaging 16,000 cycles to its first overhaul, this engine will likely not see off-wing scheduled maintenance for the life of the B-52

Performance specifications

Maximum takeoff thrust	20,360 lbs
Bypass ratio	5.4:1
Maximum overall pressure ratio	29:1
Fan diameter	53 in
Length	88.7 in (engine base)
Weight	3,760 lbs
Noise	Chapter 4 Meets or surpasses
Emissions	CAEP/6 Meets or surpasses
Specific fuel consumption	35K/0.80 Mn max cruise .640
Control system	Dual-channel FADEC

PASSPORT

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- Lowest fuel burn of any engine in its thrust class, 30% better than the B-52's current engine
- Durable design heritage purpose-built for 14,000 hours time-on-wing
- Lowest emissions in its class
- Designed for endurance, recently powering one of history's longest non-stop business jet flights (8,152 nm)
- FADEC (Full Authority Digital Engine Control) redundancy guards against combat mission disruption

Performance specifications

Maximum takeoff thrust	18,900 lbs
Bypass ratio	5.8:1
Maximum overall pressure ratio	51:1
Fan diameter	52 in
Length	102.7 in (engine base)
Weight	3,950 lbs
Noise	Chapter 4 Meets or surpasses
Emissions	CAEP8 Meets or surpasses
Specific fuel consumption	47K/0.85 Mn max cruise .615
Control system	Distributed FADEC

The proposal to re-engine the E-3 is not new, and it is also not exclusive to the United States AWACS. In 2001, there was extensive talk about re-engining the NATO E-3A fleet. The European Aeronautic Defense and Space (EADS) company announced in 2001 they had joined with Northrop Grumman, Pratt & Whitney and several other companies to re-engine the E-3A fleet from the TF33 to the Pratt & Whitney JT8D-219 (Northrop Grumman/EADS, 2001). EADS was to be the prime contractor to perform the modification and Northrop Grumman would provide engineering support for the 17 E-3A NATO fleet. The JT8D-219 had 12,000 engines installed world-wide thus, a strong support network and ongoing manufacturing for spare parts (Northrop Grumman/EADS, 2001). This modification was to bring the fleet within regulation emissions and reduce noise as well reduce fuel consumption. However, the fleet was never re-engined. There are now 14 E-3A aircraft in the NATO Fleet, all of which still have the TF33-100A turbofan engine. The money that was once allocated for the 2001 re-engine proposal went instead to upgraded radar and navigation systems (NATO, n.d.) (NATO, 2019).

The NATO E-3A and the USAF E-3 Fleet are very similar in many respects; however, the NATO fleet usually gets upgraded earlier than the U.S. fleet. For example, the DRAGON modification or glass cockpit navigation upgrade was completed on all 14 NATO aircraft by 2018, as compared to the U.S. Fleet which only has one aircraft of its 31 modified and has not completed test phase yet. In November 2019, NATO secretary General Jens Stoltenberg authorized $1 billion in funding to develop another update to the NATO fleet. Though specific details of the upgrade has not been released, it is speculated that the upgrade will replace the TF33 with more modern engines (Roblin, 2019). NATO plans to retire the E-3 in 2035 and has already started working with the private sector to develop alternative platforms with the Alliance Future Surveillance and Control (AFSC) (Roblin, 2019). The studies to re-engine the USAF E-3 in the 1990s and in the 2010s were both rejected due to the expected service life of the AWACS. The Air Force is currently spending $2.6 billion to upgrade the fleet to the new 40/45 standard which features "open-architecture computers, more reliable electromagnetic sensors, single-track fusion of its multiple sensors, and faster datalinks" (Roblin, 2019). Despite this massive upgrade cost, a recent study by the Center for Strategic and International Studies (CSIS) listed the E-3 as a potential to be retired in five years. There is currently no replacement for the E-3 scheduled and the platform will still be undergoing 40/45, IPEC, and Dragon modifications in 2025, meaning retiring the fleet now would potentially negate the returns on investment for upgrading the fleet. Regarding the question for re-engine, it is likely this CSIS study will be touted, as in the 1990s and 2007 proposals, where the Air Force will state studies have been conducted espousing the end of the AWACS life cycle therefore negating re-engine plans. If decision makers in the 1990s had known that the E-3 would still be flying in 2020 with no replacement in sight, perhaps they would have decided to re-engine. Will it be 2040 with an extended service life of the E-3 to 2060, while the field is maintaining a completely unsustainable TF33 engine before a re-engine decision is made? It is time for decision makers to realize that the E-3 is not going away, and the sustainability and supportability of the TF33 is rapidly reducing the combat capability of a vital war machine. Another alternative would be to phase out the E-3 in favor of the new Boeing 737 based E-7 Wedgetail, used by Australia, Britain, and Turkey (Roblin, 2019). NATO may also retire the E-3 in favor of more ground based or unmanned combat command and control intelligence surveillance and reconnaissance (Roblin, 2019). There has been discussion in the Air Force that these alternatives are why a new platform is not in the works. As the sensors on other aircraft become more advanced and ground station capabilities increase, it may make more sense in the future to change the concept of how warfighters control the air space. If re-engine is not ever going to be on the table, then the idea of sunsetting the E-3 in favor of an entirely new platform, either aerial, ground-based, or unmanned has to become more than an idea as the TF33's life is running out.

As the Air Force looks at retiring more legacy systems to free up funding, the Department of Defense (DoD) research and development continues to evolve drone, space, and ground-based alternatives (Roblin, 2019). As communication systems capabilities improve, "the service plans to have the systems relay data and command-and-control links to a ground-based facility in Robin Air Force Base, Georgia" (Roblin, 2019). The Air Force has begun initial steps to shut down the E-8 J-stars with the new Advanced Battlefield Management System (ABMS) being prepared to replace it. This ABMS may also expand to take over the roles of the RC-135 and E-3 (Roblin, 2019) although the system is not fully operational yet and sits more as a theoretical concept. Retiring the E-3 in the next five years is projected to save the Air Force approximately $5 billion, but as has been previously stated, there is no replacement and the Air Force is still heavily investing in upgrading the Sentry fleet (Harrison, 2019). The Chief of Staff of the Air Force (CSAF) outlined a four point plan for which he intends to utilize the potential savings of retiring legacy systems which include but are not limited to: $3 billion towards hardening forward bases to increase missile defense, $27 billion to generating combat power, offensive and defensive space capabilities, improving connectivity of sensor and command-control across the joint force. (Harrison, 2019). This concept of multi-platform connectivity is seen across the services from the Navy's Cooperative Engagement Technology to the Army's Multi-Domain Battle Doctrine (Roblin, 2019). The retirement of any legacy system would not be instantaneous…the Department of Defense recognizes that sunsetting a platform would generate savings over an extended period of time (Harrison, 2019). It is also noted that the final say to retire a platform rests with Congress which has previously denied such proposals as with the A-10, U-2 and RQ-4 (Harrison, 2019). It is highly unlikely that Congress would sign off on retiring any legacy platform such as the E-3 unless the mission it supports can be fulfilled by some other means which is not currently available.

Figure 8: Estimated Cost Savings of Retirement by Platform (Harrison, 2019)

Table of Estimated Savings

Aircraft Type	Savings Type	FY21	FY22	FY23	FY24	FY25	Total
KC-10	O&S	$0.13B	$0.84B	$0.99B	$0.00B	$0.00B	$1.96B
B-1	O&S	$0.21B	$0.43B	$1.24B	$1.27B	$1.30B	$4.46B
	Procurement	$0.08B	$0.07B	$0.11B	$0.06B	$0.00B	$0.33B
	RDT&E	$0.03B	$0.01B	$0.01B	$0.00B	$0.00B	$0.05B
B-2	O&S	$0.05B	$0.10B	$0.76B	$0.78B	$0.79B	$2.47B
	Procurement	$0.04B	$0.06B	$0.06B	$0.15B	$0.00B	$0.31B
	RDT&E	$0.05B	$0.05B	$0.03B	$0.01B	$0.01B	$0.15B
A-10	O&S	$0.21B	$0.43B	$1.77B	$1.81B	$1.85B	$6.06B
	Procurement	$0.14B	$0.13B	$0.14B	$0.09B	$0.00B	$0.49B
	RDT&E	$0.02B	$0.02B	$0.02B	$0.02B	$0.02B	$0.12B
E-8	O&S	$0.03B	$0.06B	$0.84B	$0.86B	$0.87B	$2.66B
RC-135	O&S	$0.04B	$0.08B	$0.88B	$0.89B	$0.91B	$2.81B
	Procurement	$0.21B	$0.20B	$0.21B	$0.09B	$0.00B	$0.70B
U-2	O&S	$0.01B	$0.02B	$0.54B	$0.55B	$0.56B	$1.67B
	Procurement	$0.11B	$0.13B	$0.08B	$0.07B	$0.00B	$0.39B
	RDT&E	$0.02B	$0.02B	$0.02B	$0.02B	$0.02B	$0.10B
E-3	O&S	$0.08B	$0.16B	$0.85B	$0.87B	$0.89B	$2.86B
	Procurement	$0.23B	$0.26B	$0.29B	$0.35B	$0.38B	$1.50B
	RDT&E	$0.17B	$0.14B	$0.10B	$0.12B	$0.12B	$0.65B

Note: All values are in then-year dollars.

A chapter of *Improving the Efficiency of Engines for Large Nonfighter Aircraft* is dedicated to TF33 series powered aircraft due to the extent, which this power plant was used across the military complex (National Research Council, 2007). In 2007, there were approximately 2,300 TF33 engines in the Air Force inventory, which is now down to approximately 1,150 (National Research Council, 2007). The researchers identified nine studies to re-engine the multitude of platforms utilizing the TF33 engine since 1984, and this number has since grown to approximately 15 by 2019. The U.S. private sector stopped using TF33 or JT3D engines in the early 1990s, with the commercial international community discontinuing use in 2010 (Harrison, 2019). The research council identified several common considerations regardless of platform when it comes to re-engining. The first is “the maintenance interval of modern engines exceeds the life of these old airframes”. Essentially, putting a new engine on a platform like the E-3, KC-135, or the B-52 means the engine will outlast the airframe based on expected sunset timelines for these platforms. Regardless, the TF33 is far past its prime with many engines sitting over 30,000 flight hours. There are some engines left in the DoD inventory that have under 10,000 hours, but the spare parts and supportability from the private sector have declined with commercial industry re-engine efforts leaving the organic Air Force depots to do extensive overhaul and part refurbishment without the industry base to support. The case was made in the early 1990s as well as in 2007, that re-engining didn’t make sense as a new engine would never even see overhaul before the E-3 retired. Yet it is now 2020 and the rapidly decaying TF33 is going to overhaul twice as fast as it should, costing the Air Force lowered mission capability and increased funding. “Major overhaul accounts for most of the maintenance cost associated with engine ownership…the TF33-PW-102 depot overhaul cost has increased by 300 percent, to $1.25 million per engine in FY06 as compared to the $257,000 of FY 96” (National Research Council, 2007) and is now at $1.7 million. Studies have also indicated the TF33 was removed from service in the commercial sector for not meeting environmental regulations (National Research Council, 2007). The TF33 is also far less fuel efficient than its modern engine counterparts, yet the Air Force continues to use this engine (National Research Council, 2007). All TF33-powered KC-135s have been placed in long-term storage or re-engined to the CFM56, the B-52 re-engine is underway, and the E-8 in sunset, leaving the only major TF33 powered fleet the E-3 AWACS. As long as the E-3 remains operational, the approximately 188 personnel and 82,000 square feet of real estate supporting the TF33 depot cannot be retrained, retooled, and redesigned for future needs, nor can the $800 million TF33 inventory be disposed of or sold off entirely (National Research Council). The TF33 should be thought of as an enterprise rather than a singular airframe, therefore, “the whole of the savings from re-engining all TF33 aircraft may considerably exceed the sum of re-engining the individual platform types” (National Research Council, 2007).

Even as far back as 1996, research was being done to identify the balance between commercial versus military workload for depot level maintenance. It was and still is considered smart practice to operate and maintain engines that have commercial sector equivalents to increase supportability (Warren, 1996). In 1996, it was reported that newer engines with improvements in technology had “increased reliability… reduced the number of depot-level overhauls, and reduced depot-level maintenance requirements” (Warren, 1996). At that time the military owned 62% of all TF33s in existence and had already begun to re-engine the KC-135 for the third time from the TF33 to the CFM56 engine which had a better unscheduled engine removal rate. The TF33 at that time had an unscheduled removal rate of 48% (Warren, 1996) and is now at 92% according to the data gathered in this research from 2007-2019. To save money, the Air Force consolidated engine repair facilities, decreasing from eight to six between 1990 and 1994, to eliminate duplicate sources of repair, also farming out more of the work to the private sector when possible (Warren, 1996). Great emphasis was placed on the value in having commercial counterparts for military engines. “Where commercial carriers have significantly larger engine inventory than DoD, there is viable broad-based private sector support available that mitigates risk and affords the opportunity to reduce costs. The competitive environment that exists for these engines allow DoD to benefit from “sharing” fixedoverhead costs with the private sector customers who have substantially larger numbers of engines being serviced" (Warren, 1996). In the 1990s, the TF33 was at an advantage over many other military engines, but this is no longer the case as current state for TF33 has no private sector usage, increasing the risk and costs to the U.S. and other allied militaries. Pratt and Whitney and Aviall which previously repaired the JT3D, closed their repair operations by 1996 because of the declining commercial market and because the JT3D represented "older technology" (Warren, 1996). If the TF33 was already being called older technology in 1996, how does the engine compare now in 2020?

Air University released an Energy Strategy in 2008 that echoed many of the same conclusions that the 2007 Research Council developed. Namely that the TF33 engine should be phased out holistically, there was a 300 percent increase in overhaul cost compared to a FY03 account, and the increased capability and lowered costs in terms of both maintenance and fuel consumption of modern engines (Lengyel, 2008). These were all key components of the research councils document in 2007, but a key difference that the Energy Strategy put forth, is the personnel and real estate aspect that could be freed up, modernized, and used towards the sustainability of modern engines (Lengyel, 2008). It is noted at present that neither the research council's, nor the energy strategy's recommendations were heeded. The KC-135 has been re-engined singularly since, and the B-52 is now undergoing re-engine by itself. Yet the E-8, E-3, WC-135, and OC-135 fleets still retain the TF33 with no re-engine in sight. Nevertheless, the research and advice put forth by the energy strategy in 2008 still holds value today. It was calculated that re-engining would reduce "overall fuel consumption by about 35% and in-flight refueling demand from 50-66% giving an estimated overall savings of nearly $8 billion through

2037" (Lengyel, 2008). The account goes on to cite increased aircraft performance adding lethality to the re-engined platforms. The strategy focuses several pages on the Versatile, Affordable, and Advanced Turbine Engines for the National Turbine-Engine Technology Plan. This plan was comprised of multiple government agencies as well as six major engine companies and three airframe manufacturers with the intent to produce a significantly more effective and efficient engine by 2017 (Lengyel, 2008). It is now 2020 and those engines are here. Modern day engines are more capable of transforming fuel to horsepower and doing it with less carbon emissions and noise pollution.

A joint study done by the Department of Energy and the Department of Defense in 2007 also looked at re-engining the TF33 holistically across the KC-135, E-3, E-8, and B-52. The "paid-by-savings investment potential" was deemed to be $6.4 billion - $8.7 billion (Schell, 2007). The study indicated that the TF33 was being overhauled four to six times more often than modern engines and "not only may associated logistics support costs be reduced, but freedom to perform completely new missions may result" (Schell, 2007). This study looked at factors such as mission capabilities, fuel efficiency and savings of manpower. The general characteristics such as improved thrust, increased on-station time, reduced use of imported oil and reductions to air and noise pollution were all stated as potential positives to a re-engining, but a specific money value was not calculated. (Schell, 2007). Most of the research conducted in this report indicated that based on fuel savings alone, re-engining of the E-3 would pay itself back within 20 years if fuel costs did not decrease and in even less time if fuel costs increase. (Schell, 2007). However, it also stated that no platform had been re-engined based on fuel savings alone and therefore went into maintenance and manpower savings as well. This case intends to add to this body of literature with sustainability characteristics by looking at engine removal data over the past two decades.

Methodology

Research Procedures

The first step of this study was to review literature on TF33 engines and previous re-engine studies. Once a solid grasp of the foundation was achieved, the next step was to conduct interviews with TF33 experts in the field. A subsequent brainstorming session was conducted with E-3 propulsion technicians and production superintendents from the 552^{nd} Aircraft Maintenance Squadron. From those brainstorming sessions, a series of engine specific variables were identified as important factors that could contribute to the body of knowledge available on TF33 engines and support a new case to re-engine the E-3. Once enough variables were identified, requests were made to the 552^{nd} Maintenance Group engine managers for assistance in data collection. The engine managers pulled raw data and taught the researcher how to pull data and interpret it from two separate computer information systems. Once the raw data was collected, it needed to be refined into readable formats within Microsoft Excel. These spreadsheets were then scrutinized and sanitized of any potential information that may be For Official Use Only or irrelevant to the current research. Some data that was collected was incomplete due to missing information in the system, either due to improper input or lack of input. The data was then categorized and refined, and subsequent plots generated to benefit interpretation of trends within the dataset.

Access to TF33 operational data was acquired as a by-product of the researcher's position in the E-3 maintenance community. The data collected from 2007 - 2019 was selected due to the extensive log-keeping by engine managers during that time period. Engine change records were also available from 1994 - 2006 but lacked several categorical data points that the 2007 - 2019 dataset had, therefore the older data was not utilized.

Data Collection

The data used in this proposal was pulled from commonly used maintenance information databases operated by the Air Force. The information is initially collected after each sortie from the aircraft by maintainers and input into the Integrated Maintenance Data System (IMDS). Information is then transferred from IMDS to the Comprehensive Engine Management System (CEMS). CEMS is used by depot engineers and engine managers to track detailed information and run analysis on engines in the Air Force inventory. Both databases have controlled access and require skilled understanding to run the reports necessary and interpret the raw data that is provided by the database. Help was received by the 552nd Maintenance Group engine managers in processing the data for this research.

Human Subjects Review

This study was aided by interviews and brainstorming sessions with 552nd Aircraft Maintenance group engine mechanics, production superintendents, engine managers and Oklahoma City Air Logistics Complex Employees. These individuals helped to shape this study and guide the selection of data to be examined. Engine managers from the 552nd Maintenance Group were critical to this study as they assisted with the collection of data from CEMS and IMDS.

Ethics Statement

All research was conducted with the highest respect for the researchers and literature cited and all individuals that aided this study. All intents and purposes of this research is to produce quality analysis that will both contribute to the academic studies of the TF33 engine and the E-3 AWACS program while also benefitting the E-3 maintenance community. Consent was asked of all troops and employees that aided this study, and their assistance was given voluntarily with no expectation of personal gain. (ethicsguidebook.ac.uk)

Data

The primary dataset used in this research was Tinker Air Force Base E-3 AWACS Fleet Engine Removal and Replacement data. This information is logged by aircraft maintainers each time an engine is removed from an E-3 aircraft. This data is captured in printed aircraft forms as well as Air Force online data bases IMDS and CEMS. Engine Managers from the 552 Aircraft Maintenance Group manage an Excel document with raw data for all engine changes populated through information from CEMS. This spreadsheet has been kept since fiscal year 1994. The number of characteristics captured in this document have changed over the years, and the format in which data has been logged has also changed from year to year. The data input into the data bases and transcribed into the engine managers spreadsheet is largely raw numbers. This research did not use the data from fiscal years 1994 to 2006 as the inconsistencies and fidelity of information compared to post fiscal year 2007 was not as high. To enable Excel formula functions and charts to be made, this research refined the dataset, but did not corrupt any information. Each column heading will be explained, and examples of data refinement and changes made by the author will be provided. Charts, trends, summaries, and implications of this data with regards to the sustainability of the TF33 and the case for re-engining the E-3 will be elaborated on in the charts and trends and preliminary findings sections.

Figure 9: Example Engine Removal/Replacement Data Table

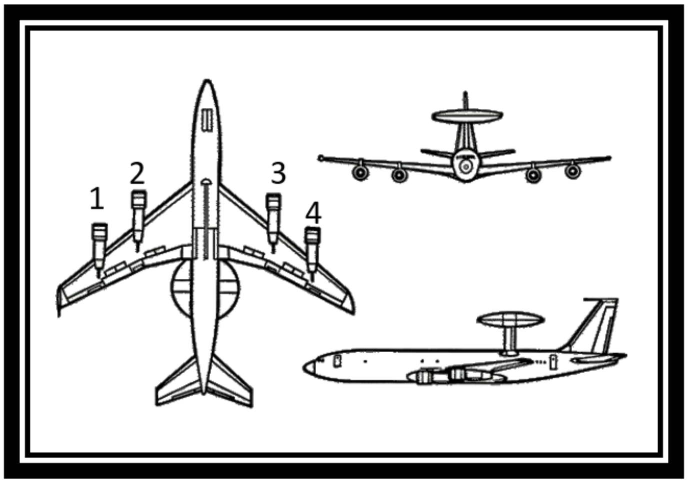
S/N	ACFT	POS	FYQ	NEW S/N	DATE	Category	DEFECT	DR	Sched	Repair Site	TT	TOW	LOC	Remaining	Accum	Remarks
686859	A0009	4	17A	69683 8	16288	fod	FOD 1st, 2Nd, stg balde &stator 3rd stg stator	N	N	RE21	2117.3	11.6	Tinker	3681.8	2318.2	ENgiNe goiNg to RE21 SRAN 2038

S/N: Engine serial numbers – Each TF33 engine is designated by a specific serial number. The first two digits of the serial number identify the year the engine was produced, followed by a series of unique numbers for each engine. The serial number column indicates that serial numbered engine was removed with the characteristics per each row's data linked to that specific serial number. The data from 2007 - 2019 was generally consistent, but a few minor adjustments were made to enable functionality in Excel. Most serial numbers were six digit numbers such as 660109. 35 of 302 rows were annotated with modifiers such as 707015-Not or PW00707042 or annotated in a non-standard format. 33 of these inconsistencies were removed by deleting the "-Not" and "PW00", leaving a usable 6 digit format. Two inconsistencies, E6885 & E9792, were left and ultimately omitted from serial number driven analysis.

ACFT: Aircraft Tail Number – Every USAF E-3 is designated with a specific tail number. This column indicates what tail number aircraft the associated serial number engine was on, at time of removal.

POS: Position of Engine – The E-3 AWACS has four engine positions. Aft facing forward they are numbered left to right per each pylon as shown in figure 10. The position column indicates what position on the aircraft the engine was, at time of removal.

Figure 10: AWACS Engine Positions (FAS.org, 2000)



FYQ: Fiscal Year Quarter – This column indicates which fiscal year quarter the associated engine was removed. The nomenclature is two digit year followed by (A) for October through December; (B) for Jan through March; (C) for April through June; and (D) for July through September. This can be useful to identify seasonal engine changes, (A) for Fall; (B) for Winter; (C) for Spring; and (D) for Summer. There were substantial inconsistencies of data in this column from year to year. An example is 696802's engine change in 2010 which was originally a 10C removed on 23 August 2010, this was updated to reflect the FYQ as 10D for this research. FYQ annotation was changed for all discrepancies to match the calendar date.

New S/N: New Serial Number – This column indicates the serial number of the new engine which replaced the removed serial number engine on the associated tail numbered E-3.

Date: This column indicates the date the associated engine was removed. Across the years approximately four different styles of annotation were used: three Julian Date styles (e.g., 9140, 13323, 2018201) and one calendar date style (e.g., 10-May-08). To create conformity and enable use in charts, the Julian dates were refined into a single style so that the above examples would all conform to this output/nomenclature: 09140, 13323, 18201. Then a second column G was made and a formula used to convert the Julian dates in column F to a calendar style using the following formula:

```
=("1/1/"&(IF(LEFT(F61,2)*1<20,2000,1900)+LEFT(F61,2)))+MOD(F61,1000)-1
```

The dates that were already calendar dates were simply carried over to column G.

Category: category of defects – This column organizes engine removal causes or defects into broad categories. The concept of organizing engine removals by defect category was not started by 552nd engine managers until fiscal year 2017, therefore all previously captured data did not have a category column. Annotating data from fiscal year 2007 to 2016 into categories was completed by this research with the help of E-3 engine mechanics. The types of categories are as follows: Bearing, Blade Damage, CANN, Comp Stall, Crack, EGT, Flameout, FOD, Metal Shaving, Other, Oil, Overtemp, PTO Shaft, Scheduled Time Change, Sheet Metal, TCTO.

CANN	Cannibalization, meaning the engine was removed from one aircraft to fix another
Comp Stall	Compressor stall
EGT	Exhaust gas temperature
FOD	Foreign object debris
Overtemp	Overtemperature
PTO Shaft	Power take-off shaft
TCTO	Time compliance technical order

Defect: Reason for engine change – This column indicates the reason the engine was changed.

DR: Deficiency Report – This column indicates if a deficiency report was filed or not. Deficiency reports are generally filed if there are indications that the defect is from a recently installed component or if the engine was recently overhauled and there are indications that the deficiency existed or was caused while in overhaul.

Scheduled: Scheduled Engine Change – Aircraft maintenance uses engineering and historical data to schedule major maintenance actions at specified intervals. TF33 Engines are required to be overhauled every 6,000 flight hours. This column indicates if the associated engine was changed at a scheduled interval or not. Unscheduled engine removals often occur due to unexpected external damage or internal failures.

Repair Site – This column annotates where the removed engine was sent for repair of the defect. 552nd engine managers began capturing this data in fiscal year 2010, only capturing minor details. The nomenclature is generally a simple “Depot,” “RE21,” or often “?” This column is lacking specifically wherein the Air Logistics Complex the engine was repaired and what was done to fix the associated engine. The assumption is made that depot indicates the engine was sent to overhaul and RE21 was a specific repair of the defect and returned to field. Often the decision was based on hours accumulated, if the engine was under half the 6,000-hour requirement it would usually be repaired and returned. No attempt was made in this research to refine this column of data, as there were three years of missing data and inconsistencies throughout. Instead this column was disregarded for analysis.

TT: Total Time of hours on engine - This column indicates the total time the associated engine has operated since its production date until the removal event.

Time on wing [TOW] – Engines are not always tied to one specific location on the aircraft. Engines may be swapped between position or tail number between scheduled engine changes. This column identifies how long an engine has been in a specific position on the aircraft at the time of removal. This variable is helpful to identify if the engine has been on different aircraft or in different positions since its last overhaul.

LOC: Location – This column annotates the geographical location the associated engine was removed and replaced. This dataset was refined to increase consistency across years and generalization by geographic location. The 552nd Aircraft Maintenance Group has two primary aircraft maintenance units, Red and White, as well as an Isochronal Inspection Maintenance Flight, and also previously had a third unit, Blue, all of which have engine removal and replacement capabilities. Example annotations may have stated “Red”, “ISO”, “RED/Tinker,” etc. Anything that was done by 552 Maintenance Group was converted to “Tinker.” Variances between years were also indicated for Al Dhafra Air Base, the primary deployed location for the 552nd, with examples: “SWA,” “Dhafra,” “ADAB” ;these were all refined to “SWA.”

Remaining: Remaining time to 6,000-hour overhaul interval – Every 6,000 hours, TF33 engines are required to be removed from the aircraft and transferred to the engine depot for overhaul. This column annotates the number of hours left on the associated engine until the 6,000-hour engine change interval.

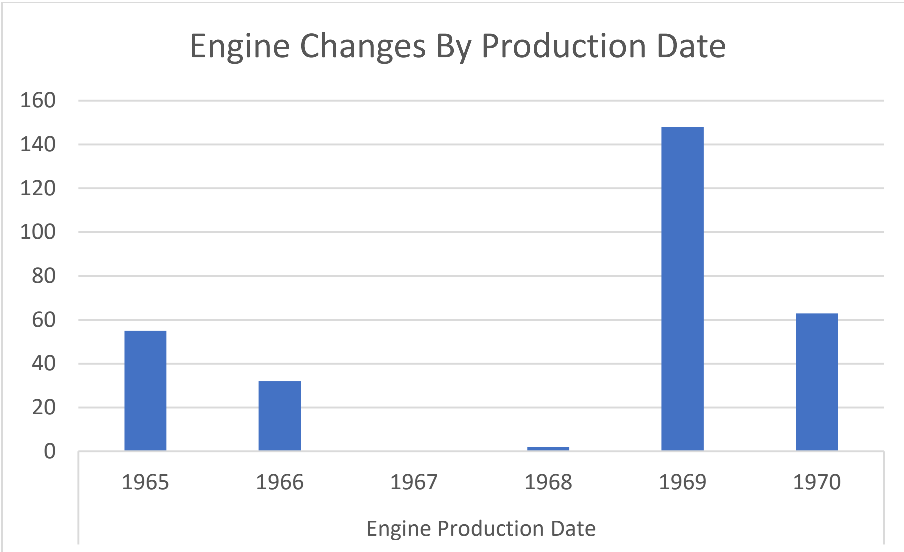
Accumulated: Hours accumulated since overhaul – This column annotates the number of hours accumulated on the associated engine since last overhaul.

Remarks: General remarks by 552nd engine managers. This column was not used in this research.

Results and Discussion

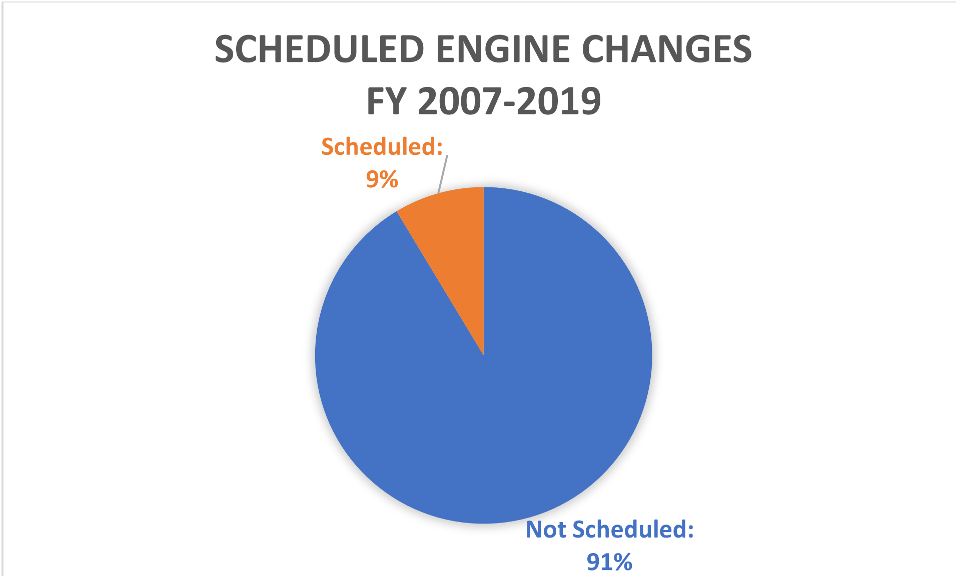
On average TF33s are not meeting their scheduled removal intervals and are being changed irregularly at locations around the world. This inability of the TF33 to last its expected operating hours between overhaul cycle is causing disruption to operational requirements, unexpected logistics cost to transport engines, tools, and maintainers to change engines in non-standard locations. This significant unscheduled maintenance is wreaking havoc on depot maintenance expectations for engine inputs. From 2007-2019 there have been 302 engine changes: 188 at Tinker, 114 not at Tinker, and 275 of those unscheduled. This means that only 8.6% of engine changes were scheduled. The refined data and charts below were produced to better visually understand TF33 sustainability based on engine removals. Data was also collected from IMDS to show non-mission capable and aircraft availability rates.

Figure 11: Engine Changes by Production Date



The engines examined in this study were all produced between 1965 and 1970. Of the 302 engine removals, two of them were omitted from the above chart due to the production date not being available. Although the number of removals is higher for engines produced in 1969 than the other five production years, this is considered a by-product of the overall population of TF33s, rather than an indicator of issues with the 1969 engines. There are more engines in the inventory from production year 1969 then other years, hence more changes from that population.

Figure 12: Scheduled Engine Changes 2007-2019



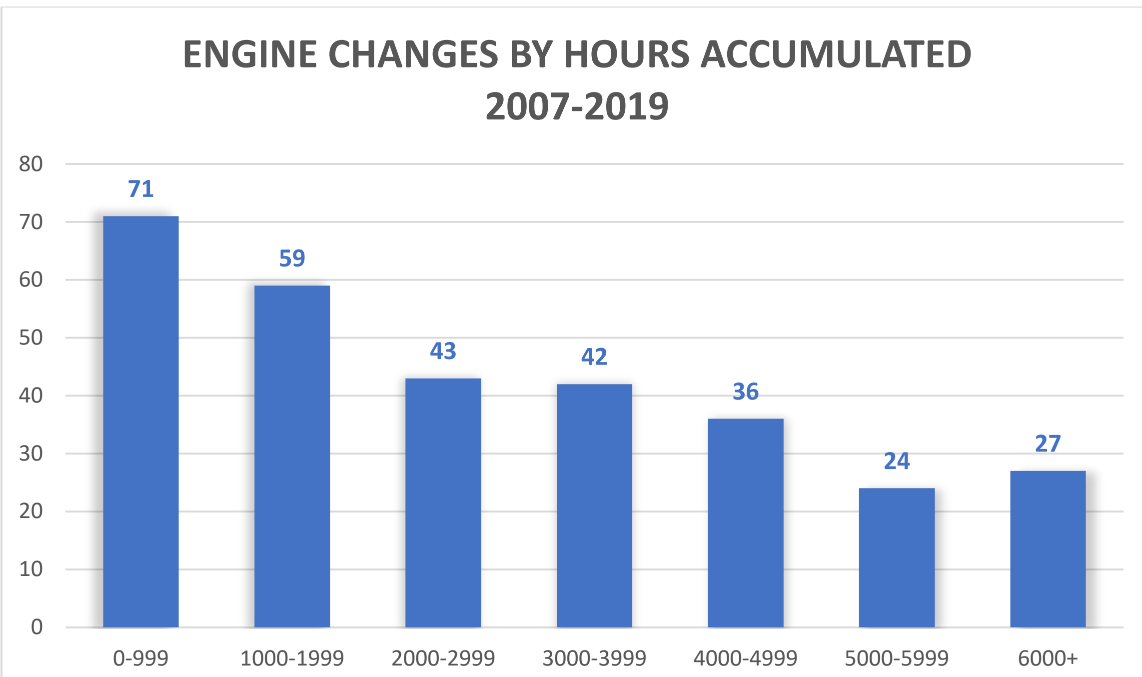
Aircraft engine maintenance is strictly managed to ensure flight safety and maintain optimal engine performance. Every engine type has depot level maintenance inspections that are required after a certain number of flight hours or calendar days. The TF33 engine is scheduled for mandatory overhaul every 6,000 hours. This schedule allows field level maintenance to plan where the aircraft is for ideal removal and replacement of the engine and depot level maintenance to plan induction and work scope for the incoming engine. It is ideal to change engines at home-station which for the E-3 fleet being examined is at Tinker AFB. This enables the right number of maintenance personnel, tools, and a spare engine to be available. Depot also gains many benefits for their schedule as they can plan for engine inception and adequate follow-on procedures when they know when an engine is slated for overhaul. From FY 2007 to 2019 there were 302 engine changes across the Tinker E-3 Fleet. 26 of those engine changes were scheduled accounting for 9% of all engine changes and 275 were not scheduled accounting for 91% of all engine changes.

Figure 13: Table of Scheduled Engine Changes over years

Scheduled Engine Changes over years													
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total / Avg
Scheduled	1	1	3	3	1	1	4	1	2	2	4	1	24
Unscheduled	28	27	27	22	23	22	14	15	17	24	22	24	265
Total	29	28	30	25	24	23	18	16	19	26	26	25	289
Percent Scheduled	3.4%	3.6%	10.0%	12.0%	4.2%	4.3%	22.2%	6.3%	10.5%	7.7%	15.4%	4.0%	8.6%
Percent Unscheduled	96.6%	96.4%	90.0%	88.0%	95.8%	95.7%	77.8%	93.8%	89.5%	92.3%	84.6%	96.0%	91.4%

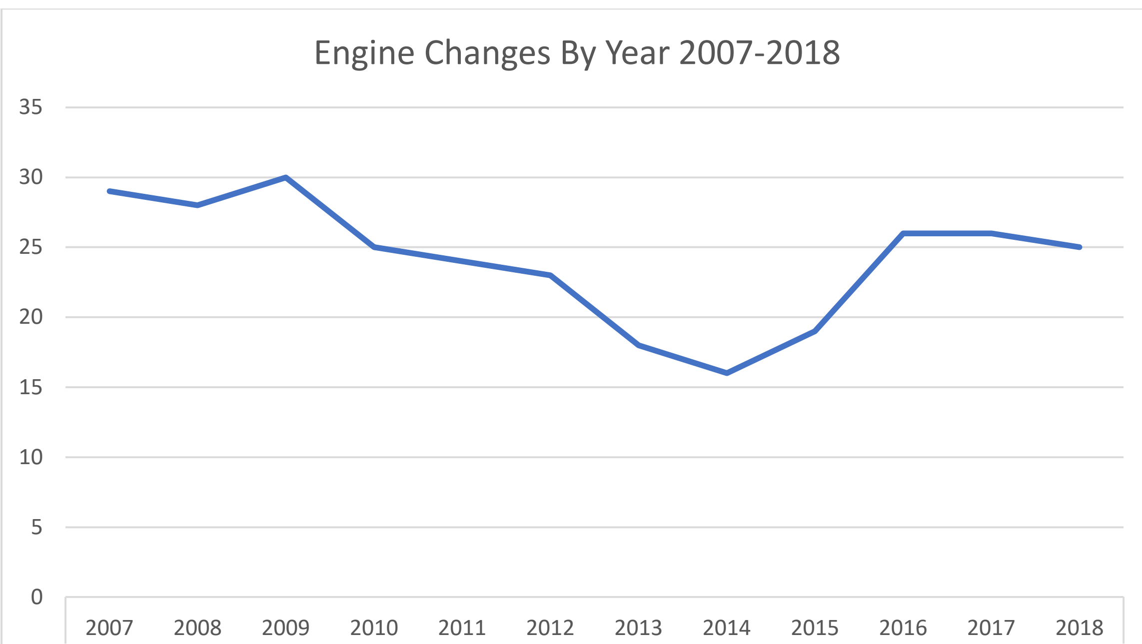
The chart above is straightforward and shows the concern that less than nine percent of engine changes are scheduled. Year after year only one to four engine changes are conducted when decision makers want them to be. Data from 2019 was omitted as the data collected was not complete through the year.

Figure 14: Engine Changes by Hours Accumulated 2007-2019



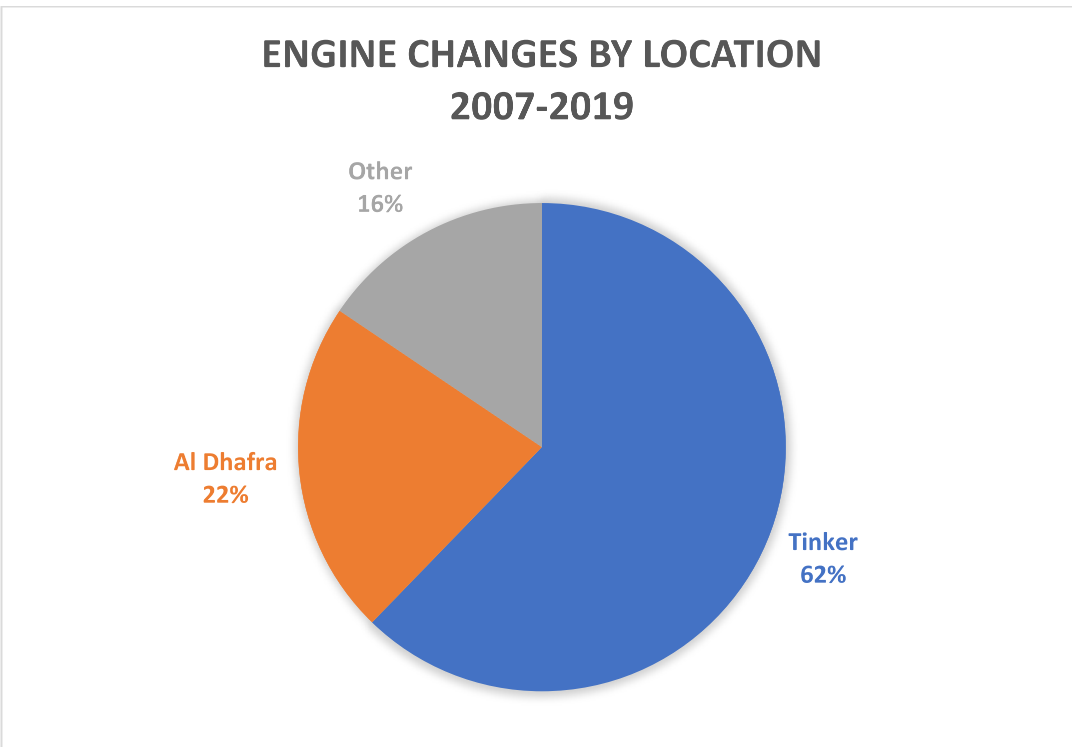
The prescribed engine overhaul hour requirement is 6,000 hours. However due to the increasing age of the TF33, 91% of the Tinker E-3 engines do not make it to the 6,000-hour requirement. The above chart shows the breakdown of the 302 engine changes examined since 2007 regarding how many hours they accumulated from their previous overhaul to replacement. Only 27 of the 302 were changed at 6,000 hours or more, with the highest category, 71, being engine changes between 0 and 999 hours. The TF33 time to overhaul was not always 6,000 hours and the time can be reduced by Air Force Engineering. Originally the TF33 had a 4,500-hour requirement to overhaul, but numerous analytical condition inspections were conducted and increased the time to 6,000 during the 1990's (Babb, 2020). Engineering even tried to extend it further, but several component test indicated it was not feasible. As can be seen in the chart above the time should never have been extended in the first place. If the time to overhaul was still at 4,500, 100 of the 302 engines examined would have made it to overhaul on time which is 33%, still not great but much better than 9%.

Figure 15: Engine Changes by Year 2007-2018



The engine changes examined from 2019 were omitted from the above chart, as data was only collected up to May 2019. On average there are 24 engines changes per year. The most engines changed was 30 in 2009 and least was 16 in 2014. Engine changes should be able to be roughly predicted based on flying hours and utilization rates. However, considering that 91.4% of engine changes are unscheduled and well before their 6,000-hour mark, it is difficult to correlate the above chart to use. 2009 had three scheduled engine changes, all the rest were due to FOD, oil pressure, cracks, and other unexpected discrepancies.

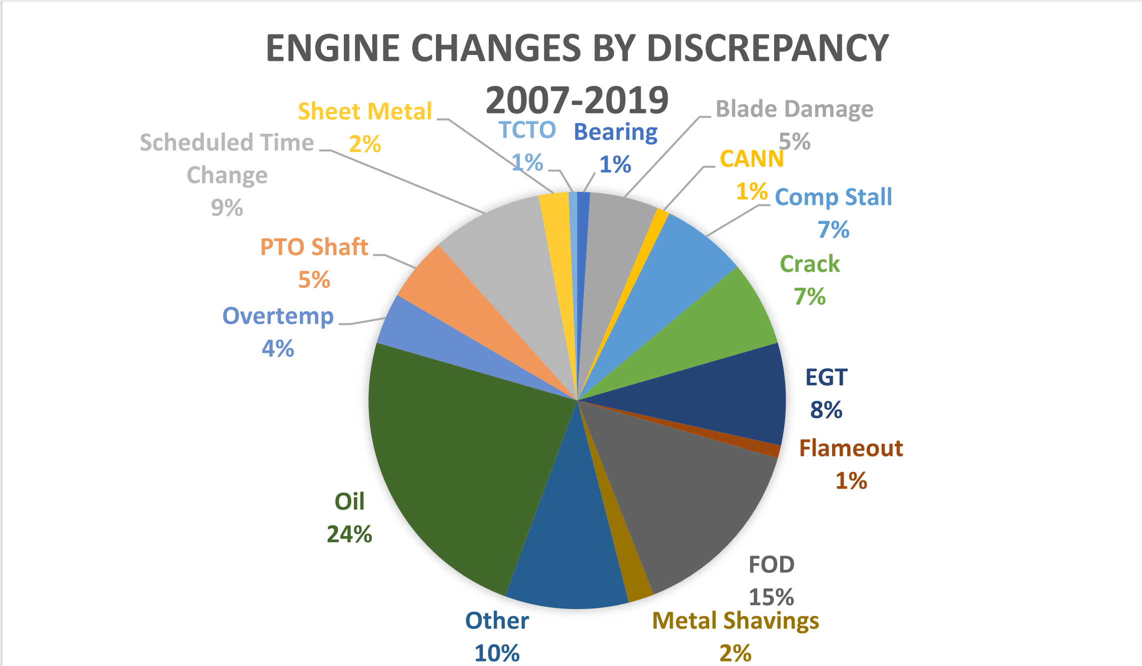
Figure 16: Engine Changes by Location 2007-2019



Scheduling engine changes allows the engine to be removed and replaced at an ideal location with adequate manpower tools and equipment. Of the 302 engine changes examined in this study, 188 were replaced at Tinker Air Force Base, 67 at Al Dhafra Air

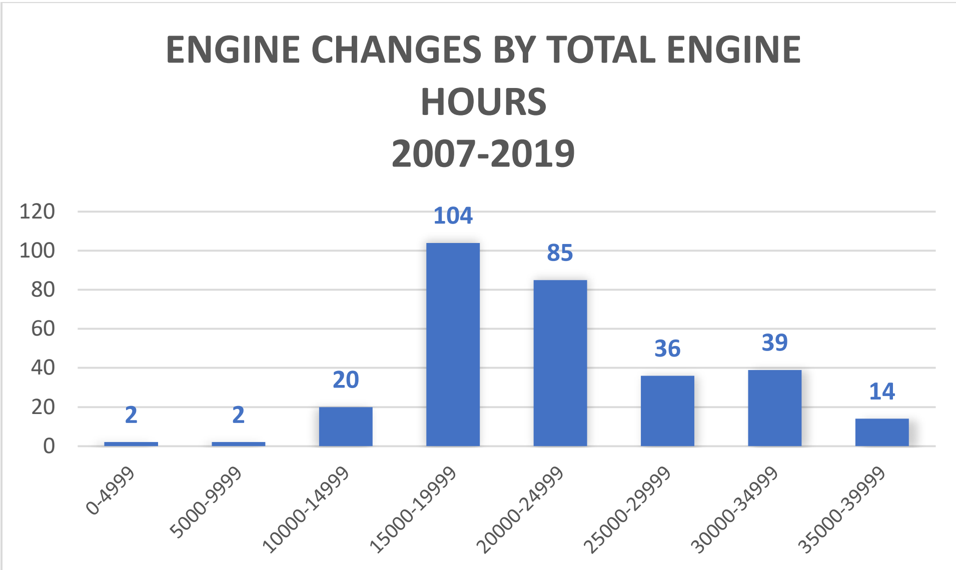
Base, and 47 at various locations across the globe. Al Dhafra Air Base is the primary deployed location for the 552nd Air Control Wing and as such has a standing maintenance team and is allocated TF33 engine spares. It is still not ideal to change engines in a deployed setting as the aircraft and maintainers are needed for high operations tempo and other war-time mission requirements. For the 47 other engine changes conducted around the world, it is an extremely cumbersome and costly task. A significant amount of resources and coordination is required when an engine change occurs at non-E-3 operating bases. Exact costs will change dependent on location, transportation to ship the engine, engine stands, and tools, and personnel costs. Assuming a generic location with normalized costs and a maintenance team of five personnel, an engine change not at Tinker or Al Dhafra can cost between $10,000-$30,000 and three to seven days of lost aircraft availability. Assuming the worst-case scenario for the 47 engine changes since 2007, this may have cost the Air Force up to $1,410,000 and 329 days of lost aircraft availability.

Figure 17: Engine Changes by Discrepancy 2007-2019



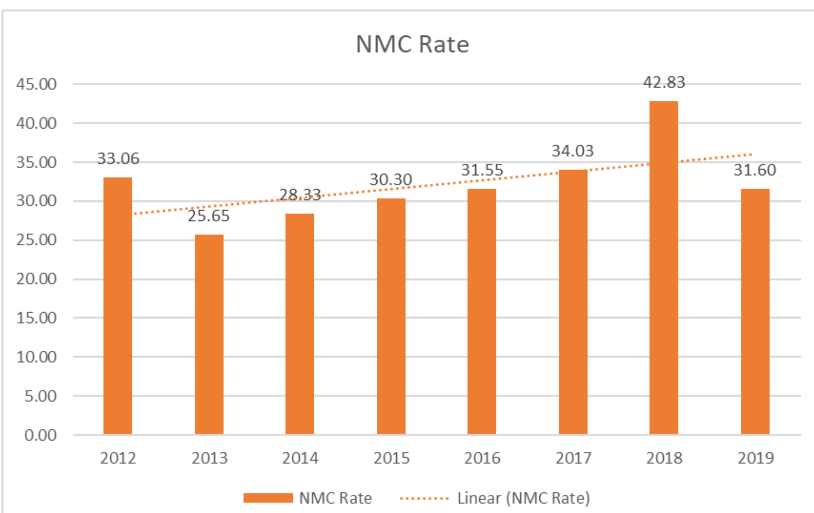
Engines go bad for a multitude of reasons from general wear or use to damage received by foreign objects and debris. The above chart breaks down the reasons for TF33 replacement on the E-3 aircraft since 2007. The top reason is due to oil discrepancies. The preponderance of these oil write-ups were oil leaks from the gearbox, bearings, lines, or seals. The oil category also includes excessive consumption and oil pressure issues. The second highest reason was due to foreign object debris (FOD). This FOD damage occurred due to bird strikes, ice, rocks, and other debris ingested by the engine during use. The third highest cause for replacement was due to exhaust gas temperature (EGT) discrepancies. Per engineering and technical guidance, when a TF33 engine experiences an EGT above 555 degrees Fahrenheit, it must be replaced. 83% of the EGT write-ups were due to excessive temperatures exceeding the limit.

Figure 18: Engine Changes by Total Engine Hours 2007-2019



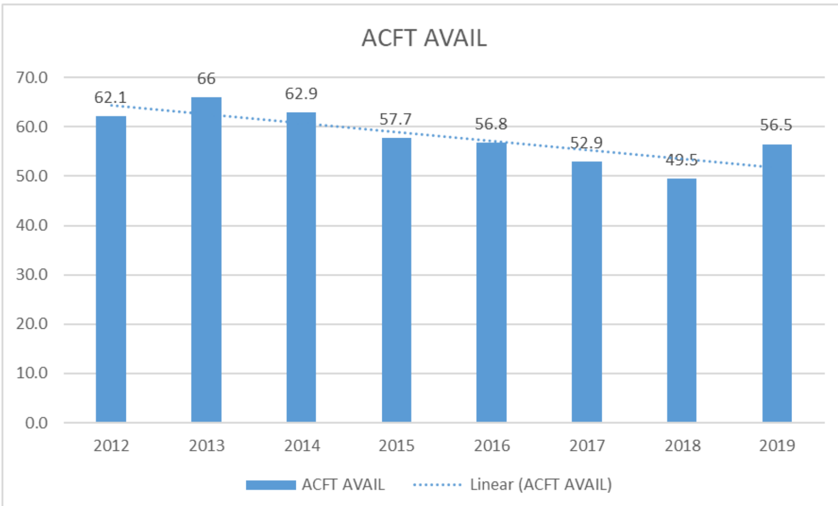
The above chart shows the total hours accumulated at time of engine change (TT) on the 302 samples from 2007-2019. The average TT of a TF33 Engine is 22,511 hours. It is important to note that the bulk of engine changes are between 15,000 and 25,000, which correlates to the fact that most TF33 engines currently in use have that many hours.

Figure 19: NMC Rate



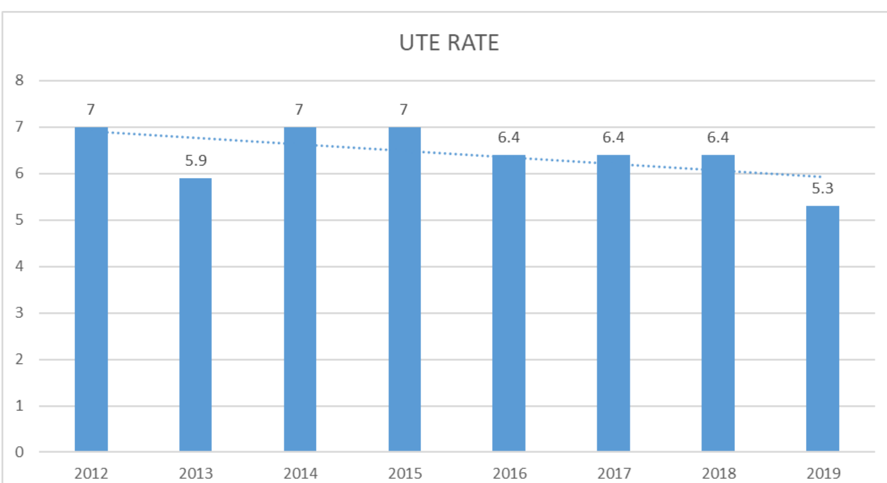
The above chart shows the non-mission capable rate of the Tinker E-3 Fleet. While there are many factors that drive the aircraft to be non-mission capable, engine related issues are a significant driver and are directly affecting this negative trend. The non-mission capable rate has been steadily increasing since 2012, making the E-3 less capable of performing its mission.

Figure 20: Aircraft Availability Rate



The above chart shows the aircraft availability rate for the Tinker E-3 fleet. This rate is trending down which is not good. This indicates that the aircraft of this fleet are less available to perform their mission. While there are many different factors that drive this rate, engine related issues are a significant factor.

Figure 21: Utilization Rate



The above chart shows the utilization rate of the Tinker E-3 Fleet. The non-mission capable and aircraft availability rates are tied to the utilization rate. Usually if the aircraft is being utilized more, there is higher chance of the aircraft breaking due to overuse. What is interesting in the E-3 fleet, is that utilization has been going down, yet NMC rate is going up and AA is going down, which is the opposite of what one would expect to see. This trend is indicative of the waning supportability and ability to maintain this fleet's engines.

Discussion with Experts at Tinker Air Logistics Complex

According to experts at the Tinker Air Logistics Complex more parts are having to be made by the Commodities Maintenance Group for the TF33 than ever before and industry supportability for spare parts has been decreasing with every passing year (Medrano, 2020). There are currently 262 cold start national stock numbers for TF33 and the Propulsion Maintenance Group anticipates this number to rise (Loska, 2020). To highlight this issue, the TF33 gearbox alone has 22 sole source no-bids and condemnation rates are increasing causing depot production work stoppage (Loska, 2020). Due to this lack of supportability from the private sector, the Commodities Maintenance Group at Tinker Air Force Base is exerting extra manpower to monitor parts delivery, submit and work engineering solutions, and organically produce parts like hydraulic, fuel, and gearbox pumps which were previously sourced from outside the complex (Kalin, 2019). Pratt and Whitney still support the program, but according to the technicians on the ground, it feels like they have moved on and are not devoted to continued support of the 60-year-old TF33 (Medrano, 2020). To complicate matters, many of the parts that are no longer available for purchase were procured from the private sector for so many years, and acquisition of intellectual property was so long ago, that the manufacturing processes for these parts aren't available or don't exist (Medrano, 2020). The original documentation, despite a digital undertaking in the 1980s, was never digitized and has been lost since the 1950s, this technical data is now needed as supportability wanes. Re-engining the E-3 would ensure commercial supportability as well digital technical data. This lack of industry supportability for TF33 is driving the Complex to do "work-arounds" and "over and above" maintenance to keep the TF33 operational which uses up additional funds and results in behind schedule overhauls (Medrano, 2020).

Results on the Hypotheses

Hypothesis 1: Engines with higher total operating hours will be more likely to fail before the overhaul interval.

The median total time on engine for the data set collected was 20,963.35 hours, with 151 engine changes below this number and 151 above it. The data set was broken down into two categories to express "higher total engine hours" being the 151 above the median. To answer this question scheduled versus unscheduled engine changes and average accumulated time was examined for these two categories to see if the engine was more likely to fail before the scheduled replacement point.

Figure 22: Hypothesis 1 Engine Breakdown by Median

Median	Scheduled Engine Changes	Unscheduled Engine Changes	Avg Accumulated Time
<20963.35	10	141	2499.5
>20963.35	16	135	3037.2

Examining the data of the above chart, engines with lower total engine hours are more likely to fail before the scheduled replacement point. Engines below 20,963.35 total hours have a 6.6% scheduled engine change rate as compared to engines above which are at a 10.5% scheduled engine change rate. Although *hypothesis 1* was not supported, it is also not as important as originally thought when this study began. As can be noted from the numbers, regardless of whether the TF33 has more or less total hours, the average accumulated time is approximately 3,000 hours or less before overhaul and the unscheduled engine change rate is 89% or 93% both of which are terrible rates.

Hypothesis 2: The majority of engine defects causing the need for engine changes are non-preventable.

Using the data which generated Figure 16, preventable discrepancy categories are Scheduled Time Changes, TCTOs, and CANN which accounts for 11% of engine changes. The other 89% were non-preventable. Therefore, this hypothesis is supported.

Hypothesis 3: The cost of unscheduled and off-location engine changes justifies re-engine and would pay back re-engine within a decade.

The cost to re-engine the E-3 was crudely estimated in this study as approximately $500 million. This was calculated referencing the B-52 re-engine program, and actual costs would be more or less than this number, but for the sake of this research $500 million will be assumed a reasonable cost. It was also roughly calculated that non Tinker/Al Dhafra engine changes cost the Air Force $1.4 million. Unfortunately, the cost of the 67 engine changes at Al Dhafra was not available, and a true cost estimate of what a 91% unscheduled engine change rate for 302 engines over a 12 year period was also unable to be calculated. It is inherently understood that 67 engine changes at a deployed location and a 91% unscheduled engine rate are not positive indicators, but not having the cost associated with these metrics disables this research from answering this hypothesis.

Hypothesis 3 was attempting to account for engine changes, but ultimately is trying to show that a re-engine would pay for itself on the E-3. To that point, a re-engine would likely pay itself back through cost savings from fuel efficiency and overhaul costs therefore increasing scheduled and on location changes would be a bonus side-effect. The overhaul costs for the 302 engine changes examined here was approximately $513.4 million, and re-engining could potentially cut down engine overhauls for the next 12 years to 60 equating to $102 million, a $400 million savings.

Courses of Action

This research proposes two primary courses of action the Air Force could take to increase safety of flight, operational capability, and reduce field and depot maintenance costs for the AWACS. The first recommendation is the retirement of all TF33 engines and the re-engining of all platforms that currently use it. The second course of action would be to retire the E-3 altogether in favor of a new platform. To accept either of these courses of action or one over the other, a cost comparison between re-engining versus a new platform must be conducted. A new platform is not a question of if, but rather a question of when. It may not have made sense to re-engine the E-3 in 2007, when the council expected a new platform to be on the horizon. Now it is 2020 and the TF33 is projected to be unsustainable by 2030 which means the E-3 may not even make it through the time it takes for an acquisitions process to produce the next platform. New engines could be purchased for the E-3, and upon retirement of the aircraft, moved over to another platform.

Re-Engine

Global Strike Command began looking into potential engines to replace the TF33 on the B-52 fleet in 2017 and has since given the green light to re-engine the fleet. Pratt & Whitney promotes the TF34 as a low-cost alternative to acquiring a new engine. (Insinna, 2017). Matthew Bromberg of Pratt & Whitney stated that the company would look at designing a new engine if that was the requirement the Air Force proposed. However, Pratt Whitney is not the only option on the market. Rolls Royce proposed the BR725, a variant of the F130, which is already used on the E-11 and C-37 fleets (Insinna, 2017). The BR725 is a modern engine which would increase fuel efficiency, while also providing more thrust, quieter operation, less carbon emissions, and increased maintenance intervals, which would lower the total lifecycle costs of the power plant (Rolls Royce, 2019). Though there are many options available, there are several drawbacks beyond just the cost of new engines that would setback the Air Force during a re-engine. There also exists an opportunity to replace the TF33 with the CFM56. The CFM56 is already used on British, French, and Saudi E-3 platforms, so the modifications required to re-engine an E-3 to the CFM56 would be minimal and the knowledge to do so already exists. Furthermore as the KC-135 retires, the CFM56's from that fleet could be pulled over, to support the E-3. Private Sector supportability remains largely available for the CFM56, and existing depot overhaul capabilities are in place and would only need to be expanded. Much of the infrastructure and manning in the TF33 section could be transferred over to increase capacity of the CFM56 line with minimal impact. The CFM56, or the F108 Air Force designation, depot line is currently built to handle a capacity of 12 engines per month (Marasco, 2020). The depot is halfway complete with the newest F108 "C-PUP" upgrade and expects engine outputs to stay on wing for 10-15 year (Marasco, 2020). Analysts are expecting the workload in the F108 section to decrease to 6 engines a month by FY24 and 2 engines a month by FY29(Marasco, 2020). This means the F108 line will have ample capacity over the next decade if the E-3 was to re-engine to the CFM56. The CFM56 may be the perfect choice if the E-3 stays in commission for another 10 years or more. With the New 40/45 upgrade, IPEC, and Dragon modifications that were just expended on the AWACS, the likelihood of the E-3 staying in service beyond 10 years is likely, which puts the platform far beyond the expected life of the TF33 and a re-engine with the CFM56 very desirable. Re-engining will not come cheap though, nor will it be an easy solution to implement without some detriment.

Retiring the TF33 will cause a significant upheaval to the 76th Propulsion Maintenance Group at the Tinker Air Logistics Complex. One of the depot's functions is to repair and overhaul the TF33 for the E-3 and B-52 fleets. The B-52 is now underway with its re-engine; however, if both fleets retire the TF33, and the F108 line is not chosen to replace the TF33, a second order effect would be that the depot would need to shut down the TF33 overhaul facilities to retool and reorganize a significant portion of their equipment and personnel. With the extended lifespan of new engines, if a modern engine is chosen, this could eliminate the overhaul process until 2050, saving the Air Force "$68 million per year for 16 years, thus a potential savings of $1billion over that timeframe" (Kalin, 2019). While big Air Force may save money, if the workload lost due to retiring the TF33 isn't replenished, the Tinker Air Logistics Complex could lose a significant stream of revenue and many jobs, which could drive Political considerations and potential Congressional pressure. This implication leads more credence to the potential of the CFM56 which has already been tried and tested as an effective and cost saving replacement for other 707 variants.

The flying community and combat commanders would be the first to reap the benefits of new engines. There has been a significant increase in late take-offs and cancelled sorties due to engine discrepancies in the past two years at Tinker AFB. Of note, one aircraft flew as far as the Atlantic Ocean, experienced a compressor stall mid-flight and turned back despite an important need by combat commanders to have increased AWACS presence in the Central Command Area of Responsibility. Having new engines would lead to more reliable sortie generation, thereby increasing training opportunities for flyers back home and mission effectiveness downrange. Field and depot level maintenance would also experience high returns on investment for replacing the TF33. The current scheduled time to overhaul a TF33 is 6,000 hours. On average a TF33 at Tinker AFB is making 2,768, whereas a modern engine is expected to last 10,000 hours or more before overhaul is even required (National Research Council, 2007). This would reduce the time, field level maintainers are removing and replacing engines and sending to depot, which would also cut back logistics costs, and reduce the number of engines taken from the programmed depot line to support the field. In February 2019, there were approximately nine depot paybacks that the 552nd Maintenance Group owed the depot due to cannibalizations from the program line due to unscheduled maintenance issues on operational aircraft. Re-engining would also cut down on other maintenance issues other than the removing and replacing of engines. The TF33 has limited capabilities to monitor operating parameters, and most of that data keeping is reliant on flight engineers and maintainers prone to human error. A modern engine would be equipped with sensors and computers that keep track of engine performance digitally which can be downloaded and analyzed. The adoption and usefulness of data analytics is growing as predictive software is developed to forecast part failures which leads to better time change maintenance and posturing of supply. But TF33 engines have limited ability to make use of data analytics. There are also many smaller discrepancies that often cause late takeoffs, such as broken nose cowl anti-ice valves and ignitor leads. These discrepancies would be significantly reduced with a new engine. Ultimately, the maintenance community would gain increased focus and time to work on other issues if they did not spend as much time working on 40-year-old decaying engines.

New Aircraft

Alternative to replacing the engine, the Air Force could retire the E-3 and acquire a new airframe altogether. Leveraging the defense industry to design and construct a new platform based on mission requirements is an option; however, there are several platforms already in use by allied countries. The Royal Australian Air Force currently has six Boeing E-7A Wedgetails (Australian Royal Air Force, 2017). Able to provide combat command control similar to the E-3, this platform can control four million square kilometers in a 10 hour mission. (Australian Royal Air Force, 2017). Based on the Boeing 737-700, the Wedgetail has 10 Air Battle Manager Consoles, which is fewer than the E-3, but the software and user interface are more modern. Regarding the propulsion system, it uses two CFM 56-7 turbofans capable of a range up to 7,000 kilometers and a ceiling up to 41,000 feet (Australian Royal Air Force, 2017). Britain made a $2 billion deal in March 2019 with Boeing to acquire five Wedgetail aircraft replacing the aging E-3D platform which has "suffered groundings and high unavailability rates in recent years" similar to the Air Force E-3 fleet (Australian Royal Air Force, 2017). As more U.S. partners begin to acquire the American made E-7, it will create better interoperability between the Air Forces. A statement by the ministry of defense concluded "this deal (purchase of E-7) strengthens our vital military partnership with Australia… this announcement will help us work even more closely together" (Chuter, 2019). The 737, which the E-7 is based on, is still widely used in the private sector and well supported as compared to the 707 which has lost extensive supportability due to disuse by the airlines. With the British purchase of the E-7, it is now used by four U.S. allies: Australia, South Korea, United Kingdom, and Turkey — but not by the U.S. military (Chuter, 2019). There are other options besides the Wedgetail such as using an Airbus 330 with a Saab Erieye radar. The British stated that the E-7 was so far ahead and superior to any other platform available, they sole source selected the Boeing E-7, stating that holding a competition would be "a waste of time and money…considering the E-7 Wedgetail, there was such a clear distinction over any other options it was felt that running any type of competition would unnecessarily consume Ministry of Defense and industry resources, whilst the gap between U.K. capability and the evolving threat would be expected to widen" (Chuter, 2018).

Limitations

There were several limitations to this research that were predominately due to incomplete data and complexity of data. Detailed analysis regarding specific discrepancies that caused the requirement for engine removal was beyond the scope of this paper. Some engine removals were due to oil leaks, some to compressor stalls, foreign debris, etc. This research looked at these categories broadly without analysis for each individual cause. The EGT margin is a major indicator for the life cycle and overhaul requirement of military jet engines. However, EGT was not previously annotated on common engine removal forms and was not readily accessible. Cycles is also a major indicator for the life cycle of jet engines, but this data was also not readily available and therefore not utilized. This data is only 552 Air Control Wing field level data, and does not account for engine changes by other Air Force AWACS fleets or depot level engine changes.

Conclusion

The TF33 has reached the end of its lifecycle, with the Air Force Life Cycle Management Center projecting unsustainability by 2030 (Wilcox, 2018). Unscheduled engine changes lower E-3 lethality and increase maintenance costs, with no replacement on the way driving a clear need for re-engine. The operational and maintenance communities are fielding the brunt of the effort to maintain this aging power plant, meanwhile the defense industry stands by to meet the Air Force's need. It is time for the E-3 enterprise to petition Air Combat Command with the concerns affecting the platform and call for a coordinated re-engine by utilizing the CERP process and Section 804 rapid prototyping already underway for the B-52 (Wilcox, 2018). An endeavor of this caliber would not be accomplished without costs, but the benefits far outweigh the risks. The 2018 National Defense Strategy made it clear "We cannot expect success fighting tomorrow's conflicts with yesterday's weapons and equipment…we must invest in modernization of key capabilities…"(Mattis, 2018). The E-3 mission of combat command and control is vital to American national security and without new power plants, AWACS mission effectiveness will continue to decrease and potentially flat-line by 2030.

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14. ABSTRACT
The 1950s P&W TF33 jet engine was used widely in the airlines and military for over fifty years. Jet engine technology has advanced greatly since, with new engines fielding better fuel efficiency, lowered carbon emissions & noise pollution, & longer maintenance intervals. The airlines have completely retired the TF33 but the Air Force still maintains thousands on critical platforms like the E-3 and B-52. Several studies were conducted in the 1990s & 2000s proposing the re-engining of all TF33 powered aircraft. This research will take a look at those studies, the current re-engine program for the B-52, and an analysis of engine replacement data for Tinker AFB AWACS from 2007 to 2019 in a case for re-engining or retiring the E-3.

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