AN ANALYSIS OF COAST GUARD HH-65 ENGINE RELIABILITY:

A COMPARISON OF MALFUNCTIONS TO COMPONENT REMOVALS

THESIS

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AFIT/GIR/ENC/04-01

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THESIS

Presented to the Faculty

Department of Mathematics and Statistics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Information Resource Management

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March 2004

AFIT/GIR/ENC/04-01

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Abstract

The Coast Guard HH-65 helicopter experienced 31 in-flight loss of power incidents during FY 2003 and 21 during the first two months of FY 2003. Concurrent with this apparent decrease in reliability, the Coast Guard seeks ways to expand the HH-65's Airborne Use of Force capabilities as a result of the September 11th, 2001 terrorists' attacks.

This study is an exploratory, empirical analysis of engine and airframe component replacements as related to engine mishaps and reliability in the HH-65. We use contingency table analysis, ordinary least squares regression, and logistic regression to examine the mishap history and component replacement history of ten different HH-65 components from 1997 through March of 2003. Additionally, we examine the literature to determine the factors impeding improvements to the HH-65 powerplant.

This study reveals three critical issues associated with the HH-65 powerplant, namely, lack of power reserve associated with the LTS-101-750, poor reliability associated with the fuel-control system, and excessive trouble removals due to excessive time between scheduled overhaul times. Moreover, we find lack of funding and political pressure forcing the Coast Guard toward a less than optimum fix that could adversely affect overall mission effectiveness and Homeland Security.

Acknowledgements

I would like to express my gratitude to my thesis advisor, Dr. Tony White, for his outstanding assistance and inspiration. In my almost 18 years of formal education, Dr. White is one of the finest teachers I have ever had. His love for teaching is obvious and his passion for statistics contagious. His gift as an educator is surpassed only by the quality of his character; he truly embodies the Air Force's Core values of integrity, service, and excellence.

I would also like to thank Lt Col Summer Bartczak for her support and encouragement. A superb educator and caring leader, she brings a unique enthusiasm to the classroom that makes one want to learn. Special thanks go to LCDR Lorinda Couch for keeping me up to date and ensuring my facts were indeed factual. I am also indebted to my husband for his undying support and patience during this effort. Finally, I would like to thank my Savior, Jesus Christ, who has given me forgiveness for my past, strength for the present, and hope for the future.

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AN ANALYSIS OF COAST GUARD HH-65 ENGINE RELIABILITY:

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I. Introduction

Overview

The HH-65 Dolphin helicopter has been in service as the Coast Guard's short-range search and rescue helicopter since 1984. During the early years of service, its engine, the Lycoming LTS-101, suffered from several reliability problems which were remedied by 1990 (Kandebo, 1990b:25). However, the reliability of this engine has again come into question. The HH-65 experienced 31 in-flight power loss events during fiscal year 2003, and 21 events during the first two months of fiscal year 2004; the later figure corresponds to approximately one event every three days (Couch, 2003a). In the past year, the HH-65 helicopter experienced 61 power loss incidents per 100,000 flight hours. During the same period, the Coast Guard's other helicopter, the HH-60J had zero incidents (CG PACAREA Oct 30, 2003). RADM D. S. Belz, the Coast Guard Chief of Operations, has made the "safety and reliability of the H65 powerplant [the] number one priority for USCG aviation" (COGARD Oct 03, 2003).

With the terrorists' attacks of September 11th and the increased emphasis on Homeland Security, the Coast Guard's mission of Maritime Law Enforcement (MLE) has expanded. As a result, the Coast Guard is looking to equip the HH-65 with various

Airborne Use of Force (AUF) capabilities. These include use as a delivery vehicle for law enforcement boarding teams and installation of flexible mounted machine guns. These capabilities require a reliable and more powerful engine in order to allow for the necessary increase in the maximum gross weight of the HH-65 (Burgess, 2003).

With a current inventory of 95 airframes, the Coast Guard owns and operates more HH-65s than any other type of aircraft. The fleet of HH-65s accounts for 87,500 hours of annual flight time and has accumulated over 750,000 total flight hours since 1984 (Padfield, 2003). Any problem associated with this critical asset has a negative impact on every Coast Guard mission. As senior leaders within the Coast Guard aviation community struggle to meet the expanded mission requirements of the HH-65, they face an apparent decrease in reliability of the HH-65 engines. Senior leaders cannot make an informed decision to upgrade the HH-65's current engine or to purchase an entirely new engine without a full understanding of the problems that affect the current powerplant. Many of the engine malfunctions are attributable to an aging Anticipator System, which serves to match engine torques. However, many experts believe that recent component faults within Fuel Governing System are masked by the Anticipator System (Serrano, 2003). This research assists decision makers in deciding which system – the Fuel Governing System or the Anticipator System - is causing the majority of engine malfunctions and whether to upgrade the current engine or purchase an entirely new engine for the HH-65. This study also examines the history of the problem of inadequate power in the HH-65 and its impact on the mission effectiveness of the aircraft. Finally, this study examines various cultural and political factors that have impeded improvements to the HH-65 powerplant.

Research Questions

1. Has the HH-65 become less reliable over time?

    - Has the number of engine malfunctions increased over time?

    - Is the age of the engine components a factor in the recent increase of engine-related mishaps?

    - Is the failure rate or mishap rate higher among older components?

2. What primary factors are driving failures in the LTS 101 engine?

    - Is there a correlation between certain malfunctions and specific components?

    - Is there a correlation between certain malfunctions and type of system?

    - Can more trouble removals be attributed to either the Anticipator System or Fuel Governing System?

3. Should the overhaul times be changed?

    - How often are components being removed for trouble? For time?

    - Is the Time Since Overhaul at the time of failure a predictor of reliability?

4. What primary factors are impeding powerplant improvements of the HH-65?

Methodology

This study is an exploratory, empirical analysis of engine and airframe component replacements as related to the LTS 101 engine failure rates and reliability in the HH-65 Dolphin. This study also explores the history, background, and political issues associated with the upgrade and replacement of this engine.

We answer research question one through an examination of trouble removals and mishaps over time. We use contingency table analysis to compare component type and number of trouble removals. We compare the average age of a component to the number of trouble removals, number of mishaps, and overall reliability.

We answer question two by examining the number of trouble removals by component and type of malfunction through contingency table analysis. We also compare the number of trouble removals by system over time. Finally, we examine the ratio of anticipator to fuel-governing system removals over time using Ordinary Least Squares.

We answer question three by an initial comparison of time versus trouble removals by component and the Mean Time Since Overhaul to the Scheduled Time Since Overhaul. We examine the predictive value of the Mean Time Since Overhaul and the Difference of the Mean Time Since Overhaul. We use these variables in a logistic model to predict failure and in a linear model to predict Mean Time Between Failures. Finally, using the average rate of increase over the last five years, we predict the number of trouble removals for 2003 and project a decline in trouble removals through a change in the Scheduled Overhaul Times. We answer question four through an examination of the literature related to the HH-65 history and background.

Scope

The scope of this study is limited to examination of the component replacement history of ten different HH-65 components from 1997 through March of 2003. Engine failure and component failure analysis is limited to the same time period. We examine two types of data as part of this study, engine-related mishap data and component replacement data.

Significance

This study provides Coast Guard senior leaders information that better enables them to make informed decisions concerning the future upgrade or replacement of the HH-65 powerplant. By determining the significant limitations affecting the HH-65 and determining which components or systems are causing the majority of engine malfunctions, the Coast Guard can focus its efforts toward a fix or replacement on the critical failure point(s). A fix of these failures and an increase in the reliability of the HH-65 engines will increase aircraft dispatch rates as well as safety and mission effectiveness for HH-65 aircrews.

Thesis Overview

Chapter One contains subject matter background, the research questions, and a brief description of the study. Chapter Two contains a comprehensive review of the history and background of the HH-65, its mission requirements, power requirements, and weight growth. Also discussed are the LTS-101 engine, engine alternatives, recent events, political issues, and the future of the HH-65 as it relates to this study. Chapter Three discusses the research methodology used in this study, provides descriptive statistical information of the data gathered, an analysis of the collected data, and the findings from this analysis. Finally, Chapter Four provides discussions, conclusions, recommendations, and suggestions for further research.

II. Background

This chapter reviews the background and history of the HH-65 and the LTS-101 engine. We use the term *HH-65* to include both the HH-65A and HH-65B, both of which are currently in use. We specify the actual model – A or B –when necessary to address differences between the two. Areas covered include the history and background of the Coast Guard HH-65, its mission requirements, power requirements, and weight growth. Also discussed are the LTS-101 engine, engine alternatives, recent events, political issues, and the future of the HH-65 powerplant as it relates to this study.

History of the Coast Guard HH-65

The HH-65 Dolphin Helicopter is the Coast Guard's twin-engine, Short-Range Rescue (SRR) helicopter. Developed as the replacement for the single-engine HH-52A Pelican, it was manufactured by Aerospatiale Helicopter Corporation (AHC) – now known as American Eurocopter (Mason, 2002:1). The Coast Guard awarded AHC the contract for production in 1979. The HH-65A (366G) is a modified version of AHC's commercially-made (365N1) Dauphin Helicopter (Schlatter, 1997:3; Couch, 2003c). Of the approximately 200 aircraft operated by the Coast Guard, the HH-65 accounts for almost half of the Coast Guard's aircraft inventory as well as approximately half of the Coast Guard's total annual helicopter hours (Connor, Devoe et al., 1998:7; "Honeywell Develops Improved Controls," 2002). The Coast Guard took delivery of the first HH-65A in 1984 and received a total of 96 helicopters by 1989 (Schlatter, 1997:1). The current inventory includes 95 – the Coast Guard purchased two used airframes after three HH-65 Helicopters were lost in separate crashes (Couch, 2003).

Mission Requirements

The Coast Guard developed the HH-65A mission requirements based on Title 14 USC 2. This law mandates the Coast Guard with responsibility for Search and Rescue (SAR) on the high seas and navigable waters of the U.S. This jurisdiction extends to 150 miles offshore. "Over 98% percent of all SAR cases occur within this zone, for which the SRR helicopter provides the primary response capability" (Schlatter, 1997:1). In order to meet these requirements, modifications to the commercial version of the Dolphin, the (365N1) Dauphin, had to be made (Couch, 2003c). The modifications included the following:

- Larger and modified tail section
- Increased seat structure for better crash worthiness
- Second Loran rack
- Freon Air Conditioning system
- Modification of original engine to allow for cold-weather (polar) operations
- Electromagnetic Interference Protection
- Filter on Radar Altimeter

In total, these modifications resulted in an aircraft that was significantly heavier than the commercial model. These modifications marked the beginning of the history of the HH-65's weight growth and were a factor in drastically reducing the delivered aircraft's reserve power and mission capability.

Power Required vs. Power Available

Weight growth in any aircraft is an important issue. In a small aircraft, like the HH-65, it can be crucial in the eventual performance and safety of the aircraft. Weight added to the airframe results in a decrease in the power available and that results in a decrease in power reserve. Power reserve is the difference between power available and power required. Power required is dependent on the type of maneuver performed, such as take-off or hovering. Power available depends on many factors including air temperature, humidity, barometric pressure, density altitude, and aircraft weight. The greater the power reserve, the greater the capability of an aircraft to perform high-power operations. For the HH-65, high-power operations include takeoff, hovering (to include hoisting), and landing to a confined area. These high-power operations are standard operations for the HH-65 in the normal course of its mission profile (*HH-65 Flight Manual,* 1996:5-15, A-19) .

As the power reserve decreases, high-power-required maneuvers become more demanding. Factors such as increased aircraft weight, hotter air temperature, higher humidity, and higher altitude are variables that decrease the power available to an aircraft. Any factor that decreases power available must result in a corresponding decrease in the takeoff fuel load to stay beneath the allowable gross weight and/or engine limitations. Each decrease in fuel corresponds to a decrease in maximum range and endurance. In the case of added weight, an increase in airframe weight requires a corresponding trade-off in the allowable amount of maximum fuel at take-off in order to stay under the maximum allowable gross weight. (Six-hundred pounds of fuel roughly equates to sixty minutes of flight time in the HH-65.) A reduction in fuel results in a parallel reduction in the maximum range the helicopter can fly (Schlatter, 1997:9).

Weight Growth

Upon initial delivery in 1984, the HH-65A met the mission requirements previously discussed with a crew of three to include a pilot, copilot, and flight mechanic. Modifications made to meet these requirements accounted for a 605 lb. weight increase over the original 366G Dauphin (Schlatter, 1997:3). In all, the modifications resulted in a launch weight of 8895 lbs., which was only five pounds under the maximum allowable gross weight at the time. The initial delivered model could hold a maximum of 1866 lbs. of fuel on takeoff and had only an 8% power reserve due to the increase in weight (Schlatter, 1997:8). Figure 1 outlines the timeline of the various HH-65 upgrades and changes since becoming operational.

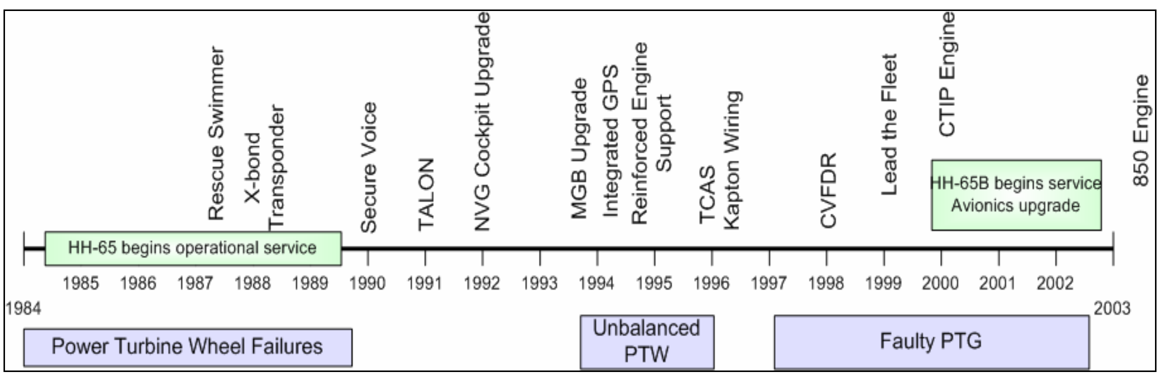

Figure 1. HH-65 Timeline 1984 – 2003

The lack of power reserve continued to decline as the HH-65 evolved. Table 1 outlines the evolution of the HH-65 and the resulting effects on maximum fuel load and range. Most modifications were official in nature and documented by Coast Guard leadership.

Table 1. HH-65 Weight Growth History (Schlatter, 1997:3, 8-13)

year	modification	weight increase/ (decrease)	basic weight	max gross weight	Crew & Equip Weight*	Launch weight	power reserve (standard day)	fuel load on takeoff	endurance (600 lbs/hr burn rate)	max range (NM) @ 120 kts cruise (no wind)
1979	original 366G		5592	8400						150
1984	delivered HH-65A	607.90	6200	8900	842	8900	8.3	1858	2.8	150
1988	x-bond transponder	5.50	6205	8900	842	8900	8.3	1853	2.8	149
1988	Rescue Swimmer	0.00	6205	8900	1042	8900	6.5	1653	2.4	127
1990	Secure voice	4.00	6209	8900	1042	8900	6.5	1649	2.4	126
1991	TALON	46.00	6255	8900	1042	8900		1603	2.3	121
1994	Reinforced Engine support	5.00	6260	8900	1042	8900		1598	2.3	121
1994	Integrated GPS	12.80	6273	8900	1042	8900		1585	2.3	119
1994	Undocumented	80.00	6353	8900	1042	8900		1505	2.2	110
1994	MGB upgrade	0.00	6353	9200	1042	9017	5.2	1622	2.4	123
1992	NVG cockpit upgrade	3.00	6356	9200	1042	9018.2	5.2	1620	2.4	123
1996	Kapton wiring	10.00	6366	9200	1042	9008.2	5.2	1600	2.3	121
1996	TCAS	30.30	6397	9200	1042	9038.5	5.2	1600	2.3	121
1998	CVFDR	4.50	6401	9200	1042	9043	5.2	1600	2.3	121
1998	Standby Att Ind	10.00	6411	9200	1042	9053	5.2	1600	2.3	121
2000	Avionics Upgrade (HH-65B only)	(90.00)	6321	9200	1042	8963	5.2	1600	2.3	121

Additional unofficial and undocumented modifications, such as structural repairs, water/oil entrapment inside honeycomb structures, repeated paint applications and over 400 change orders of weight additions less than five pounds, were made as a result of unrelated maintenance issues or due to environmental factors (Schlatter, 1997:8-10). Note that although the maximum allowable weight remained at 8900 lbs. until 1994, the basic weight of the aircraft steadily increased and the power reserve has never exceeded 10 percent.

The HH-65 Flight Manual states the following in reference to the importance of power reserve:

> Warning: When the maximum power available is not a minimum of 10 percent greater than that required to hover at 50 feet, the maneuver becomes very demanding and should not be attempted unless mission urgency dictates. (*HH-65 Flight Manual,* 1996:2-22)

As shown in the far right column of Table 1, this increase in weight resulted in a corresponding decrease in the maximum range until 1994. Since then, more increases to the basic weight have made for a steady decrease in the maximum range up to the present.

In contrast to the negative aspects associated with weight growth, positive modifications in terms of power available and allowable gross weight included a 1994 Main Gearbox (MGB) upgrade that significantly increased torque limits and power limitations based on the transmission system. This modification increased the maximum allowable gross weight to 9200 lbs. for restricted operations (*HH-65 Flight Manual,* 1996:5-15; Schlatter, 1997:9).

Subsequent developments since 1994 have accounted for a net weight increase of approximately 50 lbs. on the HH-65A (Schlatter, 1997:11). However, the HH-65 Bravo model upgrade accounts for a 90 lb. decrease in the helicopter's basic weight. Currently, there are 47 Bravo models in operational use (Couch, 2003e).

Even with this improvement, however, the fact that the HH-65 takes off at or near its gross weight for every mission means that HH-65 crews continue to perform demanding missions with a very thin power margin (*HH-65 Flight Manual,* 1996:5-15, A-19). This severely restricts the HH-65's ability to recover multiple survivors or effect rescues more than 100 miles offshore.

The LTS 101-750-B2 Power Plant

The HH-65 is powered by two LTS-101-750-B2 engines which produce 735 shaft horse power (SHP) each for single-engine operations and 680 SHP each for dual engine operations (Schlatter, 1997:5). The *Buy American* act requires the Department of Defense and the Coast Guard to purchase products "substantially all from articles, materials, or supplies mined, produced, or manufactured in the United States." An end product is considered in compliance with this law if greater than 50% of all its components are purchased from domestic sources. As applied to the HH-65, *Buy American* required that 50% of the aircraft's value come from U. S. sources (*Buy American Act*, 1954). With the engines as the logical candidate (Couch, 2003c), AHC subcontracted Textron-Lycoming (TLC) for development of the LTS-101 which was developed for the Coast Guard HH-65 (*Ballew vs. US DoJ*, 1999:4.3). This engine experienced several problems during the early years of the HH-65 (Tung, Jacobs et al., 1989:xiii-xiv).

The cost of maintaining the LTS-101 was very high during the first few years of service due to several factors. Originally designed to allow repair at the unit level, the Coast Guard found this impossible and was forced to perform engine overhauls at their Aircraft Repair and Supply Center (AR&SC) in North Carolina (Hughes, 1989:20). Not only were these overhauls more expensive than originally planned for, but they were also required more frequently.

According to the original contract with TLC, the expected mean time between overhauls of the LTS-101 was to be 2400 hours. However, from July 1988 through August 1989, this figure was actually around 400 hours. Similarly, a 600-hour engine removal inspection developed for initial quality assurance was modified to a 60-hour inspection to insure engine integrity (Tung, Jacobs et al., 1989:11). This increase in required maintenance in combination with premature critical engine part failures and lack of spare parts allowed for an HH-65 availability of only 60% during the first six years of service (Hughes, 1989:19; Schlatter, 1997:7). Availability is a measure of the percentage of time an asset is available to perform its mission (Couch, 2003d). As compared to the Coast Guard's stated availability goal of 71% for the HH-65, this initial availability was quite low and had a direct impact on operational effectiveness.

An incident off the Oregon coast in 1989 provided an example of the consequences of the lack of availability. When two crewmembers bailed out of their National Guard F-4, the Coast Guard dispatched a helicopter from Air Station Astoria. Only two of the three helicopters at this unit were available for launch (the third was down due to maintenance). The first helicopter dispatched was forced to abort due to a mechanical failure and although a second helicopter eventually reached the scene, only one of the crewmen survived and was successfully rescued (Hughes, 1989:19). While not directly related to the LTS-101, this incident prompted an investigation by the State Representative from Oregon, Representative Denny Smith (R-Ore). Upon investigation, Representative Smith discovered the many problems associated with the HH-65 at the time and recommended to the Commandant at the time, Admiral Paul Yost, that the Coast Guard consider replacing the engine (Hughes, 1989:20).

Another incident that *was* directly attributable to the LTS-101 was a forced ditching of an HH-65 off Puerto Rico in January of 1989 due to a power turbine wheel fracture (Hughes, 1989:19). Including the Puerto Rico mishap, there were five such incidents between 1987 and 1989. As a result, the Coast Guard temporarily reduced the maximum cruise operating temperature from 749° C to 700° C and the allowable gross weight from 8700 lbs. to 8200 lbs. In response to the problems with the power turbine wheel, Lycoming performed a special inspection on all the LTS-101 in the Coast Guard inventory at the time and replaced any power turbine wheels with over 300 hours of flight time.

The power turbine wheel failures began in 1984, but the cause was not determined until 1988 (Kandebo, 1990a:28). It was found that the blade cracks were caused by the blade and disk portion heating and cooling at differing rates. An FAA Airworthiness directive issued in 1987 required a dye inspection every 50 hours for early detection of these cracks. The failure in late 1989 prompted the Coast Guard to reduce this interval to 30 hours (Kandebo, 1990a:29). In spite of increased inspections, some cracks went undetected due to incorrect inspection procedures and poorly designed inspection equipment. In response, the Coast Guard redesigned the inspection equipment and limited the number of personnel involved in performing the inspections (Kandebo, 1990a:29). Eventually, Lycoming changed the design of the power turbine wheel blade that reduced the heat-induced stress of the original design. The new blades delivered in December of 1989 increased reliability of the LTS-101 and reduced the required maintenance man-hours (Tung, Jacobs et al., 1989:22; Kandebo, 1990b:24-25). The Coast Guard lifted the temporary restrictions after TLC replaced the flawed power turbine wheels in 1991. Unfortunately, with the resolution of one problem, another surfaced.

A second problem with the engine surfaced in 1994. The power turbine wheel became unbalanced due to movement of the blades. The turbine blades attached to the hub by a countersunk rivet. This allowed for small movement of the blades, which unbalanced the wheel. Allied-Signal, which acquired Textron Lycoming in 1994, took responsibility for fixing this problem. A new solid-bore rivet was designed to remove the chance of blade movement (Kandebo, 1996:70).

As of 1996, the LTS-101 had an unscheduled removal rate of 1.5 per 1000 hours. Through several improvements, Allied-Signal sought to reduce this rate to 0.4. In addition to the redesigned blade attachment, other improvements included a new ‘Plus 2’ powerplant which included an upgraded gas producer nozzle, rear support housing and number 2 and 3 bearings (Kandebo, 1996:22). Other improvements included adding a low coke combustor and flexible fuel manifold because carbon build-up was causing blade corrosion. The low coke combustor was designed to reduce oil coking that was occurring in the rear bearing support housing when the oil formed carbon at high temperatures (Tung, Jacobs et al., 1989:22). The flexible fuel manifold replaced a rigid fuel manifold design to eliminate frequent required inspections (Kandebo, 1996:70).

The LTS-101-750 engine is no longer in production. Currently maintained by Honeywell International, Inc, the Coast Guard owns approximately 11% of the LTS-101-750s in the world (Couch, 2003c). After Allied Signal acquired Textron-Lycoming’s gas turbine business in 1994 (Kandebo, 1996:70), Honeywell merged with Allied Signal in 1999 (Murray and Deogun, 2001).

LTS 101 Fuel Governing System

The conventional pneumatic fuel control (also known as engine control) system in the HH-65 was developed specifically for the LTS-101 in order to meet Coast Guard requirements. While this system did meet the requirements, it did so at considerable cost. Alternatives considered were an analog-electronic fuel governing system developed while the HH-65 was still in the developmental phase and a Full Authority Digital Engine Control (FADEC) system (Chisom, 1984:189).

In 1982, Lucas Aerospace developed a FADEC system for the HH-65. While test flights of this system were successful in demonstrating the feasibility of the Lucas FADEC for the HH-65, there were problems associated with a lack of redundancy of the Engine Control Computer software and lack of cockpit compatibility. Since the expected benefits of the FADEC were small in relation to the cost of further development, it was not installed on the HH-65 (Chisom, 1984:189-192). Instead of FADEC, the Coast Guard opted for a custom-made engine control system.

Lawsuit leads to Engine Improvements

A major turning point in the mission effectiveness of the HH-65 came in 1990, when the Coast Guard won a lawsuit against TLC. In 1987, Lycoming predicted that problems with the LTS-101 would take two years to resolve. By 1989, however, there had been little improvement in the situation. In 1989, due to allegations of defective parts installed on the LTS-101, Lycoming became the subject of investigations by the Department of Justice and the U.S. Attorney's Office. Concurrently, the Coast Guard began the process of seeking compensation from TLC, but put the investigation on hold pending the Department of Justice action (Hughes, 1989:19).

A two-year investigation revealed that the engines were operating at excessive temperatures and as a result were deteriorating faster than expected. This resulted in numerous engine problems such as the previously discussed turbine-wheel cracking (Kandebo, 1990b:24-25). The Coast Guard also discovered from a *whistleblower* that when TLC made modifications to allow the engines to fly in snow, it charged the Coast Guard for unrelated modifications in order to eliminate other defects. Although TLC admitted no wrongdoing, they were required to pay the Coast Guard $17.9 million (Kandebo, 1990b).

Additionally, as part of the settlement, TLC was required to institute an LTS-101 improvement program and take responsibility for the potential $60 million cost of future unscheduled engine maintenance and supply of replacement parts for six years. This Power-By-The-Hour arrangement required the Coast Guard to pay a fee based on the number of engine hours flown. This greatly increased TLC's share of the costs in engine replacement and overhaul and subsequently increased the company's incentive to make necessary improvements to the engines (Kandebo, 1990a:24-25). This contract has been in effect continuously since 1990 and was most recently extended to 2006 (Kandebo, 1990a; "Power by the Hour Agreement," 2002).

Engine Alternatives

Although the LTS-101 was designed with the same life expectancy as the airframe (20 years), the Coast Guard considered replacing the engine early due to the aforementioned reliability problems as well as its lack of weight growth potential (Hughes, 1989:19). A 1989 report by the Department of Transportation examined the

Light Helicopter Turbine Engine Company (LHTEC) T800 and the Turbomeca Arriel 1C as viable alternatives to the LTS-101 (Tung, Jacobs et al., 1989:xii).

While the Army's more-powerful T800 was the primary focus of the study, the researchers also studied six other engines. Each engine was either heavier than the LTS-101 or less fuel-efficient than the T800. While the T800 was considered a low technical risk in terms of its performance and reliability, it would have required costly and extensive re-engineering to modify the HH-65 (Tung, Jacobs et al., 1989:38). The T800 did offer lower operating and support costs due to the ability to share costs with the Army. This was projected to reduce the operating costs from $175 per hour (LTS-101) to $70 per hour (T800). Additionally, the T800 would have provided the HH-65 with an additional 550 SHP per engine giving it enough power to hover on one engine in the event of a single-engine power loss. The disadvantage of the T800 was the requirement for a reduction gear box retrofit and the fact the engine was not fully developed at the time of consideration (Hughes, 1989:20).

The second engine considered was the Arriel 1C. The Arriel had the advantage of being a quick fix since there were 2000 engines in use with the SA 365 (the commercial version of the HH-65). The Arriel would not have provided as much power as the T800 but was considered more reliable due to its proven performance record (Hughes, 1989:20). However, the Arriel had to overcome prejudices that were and are still common within the government today; then-Commandant Yost, vowed to never again "buy a helicopter or an airplane that was not a DOD-supported piece of equipment" (Kandebo, 1990b:25).

In the final analysis, the authors of the DOT study recommended that the Coast Guard continue with and closely monitor the LTS-101 engine improvement program that was in progress at that time. Additionally they recommended that the proof of concept of the T800 be completed and an examination be made into the airframe modifications that would be required for the T800 (Tung, Jacobs et al., 1989:xviii). As such, a contract was awarded to Allison/Garrett in 1989 to conduct a 50-hour proof-of-concept of the Light Helicopter Turbine Engine Company (LHTEC) T800 (Kolcum, 1989:38). In 1991, an HH-65 outfitted with the LHTEC T800 engines flew "flawlessly" during a 56-minute test flight ("T800 Milestones," 1991). No further test flights were completed, however, as the Coast Guard ended plans in 1991 to replace the LTS-101 after TLC made significant improvements to the engine following the lawsuit settlement ("CG Drops Reengining," 1990).

Recent Events

There has been a recent increase in engine failures and overall engine reliability in the HH-65 since 1997 (COGARD MAY 14, 2003). As illustrated in Figure 2, availability has decreased while dispatch failure due to engine malfunctions has increased in the last five years (COGARD MAR 27, 2003). A successful dispatch occurs when an aircraft meets its scheduled takeoff time and accomplishes its scheduled mission. Dispatch failure is the ratio of successful dispatches to delayed and aborted dispatches. A failed dispatch can be a result of maintenance, weather, pilot availability, and other factors (Couch, 2003d). In the context of this discussion, only those cancellations or aborts due to engine-related malfunctions are included.

Experts have attributed this increase in dispatch failure to a failing engine component. Honeywell Corporation produces and overhauls the Power Turbine Governor (PTG) in Greer, South Carolina. After the increase in PTG failures, the Coast Guard discovered that Honeywell had subcontracted production and overhaul of the PTG to a subcontractor (Couch, 2003b).

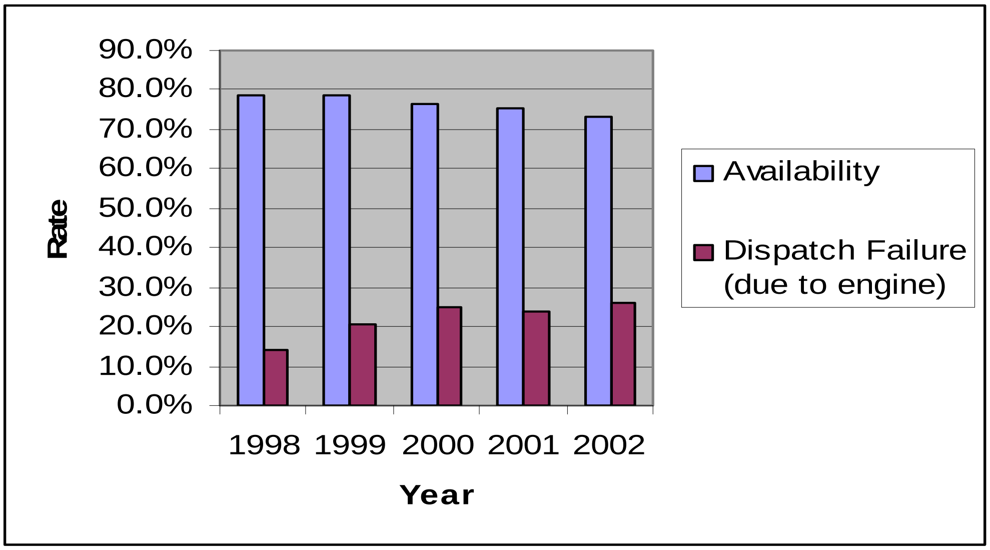

Figure 2. Annual HH65 Reliability vs. Dispatch Rate (COGARD MAR 27, 2003)

Faulty Power Turbine Governor

Coast Guard experts suspect that the PTG contains a faulty bearing that changes the output signal of the governor. The aircraft's anticipator system is able to mask this faulty signal up to a certain point. However, once the signal gets too far out of range, the anticipator can no longer compensate and a difference in torques between the engines becomes apparent. This is commonly referred to as a *Torque Split* (*HH-65 Flight Manual,* 1996:3-16-3-17; Serrano, 2003). Up until April of 2003, there was no procedure to rule out the PTG as the root cause of a Torque Split. As a result, many maintenance teams were replacing other related components once the problem manifested itself. Unfortunately, this did not remedy the problem and led to serious engine malfunctions later on (Serrano, 2003). Because of these developments, the Coast Guard and Honeywell initiated a recall of all faulty PTGs in the inventory. It is expected to take several months to replace all the faulty PTGs in the Coast Guard and civil fleet (Couch, 2003b; f; Serrano, 2003).

HH-65 Operations Restricted

Due to the recent increase in power loss incidents, including two involving deployed helicopters that were forced to land on a ship with only one engine operative, the Coast Guard Chief of Operations has issued special guidance and restrictions on HH-65 operations aimed at reducing extended hover operations (COGARD Oct 03, 2003; CG PACAREA Oct 30, 2003). This includes limiting landings to confined areas such as hospital pads and reducing the weight of the aircraft by removal of gear and/or personnel not operationally critical. These restrictions include limiting the use of two of an extra rescue swimmer for routine training, marine safety observers, cameras, and portable hoist recording equipment. This guidance also restricts the HH-65 takeoff weight from a ship to a weight that allows an absolute altitude loss of fifty feet in case of single engine failure. This restriction severely restricts the amount of fuel a helicopter can take off with and thus reduces the endurance of the helicopter to approximately one hour per sortie. These restrictions reduce mission effectiveness by decreasing the length of training flights, delaying launch in order to defuel, decreasing the ability of an already airborne helicopter to divert due to low fuel or lack of rescue swimmer, and restricting landings in confined areas for patient pick up or delivery (COGARD Oct 03, 2003; CG LANTAREA Oct 16, 2003).

As the reliability of the HH-65 declines, one of the Coast Guard's Deepwater initiatives seeks to upgrade the aircraft. Deepwater is the Coast Guard's long-term recapitalization of aging assets, including aircraft. The Coast Guard plans to keep the HH-65 in service through various avionics and engine upgrades. The avionics upgrades have already begun with the HH-65B. More powerful engines are required, not only to catch up with weight increases already made, but also to allow the aircraft to evolve with the increased mission requirements of Homeland Security (Padfield, 2003). However, "arming the helo and vertical insertion is currently not possible due to inadequate power" (CG PACAREA Oct 30, 2003).

Improvements

In fiscal year 1999, in order to improve overall engine performance, the Coast Guard agreed to purchase nine prototype Lead-the-Fleet (LTF) engines as a proof of concept. These engines experienced a high number of chip events (metal particles in the engine oil) due to faulty rework of the existing gearboxes. Although the LTF engines proved less than promising, some of the individual components were found to offer significant improvements. To take advantage of these components, the Coast Guard established the Component Technology Insertion Program (CTIP) in 2000. The first component purchased under this program was the Rear Bearing Support Housing (RBSH). It offered many improvements including a reduction in oil coking which damages the engine, and improvements in engine oil lubrication and cooling. After Honeywell ceased production of the RBSH, the Coast Guard's initial order of 25 RBSH's was reduced to ten and the Coast Guard used the leftover funds to purchase new effusion liners. The new liners eliminate carbon build-up on the engine gas producer and power turbine blades. This, in turn, increases engine longevity and improves the power margin. The CTIP engines provide more power and run cooler. This is especially critical to the many air stations located in tropical climates. In all, the Coast Guard spent $765K on 18 LTF engines and $4.5M on 104 CTIP engines (Dyer, 2003).

In addition to the LTF and CTIP engines, the Coast Guard and Honeywell implemented the Incremental Power Increase Engine (IPI) (COGARD MAY 14, 2003). This engine projects an 8% increase in power (Dyer, 2003). Distribution to hot-climate units began in early September 2003 (COGARD MAY 14, 2003; Dyer, 2003). Part of this comes from a new Gas Producer Turbine for the LTS-101-850. Yet in spite of promised improvements, problems persist.

Two 850 engines seized after shutdown after being installed on overhauled helicopters at the Coast Guard's Aircraft Repair and Supply Center. Because of this, two helicopters with the new engines at Air Station Miami were grounded (CG AR&SC Nov 14, 2003). Upon investigation, the Coast Guard discovered that Honeywell had increased the turbine blade length in order to produce more power. However, when the engine temperature increased, the blades expanded and fused themselves to the wall of the engine (Couch, 2003a)

Honeywell's closest competitor in the battle to re-engine the HH-65 is the Turbomeca Arriel 2C2. The first successful test flight of an HH-65 powered by the Turbomeca Arriel 2C1 engines took place in October of 2002. An Arriel 2C2 was tested as part of Phase II of the HH-65 Engine Power Project (Couch, 2003c). Certified in July

2002, the latest version of the Arriel, the 2C2, provides 1054 SHP per engine. Since the Arriel is common to the EC-155 commercial helicopter, it would likely reduce overall operating costs for the HH-65 while offering significant increases in power and range ("First Flight," 2002; Harvey, 2002).

Honeywell's long-term solution is the HTS-900, an advanced growth version of the current LTS-101 (Couch, 2003c). The FAA expects to certify this engine in mid-2006 at the earliest The new compressor, which is expected to take 24 months to fully develop, will include a cooled turbine and an improved airflow modulator that is expected to increase existing engine reliability fourfold (Wagstaff, 2003). The 900 will also include a 2 stage PT wheel which will likely require the addition of a reduction gearbox (Couch, 2003c). Built in modules, the 900 allows for upgrade of existing versions of the LTS-101 (Wagstaff, 2003).

The Future

The HH-65 average fleet age is almost 20 years old and most aircraft have accumulated well over 5000 hours. The HH-65 operates in harsh environmental conditions that include low-level flight over salt water and ship-based operations. The age of the aircraft and a harsh operating environment combined with the Coast Guard's traditionally austere budget has made the maintenance and upgrade of this valuable resource a continuing challenge. The HH-65 is now scheduled to remain in service until 2015 (Connor, Devoe et al., 1998:8).

Chapter Review

This chapter discussed the background and history of the HH-65 as well as the development of its engine, the LTS-101. While specific literature related to the Coast Guard HH-65 or the LTS-101-750 was limited, this chapter provides a comprehensive examination of what is available both publicly and corporately (within the Coast Guard). Specifically, we focused on the early reliability issues, evolution of the LTS-101-750, the lack of power reserve, and its negative impact on the mission effectiveness of the HH-65. Finally, we highlighted recent improvements to the HH-65 powerplant, the current operational restrictions, and projections for the future of this critical asset.

III. Methodology

This chapter describes the research methods used and the analysis performed in our study of the engine reliability of the HH-65. In general, this study involves an exploratory analysis of recent engine malfunctions and engine-related mishaps of the HH-65 helicopter. We focus on answering research questions one through three as outlined in Chapter One.

Engine Mishap Data

The Coast Guard's Aviation Safety office provided the engine mishap data for 127 mishaps. We receive the raw data in text form. It consists of summarized mishap messages from 1997 through May of 2003. We examine only those aviation mishaps related to the LTS-101 engine and/or its components in our analysis. After review, we consolidate this data into spreadsheet format, which includes the following categories:

- Mishap number as assigned by the Coast Guard Safety Office
- Date of mishap – day, month, year
- Year - to allow for examination by year
- Aircraft tail number
- Cost of mishap – accounts for component repair, replacement and man hours
- Phase of flight – takeoff, landing, level flight, etc
- Mission – such as Search and Rescue (SAR) or Law Enforcement (LE)
- Action – applies to action taken to the engine – replacement or inspection
- Faulty Component – the component or components replaced as a result of the mishap

- Multi-component – a binary response category where we indicate that only zero or one component was replaced with a '0' and more than one component was replaced with a '1'
- Comments
- Ship Operations – a binary response category accounting for mishaps that occurred during operations with a Coast Guard Cutter or Navy Ship

We count those mishaps that resulted in more than one replaced or faulty component as many times as necessary to account for all suspected components. This ensures a complete analysis of all components. In addition, we code these mishaps with a '1' in the multi-component column to ensure that we do not count these mishaps more than once for any other analysis. Once in spreadsheet form, we examine this data using Excel (*Microsoft Excel*, 2002).

Limits of Safety Data

The safety data is comprised of a synopsis of mishap messages. Due to latitude in the reporting requirements, this data may not include all engine-related mishaps that occurred during the period of study. Unit safety officers write mishap messages. While these officers attend formal Aviation Safety Officer Training, there is still an element of investigative technique involved in determining the cause of mishaps. Also, in the case of a component such as the Power Turbine Governor (PTG), which was not known to be faulty until recently, there may have been past mishaps caused by this component that were not discovered until recently.

Component Replacement History Data

We obtained component replacement history data from the Coast Guard's Aviation Computerized Maintenance System. The raw data is in the form of ten Excel spreadsheets covering the replacement history of ten different components as listed below: (Appendix A: Definition of Terms contains descriptions of each component)

- Airflow Modulator
- Anticipator Actuator
- Anticipator Control Box
- Engine (Accessory Reduction Gearbox)
- Fuel Control
- Fuel Pump
- Overspeed Limiter
- Power Turbine Governor
- Temperature Compensator
- Torque Transducer

This data includes 13,565 component replacements during the period of study. We examine this data to determine trends over time and possible correlations between types of malfunctions and components causing the malfunctions. In the case of component replacement data, we generally treat the type of malfunction as the response variable, while the replaced component acts as the explanatory variable.

Building the Database

Before analysis, we inspect the data for errors and inconsistencies. In addition, we consolidate the ten individual spreadsheets to allow for easier analysis. We also use the comments provided by the maintainers to categorize each trouble removal into a particular malfunction. For example, we grouped the comments, '*removed for torque splits*' '*torque split's*, and '*unable to match torques'* as *torque splits*.

This consolidated spreadsheet includes the following categories (columns):
(See Appendix B: Data Categories for a complete listing)

- Component serial number
- Component name – includes ten different components
- Reason for removal – trouble, time, other, or cannibalization
- Date of removal
- Time Since New (TSN) in hours – indicates how many hours the component has operated since new
- Time Since Overhaul (TSO) in hours – indicates the number of hours the component has operated since its last overhaul
- Associated engine or airframe number – some components are considered part of the engine while others are considered airframe components.
- Activity – the unit responsible for the removal
- Malfunction – specific reason for component removal as determined and categorized from comments
- Cross Component – a binary response where '0' indicates that the malfunction is related to only one component. A '1' indicates that more than one component was replaced in response to this malfunction type.
- Comments – raw comments as written by the maintainers or pilot

Limits of the Component Replacement Data

We analyze removed components in relation to the written symptom or malfunction as specified by the pilot or maintainer. These descriptions are subjective in nature. Many are very detailed, while others are cryptic. To quantify the data, we group these descriptions into categories of malfunctions. In many cases, interpretation of what the original writer of the symptom meant is necessary in order to fit each trouble removal into a malfunction category. See Appendix C: Torque Splits - Classified by Comments for a coding example. Additionally we assume these comments are accurate. In some cases, comments indicating the possible malfunction may be incorrect, however, this error may be unknown until after a repair is completed and the same or similar malfunction occurs again on the same aircraft. In addition, due to the complexity and interaction of the fuel governing and anticipator systems, it is often difficult to pinpoint the exact cause of the malfunction to one specific component. As a result, the maintainers sometimes replace more than one component at the same time. In these cases, it is impossible to know which component was truly at fault (Couch, 2003b).

Many variables, other than what we examine in this study, affect engine reliability. Some confounding variables are the location of the air station, the experience of the maintainers at a given location, the number of helicopters at a given station, and the average number of deployment days at a given unit. For example an Air Station located in a heavy salt-water environment will likely experience more corrosion than one located near the Great Lakes. In this type of situation, we would only see the decline in reliability, not necessarily the real reason behind it.

Contingency Table Analysis

Much of our analysis involves examining the association between different types of categories. For example, malfunction to component or mishap to component. In order to analyze associations between categorical data, it is necessary to use contingency table analysis. Contingency table analysis provides an instrument for analyzing possible relationships between nominal data with more than two outcomes. Since the data of this study consists of several categorical variables, this method of analysis proves highly useful.

In the case of contingency table analysis, the null hypothesis assumes that the two classifications are independent. We test for independence by comparing the actual cell count to the expected cell count. We use the chi-squared (χ^2) test statistic, where $\chi^2 = \sum_{i=1}^{i} \frac{(O_i - E_i)^2}{E_i}$, and *i* is the number of cells. Large values of χ^2 indicate that the actual counts do not match the expected counts and the assumption of independence is likely false. See McClave, 2001 for further details.

We test the null hypothesis at the 0.05 level. This means we accept a five percent chance that we conclude the variables are dependent when in fact they are independent. In order for contingency table analysis to be valid, the expected cell counts in each cell usually must be greater than five. However, we accept the results as valid if no more than 20% of the cells of a given table have an expected cell count less than five. We do not accept an expected cell count of less than 1.0 for any cell in a given table.

Ordinary Least Squares Regression

We use Ordinary Least Squares (OLS) regression analysis in order to find correlations between continuous variables. A regression model demonstrates a mathematical association between variables. It attempts to predict behavior of a population based upon a sample of that population, or, as is the case with the data used in this study, to predict future outcomes based on past observations. Regression alone cannot prove causation; it shows only correlations or relationships between variables. Other factors such as consistency, plausibility, and experimental evidence *may* demonstrate that an association is also causation (Simon, 2002).

In addition, the error or residuals of a regression model should satisfy several assumptions – constant variance, normality, independence, and identical distribution. In working with observed data, however, these assumptions are rarely fully satisfied (Blasnick, 1995). However, OLS is a robust measure against deviations from normality and constant variance (Neter, Kutner et al., 1996:106).

Logistic Regression

Logistic regression describes the relationship between a dichotomous outcome and an independent variable or variables. Practically, OLS and logistic regression are very similar in that they both predict a dependent variable based on one or more independent variables (Dallal). The main difference between linear and logistic regression is that linear regression predicts a particular value of the dependent variable while logistic regression predicts the probability or likelihood of a particular outcome.

With logistic regression, the outcome of interest is dichotomous – yes or no, success or failure, on or off. The outcome of logistic regression is expressed as a positive number between zero and one, which represents the probability of success. For example, an outcome of 0.5 indicates that there is a 50% probability of a particular outcome occurring given specific values of the independent variable(s) (Hosmer and Lemeshow, 2000).

The use of a linear model to determine a binary response would *work* in terms of the sign and significance levels of the coefficients; however, the predicted probabilities would be inaccurate. This is due to two reasons. First, the assumptions necessary for the error or residuals of a linear regression model (constant variance and normality) do not hold true if the dependent variable is a binary response, and second, the predicted probabilities can be greater than one and less than zero. The use of the logistic regression model solves these problems by transforming the linear regression model by taking the natural log of the ratio of the probability of an outcome occurring divided by the probability of it not occurring (Whitehead, 2001).

While a graphical depiction of a linear regression model ranges from negative infinity to positive infinity, a logistic regression model ranges from zero to one. Figure 3 demonstrates this difference graphically. The logistic model mirrors the cumulative probability function of a random variable. The distribution is S-shaped which indicates the probability of the outcome increases slowly (with changes in the independent variable(s)) at first then increases rapidly before decreasing again as the probability approaches 1.0 or 100%.

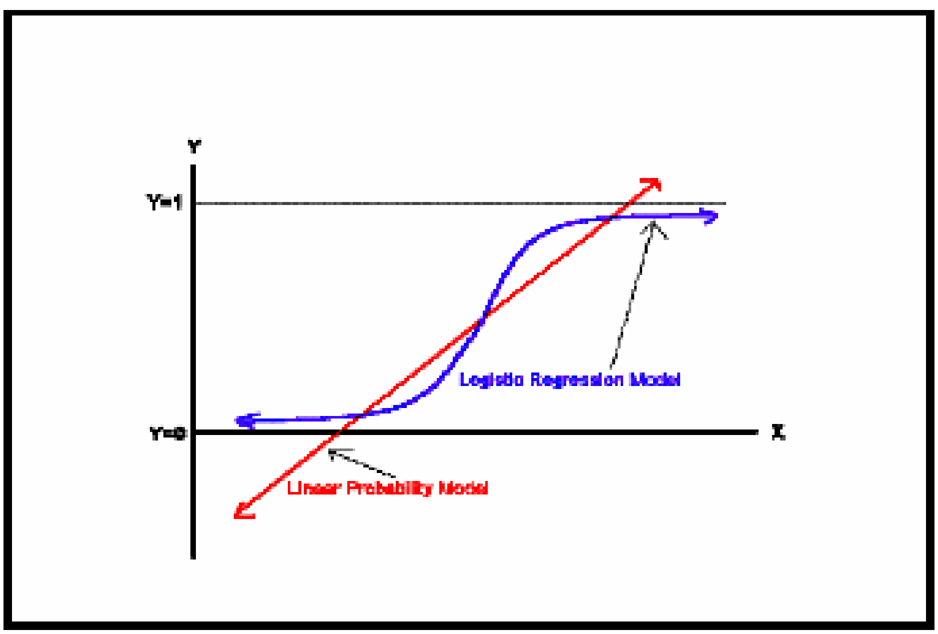

Figure 3. Graphical Comparison of Linear and Logistic Regression Models (Whitehead, 2001)

Data Analysis

In the following section, we analyze the data using the statistical methods outlined above. Since both data sets are in the form of spreadsheets, we use Excel (*Microsoft Excel*, 2002) in order to provide descriptive statistics. For in-depth analysis, we use JMP® Version 5.0.1.2 (*JMP*, 2003). In all cases, alpha = 0.05 for the purposes of hypothesis testing.

Research Question One

The first research question asks, "Has the HH-65 become less reliable over time?" In order to answer this question we examine the number of trouble removals over time, the number of engine-related mishaps over time, and the relationship of the age of a component to the number of trouble removals.

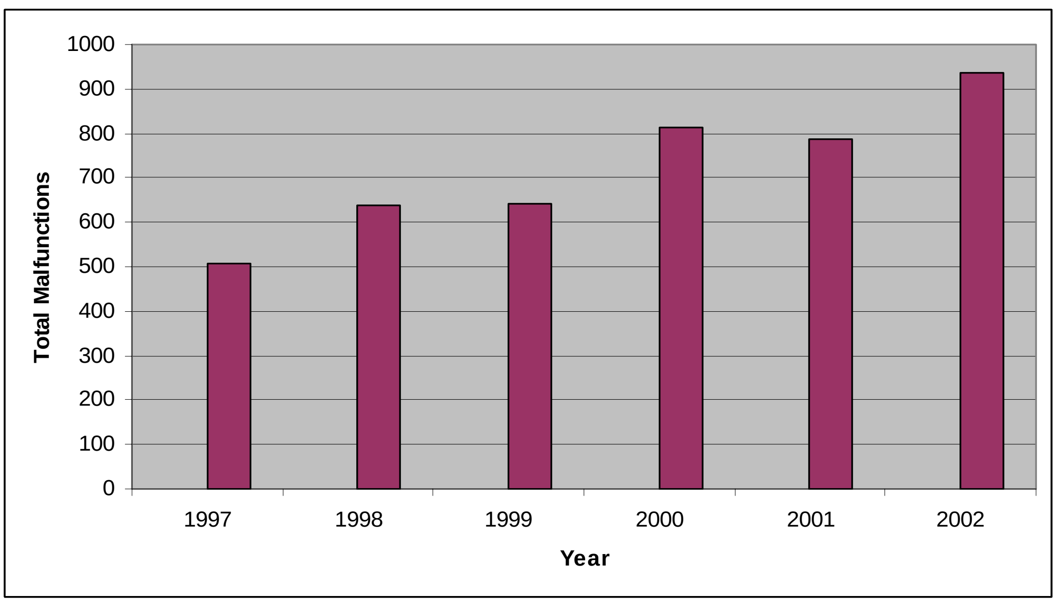

Figure 4. Total Trouble Removals by Year

Trouble Removals by Year

We compile Figure 4 from component removal data. This figure compares the total number of engine component trouble removals for the past six years. We visually detect a general increasing trend and statistically confirm this trend of trouble removals using regression analysis. In this case, we again measure time in years but we treat time as a continuous variable. We use the linear regression model, $Y = B_o + B_1X + \varepsilon$, where Y is the number of trouble removals and X is time in years. We compute an adjusted R^2 of 0.90 and whole-model P-value of 0.0024 with B_1 equaling 78.54. Thus, we reject the null hypothesis, H_o: B_1 = zero, since this P-value is less than our alpha of 0.05. We accept the alternate hypothesis, H_a: $B_1 \neq 0$. In other words, trouble removals increase positively with time.

The residuals of this regression model satisfy the assumptions of normality, constant variance, and independence. There is one minor influential data point (Cook's Distance greater than 0.25) and no major influential data points. In this case, the influential data point is the year 2001. Due to the small sample size (n = 6), this is not unusual nor a source of concern.

Trouble removals by Individual Component and Year

Next, we examine trouble removals by individual component and year. We again use the removal history data for this analysis. Figure 5 does not indicate a common trend over time among individual components. Some components show a general increase in the number of removals (Airflow Modulator and Anticipator Actuator); others (Fuel Pump and Overspeed limiter) show a decrease in the number of removals over time. While we do not see a strictly increasing or decreasing relationship between year and the number of trouble removals, there does appear to be a relationship between the type of component and the number of trouble removals. Figure 6 depicts the total number of trouble removals by component.

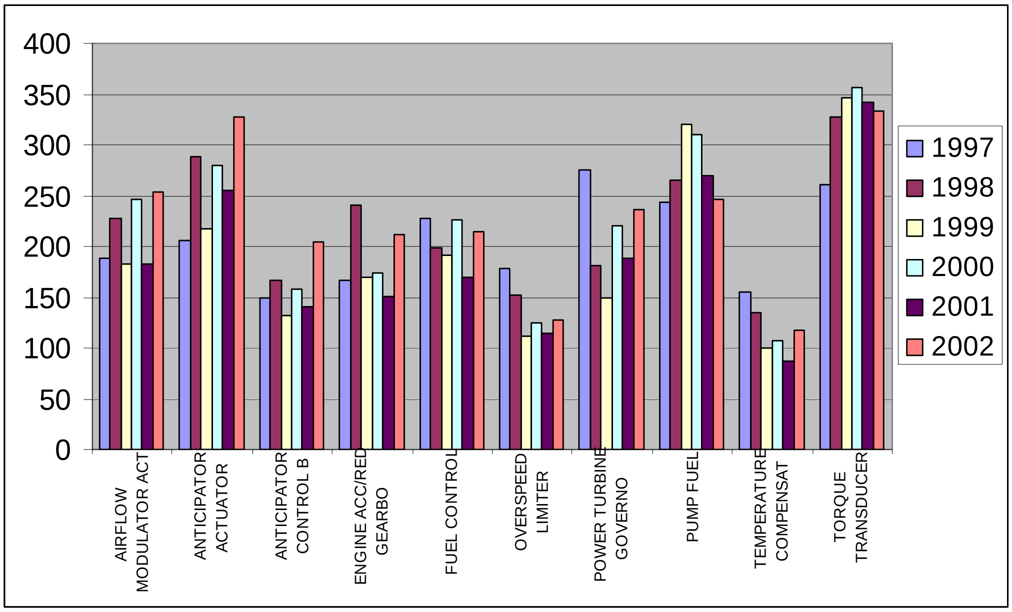

Figure 5. Number of Removal Counts for Trouble by Year and Component Excluding 2003

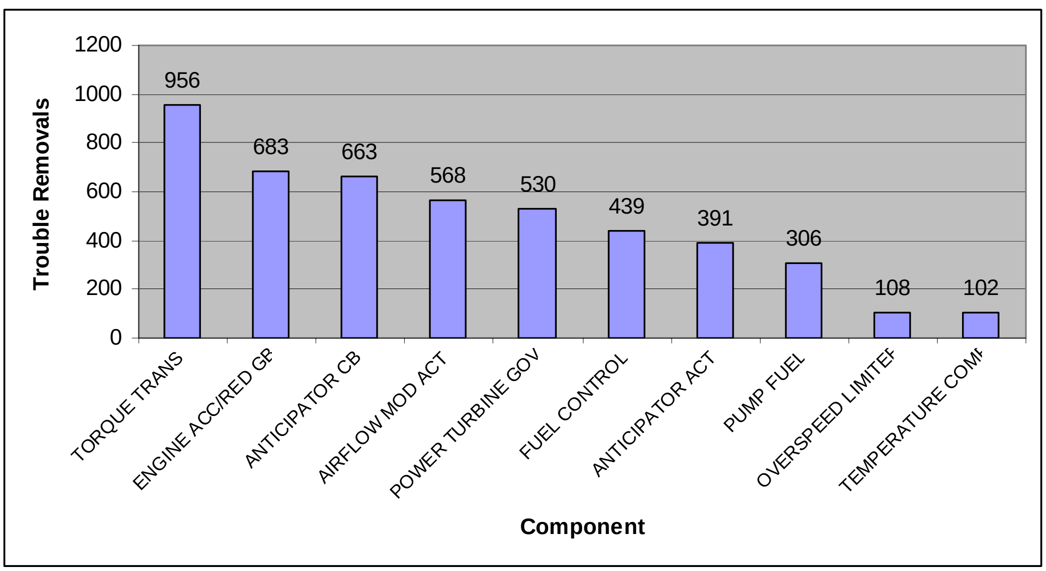

Figure 6. Total Trouble Removals by Component

Although we discuss the issue of overhaul times later in this section, we note here that the Torque Transducer and the Anticipator Control Box do not undergo regular overhaul. This means that they are kept in operation until failure. It would be logical that these components would have higher numbers of trouble removals than those components that undergo a regular overhaul. For this reason, we compare components by the total number of trouble and time removals. We see that some components that have a lower number of trouble removals, such as the fuel pump, have a high number of total removals. This is significant since whether a component is removed for trouble or time, there are still costs in terms of man-hours and aircraft availability. Figure 7 shows the total of time and trouble removals by component.

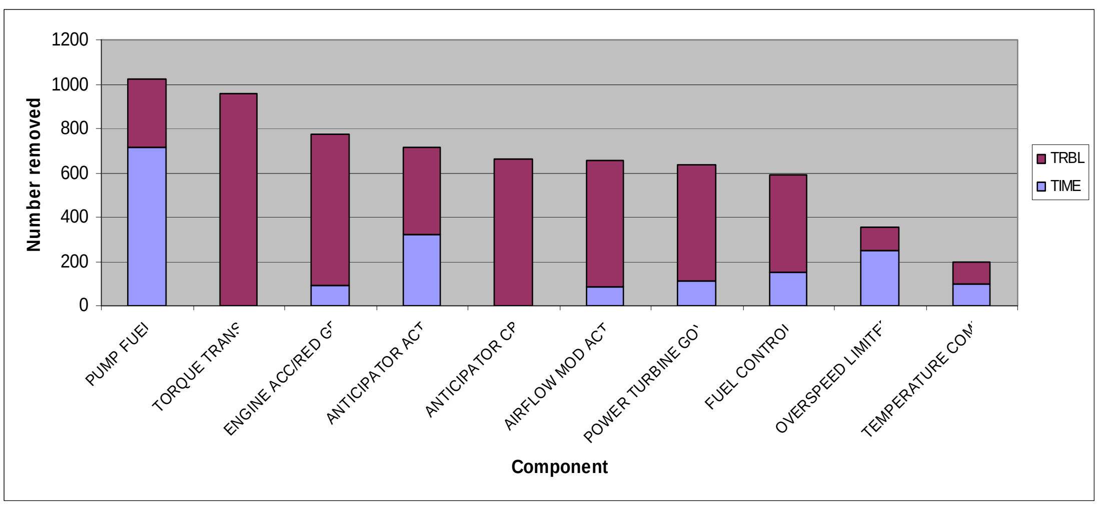

Figure 7. Time and Trouble Removals by Component

Table 2 outlines the count of trouble removals by component. We note that the five most frequently removed components account for over 70% of all component removals during the period of this study. We attribute the increasing trend of total trouble removals over time to these components.

Table 2. Summary of Trouble Removals by Component

DESCRIPTION	Grand Total	Percentage	Cumulative
TORQUE TRANSDUCER	956	20%	20%
ENGINE ACC/RED GEARBOX	683	14%	35%
ANTICIPATOR CONTROL B	663	14%	49%
AIRFLOW MODULATOR ACT	568	12%	60%
POWER TURBINE GOVERNO	530	11%	72%
FUEL CONTROL	439	9%	81%
ANTICIPATOR ACTUATOR	391	8%	89%
PUMP FUEL	306	6%	96%
OVERSPEED LIMITER	108	2%	98%
TEMPERATURE COMPENSAT	102	2%	100%
TOTAL	4746	100%	100%

Table 3 is a contingency table analysis of the number of trouble removals by component type. The low P-value indicates that the number of trouble removals by component are not independent and that there is a strong correlation between type of component and the total number of trouble removals over the period of study.

Table 3. Contingency Table Trouble Removals by Component

Component	TORQUE TRANSDUCER	ENGINE ACC/RED GEARBO	ANTICIPATOR CONTROL B	AIRFLOW MODULATOR ACT	POWER TURBINE GOVERNO	FUEL CONTROL	ANTICIPATOR ACTUATOR	PUMP FUEL	OVERSPEED LIMITER	TEMPERATURE COMPENSAT
Actual Values	956.00	683.00	663.00	568.00	530.00	439.00	391.00	306.00	108.00	102.00
Expected Values	474.60	474.60	474.60	474.60	474.60	474.60	474.60	474.60	474.60	474.60
Actual - Expected	481.40	208.40	188.40	93.40	55.40	-35.60	-83.60	- 168.60	- 366.60	-372.60
Chi-Squared Statistic =	**1332.43**	**P Value**	**3.1E-281**							

Mishaps by Component and Year

We now move to an analysis of mishap data. Figure 8 compares the total number of mishaps by component for the last six years (through May 2003). Since more than one component is at fault during many of these mishaps, the total number of mishaps through the same period is less than the sum of the numbers in Figure 8.

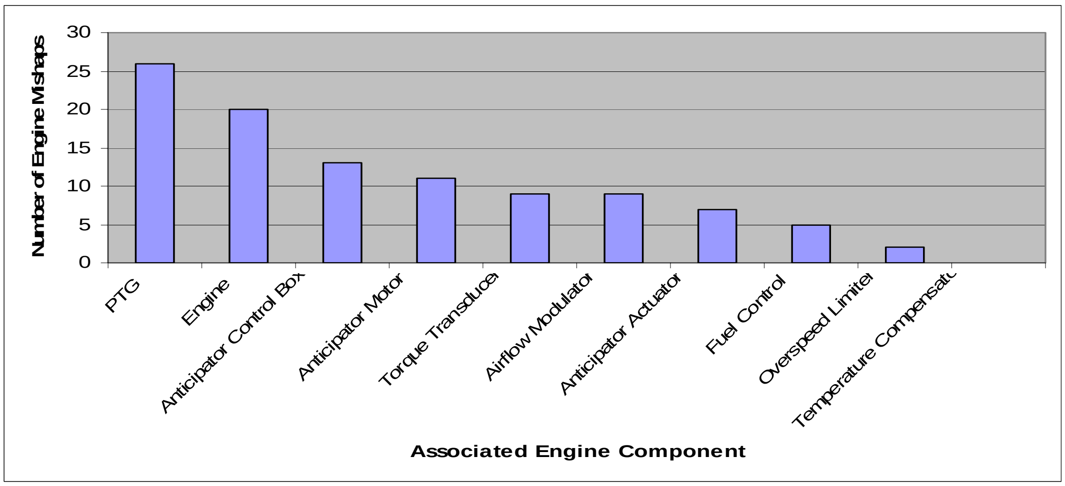

Figure 8. Engine Related Mishaps by Faulty Component

Figure 9 shows a comparison of mishaps by year. There appears to be no trend in mishaps over time. We note, however, that the percentage of mishaps caused by the Power Turbine Governor was disproportionately high during 2002 and the first five months of 2003. The number of mishaps through May of 2003 exceeds the total for 2003. Half of these mishaps were caused by the PTG. We attribute this to the known faulty power turbine governor, which was recalled and 80% replaced as of this writing.

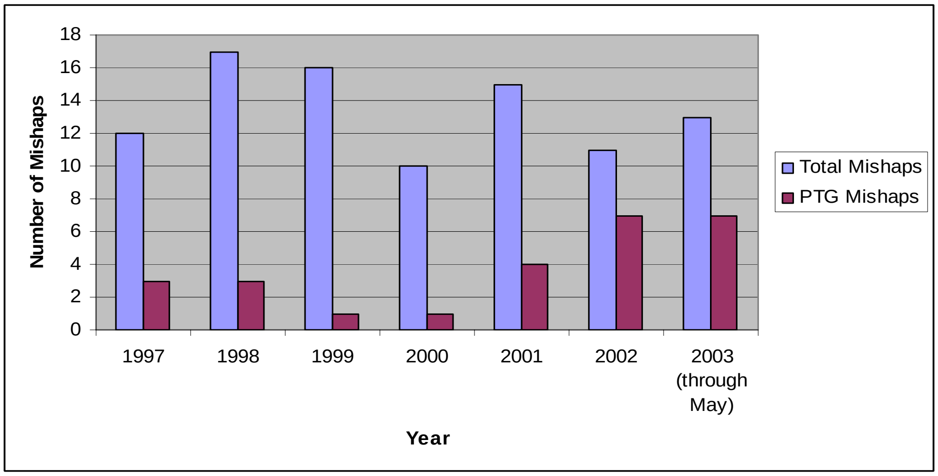

Figure 9. Number of Mishaps by Year

Comparison of MTSN, Trouble Removals, and Number of Mishaps

In order to determine whether age influences mishap rate, we analyze number of mishaps in relation to the age of the component. Table 4 shows a comparison of component average age, the number of mishaps, number of trouble removals, and the total number of time and trouble removals by component during the period of study.

Table 4. Comparison of MTSN, Number of Mishaps, Number of Removals by Component

Component	MTSN	MTSN/10	Number of Mishaps	Number of Trouble Removals	Total Removals (Trouble + Time
ENGINE ACC/RED GEARBO#	4621.44	462.144	20	683	777
FUEL CONTROL	3890.68	389.068	5	439	587
TEMPERATURE COMPENSAT	3762.98	376.298	0	102	200
AIRFLOW MODULATOR ACT	3692.53	369.253	9	568	653
POWER TURBINE GOVERNO	3622.81	362.281	26	530	639
OVERSPEED LIMITER	3589.49	358.949	2	108	355
PUMP FUEL	3376.11	337.611	2	306	1024
ANTICIPATOR CONTROL B*	1326.84	132.684	13	663	663
ANTICIPATOR ACTUATOR	1268.98	126.898	7	391	713
TORQUE TRANSDUCER*	616.54	61.654	9	956	956
# Does not undergo normal overhaul		* Does not undergo overhaul			

In order to determine how age affects reliability, we visually examine the relationship of the average age of a component to the number of mishaps attributed to that component and to the number of trouble removals by component. Figure 10 demonstrates that there is no obvious association between the age of a component and the number of mishaps attributed to it.

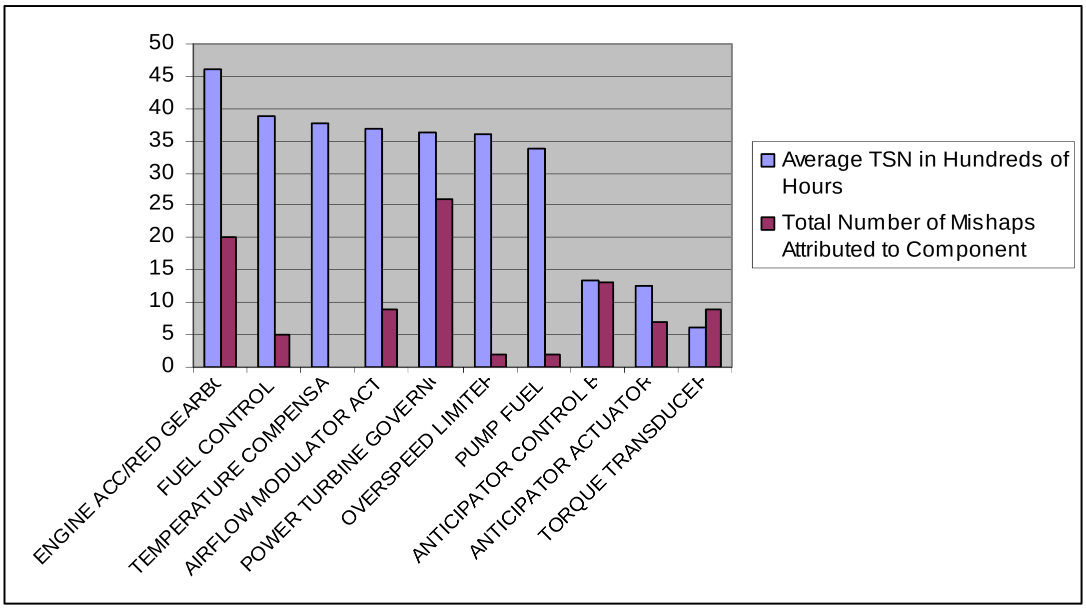

Figure 10. Comparison of Average TSN (in hundreds of hours) and Number of Mishaps by Component

Figure 11 shows a similar situation. There is no obvious relationship to the age of component and the number of trouble removals over the period of study. While the Temperature Compensator is one of the older components, it has one of the lowest rates of trouble removals. Conversely, the Torque Transducer is the newest component yet has the most number of trouble removals.

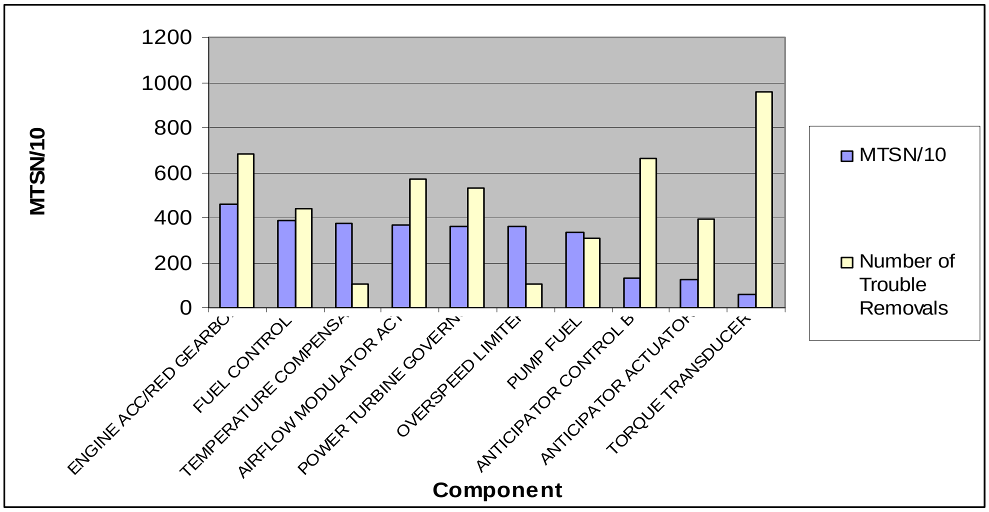

Figure 11. Comparison of MTSN (in tens of hours) by Number of Trouble Removals by Component

<u>MTBF by MTSN</u>

Next, we examine the failure rate of each component in relation to its average age. We compare the average age of a component to the Mean Time Between Failures (MTBF). We compute MTBF by taking the average time (in hours) using the Time Since New (TSN) between trouble replacements for each component from 1997 through May of 2003.

Table 5. Comparison of Mean Time Between Failures and Mean Time Since New by Component

Component	MTBF	MTSN	MTSN/10	Ratio of MTBF/MTSN
TORQUE TRANSDUCER	278.72	616.54	61.654	0.45
ANTICIPATOR ACTUATOR	558.48	1268.98	126.9	0.44
ANTICIPATOR CONTROL B	335.21	1326.84	132.68	0.25
OVERSPEED LIMITER	855.00	3589.49	358.95	0.24
TEMPERATURE COMPENSAT	675.36	3762.98	376.3	0.18
POWER TURBINE GOVERNO	509.64	3622.81	362.28	0.14
AIRFLOW MODULATOR ACT	489.97	3692.53	369.25	0.13
ENGINE ACC/RED GEARBO	586.46	4621.44	462.14	0.13
FUEL CONTROL	451.77	3890.68	389.07	0.12
PUMP FUEL	339.77	3376.11	337.61	0.10

Individual components with a sample size of one were not included in this computation since there was no previous data available to determine the TSN of the last failure. Table 5 shows the MTBF and MTSN for each component. A higher MTBF is indicative a lower failure rate. A high MTSN is indicative of an older component.

Figure 12 is a graphical representation of the MTBF for each component. A higher number indicates a lower failure rate.

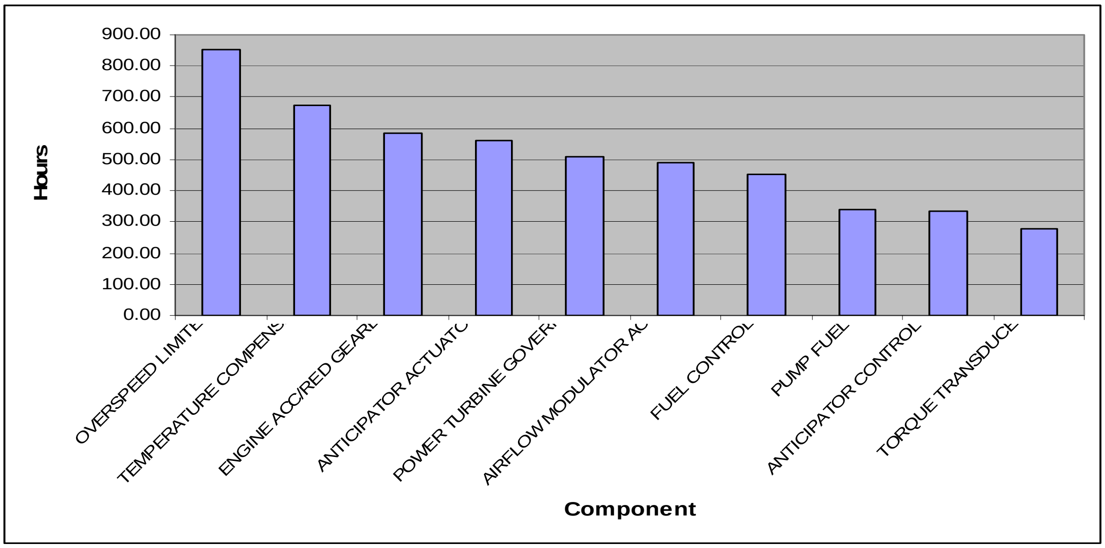

Figure 12. Average Time Between Trouble Removals by Component

Figure 13 shows a comparison of MTBF and MTSN (in tens of hours) by component. One might expect that older components would have a shorter MTBF. However, this is not the case. The engine, which is the oldest component, has the third highest MTBF, while the Torque Transducer, the newest component, has the shortest MTBF. There appears to be no relationship between MTBF and MTSN.

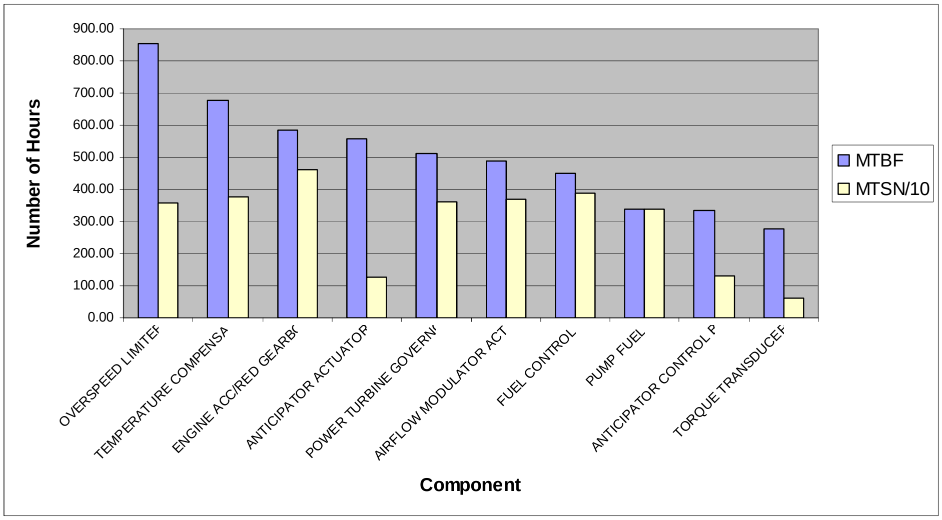

Figure 13. Comparison of MTBF and MTSN by Component

Figure 14 shows a graphical representation of the ratio of MTBF to MTSN for each component. In this case, the higher the number indicates a higher the failure rate given the age of the component. We listed components from worst to best in terms of performance in relation to age.

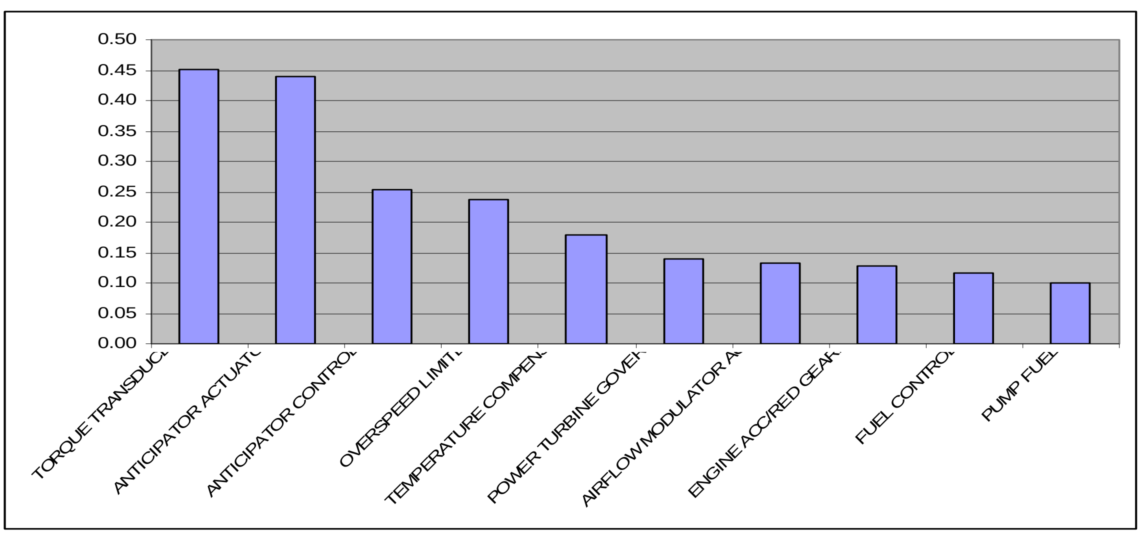

Figure 14. Ratio of MTBF to MTSN by Component

Summary of Question One

We find that while the overall number of trouble removals has increased over time, the number of removals by individual components has not increased with any regularity. We attribute the increasing trend in the overall trouble removals to a few components. With the exception of a higher rate of mishaps during the beginning of 2003, the number of mishaps over time has not increased. While there is no clear relationship between time and the number of trouble removals by component, there does appear to be a strong relationship between the type of component and the number of trouble removals. There appears to be no relationship between the average age of a component and the number of trouble removals or the number of mishaps attributed to a component. Table 6 shows the relative ranking of the components in terms of trouble removals, total of time and trouble removals, and Mean Time Between Failures. A number one ranking indicates the worst reliability while a ten indicates the best.

Table 6. Component Reliability Ranking

	Rank of Trouble	Rank for Total	Rank of Mishaps	Rank of MTBF	Average Rank
TEMPERATURE COMPENSATOR	10	10	10	9	9.75
OVERSPEED LIMITER	9	9	8	10	9
FUEL CONTROL	6	8	7	4	6.25
ANTICIPATOR ACTUATOR	7	4	6	7	6
PUMP FUEL	8	1	9	3	5.25
AIRFLOW MODULATOR ACT	4	6	4	5	4.75
POWER TURBINE GOVERNOR	5	7	1	6	4.75
ENGINE ACC/RED GEARBOX#	2	3	2	8	3.75
ANTICIPATOR CONTROL BOX#	3	5	3	2	3.25
TORQUE TRANSDUCER#	1	2	5	1	2.25
		#Does not undergo normal overhaul			

We see that according to these measures, the Torque Transducer and the Anticipator Control Box are the least reliable components, while the Temperature Compensator and Overspeed Limiter are the most reliable.

Research Question Two

The second research question asks, "What primary factors are driving failures in the LTS 101 engine?" We answer this by determining if there are any correlations between certain malfunctions and specific components or if there are any associations between certain malfunctions and specific systems.

<u>Trouble Removals by Component and Malfunction Type</u>

Figure 15 shows the percentage of components replaced for the fifteen most frequent malfunctions. For example, this figure shows that a faulty torque transducer causes 100% of the *Torque Indication Zero* malfunction.

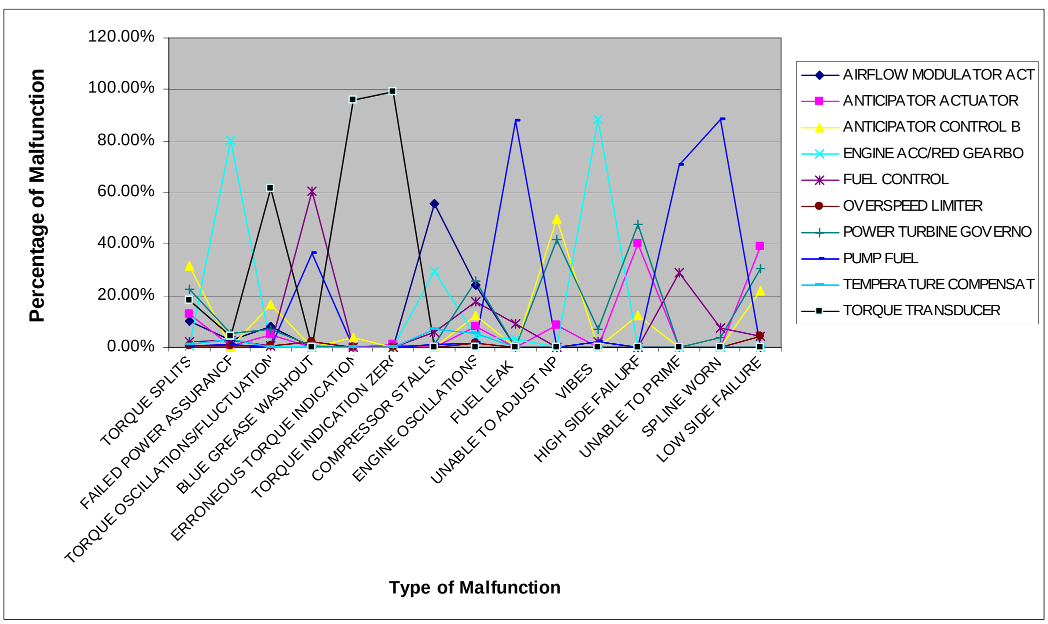

Figure 15. Percentage of Component Replacement per Malfunction

We examine the same classifications statistically using contingency table analysis. We compute a χ^2 statistic of 2800.1 and P-value of less than 0.0001. This statistically confirms what we see in Figure 15; there is a strong correlation between the type of malfunction and faulty component.

Table 7. Summary of Most Frequent Malfunctions by Component

COMMENTS	AIRFLOW MODULATOR ACT	ANTICIPATOR ACTUATOR	ANTICIPATOR CONTROL B	ENGINE ACC/RED GEARBO	FUEL CONTROL	OVERSPEED LIMITER	POWER TURBINE GOVERNO	PUMP FUEL	TEMPERATURE COMPENSAT	TORQUE TRANSDUCER	Malfunction Percentage of Total	Cumulative Percentage of Malfunction
TORQUE SPLITS	10.12 %	13.01 %	31.71 %	0.27 %	2.17 %	0.54 %	22.58 %	0.27 %	1.08 %	18.25 %	23.32 %	23.32 %
FAILED POWER ASSURANCE	2.65%	0.38 %	0.00 %	80.30 %	2.65 %	0.38 %	5.30 %	1.14 %	3.03 %	4.17%	5.56 %	28.89 %
TORQUE OSCILLATIONS/FLUCTUATIONS	8.18%	5.03 %	16.35 %	0.63 %	0.63 %	0.63 %	6.92 %	0.00 %	0.00 %	61.64 %	3.35 %	32.24 %
UNABLE TO CALIBRATE TRANSDUCER	0.00%	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00%	3.08 %	35.31 %
BLUE GREASE WASHOUT	0.00%	0.00 %	0.00 %	0.00 %	60.69 %	2.07 %	0.69 %	36.55 %	0.00 %	0.00%	3.06 %	38.37 %
WOULD NOT OPEN	100.00%	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00%	3.01 %	41.38 %
ERRONEOUS TORQUE INDICATIONS	0.00%	0.00 %	3.85 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	96.15 %	2.74 %	44.12 %
TORQUE INDICATION ZERO	0.00%	0.94 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	99.06 %	2.23 %	46.35 %
COMPRESSOR STALLS	55.88 %	0.00 %	0.00 %	29.41 %	5.88 %	0.00 %	0.98 %	0.98 %	6.86 %	0.00%	2.15 %	48.50 %
TORQUE INDICATION FULL SCALE	0.00%	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00%	2.02 %	50.53 %

There are 425 distinct malfunctions described in the component removal data. See Appendix D: List and Count of Individual Malfunctions for a complete listing. Of these, the ten most frequent malfunctions account for 50% of all malfunctions. Table 7 lists these malfunctions and the components associated with each. We note that the fourth and tenth most frequent malfunctions, *Unable to Calibrate Transducer* and *Torque Indication Full Scale,* are 100% attributable to the torque transducer. This confirms our findings in question one since the Torque Transducer ranked last in overall reliability.

Trouble Removals by System

In order to determine if there is a relationship between system type and specific malfunctions, we categorize each component into its respective system and count the number of trouble removals (or faulty components) by system. Table 8 shows the number of trouble removals by component and system. We note that both the Bleed Air and Engine systems consist of only one component (in terms of this study). The Anticipator system consists of three components, while the Fuel Governing system consists of five components.

Table 8. Components Categorized by System and Trouble Removals

COMPONENT	ANTICIPATOR	BLEED AIR	ENGINE	FUEL GOVERNING
TORQUE TRANSDUCER	956			
ENGINE ACC/RED GEARBO			683	
ANTICIPATOR CONTROL B	663			
AIRFLOW MODULATOR ACT		568		
POWER TURBINE GOVERNO				530
FUEL CONTROL				439
ANTICIPATOR ACTUATOR	391			
PUMP FUEL				306
OVERSPEED LIMITER				108
TEMPERATURE COMPENSAT				102

Figure 16 depicts the number of trouble removals by system. The Anticipator and Fuel Governing systems account for the majority of trouble removals.

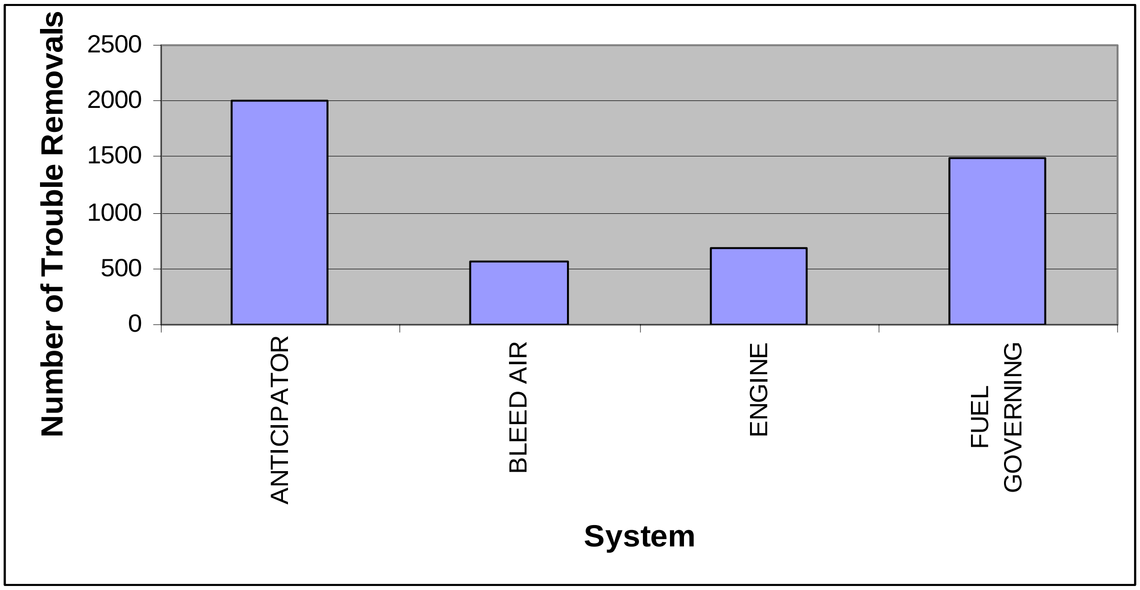

Figure 16. Number of Trouble Removals by System

Table 9 summarizes the most frequent malfunctions by faulty system. Anticipator and Fuel Governing components account for 1820 removals, which account for 75% of all removals among the ten most frequent malfunctions.

Table 9. Summary of Most Frequent Malfunction by System

MALFUNCTION	ANTICIPATOR	FUEL GOVERNING	BLEED AIR	ENGINE	Total
TORQUE SPLITS	697	295	112	3	1107
FAILED POWER ASSURANCE	12	33	7	212	264
TORQUE OSCILLATIONS/FLUCTUATIONS	132	13	13	1	159
UNABLE TO CALIBRATE TRANSDUCER	146				146
BLUE GREASE WASHOUT		145			145
WOULD NOT OPEN			143		143
ERRONEOUS TORQUE INDICATIONS	130				130
TORQUE INDICATION ZERO	106				106
COMPRESSOR STALLS		15	57	30	102
TORQUE INDICATION FULL SCALE	96				96
	1319	501	332	246	2398

Next, we compare trouble removals by system and year to determine any trends over time. Figure 17 and Table 10 show a breakdown of trouble removals by system and year. We can see that the percentage of Anticipator System trouble removals has decreased over time while the percentage of Fuel Governing System Removals has increased.

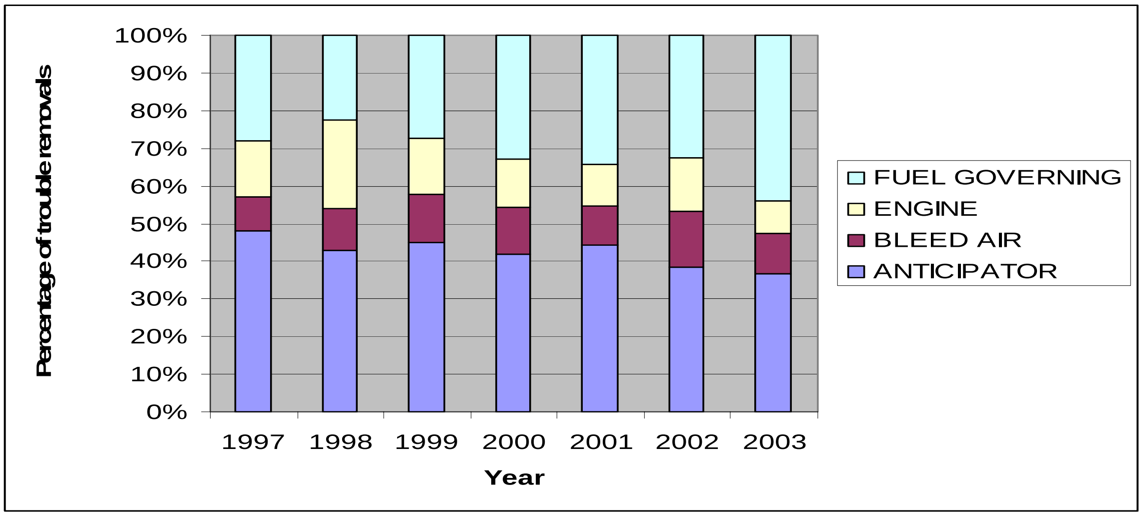

Figure 17. Comparison of Percentage of Trouble Removals by System by Year

Table 10. Trouble Removals by System

DATE	ANTICIPATOR	BLEED AIR	ENGINE	FUEL GOVERNING	Ratio of Anticipator to Fuel Governing Trouble Removals
1997	245	46	75	143	1.713287
1998	274	72	149	144	1.902778
1999	289	81	97	175	1.651429
2000	340	103	105	267	1.273408
2001	349	82	87	268	1.302239
2002	360	139	133	304	1.184211
2003	153	45	37	184	0.831522

We confirm the relationship between year and ratio statistically using OLS regression and find a strong correlation (Adjusted $R^2 = 0.84$) between Year and the Ratio of Anticipator System trouble removals to Fuel Governing System trouble removals. We compute a P-value of 0.0023, and a B_1 estimate of -0.158. Since the P-value is less than 0.05, we reject the null hypothesis that B_1 = zero. In this case, we find a negative correlation; as the year increases, the ratio decreases. Our model satisfies the assumptions of normality, independence, and constant variance. We find that the year 1997 acts as a major influential data point and the years 1998 and 2003 act as minor influential data points. Given the small sample size, this is not surprising and does not affect our overall conclusion.

Summary of Question Two

The type of component shows a strong correlation to the type of malfunction. Similarly, the type of system shows a strong correlation to the type of malfunction. The ten most frequent malfunctions account for 50% of all distinct malfunctions counted. The most frequent malfunction, *Torque Splits*, was reported on 1107 occasions and accounts for 23% of all malfunctions. The second most frequent malfunction, Failed Power Assurance, occurred 264 times. The Anticipator System accounts for the majority of trouble removals both overall and in response to *Torque Splits*. However, there has been a decline of Anticipator System removals over time with a corresponding increase in Fuel Governing system removals.

Research Question Three

We answer the final research question, “Should the overhaul times be changed?” by comparing the number of removals for trouble to removals for time and the average

Time Since Overhaul of each component at the time of trouble removal or failure. We added this question to our study after discussion with CWO Hector Serrano, the Coast Guard Contract Manager for the LTS-101 engines. Mr. Serrano mentioned that the Coast Guard was undertaking an effort to revise the current overhaul times.

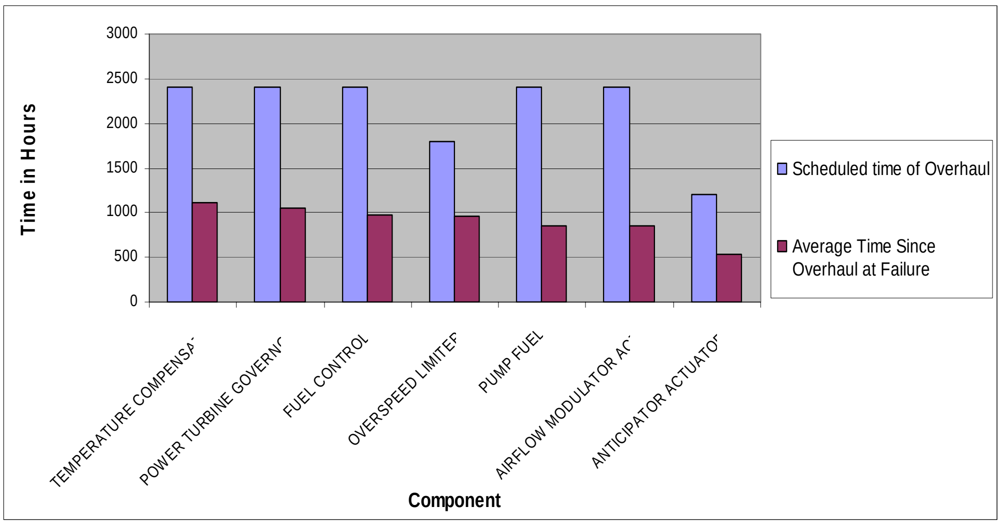

Figure 18. Comparison of MTSO at Failure and Scheduled Time of Overhaul

Our initial analysis of time versus trouble removals shows this to be a serious issue for the Coast Guard HH-65. Figure 18 shows that all overhauled components are failing at less than half their scheduled overhaul time.

<u>Time versus Trouble Removals</u>

Figure 19 shows a comparison of these trouble and time removals by component. We can see that the Temperature Compensator has the least amount of removals for trouble, while the Airflow Modulator has the most. With the exception of the Fuel Pump and Overspeed Limiter, all components were removed more often for trouble than time.

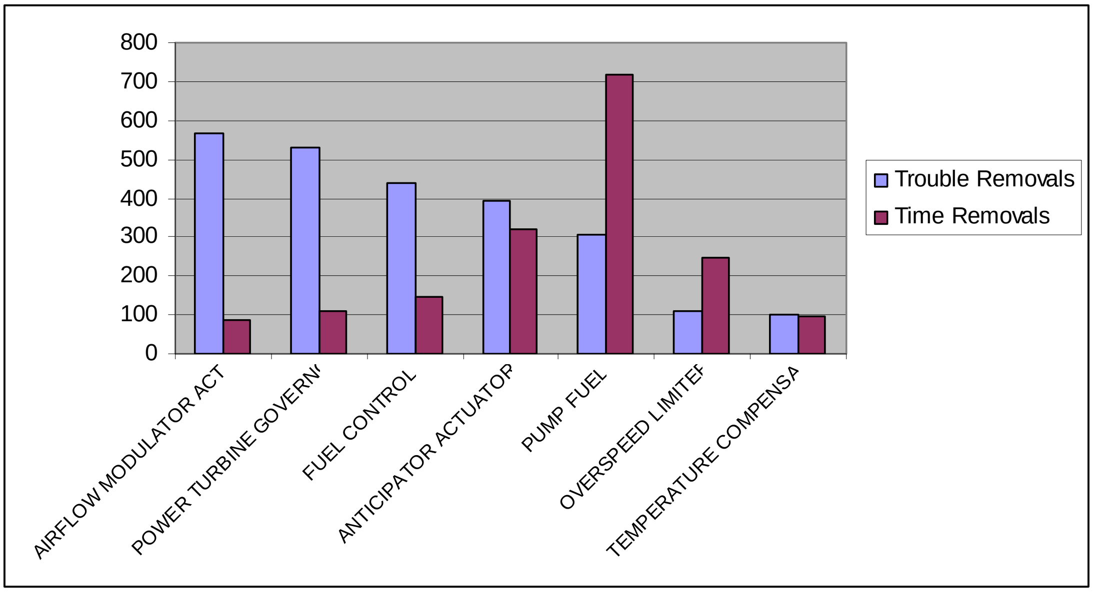

Figure 19. Comparison of Trouble Removals to Time Removals

<u>Mean time Since Overhaul versus Scheduled Time of Overhaul</u>

Next, we compare the scheduled overhaul time with the Mean Time Since Overhaul (MTSO) for those components that undergo scheduled overhaul. We figure the MTSO by taking an average of the Time Since Overhaul (TSO) at the time of trouble removal for each component. Figure 20 shows the difference in hours between the scheduled overhaul and the MTSO alongside the number of trouble removals for each component. The higher the number, the more hours in advance of its regular scheduled overhaul time a component is failing. A higher number could indicate a component with decreasing reliability. Although, the Airflow Modulator has the greatest difference between its MTSO and Scheduled Overhaul Time and has the most trouble removals, this figure depicts no general trend or pattern between the difference between scheduled overhaul time and MTSO and the number of trouble removals.

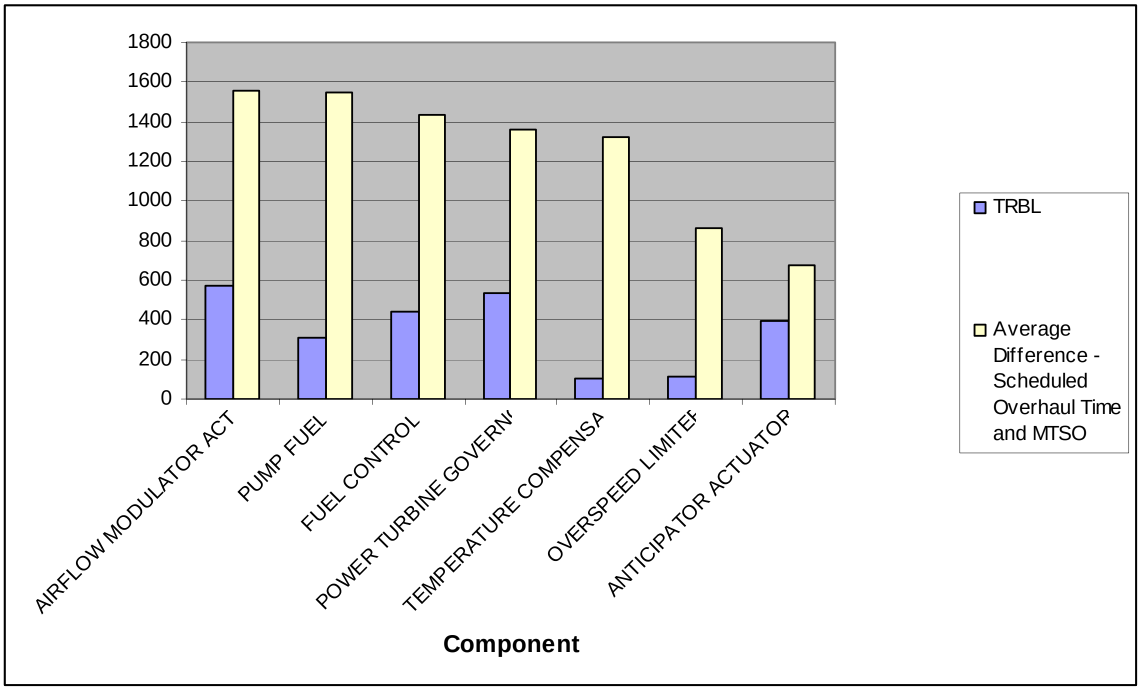

Figure 20. Comparison of Trouble Removals and Difference of Scheduled Overhaul Time and MTSO by Component

We further analyze how the difference between the Scheduled Overhaul Times and the TSO at the time of failure affects the reliability using a logistic regression model. We use logistic regression for this analysis because we attempt to predict a binary response; in this case, fail or not fail prior to scheduled overhaul time. This model (see Table 11) has an adjusted R^2 of 0.49 and a P-value of less than 0.0001. We find that the Time Since Overhaul and the difference between the Scheduled Overhaul Time squared are very strong predictors of component failure since they have a high Chi-Squared (χ^2) test statistic. Additionally, this model demonstrates that the Anticipator Actuator, the Fuel Control, the Overspeed Limiter, and the Fuel Pump also act as predictors of component failure. This does not necessarily mean that these components are more likely to fail; it only indicates that in combination with the TSO and Difference Squared, they are strong predictors of component failure.

Table 11. Logistic Regression Model Predicting Component Failure

Predicting Component Failure	Test Statistic	P-value
Whole Model	2765.009	$<10^{-4}$
Time Since Overhaul at time of Failure	638.43	< 0.0001
Difference between Time Since Overhaul and Scheduled Overhaul Squared	295.82	< 0.0001
Anticipator Actuator	573.02	< 0.0001
Fuel Control	17.14	< 0.0001
Overspeed Limiter	401.90	< 0.0001
Fuel Pump	758.23	< 0.0001

We also examine the relationship between Mean Time Between Overhauls and reliability using OLS regression. In this case, the measure of reliability is the Mean Time Between Failure (MTBF). This model (Adjusted $R^2 = 0.91$) demonstrates that the Mean Time Since Overhaul and the Difference between the MTSO and the Scheduled Overhaul times are predictive of the MTBF regardless of component.

Table 12. OLS Model Predicting Mean Time Between Failures

Predicting Component Failure (OLS)	Estimate	P-value
Whole Model (n = 7)		0.0165
Time Since Overhaul at time of Failure	3.305	0.0272
Difference between Time Since Overhaul and Scheduled Overhaul	-15.031	0.0272
Difference between Time Since Overhaul and Scheduled Overhaul Squared	0.00616	0.0464

Table 12 shows that the variables Mean Time Since Overhaul at time of failure, Difference between MTSO and scheduled overhaul times, and the Difference squared are strong predictors of MTBF. The model residuals meet the assumptions of constant variance, normality, and independence. We find one major influential data point (Airflow Modulator) and one minor influential data point (Fuel Pump). While these data points may weaken the predictive value of the model, we leave them in due to the small sample size of the model. The fact that both the logistic and OLS model both show that the Difference between Time Since Overhaul and Scheduled Overhaul Squared as predictors of failure is significant. We also note that both models have a relatively high R^2 value in spite of the very low sample size (n=7). Table 13 summarizes these findings.

Table 13. Significant Models and Predictor of Component Failure

	Logistic Model	OLS Model
R^2	0.49	0.91
Whole Model P-value	0.0000	0.0165
(Time of Scheduled Overhaul - MTSO)^2 (P-Value)	< 0.0001	0.0272

Table 14 shows the Scheduled Overhaul Times, the MTSO, and the Ratio of the two for each component. The ratio gives us a measure of the relative performance of a given component relative to its scheduled overhaul time. The closer this ratio is to one, the better the component is performing. A number closer to zero indicates a poorer performing component. We have listed the components from best performing to worst performing.

Table 14. Summary of Scheduled Overhaul Times, MTSO and Ratio by Component

COMPONENT	Scheduled Time of Overhaul	MTSO at Failure	Ratio of MTSO to Scheduled Overhaul Time
OVERSPEED LIMITER	1800	952.21	0.53
TEMPERATURE COMPENSAT	2400	1117.18	0.47
ANTICIPATOR ACTUATOR	1200	535.10	0.45
POWER TURBINE GOVERNO	2400	1045.26	0.44
FUEL CONTROL	2400	972.87	0.41
PUMP FUEL	2400	857.76	0.36
AIRFLOW MODULATOR ACT	2400	847.22	0.35

Table 15 shows a summary of survival times for each component. We take special note of the column labeled 75% Failures. This column shows the MTSO at which 75% of components fail. An NA indicates that this component does not undergo regular overhaul.

Table 15. Summary of Survival Hours by Component

Component	Median Time	Lower95%	Upper95%	25% Failures	**75% Failures**	Current Scheduled Overhaul Time
AIRFLOW MODULATOR ACT	750	630	811	325	**1312**	2400
ANTICIPATOR ACTUATOR	511	469	577	254	**802**	1200
ANTICIPATOR CONTROL B	1258	1175	1346	762	**1856**	NA
ENGINE ACC/RED GEARBO	4533	4442	4635	3852	**5294**	NA
FUEL CONTROL	909	818	993	415	**1524**	2400
OVERSPEED LIMITER	1050	843	1138	507	**1423**	1800
POWER TURBINE GOVERNOR	1009	909	1104	475	**1576**	2400
PUMP FUEL	842	746	891	405	**1286**	2400
TEMPERATURE COMPENSAT	982	888	1211	594	**1599**	2400
TORQUE TRANSDUCER	454	408	501	221	**825**	NA

Percentage of Time versus Trouble Removals

Table 16 shows the average breakdown of time versus trouble removals by year and component. Using the average of the yearly change in types of removals, we projected the breakdown of removals for 2003 assuming that conditions remain the same.

Table 16. Percentage of Time vs. Trouble Removals

Component	Average last 7 years		2003 Projection	
	Time	Trouble	Time	Trouble
Airflow Mod	14%	86%	4%	96%
Power Turbine Governor	18%	82%	8%	92%
Fuel Control	26%	74%	12%	88%
Temperature Compensator	46%	54%	26%	74%
Anticipator Act	44%	56%	45%	55%
Fuel Pump	69%	31%	52%	48%
Overspeed Limiter	70%	30%	81%	19%

Figure 21 shows a graph of the projected removal breakdown for 2003. As one can see, if the overhaul times remain the same, the number of trouble removals is likely to increase.

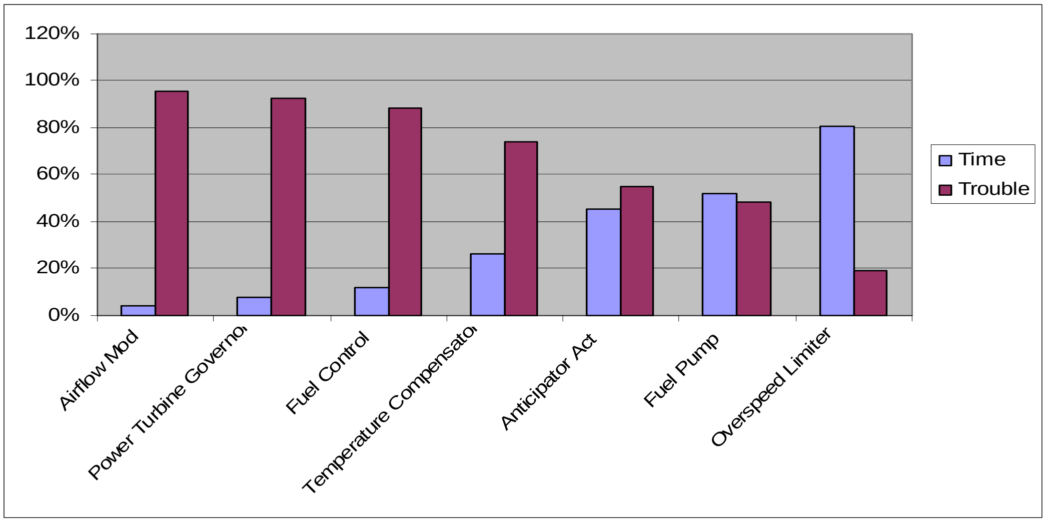

Figure 21. Comparison of Projected Time versus Trouble Removals for 2003

The question now becomes, "What is the correct overhaul time for each component?" Perhaps the 75% failure rate as shown in Table 15 is a good place to start. Table 17 shows the reduction in trouble removals that would likely result by setting the scheduled overhaul times at the 75% failure level.

Table 17. Removal Rate Comparison between Current and Projected Overhaul Times

Component		Average last 7 years		2003 Projection using current Overhaul times		Projected removals using revised Overhaul times (75%)		Reduction in trouble removals (Revised overhaul times)
		Time	Trouble	Time	Trouble	Time	Trouble	Trouble
Airflow Mod	Percentage	14%	86%	4%	96%	31%	69%	28%
	Count	12	81	8	179	58	129	21
Anticipator Act	Percentage	44%	56%	45%	55%	60%	40%	27%
	Count	46	56	75	91	100	66	14
Fuel Control	Percentage	26%	74%	12%	88%	35%	65%	26%
	Count	21	63	26	197	77	146	16
Overspeed Limiter	Percentage	70%	30%	81%	19%	87%	13%	32%
	Count	35	15	50	12	54	8	4
Power Turbine Governor	Percentage	18%	82%	8%	92%	29%	71%	23%
	Count	16	76	12	146	46	112	18
Fuel Pump	Percentage	69%	31%	52%	48%	62%	38%	21%
	Count	103	44	97	90	116	71	11
Temperature Compensator	Percentage	46%	54%	26%	74%	45%	55%	25%
	Count	14	15	6	17	10	13	4

Figure 22 shows a side-by-side comparison of the projected trouble removals if no changes are made to the overhaul times against the predicted trouble removals using the 75% failure rate.

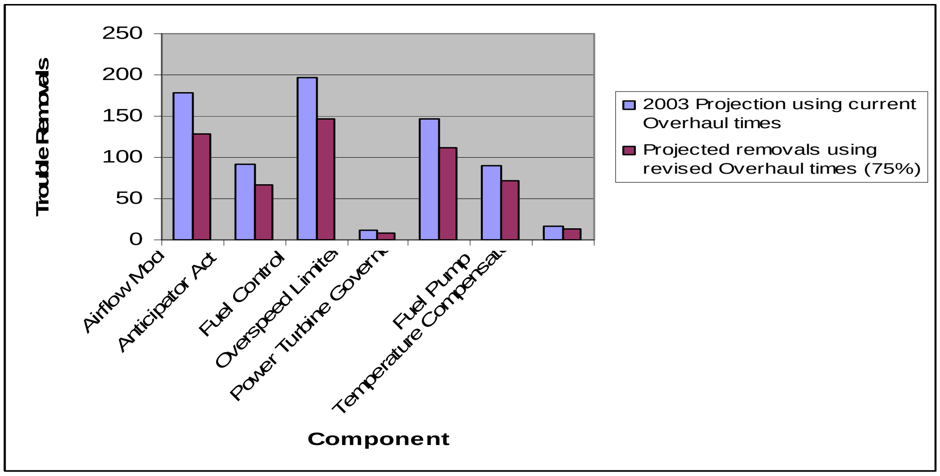

Figure 22. Comparison of 2003 Projected Trouble Removals

<u>Summary of Question Three</u>

It is readily apparent that the scheduled overhaul times are too long; with the exception of the Overspeed Limiter and the Fuel Pump, there are more removals for trouble than time for all components. Additionally, all components are failing at an average of half their respective scheduled overhaul time or sooner. By revising the current scheduled overhaul times to the 75% failure level, the number of trouble removals could be reduced by an average of 25%.

Chapter Summary

The total number of trouble removals has increased over time; however, we find no correlation between time and trouble removals by individual component. We find a strong relationship between the type of component and the number of trouble removals. There appears to be no relationship between the average age of a component and the number of trouble removals or the number of mishaps attributed to a component. The type of component shows a strong correlation to the type of malfunction. Similarly, the type of system shows a strong correlation to the type of malfunction. There has been a slight decline of removals of anticipator system components over time with a corresponding increase in fuel governing system removals. We find that the scheduled overhaul times are too long, resulting in an excessive number of trouble removals for all components.

This chapter describes the types of statistical methodologies we use in this study, namely contingency table analysis, OLS regression analysis and logistic regression analysis. We describe the mishap data and component removal data and discuss the modifications and limitations of each. We apply the discussed statistical methods on the data to answer each research question individually. In the next chapter, we discuss the findings from this chapter and address research question four, “what primary factors are impeding powerplant improvements of the HH-65?”

IV. Discussion, Conclusions, and Recommendations

In this chapter, we answer research question four. Additionally, we discuss our conclusions, recommendations, and suggestions for future research.

Research Question Four

The forth research questions asks, "What primary factors are impeding powerplant improvements of the HH-65?" Through an examination of the literature and data analysis, we find the lack of HH-65 powerplant improvements due to four main reasons; Coast Guard culture, apparent reliability improvement after the LTC lawsuit, lack of funding, failure to measure intangible costs associated with engine's lack of power, and political pressures.

Coast Guard Culture

Prevalent within Coast Guard culture is the attitude of doing more with less. Admiral James Loy, former Coast Guard Commandant, recognized that the eventuality of this attitude is that one may end up doing everything with nothing (Loy, 1999b). Getting the job done, whether it a rescue or a drug bust, in spite of old or unsafe equipment is what the Coast Guard has done for over 200 years. Unfortunately, it is this very attitude that has hampered improvements of the HH-65. Coast Guard leaders accepted the aircraft in spite of its inadequate power reserve. Coast Guard pilots continued to accept and accomplish missions in spite of the aircraft's lack of power and unreliability. The fact that these missions were accomplished made for an insidious complacency and lulled the organization into a false sense of security (Loy, 1999a). Like the driver who continues to drive without a seatbelt because he has never had an accident, the Coast

Guard continues to fly the HH-65 because those who fly it continue to get the job done in spite of the aircraft's problems. The Coast Guard must take some responsibility for the lack of improvements to the HH-65.

Reliability Improves

As discussed in Chapter Two, after the initial problems, the reliability of the LTS-101 improved, particularly after the Coast Guard won its lawsuit against TLC in 1990. This, coupled with the subsequent Power-by-the-Hour agreement, caused the Coast Guard to stick with the LTS-101 and scrap Proof-of-Concept testing of the T800 since it was economical to do so and there were no serious safety issues at the time (Kandebo, 1990b:25).

Lack of Funding

The Coast Guard's history of budget shortfalls is arguably the most influential of factors hampering improvements to the HH-65 powerplant. Each upgrade or improvement must show a positive return on investment. Proving a direct relationship between airframe weight and cost savings has been problematic. It has been much easier to upgrade other systems such as avionics due to obsolescence and the more obvious cost benefit of such upgrades. This approach has failed to account for the full impact of the intangible and life-cycle costs of increased aircraft weight and reduced power reserves in terms of safety and operational capability (Schlatter, 1997:14).

Intangible Costs

The Coast Guard underestimated the importance of intangible costs associated with the HH-65. While difficult to measure, these types of costs are nonetheless very real and potentially very costly, especially when calculated over the service life of the helicopter. These costs include, but are not limited to the following:

- Lack of availability – Aircraft is unavailable due to maintenance.
- Mission effectiveness – The aircraft is available but is unable to launch or is required to abort due to a maintenance problem.
- Lack of Power Reserve – The aircraft is unable to perform the type of missions it was originally designed for due to weight growth and lack of power reserve (See Table 1, page 10).

In terms of these intangibles, the current engine has cost the Coast Guard far more than has been saved by not upgrading early on. The Coast Guard has used availability as a measure of reliability throughout the history of the HH-65. Dispatch failure, which is an indirect measure of reliability and mission effectiveness, has only been measured since 1997. The lack of power reserve is a critical aspect of mission effectiveness. However, neither dispatch failure nor availability measure the missions not attempted.

Political Issues

As the Coast Guard searches for the best value in a new HH-65 power plant, politics have slowed the improvement process. The Coast Guard's interest in the Turbomeca engine as replacement for the LTS-101 has resulted in the perception that the service is "turning its back on its proven LTS-101" (Harvey, 2002:1). As this study has shown, however, the reliability of the LTS-101 was anything but proven until 1999 and the engine has never been a proven performer in terms of power reserve.

The Coast Guard is considering replacing the current engines with the Turbomeca Arriel 2C2. The world's leading helicopter engine maker, Turbomeca is a subsidiary of Snecma Group. Turbomeca teamed with Snecma Group in 2000. Previously Société

Nationale d'Étude et de Construction de Moteurs d'Avion and the oldest engine maker in the world, Snecma Group is the leading European Aerospace Company and is the fourth ranked engine-maker in the world. It is 97% owned by the French government ("First Flight," 2002). Although Turbomeca is foreign-owned, the Arriel 2C2 engine is manufactured in Prairie View, Texas (Couch, 2003a).

The service's interest in Turbomeca has drawn the attention of some in Congress who are concerned about off-shore purchases – especially those from French companies (Harvey, 2002). The Coast Guard is seen by some in Washington and the U. S. helicopter industry as having a tendency for going toward non-domestic sources to meet its operational requirements. Along with the French-made HH-65, the service also leases the Italian-made Augusta A-109 for its anti-drug armed helicopters (Harvey, 2002). Additionally, the European Aeronautics Defence and Space Company (EADS) has been subcontracted by the Integrated Coast Guard Systems to provide the Coast Guard with a new Maritime Surveillance Aircraft and upgrade the HH-65 as part of the recently awarded $17 million Deepwater contract (Tiron, 2002:3).

The Coast Guard has had to defend its interest in the French-owned Turbomeca engines. South Carolina Senator Fritz Hollings has put pressure on the Coast Guard to work with Honeywell to assist with the remedy of the HH-65 engine (Davis, 2003). The Honeywell plant that manufactures and overhauls the LTS-101 is located in Greer, South Carolina. Senator Hollings took issue with the Coast Guard's expenditure of federal dollars on a foreign manufacturer (Turbomeca) in the service's effort to upgrade the HH-65 engines. The Coast Guard received a total of $14 million from the FY 2000 and FY 2001 Department of Transportation Appropriations bill to upgrade the HH-65 engines.

From this, the Coast Guard provided $5.9 million to Honeywell to assist them in competing for the engine production contract (Davis, 2003).

Perhaps to silence this type of opposition, Eurocopter America recently purchased a facility in Mississippi for the manufacture of components of the Eurocopter AS350, EC130, and AS355 helicopters (Harvey, 2002; Tiron, 2002:4). More likely, though, Eurocopter and its parent company, EADS, are aiming to gain a strategic foothold in the U. S. Market and strengthen ties with DOD. Currently, the U. S. represents 7% of EADS defense revenues and the company would like to increase this number (Mason, 2002:2). Experts believe this increased competition will invigorate U. S. companies by giving them some much-needed competition. There is also a fear that if the U. S. shuts out the European companies, the Europeans may shut out U.S. companies (Tiron, 2002:1). Frank Cevasco, former Assistant Deputy Under-Secretary of Defense believes that the U.S. military cannot afford to shut out European firms; "If the U. S. government is perceived as being even more protectionist [than it is now], I fear that we will get an even bigger reaction from the European Companies. They can harm us much more than we can hurt them" (Tiron, 2002:1).

Many sectors of the U. S. defense industry now consist of single suppliers. Some see this lack of competition as a hindrance to a healthy and competitive acquisition process. The introduction of Europeans firms will give the government more than one alternative in the source selection process (Tiron, 2002:2).

Conclusions and Recommendations

While the current engine alone may not be suffering from severe reliability problems, it does suffer from a severe lack of power. The current engine has a documented power deficit of 23% (Burgess, 2003). As discussed in Chapter Two, Power Required vs. Power Available, this severely limits the mission capability of the HH-65. This also means that the current engine provides no room for the additional weight growth required for any AUF capabilities. The two engines under consideration for the HH-65 powerplant upgrade are the Honeywell HTS-900 and the Turbomeca Arriel 2C2. Of all of the commercial Dauphin operators in the world, the Coast Guard HH-65 is the only one not powered by Arriel engines (Burgess, 2003). The Honeywell HTS-900 provides a 14% power increase over the current version and is predicted to save $130M over a complete replacement (Wagstaff, 2003). On the other hand, the Turbomeca 2C2 provides a 40% increase. Both engines will require a main gearbox upgrade to handle the increase in power (Padfield, 2003). If the Coast Guard goes with the 850, the HH-65 will have a 9% power deficit while the 2C2 will provide a 17% power reserve. While the choice may seem obvious, even a 17% power reserve may not be enough to provide the HH-65 with the power it needs to accomplish AUF missions.

Fuel Control

While the reliability of the engine itself may not be decreasing, the existing engine control system, which consists of the fuel-governing and anticipator systems, suffers from a severe reliability problem. Developed solely for the Coast Guard HH-65, this engine control system came with many problems. Malfunctions with this system are both difficult to diagnose in-flight and troubleshoot and repair on the ground (Connor, Devoe et al., 1998:8) As our analysis in Chapter Three showed, the great majority of malfunctions associated with the current powerplant are due to the Anticipator and Fuel-Governing System. We find the Torque Transducer and the Anticipator Control Box, both components of the anticipator system, to be the least reliable components associated with the engine. Additionally, of the ten most frequent malfunctions during the period of study, six are directly related to either the fuel governing or anticipator system.

The decline of anticipator system removals and concurrent increase in fuel-governing system removals over the last six years is most likely due to a faulty Power Turbine Governor. As discussed in Chapter Two, Recent Events, maintenance experts identified this component as faulty earlier this year and recalled it from service. As of this writing, the recall is 80% complete with only low-time PTGs still in service. This recall was necessary in resolving a critical problem; however, it only addressed an immediate safety issue and does not address the overall problem with the current systems, which are woefully obsolete and very costly.

An improved and updated fuel control system is just as important as an improved powerplant. It is imperative that the Coast Guard replace this system with a more reliable one. One option under consideration to replace the current system is an updated version of a Full Authority Digital Engine Control (FADEC). Like an automobile fuel injection system, FADEC works electronically to deliver the precise ratio of fuel and air to the engine. A FADEC system would replace the current fuel governing and anticipator systems. Considered the industry standard for helicopter engine control, FADEC is safer and easier to maintain than the current system. It also allows for future power growth to accommodate the inevitable mission gross weight increases that come with increased operational requirements (Connor, Devoe et al., 1998:8). A FADEC system would save the Coast Guard $725K a year (1998 dollars) in Power by the Hour costs (*HH65A Performance Study,* 1998). The LTS engine under consideration does not include a FADEC while the Arriel engine includes a proven duel channel FADEC called the Digital Engine Electronic Control Unit (Lovejoy, 2003). Honeywell began development of a FADEC engine in January 2003. Certification is expected mid-2004 (Couch, 2003c).

Political Pressure

The pressure on the Coast Guard to buy from domestic sources misses the big picture. The Coast Guard needs the HH-65 to perform as originally designed. Because it is a small service, many American companies are not even interested in working with the Coast Guard. Forcing the Coast Guard to buy from a domestic source that cannot provide the best engine for the money could cost taxpayers more in terms of loss of mission effectiveness and diminished ability to protect the homeland. In responding to this political pressure, the Coast Guard needs to focus on how intangible costs figure into the long-term cost of an underpowered HH-65 and communicate these costs to Congress.

Final Analysis

If it hopes to expand the mission capability and increase the safety of the HH-65, the Coast Guard must improve the current powerplant. This improvement must address reliability as well as power reserve. Table 18 shows a comparison between upgrade options.

Table 18. Analysis of Upgrade Options

Alternative	Power Increase	Resulting Power	Cost of FADEC
HTS-900	14%	-9%	not included
Arriel 2C2	40%	17%	included

This does not tell the whole story, however. While this study focused on learning from the past, to make the best choice, decision makers must look ahead and account for future intangible costs involved in this upgrade. Although various attempts have been made to capture the mission impact of the HH-65's lack of power, there is no Coast Guard-wide standard measure (*CG Budget Challenges,* 2000:3; CG LANTAREA Oct 16, 2003; Vigus, 2003). The Coast Guard has recognized the need to develop a metric that captures the missions not attempted due to the HH-65's lack of power (CG LANTAREA Oct 16, 2003). This should include any mission that could have been accomplished if the HH-65 met its original design requirements. (Schlatter, 1997:1-3)

Suggestions for Further Study

This study addressed the reliability of the HH-65 helicopter. As discussed above, a study of the intangible costs related to the poor reliability of the LTS-101, lack of power reserve, and complicated fuel-governing system may be useful. A study of this type may help the Coast Guard and other agencies avoid costly mistakes in the future by highlighting the importance of intangible but real costs. In addition, a comparison of expected life-cycle costs of any upgrade or replacement engine would be useful in assisting senior leaders make the correct decision in their effort to upgrade the HH-65. Additionally, a more complete analysis of proper overhaul times is necessary.

Addressing issues related to the cost of a trouble removal versus a time removal and the optimum mix of both is salient to this issue.

Chapter Summary

In this chapter, we answer research question four. We find five factors that have hampered improvements to the HH-65 powerplant, namely the prevailing Coast Guard culture, an apparent improvement in reliability in 1990, lack of funding, failure to fully quantify intangible costs, and various political issues. We conclude that the lack of power reserve and an obsolete and unreliable fuel control system are the critical issues that continue to hamper the mission capability of the HH-65 both now and in the future. We recommend that the decision on any improvements to the HH-65 be made with a long-term view and must include a comprehensive analysis of the costs associated with an underpowered aircraft. Finally, we discussed topics for future research including a study of the intangible costs incurred by sticking with the LTS-101, a comparison of life-cycle costs between the HTS-900 and Arriel 2C2, and in-depth analysis of the cost of trouble versus time removals.

Last Word

This study revealed three critical issues associated with the HH-65 powerplant, namely, lack of power reserve associated with the LTS-101-750, poor reliability associated with the fuel-control system, and excessive trouble removals due to excessive time between schedule overhaul times. Political pressure is forcing the Coast Guard toward a less than optimum fix. The fact that there has been no recent injury or loss of life as a result of these problems is a testament to the skill of the aircrews who fly the

HH-65 and who continue to make due with an underpowered aircraft every time they fly. However, the Coast Guard cannot afford to allow this apparent success to lull them into a less than optimum solution. Recent restrictions imposed on HH-65 (See Recent Events, page 19) operations indicate that Coast Guard leaders recognize the criticality of this situation. Congress must allow the Coast Guard to give its aircrews the proper tools to safely accomplish the mission. The problems associated with the LTS-101 and HH-65 are well documented. Congressional and Coast Guard leaders have a responsibility to those who fly the HH-65 as well as to the public they serve to correct the shortfalls of this critical asset. This is not only to avoid a potential mishap, but also in order to accomplish the missions for which the helicopter was originally designed.

Appendix A: Definition of Terms

Fuel Governing System – pneumatically regulates fuel flow in accordance with engine power demands and ambient temperature (*HH-65 Flight Manual,* 1996:1-8,9; LTS-101-750B-2, 2003:49; Barbazon, 2003).

Power Turbine Governor (PTG) – regulates speed of power turbine drive train system (Np). Uses pneumatic signals - regulated pressure (Pr) and N2 governor pressure (Pg) - to reset the fuel control and set speed of free turbine (Ng). PTG is controlling governor when fuel control level (FFCL) is forward through 90% Ng.

Overspeed Limiter (OSL) – Redundant governor to the PTG. Coupled directly to the fuel control through the Py air line. If Np exceeds 112%, the OSL will open the Py bleed air port to reduce engine speed.

Fuel Control Unit/ Ng Governor (FCU) – Regulates gas generator (Ng) speed through pneumatic signals received from temperature compensator (Px) and (Py) to regulate fuel flow to meet engine power demands. Monitors Ng speed through flyweight assembly and pneumatic signals from PTG.

Fuel Pump (FP) – delivers pressurized fuel to fuel control unit (FCU)

Temperature Compensator T1 Sensor (TEMPCOMP) – regulates N2 governor pressure (Pg), compressor discharge air (Pc), and deliver bleed air (Px) to fuel control. Prevents compressor surges.

One Engine Inoperative (OEI) One minute power setting – electromechanical system that resets the fuel control to provide access to higher power setting for use in extreme emergency. Must be armed prior to use by button on bottom of collective. Once armed, increased power (up to 15% shp) is available upon collective demand.

Anticipator System – 1) provides input to the PTG to maintain constant rotor speed (Nr) during main rotor pitch changes. 2) Balances engine torques during steady state operations (*HH-65 Flight Manual,* 1996:1-9; LTS-101-750B-2, 2003:75-76; Barbazon, 2003).

Anticipator Control Box (ACB) – amplifies and transmits electronic signals from dual potentiometer to anticipator actuators (AAM). In addition, uses input from copilot's torque indicator to balance torque between engines during steady state operations.

Anticipator Actuator Motor (AAM) – driven by signals from ACB. AAM positions the free power turbine governor (PTG) to maintain free power turbine speed (Np) in proportion to collective movement. During steady state operations, individual torque signals are compared for any differences in torque output. If there is a difference, an electronic signal is sent to drive the engine with the lower torque output to match the torque on the opposite engine.

Copilot's Torque Indicator – sends input signal to anticipator control box (ACB) for torque balancing during steady state operations.

Dual Potentiometer – varies 15 VDC electronic signal to anticipator control box (ACB) based on collective lever linkage position.

Torque Transducer (QXSND) – Converts oil pressure from ARG into electronic signal that is sent to copilot's torque indicator. Receives electronic signal from copilot's torque indicator and transmits differential voltage back to indictor.

Engine Anticipator Switches – secures power to the anticipator actuators (AAM). With power secured the position of the AAM is dependent upon collective position – acceleration and deceleration will be extremely slow.

Air Flow Modulator (AFM) – Designed to restrict engine air intake during low rotor speed operations in order to improve engine surge/stall margin. Controlled by compressor bleed air (P3) and ambient pressure (Pa) (LTS-101-750B-2, 2003:42; Barbazon, 2003).

Accessory Reduction Gearbox (ARG) – provides main support of the engine within the airframe. Also slows Ng and Np speeds to drive various components mounted on the ARG. (*HH-65 Flight Manual,* 19961-4; Barbazon, 2003)

Appendix B: Data Categories

Categories of Component Removal Data
SERIAL NUMBER
COMPONENT
SYSTEM
REASON REMOVED
FAIL
DATE OF REMOVAL
TIME SINCE NEW (HOURS)
TIME SINCE OVERHAUL (HOURS)
NORMAL TIME OF OVERHAUL
TIME BETWEEN MAINT ACTION
ENGINE OR AIRFRAME NUMBER
ACTIVITIY
MALFUNCTION (SPECIFIC REASON FOR REMOVAL)
CROSS COMPONENT
COMMENTS

Categories of Safety Data
Mishap #
possible faulty PTG
Date
Year
Aircraft
Cost
Type
Phase
Mission
Action
Faulty Component
Multi component
comments
Ship Ops

Appendix C: Torque Splits - Classified by Comments

Comments Coded as Torque Splits	Count of Comment
TORQUE SPLITS	141
Q SPLITS	68
TORQUE SPLITS.	50
TQ SPLITS	25
REMOVED DUE TO TORQUE	23
Q-SPLITS	21
Q SPLITS.	19
REMOVED FOR TROUBLESHOOTING	15
REMOVED FOR TORQUE SPLITS	15
CAUSING TORQUE SPLITS	13
REMOVED FOR TORQUE SPLITS.	12
CAUSES TORQUE SPLITS	11
TORQUE SPLIT	9
REMOVED FOR TORQUE SPLIT	7
REPLACED DUE TO TORQUE	6
CAUSING Q SPLITS	6
TORQUE SPLITS ON DECK.	5
SUSPECT CAUSING TORQUE	5
REPLACED FOR TORQUE SPLITS	5
REPLACED DUE TO Q SPLITS.	5
REMOVED FOR Q SPLITS.	5
REMOVED FOR Q SPLITS	5
Q SPLIT	5
TROUBLESHOOTING Q SPLITS	4
SUSPECT CAUSE OF TORQUE	4
REMOVED FOR Q SPLIT	4
REMOVED FOR	4
INTERMITTANT TORQUE SPLITS	4
CAUSING TORQUE SPLITS.	4
CAUSES TORQUE SPLITS.	4
TROUBLESHOOTING TORQUE	3
"Q" SPLITS	3
TORQUE SPLIT.	3
SUSPECTED CAUSE OF TORQUE	3
REPLACED FOR TORQUE SPLITS.	3
REMOVED DUE TO TORQUE SPLIT	3
REMOVED DUE TO Q SPLITS	3
Q-SPLITS.	3
INTERMITTENT TORQUE SPLITS	3
COMPLETED FOR TORQUE SPLIT	3
CAUSES Q SPLITS	3
UNABLE TO MATCH TORQUES	2
TROUBLE SHOOTING TORQUE	2
TORQUESPLITS	2

TORQUE SPLITS IN MID RANGE	2
TORQUE SPLITS AT MID RANGE	2
TORQUE SPLITS AT FLAT PITCH	2
TORQUE SPLITS AT FLAT	2
TORQUE SPLITS 20%	2
TORQ SPLITS	2
TORGUE SPLITS	2
SUSPECTED TO CAUSE TORQUE	2
REPLACED FOR TORQUE SPLIT	2
REPLACED FOR Q SPLITS	2
REPLACED FOR	2
REPLACED DUE TO Q-SPLITS.	2
REMOVED SUSPECTED FUEL PUMP	2
REMOVED FOR TQ SPLITS AS	2
REMOVED DUE TO Q SPLITS.	2
REMOVED DUE TO	2
REMOVED AND REPLACED FOR	2
Q SPLITS ON DECK	2
Q SPLITS AT FLAT PITCH	2
POSSIBLE CAUSE OF Q SPLITS	2
MID RANGE Q SPLITS OF 20%	2
INTERMITTENT TORQUE SPLIT	2
CONTROL BOX CAUSED TORQUE	2
CAUSED Q SPLITS	2
COMPLETED DUE TO TORQUE	2
CHANGED FOR TORQUE SPLITS	2
CHANGED DUE TO TORQUE	2
CAUSES TORQUE SPLITS AT	2
CAUSED TORQUE SPLITS.	2
WOULD NOT OPEN; Q SPLITS	1
CAUSED TORQUE SPLITS. WOULD	1
CAUSED TQ SPLITS	1
CAUSES 20% TORQUE SPLITS IN	1
CAUSES 6% TORQUE SPLITS	1
CAUSES FLAT PITCH Q-SPLITS,	1
CAUSES LOW SIDE TORQUE	1
CAUSES MID RANGE Q SPLITS.	1
CAUSES MID RANGE TORQUE	1
CAUSES OF SPLITS, CONTINUES	1
CAUSES Q SPLIT	1
30-50% ENG SPLIT DURING ALL	1
CAUSES Q SPLITS.	1
CAUSES TORQUE	1
CAUSES TORQUE SPLIT	1
CAUSES TORQUE SPLIT AT MED.	1
#2 ANTICIPATOR ACTUATOR	1
CAUSED TORQUE SPLIT WITH	1

CAUSES TORQUE SPLITS AT ALL	1
CAUSES TORQUE SPLITS AT LOW	1
CAUSES TORQUE SPLITS ON THE	1
CAUSES TORQUE SPLITS, IS	1
16 Q (#1 ENG PROBLEM SIDE)	1
CAUSES TORQUE SPLITS...	1
CAUSIING Q SPLITS AT MID	1
CAUSING "Q" SPLITS AND	1
CAUSING 30% TORQUE SPLIT	1
CAUSING INTERMITTENT TORQUE	1
CAUSING MID RANGE Q SPLITS	1
CAUSING MID RANGE TQ SPLITS	1
CAUSING MID-RANGE TORQUE	1
CAUSING Q APLITS, MOTOR	1
CAUSING Q SPLIT	1
#2 SIDE DRIVING HIGH	1
CAUSING SPLITS, WON'T	1
CAUSING TORQUE	1
CAUSING TORQUE SPLIT	1
#1 ENGINE LOW 10% AT 50%	1
CAUSING TORQUE SPLITS 8-10%	1
CAUSING TORQUE SPLITS ABOVE	1
CAUSING TORQUE SPLITS BY	1
CAUSING TORQUE SPLITS ON	1
15-20% TORQUE SPLIT WITH	1
CHANGE DUE TO Q SPLITS	1
CHANGED AS A PRECAUTION	1
CHANGED AS A PRECAUTION DUE	1
CHANGED DUE TO MID-RANGE	1
CAUSED Q SPLITS. HIGH TIME	1
CHANGED FOR "Q" SPLIT	1
CHANGED FOR ERRACTIC	1
CHANGED FOR FLAT PITCH	1
CHANGED FOR MID-RANGE	1
CHANGED FOR TORQUE SPLIT	1
CAUSED Q SPLITS DURING	1
CHANGED FOR TORQUE SPLITS.	1
CHANGED IN CONJUNCTION WITH	1
CHANGED OUT FOR TORQUE	1
CHANGING AS TROUBLESHOOTING	1
COMPLETED DUE TO Q SPLIT	1
CAUSED Q SPLITS AND MADE	1
30% TORQUE SPLITS OBSERVED	1
CONSISTENT Q SPLIT	1
CONTROL BOX CASUSES Q	1
CAUSED Q SPLITS & NP	1
CONTROL BOX CAUSING TORQUE	1

CONTROL BOX REMOVED DUE TO	1
CONTROL BOX WOULD NOT HOLD	1
CORRODED, CAUSING Q SPLITS	1
CORROSION & TORQUE SPLITS	1
CREATED TORQUE SPLIT.	1
CREATED TORQUE SPLITS	1
CREATED TORQUE SPLITS AT	1
CREATED TORQUE SPLITS IN	1
CREATES 8-10% TQ SPLIT AT	1
CUASED Q SPLITS	1
CUASES TORQUE SPLITS.	1
CUASING Q SPLITS	1
CUASING Q SPLITS HI SIDE	1
DIVERGENT TORQUE SPLITS IN	1
DROOPING NR AND Q SPLITS	1
DROPPING NR AND Q SPLITS	1
ENGINE TORQUE	1
ENGINE TORQUE SPILT	1
ERRADIC OPERATION CAUSING	1
FAILED OPS DUE TO CHETING @	1
FAULTY TQ TRANSDUCER	1
FLAT PITCH Q SPLIT MORE	1
FLAT PITCH Q SPLITS	1
FLAT PITCH TORQUE SPLITS,	1
FOR TORQUE SPLITS	1
FOUND FAULTY DURING	1
FOUND TO CAUSE TORQUE	1
FOUND TORQUE SPILT #2 NG	1
FUEL CONTROL CAUSING TORQUE	1
FUEL CONTROL FOUND LEAKING	1
HIGH POWER Q SPLITS	1
HIGH POWER SETTING 5%	1
HIGH RANGE Q SPLITS	1
HIGH SIDE TORQUE SPLITS	1
INSTALLED DUE FLAT PITCH	1
INTER MITTENT TQ SPLITS	1
INTERAL LEAK, TORQUE	1
INTERMINITTIN FLUCTUATIONS	1
15% TORQUE SPLIT, REMOVED	1
INTERMITTANT TORQUE SPLITS.	1
INTERMITTENT Q SPLITS AT	1
CAUSED MINOR Q SPLITS AT	1
30% TORQUE SPLITS	1
INTERMITTENT TORQUE SPLITS.	1
INTERMITTENT TORRQUE SPLITS	1
INTERNAL LOCK NUT ON SET	1
LOW AND MIDRANGE Q-SPLITS	1

LOW ENGINE SPEED AND TORQUE	1
MGB IS 40 - 70% "Q" RANGE	1
MGT AND NG SPLITS. SUSPECT	1
MID AND HIGH RANGE Q	1
MID RANGE Q	1
MID RANGE Q SPLIT, FOUND #2	1
MID RANGE Q SPLITS	1
CAUSED #1 ENG ANTICIPATOR	1
MID RANGE Q-SLPITS	1
MID RANGE Q-SPLITS	1
MID RANGE RATCHETING CAUSES	1
MID RANGE TORQUE SPLIT	1
MID RANGE TORQUE SPLITS	1
MID RANGE TORQUE SPLITS.	1
MIDRANGE Q-SPILTS WITH OEI	1
MOTOR RACHETING CAUSING	1
MOTOR RATCHETS, CAUSES Q	1
NOT OPENING CAUSING Q	1
NP2 78% WHEN TESTED FOR	1
NR DROOPS/Q SPLIT ON DECK,	1
OCCOLATING FROM FULL OPEN	1
OPENED AT 110 PSI CAUSED	1
OSCILLATING CAUSING Q	1
PART OFF SUSPECT COMPONENT	1
PART REMOVED FOR TORQUE	1
PERFORMED DUE TO TORQUE	1
PLUNGER NOT MOVING, CAUSING	1
POSSIBLE CAUSE OF Q SPLIT	1
CAUSE OF TORQUE SPLITS	1
POSSIBLE CAUSE TORQUE	1
POSSIBLY CAUSING LOW END Q	1
PRODUCING TQ SPLITS.	1
PT GOV IS SUSPECTED TO BE	1
PT GOVENOR ARM CONTACTING	1
PT GOVERNOR SHOW TO MATCH Q	1
10% TORQUE SPLITS - TROUBLE	1
Q SPLIT #1 HIGH IN ALL	1
Q SPLIT #2 ENG Q LOW 20%	1
Q SPLIT AT GROUND IDLE (6%)	1
Q SPLIT IN FLIGHT, FOUND TO	1
Q SPLIT R1 LOOSE	1
Q SPLIT TROUBLESHOOTING	1
Q SPLIT.	1
Q SPLIT. #2Q WENT TO FULL	1
"CHANGED FOR TORQUE SPLITS"	1
Q SPLITS - #2 DROPPED TO	1
Q SPLITS - 7TO8% ON-DECK	1

Q SPLITS - FOUND MODULATOR	1
Q SPLITS #2 ENG	1
Q SPLITS #2 SLUGGISH TO	1
Q SPLITS @MAX CONTINOUS	1
Q SPLITS 15% FLAT PITCH	1
Q SPLITS 2-5% @ MID RANGE	1
Q SPLITS AND ENGINE IS HOT	1
CAUSE OF Q-SPLITS.	1
Q SPLITS AT FLAT PITCH.	1
Q SPLITS AT FLAT SPLIT	1
Q SPLITS AT HIGH RANGE	1
Q SPLITS AT HIGHER POWER	1
Q SPLITS AT MID TO HIGH	1
Q SPLITS FLUCTUATING	1
Q SPLITS IN ALL RANGES.	1
Q SPLITS IN MID RANGE	1
Q SPLITS IN MID-RANGE	1
Q SPLITS LOW POWER	1
Q SPLITS MID RANGE	1
Q SPLITS OF 15% WITH #2 LOW	1
Q SPLITS ON #1 + #2 ENG	1
Q SPLITS ON 6579,	1
CASUING TORQUE SPLITS 1	1
Q SPLITS ON DECK #1 ENG	1
Q SPLITS ON DECK 4-8%	1
Q SPLITS ON DECK 5%	1
Q SPLITS ON DECK FLAT	1
Q SPLITS TROUBLESHOOTING	1
Q SPLITS TRUBLEHOOTING	1
Q SPLITS, ANTICIPATOR MOTOR	1
Q SPLITS, FLUCTATION	1
Q SPLITS, FLUX	1
Q SPLITS, MODULATOR WOULD	1
Q SPLITS, NO SCHR	1
Q SPLITS, NOT CLOSING ALL	1
#1 ENG HIGH END Q-SPLITS	1
Q SPLITS. ANTICIPATOR BOX	1
Q SPLITS. MOTOR SIZED	1
Q SPLITS; FAILED TO FULLY	1
Q SPLITS; WOULD NOT OPEN	1
Q SPLITS'S RATHETING	1
Q SPLITS--TORQUE TRANSDUCER	1
Q WOULD NOT MATCH	1
Q'S WOULD NOT MATCH.	1
Q'S WOULDN'T MATCH AT MAX	1
QSPILTS	1
Q-SPLIT	1

Q-SPLIT 40-50 % MGB Q, #1	1
Q-SPLIT RATCHING MOTOR	1
QSPLIT TROUBLESHOOTING	1
#1 ENG "Q" 15-20% LOWER	1
Q-SPLITS - FROZEN	1
Q-SPLITS (OUT 0F CAL)	1
Q-SPLITS' 7-8% ON DECK.	1
QSPLITS AIRFLOW MODULATOR	1
Q-SPLITS DURING TEST FLIGHT	1
Q-SPLITS- LOW SIDE FAILURE.	1
QSPLITS ON DECK 4-8 %	1
Q-SPLITS ON DECK. NP'S	1
QSPLITS SEIZED.	1
Q-SPLITS TROUBLESHOOTING	1
Q-SPLITS, #1 ENG HIGH	1
Q-SPLITS, ALSO CAUSED ENG	1
QSPLITS.	1
3.2% HIGH ON BOTH SIDES	1
Q-SPLITS. ANTICIPATOR	1
R&R TO CORRECT TORQUE	1
R/R FOR FLAT PITCH Q SPLITS	1
R/R FOR TQ SPLITS	1
RATCHETING/CAUSES Q SPLITS.	1
READING WAS 10%-15% LESS	1
REMOCED FOR Q-SPLITS	1
REMOVD FOR TORQUE SPLITS	1
REMOVED - SUSPECT CAUSING Q	1
REMOVED AND REPLACED #1 Q	1
REMOVED AND REPLACED DUE TO	1
BOX REPLACED DUE TO TORQUE	1
REMOVED AND REPLACED FOR Q	1
REMOVED AND REPLACED W/RFI	1
REMOVED AND RPLACED W/RFI	1
REMOVED ANTICIPATOR CONTROL	1
BOX CAUSES TORQUE SPLITS.	1
REMOVED DUE TO 20% TORQUE	1
REMOVED DUE TO A 6% Q SPLIT	1
REMOVED DUE TO EXCESIVE,	1
REMOVED DUE TO FLAT PITCH	1
REMOVED DUE TO LAGGING	1
REMOVED DUE TO MODULATOR	1
25-30% TQ SPLIT #2 HIGH	1
REMOVED DUE TO Q SPLITS &	1
REMOVED DUE TO Q SPLITS AND	1
REMOVED DUE TO Q SPLITS AT	1
ANTICIPATOR MOTOR WILL NOT	1
REMOVED DUE TO Q SPLITS;	1

"Q" SPLITS-FOUND PT GOV	1
25% Q AT FLAT PITCH	1
REMOVED DUE TO TORQUESPLITS	1
15% TORQUE SPLIT IN FLIGHT	1
REMOVED FOR "Q" SPLIT	1
REMOVED FOR 20% Q-SPLITS #1	1
REMOVED FOR 6 PERCENT	1
REMOVED FOR ENGINE TORQUE	1
REMOVED FOR FLAT PITCH TQ	1
REMOVED FOR GOVNER DUE TO	1
REMOVED FOR MID-RANGE	1
REMOVED FOR POTENTIAL	1
REMOVED FOR Q SPILTS	1
15 - 18% TORQUE SPLIT #1	1
REMOVED FOR Q SPLIT &	1
10% TORQUE SPLIT, NP'S 95.5	1
REMOVED FOR Q SPLITS #2	1
REMOVED FOR Q SPLITS HIGH	1
REMOVED FOR Q SPLITS WOULD	1
REMOVED FOR Q SPLITS, WOULD	1
10% TORQUE SPLIT	1
REMOVED FOR Q SPLITS. IN	1
REMOVED FOR Q SPLITS;	1
REMOVED FOR Q-SPLIT	1
REMOVED FOR Q-SPLIT, MOTOR	1
REMOVED FOR Q-SPLITS	1
REMOVED FOR RE-OCCURING	1
REMOVED FOR SUSPECT	1
REMOVED FOR SUSPECT CAUSE	1
REMOVED FOR TORQ. SPLITS	1
REMOVED FOR TORQUE	1
REMOVED FOR TORQUE DISCREP	1
#2 ENGINE LOW TORQUE SPLIT	1
REMOVED FOR TORQUE SPLIT.	1
#1 ENGINE HAS LOW TORQUEW	1
#1 TQ TRANSDUCER SUSPECT	1
REMOVED FOR TOUBLESHOOTING	1
ANTICIPATOR MOTOR	1
#1 ENG LOW TQ 4% SPLIT ON	1
REMOVED FOR T-SHOOTING	1
REMOVED FOR T-SHOOTING OF	1
REMOVED FOR T-SHOOTING Q	1
REMOVED PT GOV. FOR TORQUE	1
REMOVED REPLACED DUE TO "Q"	1
REMOVED S/N 211 DURING	1
REMOVED SUSPECT FOR GROUND	1
ANTICIPATOR CONTROL BOX	1

REMOVED TO CORRECT "Q"	1
REMOVED TO TROUBLESHOOT Q	1
RE-OCCURING Q-SPLITS THAT	1
REPACLED FOR TORQUE SPLIT	1
REPLACE DUE TO Q SPLITS.	1
REPLACED #2 AIRFLOW	1
REPLACED ANTICIPATOR	1
REPLACED BECAUSE OF	1
REPLACED CONTROL BOX DUE TO	1
REPLACED DO TO Q-SPLITS.	1
REPLACED DUE TO "Q" SPLITS	1
REPLACED DUE TO 9% Q-SPLIT	1
REPLACED DUE TO MID-RANGE Q	1
REPLACED DUE TO Q SPLITS	1
10% Q-SPLITS ON DECK FOUND	1
REPLACED DUE TO Q SPLITS;	1
REPLACED DUE TO QSPLIT #1	1
ANTIC TORQUE SPLITS. UR#	1
#2 NP FLUCTUATES & Q SPLITS	1
REPLACED DUE TO TORQUE NOT	1
REPLACED DUE TO TORQUE SPLITS	1
REPLACED F0R TORQUE SPLITS	1
AIRFLOW MODULATOR WAS	1
REPLACED FOR "Q" SPLITS,	1
AIRCRAFT HAD TORQUE SPLITS	1
REPLACED FOR Q SPLITS AT	1
REPLACED FOR Q SPLITS.	1
REPLACED FOR Q-SPLITS	1
AIRCRAFT EXPERIENCING	1
10% Q SPLITS ANYTIME	1
20-25% TORQUE SPLIT IN THE	1
REPLACED IN ORDER TO	1
REPLACED PT GOVERNOR DUE TO	1
REPLACED Q-TRANSDUCER FOR	1
RPLACED FOR TORQUE SPLIT	1
STICKY MOTOR CAUSING TORQUE	1
SUSPECT ACTUATOR IS CAUSING	1
SUSPECT AS CAUSE OF	1
SUSPECT BOX CAUSING TORQUE	1
SUSPECT CAUSE OF Q SPLIT	1
SUSPECT CAUSE OF Q SPLITS.	1
103% NG AND TORQUE SPLITS	1
SUSPECT CAUSING OF TORQUE	1
10 - 15 % TQ SPLITS	1
SUSPECT COMPONENT IN TORQUE	1
SUSPECT CONTROL BOX CAUSING	1
SUSPECT FOR TQ SPLITS.	1

SUSPECT FUEL CONTROL IS	1
SUSPECT FUEL PUMP IS	1
SUSPECT IN HIGH SCALE	1
SUSPECT POWER TURBINE	1
SUSPECT STICKY AIRFLOW	1
SUSPECT TORQUE SPLIT	1
SUSPECT TORQUE SPLITS	1
SUSPECTED BAD CAUSING Q	1
SUSPECTED CAUSE OF	1
20% TORQUE SPLITS @ FLAT	1
SUSPECTED FOR CAUSING	1
SUSPECTED OF CAUSING TORQUE	1
SUSPECTED TO BE CAUSE OF	1
SUSPECTED TO BE CAUSING Q	1
ACTUATOR SUSPECTED OF	1
SWAPPED OUT FOR Q SPLITS	1
TBLSHOOT TQ SPLITS	1
TBLSHOOTING TQ SPLIT	1
TORCH SPLIT	1
ACTUATOR OSCILATING WITH	1
TORQ	1
ACFT HAD FLAT PITCH TORQUE	1
TORQ. SPLITS	1
TORQEW SPLIT T-SHOOTING.	1
TORQUE MATCHING PROBLEM.	1
TORQUE PROBLEMS	1
TORQUE SLIPTS AT MID RANGE	1
TORQUE SPILT	1
TORQUE SPITS	1
#2 ENGINE HAD A 4-67 DEGREE	1
TORQUE SPLIT #1 ENG SUSPECT	1
TORQUE SPLIT AND THEN NO	1
TORQUE SPLIT BETWEEN #1 ENG	1
TORQUE SPLIT DURING GROUND	1
TORQUE SPLIT PROBLEMS	1
TORQUE SPLIT TO ZERO	1
20% TORQUE SPLIT ON DECK	1
TORQUE SPLIT;	1
"CAUSED TORQUE SPLITS"	1
TORQUE SPLITS - #1 AIRFLOW	1
TORQUE SPLITS - AIRFLOW	1
TORQUE SPLITS - POWER	1
TORQUE SPLITS #1 ENGINE -	1
TORQUE SPLITS #1 HIGH	1
TORQUE SPLITS #1 LOW	1
TORQUE SPLITS #1 SIDE LOW.	1
TORQUE SPLITS #2 DRIVES	1

TORQUE SPLITS #2 ENG., 5-7%	1
TORQUE SPLITS- #2 Q	1
TORQUE SPLITS 10-15% HIGH	1
90% Q SPLITS, MGT SPIKE	1
TORQUE SPLITS 30% AT 20 FT	1
TORQUE SPLITS AIRFLOW MOD	1
TORQUE SPLITS AND FAILED	1
TORQUE SPLITS AND LAGGING	1
TORQUE SPLITS AND WILL NOT	1
TORQUE SPLITS AND WORKING	1
TORQUE SPLITS AT 40 TO 50 %	1
8% TORQUE SPLITS.	1
8% TORQUE SPLIT IN THE	1
TORQUE SPLITS AT HIGH	1
TORQUE SPLITS AT HIGH POWER	1
TORQUE SPLITS AT LOW POWER	1
7% TORQUE SPLITS ON DECK #1	1
TORQUE SPLITS BETWEEN #1	1
TORQUE SPLITS CAUSE BY	1
TORQUE SPLITS CAUSES HIGH	1
TORQUE SPLITS ERRONEOUS	1
TORQUE SPLITS FOUND	1
TORQUE SPLITS IN 20-30%	1
TORQUE SPLITS IN FWD FLIGHT	1
TORQUE SPLITS IN HIGH AND	1
TORQUE SPLITS IN MID POWER	1
6% TQ SPLIT	1
TORQUE SPLITS IN MID RANGE,	1
TORQUE SPLITS INDICATING	1
TORQUE SPLITS LEAD AND LAG	1
TORQUE SPLITS MOTOR	1
TORQUE SPLITS OF 30%(AFTER	1
TORQUE SPLITS ON #1 ENG	1
TORQUE SPLITS ON DECK	1
1.5% TORQUE SPLIT	1
TORQUE SPLITS REMOVED FOR	1
TORQUE SPLITS TROUBLE	1
TORQUE SPLITS WITH ANTI-ICE	1
TORQUE SPLITS WITH NUMBER 2	1
TORQUE SPLITS WITH OEI	1
TORQUE SPLITS WOULD SHOW UP	1
TORQUE SPLITS(TORQUE WOULD	1
TORQUE SPLITS, #1 ENGINE	1
TORQUE SPLITS, #2 ENGINE	1
TORQUE SPLITS, AIRFLOW	1
TORQUE SPLITS, CAUSIING ENG	1
TORQUE SPLITS, COULD NOT	1

TORQUE SPLITS, FOUND #2 ENG	1
TORQUE SPLITS, FOUND NOT	1
TORQUE SPLITS, LOW Q ON	1
TORQUE SPLITS, MOTOR	1
TORQUE SPLITS, NP WOULD	1
TORQUE SPLITS, OPERATING	1
TORQUE SPLITS, SLOW TO	1
TORQUE SPLITS, THEN LOSS OF	1
TORQUE SPLITS, TORQUE WILL	1
TORQUE SPLITS, WOULD NOT	1
20% TO SPLIT IN MIDRANGE.	1
TORQUE SPLITS. 2% IN	1
TORQUE SPLITS. - ANTIC	1
TORQUE SPLITS. #2 ADJ SCREW	1
TORQUE SPLITS. UNABLE TO	1
TORQUE SPLITS/BAD	1
TORQUE SPLITS/ENGINE	1
TORQUE SPLITS; WOULD NOT	1
TORQUES NOT HOLDING.	1
TORQUES SPLITS	1
TORQUES WOULD NOT HOLD	1
TORQUES WOULD NOT MATCH	1
TORQUESPLIT BELOW 50% MGB	1
6% TORQUE SPLIT/WENT AWAY	1
TORWUE SPLITS	1
TQ SPILITS MID RANGE	1
TQ SPLIT	1
TQ SPLIT: #1 15-20% HIGHER	1
"Q" SPLITS; COULD NOT	1
TQ SPLITS 20% MIDRANGE	1
TQ SPLITS AT FLAT PATCH	1
TQ SPLITS AT MIDRANGE	1
TQ SPLITS INHOVER	1
TQ SPLITS.	1
TQ. SPLITS.	1
TRANSCUCER INDICATES	1
TRANSDUCER WAS CAUSING	1
TROBLESHOOTING FOR Q	1
TROBLESHOOTING TORQUE	1
TROUBLE SHOOTING "Q" SPLITS	1
50% TO 70% TORQUE SPLITS.	1
TROUBLESHOOT A TORQUE	1
TROUBLESHOOT Q SPLITS	1
TROUBLESHOOT Q-SPLIT	1
TROUBLESHOOTING (TORQUE	1
TROUBLESHOOTING FOR	1
TROUBLESHOOTING FOR TORQUE	1

TROUBLESHOOTING LOW POWER.	1
10% TORQUE SPLITS AT MIT	1
TROUBLESHOOTING Q SPLITS #2	1
TROUBLESHOOTING Q SPLITS.	1
20% Q SPLITS WITH FLAT	1
TROUBLESHOOTING TQ SPLITS	1
TROUBLESHOT SYSTEM	1
TROUBLSHOOTING TORQUE	1
TROUBSHOOTING Q SPLIT	1
T-SHOOTING FOR Q SPLITS	1
UNABLE TO BALANCE 'Q'X	1
3-7 PERCENT TORQUE SPLITS.	1
UNIT CAUSES TORQUE SPLITS	1
WATER FROM OVERHEAD ENTERED	1
WHILE TROUBLESHOOTING	1
WILL NOT FULLY OPEN, CAUSES	1
WON'T ADJUST - TORQUE SPLIT	1
WOULD NOT ACTUATE, CAUSING	1
Grand Total	1107

Appendix D: List and Count of Individual Malfunctions

	MALFUNCTION (SPECIFIC REASON FOR REMOVAL)	# of instances
1	TORQUE SPLITS	1107
2	FAILED POWER ASSURANCE	264
3	TORQUE OSCILLATIONS/FLUCTUATIONS	159
4	UNABLE TO CALIBRATE TRANSDUCER	146
5	BLUE GREASE WASHOUT	145
6	WOULD NOT OPEN	143
7	ERRONEOUS TORQUE INDICATIONS	130
8	TORQUE INDICATION ZERO	106
9	COMPRESSOR STALLS	102
10	TORQUE INDICATION FULL SCALE	96
11	ACTUATOR RATCHETING	80
12	ENGINE OSCILLATIONS	74
13	FUEL LEAK	66
14	REPAIR OR UPGRADE	64
15	NONE	56
16	CHIPS	54
17	UNABLE TO ADJUST ANTICIPATOR	49
18	UNABLE TO ADJUST NP	48
19	VIBES	44
20	#19 BEARING CHANGE	41
21	HIGH SIDE FAILURE	40
22	FOD COMPRESSOR	37
23	FAILED OPS CHECK	37
24	CONTROL BOX INOP	34
25	POT LOOSE	33
26	UNABLE TO PRIME	31
27	FOD	30
28	TORQUE SPIKES	26
29	SPLINE WORN	26
30	MOTOR INOP	26
31	FROZEN MOTOR	26
32	MOD FAILED OPS CHECK	23
33	LOW SIDE FAILURE	23
34	UNABLE TO TOP ENGINE	22
35	AIR LEAK - TEMP COMP	21
36	AIR LEAK - FUEL CONTROL	21
37	FAULTY ADJ SCREW	21
38	TORQUE DROPPED OFF LINE	20
39	SLOW ACCELERATION	20
40	FAULTY TRANSDUCER	20
41	UNABLE TO ADJUST GROUND IDLE	19
42	FAILED IBPT INSPECTION	19
43	CORROSION	19

44	NO START	18
45	MGT HIGH	18
46	WILL NOT HOLD SETTINGS	17
47	STICKING MODULATOR	17
48	NO TORQUE INDICATION	17
49	ACTUATOR WOULD NOT ROTATE	17
50	TCTO T73110	16
51	FUEL CONTROL LEAK	16
52	ENGINE SURGES	16
53	UNABLE TO ADJUST MOD	15
54	TORQUE LOW	14
55	NP HIGH	14
56	MOD RATCHETING	14
57	HOT START	14
58	FAILED VIBRATION ANALYSIS	14
59	TORQUE LAGS	13
60	FAULTY SPRING	13
61	FAULTY MOD	13
62	ENGINE LAGS	13
63	NO ACCELERATION	12
64	NP LOW	11
65	FUEL LEAK FROM DRAIN	11
66	UNKNOWN	10
67	AXIAL COMPRESSOR BLADE DAMAGE	10
68	UNABLE TO ADJUST NG	10
69	TORQUE PROBLEMS	10
70	MISSING DATA PLATE	10
71	LOW FUEL PRESSURE	10
72	FAILED LEAK CHECK	10
73	UNABLE TO ADJUST POTS	9
74	TCTO 973100	9
75	SHROUD REPLACEMENT	9
76	OIL LEAK - OUTPUT SEAL	9
77	OIL LEAK	9
78	NP UNSTABLE	9
79	MOD STICKING	9
80	MOD ERRATIC OPS	9
81	HYD FLUID CONTAMINATION	9
82	ENGINE RESPONSE SLOW	9
83	SUSPECT BEARING	8
84	SMOKE	8
85	OIL LEAK - STARTER	8
86	NG LOW	8
87	MOD LEAK	8
88	WOULD NOT CLOSE	7
89	UNABLE TO SET HIGH STOP	7
90	ENGINE FLUCTUATIONS	7

91	TCTO	7
92	SPLINE DAMAGE	7
93	NR DROOP	7
94	NP OVERSPEED	7
95	BLOW BY	7
96	UNABLE TO ADJUST NULL	6
97	ANT MOTOR INOP	6
98	UNABLE TO ADJUST ACTUATOR	6
99	SPAN ADJUSTMENT INOP	6
100	PTG BINDING	6
101	OIL LEAK - AGB	6
102	ENGINE SPOOLED DOWN	6
103	NP FLUCTUATIONS	6
104	ENGINE DROPPED OFF LINE	6
105	FUEL PUMP DRIVE SPLINE WORN	6
106	BINDING	6
107	UNABLE TO CLOCK	5
108	TORQUE LOSS	5
109	DROPPED TRANSDUCER	5
110	POWER LOSS	5
111	BYPASS OF BLEED AIR	5
112	NG UNSTABLE	5
113	ENGINE FAILURE	5
114	COMPRESSOR DAMAGE	5
115	FAULTY O-RING	5
116	FAULTY FUEL PUMP	5
117	FAULTY ANTICIPATOR	5
118	UNABLE TO ADJUST	4
119	TORQUE HIGH	4
120	STARTER GEAR SPLINES WORN	4
121	ENGINE SLOW TO RESPOND	4
122	EXCESSIVE OIL CONSUMPTION	4
123	PT WHEEL BLADE OUT OF LIMITS	4
124	OIL LEAK - TORQUEMETER HOUSING	4
125	NP OSCILLATIONS	4
126	CRACKED HOUSING	4
127	ENGINE OVERTEMP	4
128	MOD FLUCTUATES	4
129	MGT SPIKE ON START	4
130	LINKAGE WORN	4
131	LEVER ROUGH	4
132	JAM NUT INOP	4
133	GT 326	4
134	FAULTY PTG	4
135	FUEL CONTROL SPLINE DAMAGED	4
136	ENGINE PARAMETERS DROPPED	3
137	UNABLE TO SET STOPS	3

138	ERRATIC TORQUE	3
139	ANTICIPATOR MOTOR FROZEN	3
140	UNABLE TO ADJUST HIGH STOP	3
141	ACTUATOR INOP	3
142	EXCESS GREASE	3
143	TORQUE OUT OF LIMITS	3
144	FLAME OUT	3
145	ACTUATOR OVERROTATING	3
146	ACTUATOR SLOW TO RESPOND	3
147	THROTTLE ARM STIFF	3
148	ENGINE SHUT DOWN IN FLT	3
149	FAULTY BUSHING	3
150	SHAFT FROZEN	3
151	AIR LEAK - PTG	3
152	PTG FAILURE	3
153	BELLOWS FROZEN	3
154	2 AND 3 BEARING BLOCKAGE	3
155	OVERSPEED	3
156	ELBOW FITTING THREADS DAMAGED	3
157	OIL CONTAMINATION	3
158	CRACKED INLET HOUSING	3
159	ENGINE OVERSPEED	3
160	NG ERRATIC	3
161	MOD CYCLING	3
162	MGT RESERVE LOW	3
163	MGT AND NG HIGH	3
164	FAULTY POT	3
165	ARM CONTACTS HOUSING	3
166	GT-328	3
167	FUEL PUMP/CONTROL BINDING	3
168	FAULTY TEMP COMP	2
169	WOULD NOT ADVANCE PAST FLIGHT IDLE	2
170	ANTICIPATOR MOTOR WOULD NOT RESPOND	2
171	FUEL PUMP SPLINES DAMAGED	2
172	BENT PINS	2
173	FAULTY THERMOCOUPLE	2
174	UNABLE TO ADJUST O/S LIMITER	2
175	GASKET BLOWN	2
176	FAUTLY GOVERNOR SPRING	2
177	TRANSDUCER STICKING	2
178	TRANSDUCER LEAKING OIL	2
179	ARM STICKING	2
180	TRANSDUCER LEAK	2
181	HIGH 2 AND 3 BEARING PRESSURE	2
182	TORQUE UNSTABLE	2
183	CONNECTOR DAMAGE	2
184	HOLDS PRESSURE	2

185	FOD AXAIL	2
186	FAILED THERMOCOUPLE CHECK	2
187	TEMP COMP STICKY	2
188	ARM ROUGH	2
189	ROUGH BEARINGS	2
190	PTG FAILURE IN FLIGHT	2
191	FUEL CONTROL BINDING	2
192	CANNON PLUG DAMAGED	2
193	POT DAMAGED	2
194	OVERTORQUE	2
195	OVERTEMP	2
196	OIL LEAK - PLENUM	2
197	FUEL CONTROL/PUMP CONTAIMINATION	2
198	OIL LEAK - DIFFUSER	2
199	LOCKING TANG DAMAGED	2
200	LOW FUEL FLOW	2
201	EXCESSIVE STARTER SPLINE WEAR	2
202	ENGINE DIVERGENCE	2
203	O/S LIMITER TRIPS EARLY	2
204	O/S LIMIT SET TOO HIGH	2
205	ENGINE DOES NOT SPOOL DOWN	2
206	CANNON PLUG WOULD NOT LOCK	2
207	FAILED TEST CELL CHECK FUEL CONTROL	2
208	FUEL PUMP FITTING STRIPPED	2
209	NO FUEL FLOW	2
210	NO CUSHION ON CUTOFF	2
211	MGT FLUCTUATIONS	2
212	NG SPLITS	2
213	NG SECTION SEIZED	2
214	MODULATOR RING SHAFT EXCESS PLAY	2
215	FUEL PUMP DROPPED	2
216	FAILED 2 AND 3 BEARING INSPECTION	2
217	COMPRESSOR BINDING	2
218	MOD OSCILLATING	2
219	FAILED THERMOCOUPLE TEST	2
220	ZONE B EXCEEDANCE	1
221	FAILED ANTICIPATOR SYSTEM	1
222	ENGINE ERRATIC	1
223	BELLOWS INOPERATIVE	1
224	MISSING PLUG IN FUEL PUMP TAKEOFF GEAR	1
225	CONTROL PUMP BINDING	1
226	MOD OPENS EARLY	1
227	DRIFT	1
228	MGT UNSTABLE DURING START	1
229	MGT SPLIT	1
230	FAULTY O-RING AT T-FITTING	1
231	BEARING ROUGH	1

232	NF FLUCTUATIONS	1
233	NG DROPS	1
234	NG DROPS OFFLINE	1
235	FUEL PRESSURE FLUCTUATES	1
236	NG FLUCTUATION	1
237	NG HIGH	1
238	CRACKED SPLINE	1
239	NG OVERSPEED	1
240	MGT LOW NG HIGH	1
241	MGT LOW	1
242	FAILED TEST CELL O/S LIMITIER	1
243	NI DETENT	1
244	FAULTY JAM NUT	1
245	NO ACMS CARD SUBMITTED	1
246	NO BLUE GREASE	1
247	BROKEN BOLT	1
248	NO ENGINE RESPONSE	1
249	MGT ERRATIC	1
250	NO NR DROP	1
251	NO POWER	1
252	BRACKET HOLE DAMAGED	1
253	MGT DISCREPANCY	1
254	BIMETALLIC STACK WOULD NOT EXTEND	1
255	NP ACCELERATED	1
256	FACE PLATE IS BROKE	1
257	COMBUSTION DRAIN LINE LEAK	1
258	FUEL LEAK - AGB	1
259	FAULTY FUEL SCHEDULING	1
260	METERING PIN FELL OUT	1
261	METAL FOUND ON ENGINE DECK	1
262	NPS DROP WHEN HEATER ON	1
263	EXCESSIVE THROTTLE MOVEMENT	1
264	NR LOW	1
265	O/S LIMIITER OUT OF LIMTIS	1
266	MAX STOP SCREW LOOSE	1
267	O/S LIMITER FAULTY	1
268	O/S LIMITER OUT OF LIMITS	1
269	LOW SURGE/STALL MARGIN	1
270	OIL CONSUMPTION OUT OF LIMITS	1
271	FAILED BENCH TEST	1
272	LOW STOP RUBBING ON PTG	1
273	OIL LEAK - 1 AND 2 SEAL	1
274	OIL LEAK - 1 BEARING	1
275	OIL LEAK - 3 SEAL	1
276	BENT CONNECTOR	1
277	DRIVE GEAR SPLINE OUT OF LIMITS	1
278	OIL LEAK - GARLOCK SEAL	1

279	FAULTY OUTPUT SEAL HOUSING O-RING	1
280	OIL LEAK - OVERSPEED LIMITER	1
281	LEVER TIGHT	1
282	ADJUSTMENT SCREWS STRIPPED	1
283	FAULTY FUEL PUMP MOUNT STUD	1
284	OIL PUMP AXIAL OUT OF LIMITS 97216	1
285	OIL STARVATION	1
286	OIL STARVATION AND ENGINE SEIZURE	1
287	OUT OF LIMITS	1
288	OUT OF LIMITS AS PER STEP 2D3	1
289	OUTPUT SEAL HOUSING DAMAGED	1
290	OUTPUT SHAFT DAMAGED	1
291	FAULTY STARTER/GENERATOR SPLINES	1
292	OVERSPEED FAILURE	1
293	OVERSPEED LIMITER BORE DAMAGED	1
294	LEVER STEP	1
295	OVERTEMP INDICATION	1
296	FAULTY OVERSPEED CAM	1
297	PER ARSC	1
298	PER CWO FITZPATRICK	1
299	PLASTIC SPLINE MELTED	1
300	JP-8	1
301	POT INOP	1
302	ARM STIFF	1
303	POT STICKS	1
304	POTS ERRATIC	1
305	POWER LAG	1
306	FUEL PUMP MATING SURFACE CRACKED	1
307	BYPASS PORT CRACKED	1
308	PT WHEEL DAMAGED	1
309	PT WHEEL HAS BLADE MISSING PARTS	1
310	PTG ARM ROUGH	1
311	FAULTY ENGINE START	1
312	INTERNAL TORQUEMETER FAILURE	1
313	PTG FAILURE	1
314	INLET FITTING STRIPPED	1
315	PTG SEIZES	1
316	PTG SHAFT BINDING	1
317	PTG TEE FITTING LOOSE	1
318	RECALLED	1
319	FROZEN CAM	1
320	REPLACED INPUT SEAL	1
321	ROUGH ACTUATION	1
322	INCORRECT INSTALLATION	1
323	ROUGH POINTER BEARING	1
324	ROUGH SHAFT	1
325	RUBBER PLUG ROUND IN AGB SPLINE	1

326	SEAL FAILURE	1
327	SEND FOUND BETWEEN ASSEMBLIES	1
328	SET SCREW FAULTY	1
329	SHAFT BEARING CONTAIMINATED	1
330	SHAFT BEARING ROUGH	1
331	FP EXCEEDANCE	1
332	SHAFT PLAY	1
333	SHAFT WOBLE	1
334	SHORT	1
335	IMPENDING BYPASS	1
336	SLOPE TOO STEEP	1
337	BLEED PORT LEAK	1
338	SLOW START	1
339	SLUGGISH MOVEMENT	1
340	ENGINE OIL LEAK - ANT ACTUATOR	1
341	SNAP RING ON AGB	1
342	EXCESS OIL FROM TAILPIPE VENT TUBE	1
343	SPLINE BENT	1
344	FAULTY CENTRIFUGAL IMPELLER	1
345	SPLINE EXESSIVE PLAY	1
346	SPLINE MELTED	1
347	SPLINE SHAFT RATCHETING	1
348	BEARING RATCHETING	1
349	SPLINE WOULD NOT SPIN	1
350	STARTER GEAR REPLACEMENT	1
351	FOOT DAMAGED	1
352	STARTER TIME OUT OF LIMITS	1
353	STATIC	1
354	STATOR SECTION SEIZED	1
355	BUSHING WORN	1
356	STRUT CLOGGED	1
357	STUD STRIPPED	1
358	ACCELERATION UNCONTROLLED	1
359	SWIVEL ARM TIGHT	1
360	ARM RATCHETING	1
361	TCTO	1
362	TCTO 972130	1
363	TCTO 97216	1
364	TCTO 973090	1
365	DROPPED TEMP COMP	1
366	CAM STIFF	1
367	TEMP COMP HOUSING CRACKED	1
368	TEMP COMP SEIZED	1
369	IDLE DETENT STICKING	1
370	FAILED TEST CELL PTG	1
371	THROTTLE SHAFT PIN LOOSE	1
372	BLEED AIR INOPERATIVE	1

373	TORQUE ERRATIC	1
374	FAULTY BEARINGS	1
375	BAD RECEPTICAL	1
376	FLUCTUATING NG	1
377	HOLE BURNED IN COMBUSTION LINER	1
378	DROPPED FUEL CONTROL	1
379	COMBUSTER T-STRIP DEGRADED	1
380	ABNORMAL NOISES	1
381	FLEX COUPLING SEPARATING	1
382	DRAIN LINE LEAK	1
383	BAD RHEOSTAT	1
384	ANTICIPATOR SCREW THREADS STRIPPED	1
385	HIGH SIDE STOP BOLT STRIPPED	1
386	FUEL PUMP NOT PUMPING	1
387	FUEL PUMP OVERBOARD DRAIN DUMPING FUEL	1
388	GP SHROUD REPLACEMENT	1
389	BLEED AIR GASKET BLOWN	1
390	FIRE LIGHT	1
391	FILTER DAMAGE	1
392	UNABLE TO ADJUST FUEL PUMP	1
393	BLOWING OIL	1
394	GASKET WORN	1
395	AIRFLOW MOD OSCILLATONS	1
396	DOME WILL NOT ADJUST	1
397	FAULTY TRIP LEVER	1
398	ENGINEERING DISPOSITION	1
399	UNABLE TO ADJUST NVG	1
400	GASKET BROKEN	1
401	UNABLE TO ADJUST OIL PRESS	1
402	DROPPED PTG	1
403	UNABLE TO ADJUST TORQUE	1
404	UNABLE TO ARM OEI	1
405	ACCELERATION FAULTY	1
406	BLOWN FUSE	1
407	DATA BASE UPDATE	1
408	UNABLE TO RIG THROTTLE	1
409	ENGINE RUNAWAY	1
410	FUEL PUMP SEAL FAILURE	1
411	UNABLE TO SHUT DOWN	1
412	FUEL PUMP STUD STRIPPED	1
413	UNCONTROLLABLE STARTS	1
414	CRACKED STOP SCREW HOUSING	1
415	UNUSUAL HUMM	1
416	VENT COVER CRACKED	1
417	FUEL PUMP STUD LOOSE	1
418	VSI FLICKERING	1
419	WEIGHTS STICKY	1

420	BROKEN BOLT COMBUSTION CAN	1
421	WORN BUSHINGS	1
422	FUEL PUMP SHAFT WORN	1
423	FUEL PUMP SHAFT ROUGH	1
424	ACTUATOR ARM BINDING	1
425	ZERO TORQUE	1
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Vita

Commander Donna L. Cottrell graduated from Ohio University in 1982 with a Bachelor of Science degree in Education. She enlisted in the Coast Guard in 1984 where she served as an Avionics Technician at Coast Guard Air Station Houston before being selected for Officer Candidate School.

Commander Cottrell received her commission in 1987 after which she served aboard the Coast Guard Cutter Steadfast as a Deck Watch Officer until 1989. After graduating from Naval Flight Training in 1991, she was assigned to Coast Guard Air Station Chicago where she flew the HH-65A Dolphin helicopter and served as Public Works and Administration Officer. In February of 1995, she was transferred to Naval Air Station Whiting Field where she served as a helicopter flight instructor in the TH-57.

Following her tour as flight instructor, Commander Cottrell transferred to Coast Guard Group-Air Station Atlantic City. There she flew the HH-65A and served as Administration Officer and Air Operations Officer. As Air Operations Officer, she coordinated the unit's transition to Night Vision Goggle (NVG) level III which involved NVG use in approaches to the water and over-water hovers. She also coordinated the unit's transition to the HH-65B and served as Instructor Pilot on both the A and B model Dolphins.

In August of 2002, Commander Cottrell entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, she will be assigned as Chief of the Information Systems Division at the Coast Guard's Aircraft Repair and Supply Center in North Carolina.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
March-2004	**Master's Thesis**	March 2003 – March 2004

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
AN ANALYSIS OF COAST GUARD HH-65 ENGINE RELIABILITY: A COMPARISON OF MALFUNCTIONS TO COMPONENT REMOVALS	**5b. GRANT NUMBER**
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Cottrell, Donna L. Commander, U. S. Coast Guard Coast Guard Office of Aviation Engineering	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 P Street, Building 640 WPAFB OH 45433-7765	AFIT/GIR/ENC/04-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
U. S. Coast Guard **Commandant (G-SEA)** **CDR Mike Hargadon** **2100 Second Street** **Washington, DC 20593**	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Coast Guard HH-65 helicopter experienced 31 in-flight loss of power incidents during FY 2003 and 21 during the first two months of FY 2003. Concurrent with this apparent decrease in reliability, the Coast Guard seeks ways to expand the HH-65's Airborne Use of Force capabilities as a result of the September 11th, 2001 terrorists' attacks.

This study is an exploratory, empirical analysis of engine and airframe component replacements as related to engine mishaps and reliability in the HH-65. We use contingency table analysis, ordinary least squares regression, and logistic regression to examine the mishap history and component replacement history of ten different HH-65 components from 1997 through March of 2003. Additionally, we examine the literature to determine the factors impeding improvements to the HH-65 powerplant.

This study reveals three critical issues associated with the HH-65 powerplant, namely, lack of power reserve associated with the LTS-101-750, poor reliability associated with the fuel-control system, and excessive trouble removals due to excessive time between scheduled overhaul times. Moreover, we find lack of funding and political pressure forcing the Coast Guard toward a less than optimum fix that could adversely affect overall mission effectiveness and Homeland Security.

15. SUBJECT TERMS
Coast Guard aircraft, helicopter engines, reliability, regression analysis, contingency table analysis, helicopter fuel control

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Dr. Edward White, III (ENC)
REPORT	**ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU	116	937-255-3636 ext 4540