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H-53E Super Stallion/Sea Dragon Auxiliary Power Plant Power Survey

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To the Graduate Council:

I am submitting herewith a thesis written by Patrick Joseph Twomey entitled "H-53E Super Stallion/Sea Dragon Auxiliary Power Plant Power Survey." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Robert B. Richards, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Paul Solies, Dr. Ted Paludan

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Acceptance for the Council:

Anne Mayhew
Vice Chancellor and Dean of Graduate Studies

(Original signatures are on file with official student records.)

H-53E SUPER STALLION/SEA DRAGON AUXILIARY POWER PLANT POWER SURVEY

A Thesis
Presented for the Master of Science
Degree
The University of Tennessee, Knoxville

Patrick Joseph Twomey
May 2004

The ground test results contained within this thesis were obtained during United States Department of Defense sponsored Naval Air Systems Command projects conducted by the Naval Air Warfare Center Aircraft Division, Patuxent River, MD. The discussion of the data, conclusions and recommendations presented are the opinions of the author and should not be construed as an official position of the United States Department of Defense, the Naval Air Systems Command, or the Naval Air Warfare Center Aircraft Division, Patuxent River, MD.

DEDICATION

I would like to thank my major professor, Doc Richards, for his patience and guidance. Additionally, I am indebted to my wife, Gina, for her support and motivation in bringing this work to a close.

ACKNOWLEDGMENTS

This project would not have been possible without the tireless efforts of Mr. Bill Powell. His enthusiasm and insight were essential in the execution of the test program.

ABSTRACT

This research has provided possible explanations to failures experienced in the P-7-2 Auxiliary Power Plant reduction gearbox as installed on the CH-53E Super Stallion and MH-53E Sea Dragon helicopters. Ground testing with the rotors static was conducted during two separate phases from March 1995 to December 1995. Reduction gearbox loading was measured, resulting in the identification of several detrimental over- and transient loads. Loading reduction techniques are investigated, discussed, and/or evaluated for U.S. Navy and U.S. Marine Corps fleet introduction viability.

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LIST OF ABBREVIATIONS

AC	Alternating current
AFCS	Automatic Flight Control System
AGB	Accessory gearbox
AMCM	Airborne Mine Countermeasures
APP	Auxiliary Power Plant
BuNo	Bureau Number
DC	Direct current
EGT	Exhaust gas temperature
FAS	Force Augmentation System
HUMS	Health and Usage Monitoring System
HX-21	Air Test and Evaluation Squadron 21
K	1,000
K_q	Torque-to-SHP constant
MGB	Main gearbox
MMT	Minimum measurable threshold
MON	Monitor
NAMTRAGRU	Naval Air Maintenance Training Group
NATOPS	Naval Air Training Operating and Procedures Standardization program
NAVAIR	Naval Air Systems Command
NAWCAD	Naval Air Warfare Center, Aircraft Division
N_d	APP driveshaft RPM
N_g	Compressor turbine rotational speed
N_r	Main rotor rotational speed
NRWATS	Naval Rotary Wing Aircraft Test Squadron
PRI	Primary
pph	Pounds per hour
psi	Pounds per square inch
Q_d	APP driveshaft torque
RECT	Rectifier
RPM	Revolutions per minute
SHP	Shaft horsepower
T_5	Turbine outlet temperature
USMC	United States Marine Corps
USN	United States Navy

DEFINITION OF TERMS

Back cone angle: the angle of a cone whose elements are tangent to a sphere containing a trace of the pitch circle

Bevel gear: an arrangement of bevel wheels for the transmission of motion from one shaft to another on intersecting axes

Hypoid bevel gear: a bevel gear with the axes of the driving and driven shafts at right angles, but not in the same plane which causes some sliding action between the teeth.

Pitch angle: the angle between the axis of a bevel gear and the pitch cone generator, being the complement of the back cone angle

Pitch cones: the contacting cones of a bevel gear on which the normal pressure angles are equal; they are coaxial with the rotation of the gears

Pitch curves: the intersection of the tooth surfaces in the pitch cone

Reference cylinder: in helical and spur gears, the right circular cylinder on which the normal pressure angle has a specified standard value

Spiral angle: the angle between the pitch cone generator of a bevel gear and the tangent to the tooth trace at the point. The angle is positive for a right-hand gear.

Spiral bevel crown gear: a gear whose pitch curves are inclined to the pitch element at the spiral angle and are usually circular

Straight bevel crown gear: a gear whose pitch curves are straight lines, intersecting at the apex. The spiral angle at any cone distance is zero.

Tooth trace: the line of intersection of the tooth flank with the reference cylinder or pitch cone

Tooth flank: that portion of a tooth surface which lies within the working depth

Zerol® bevel gear: a spiral bevel gear with curved teeth and having a zero degree mean spiral angle.

(Sources: G.H.F. Naylor, *Dictionary of Mechanical Engineering, 4th Edition*, Butterworth-Heihemann, Oxford, and the Society of Automotive Engineers, Warrendale, PA, 1996. Philippine Agricultural Engineering Standard PAES 308: 2001, *Engineering Materials – Straight Bevel Gears for Agricultural Machines – Specifications and Applications*, Philippine Agricultural Engineering Division, 2001.)

SECTION I

INTRODUCTION

1.1 BACKGROUND.

The CH-53E Super Stallion helicopter and its Airborne Mine Countermeasures (AMCM) derivative, the MH-53E Sea Dragon, pictured in figures 1 and 2 respectively, are both equipped with the P-7-2 gas turbine auxiliary power plant (APP) (Jane's, 1997; DOTE, 1995). During the early to mid '90s, United States Marine Corps (USMC) and United States Navy (USN) units employing these helicopters experienced a number of failures occurring in the APP planetary reduction drive assembly, the assembly which transfers APP power to the accessory gearbox (AGB).

The Naval Air Systems Command (NAVAIR) tasked the Naval Rotary Wing Aircraft Test Squadron (NRWATS), through the Naval Air Warfare Center, Aircraft Division (NAWCAD), to quantify the loads applied to the APP during the pre-rotor engagement ground checks in an attempt to define quantitatively the rotors-static operating conditions. Once quantified, causal factors were to be determined and potential corrective measures suggested, where possible.

First, a study was made of the differing gear failure modes. Second, an in-depth analysis of the aircraft was completed in order to define the test scope and methodology. Next,

Figure 1
CH-53E Super Stallion
(Naval Rotary Wing Aircraft Test Squadron Internet Web Site Photo Archives)

Figure 2
MH-53E Sea Dragon
(U.S. Navy Internet website photograph archives, PH2 Michael Sandberg)

testing was conducted; data analyzed; and corrective measures suggested, implemented and evaluated, where applicable.

1.2 GEAR FAILURE MODES.

Gear failure modes can be identified by class and type, as indicated in table 1. In general, the classes of wear, scoring, interference, surface fatigue, and plastic flow are not immediately catastrophic and will, in many cases, show a progressive trend that can ultimately lead to failure. Fracture, process-related[1], and compound failures tend to be instantaneous in that little or no indication is given of the impending failure (Drago, 1988).

1.2.1 Wear.

Polishing, moderate, and excessive wear are the results of metal-to-metal contact due to an inadequate boundary of oil between the gear surfaces. When relatively hard, large particles contaminate the lubricating oil, the gear surfaces will become damaged, or will be abrasively worn. Corrosion, a result of many varying factors, can damage the gear faces, magnifying the transmitted loads due to a reduction in surface area. This augmented loading causes the gears to wear more rapidly (Drago, 1988).

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[1] Only those gears whose manufacture-related damage escapes detection prior to installation are included in this discussion.

Table 1
Gear Failure Mode Classes and Types

Class	Type	Common Cause(s)
Wear	Polishing	Insufficient oil film thickness, surface roughness, oil contamination
	Moderate	
	Excessive	
	Abrasive	
	Corrosive	
Scoring	Frosting	Load, sliding velocity, and/ or excessive oil temperature that leads to insufficient oil film thickness.
	Light	
	Moderate	
	Destructive	
	Localized	Non-uniform surface loading.
Interference	N/A	Self-explanatory
Surface Fatigue	Initial Pitting	Exceedance of material's fatigue capacity.
	Destructive Pitting	
	Spalling	Combination of high surface velocities and stresses.
	Case Crushing	Gear core softness.
Plastic Flow	Cold Flow	Insufficient material hardness.
	Hot Flow	Insufficient lubrication.
	Rippling	Insufficient material hardness and lubrication.
	Ridging	Insufficient oil film thickness and oil contamination.
Fracture	Classical Bending Fatigue	High stress.
	Overload	High, unanticipated applied loads.
	Random Fracture	Usually symptomatic of other problems.
	Root/Rim/Web	Insufficient rim thickness.
	Resonance	Self-explanatory
Process related	Quench Cracks	Improper cooling.
	Grinding Cracks	Improper grinding.
	Nicks, Scratches, and Such	Improper handling.
	Electric Arcing	Improper welding.
	Grinding Burns	Improper grinding.
	Improper Edge Breaks	Self-explanatory.
	Tool Marks	Improper finishing.
Compound	N/A	Self-explanatory.

(Source: Raymond J. Drago, *Fundamentals of Gear Design*, Butterworth Publishers, New York, NY, 1988)

1.2.2 Scoring.

As with wear, scoring is another condition caused by metal-to-metal contact. In the cases of frosting and light, moderate, and destructive scoring, temperatures build to a point such that welding of the surfaces in contact occurs. The rotation of the gears severs the weld. The severing action and the subsequent, continued rotation scores the gear faces. Localized scoring, unlike the other types of scoring, is not attributable to an excessive thermal condition, but is surface damage as the result of high localized loading (Drago, 1988).

1.2.3 Interference.

Interference manifests itself in many forms, but can generally be attributed to design imperfections. These imperfections can be in the gear tooth itself, in how it is mounted, in the choice of material, et cetera (Drago, 1988).

1.2.4 Surface Fatigue.

Surface fatigue results from the cyclic application of an exceedingly heavy load. In the case of spalling, this loading is combined with “high sliding velocities.” While pitting and spalling occur at the surface and affect a substantial number of teeth, case crushing occurs internally in case-hardened gears and damage is generally limited to a very small number of teeth. In all cases, this damage presents itself on the gear’s surface and is presented as a pit or a gouge (Drago, 1988).

1.2.5 Plastic Flow.

Gear teeth whose profiles have been altered plastically fall into this failure category. Unlike gears subjected to wear, scoring, and fatigue, flowed gears retain the original amount of material, in the early stages of failure, but have had their profile permanently changed through high loads, material hardness, poor lubrication, sliding, or some combination thereof (Drago, 1988).

1.2.6 Fracture.

Fracture failures are describe a failure in which some part of the gear experiences a crack or breakage. These cracks are the result of excessive load and can be exacerbated by other aspects, such as surface fatigue or process-related failures. As discussed in paragraph 1.2, this type of failure tends to be instantaneous and can result in significant damage, especially in the cases of root/rim/web and resonance types where major portions of the gear can separate (Drago, 1988).

1.2.7 Process Related.

Process related failures are those failures generally caused during the making of the gear (Drago, 1988).

1.2.8 Compound.

As can be surmised from the title of this mode, compound failures are the result of the interaction or progression of several singular types of failures (Drago, 1988).

1.3 AIRCRAFT DESCRIPTION.

1.3.1 General.

The H-53E is a dual-piloted, single main rotor helicopter designed and manufactured by the Sikorsky Aircraft Division of the United Technologies Corporation. The aircraft is equipped with a seven-bladed main rotor and a four-bladed composite tail rotor. The aircraft has an empty weight of approximately 36,000 pounds with a maximum gross weight of either 73,500 pounds ("C" variant) or 69,750 pounds ("M" variant). USMC missions include troop transport as well as internally- and externally-carried heavy lift. USN missions consist of AMCM and vertical onboard delivery of cargo and personnel (NAVAIR, 1999). Both variants are equipped with the P-7-2 gas turbine auxiliary power plant (APP) (Jane's, 1997).

1.3.2 Auxiliary Power Plant.

The aircraft is equipped with an APP mounted forward of the main rotor gearbox (MGB) and AGB, as depicted in figure 3. The APP provides the capability for unassisted ground operations by driving the AGB during pre-flight ground checks by allowing the generation of electric and hydraulic power. Additionally, the APP provides in-flight AGB power redundancy in the event that the main gearbox (MGB)-to-AGB drive train should fail. The APP is comprised of several subsystems, including, but not limited to, a turbine engine, a reduction drive assembly, a clutch, and a control/indicator panel (NAVAIR, 1971).

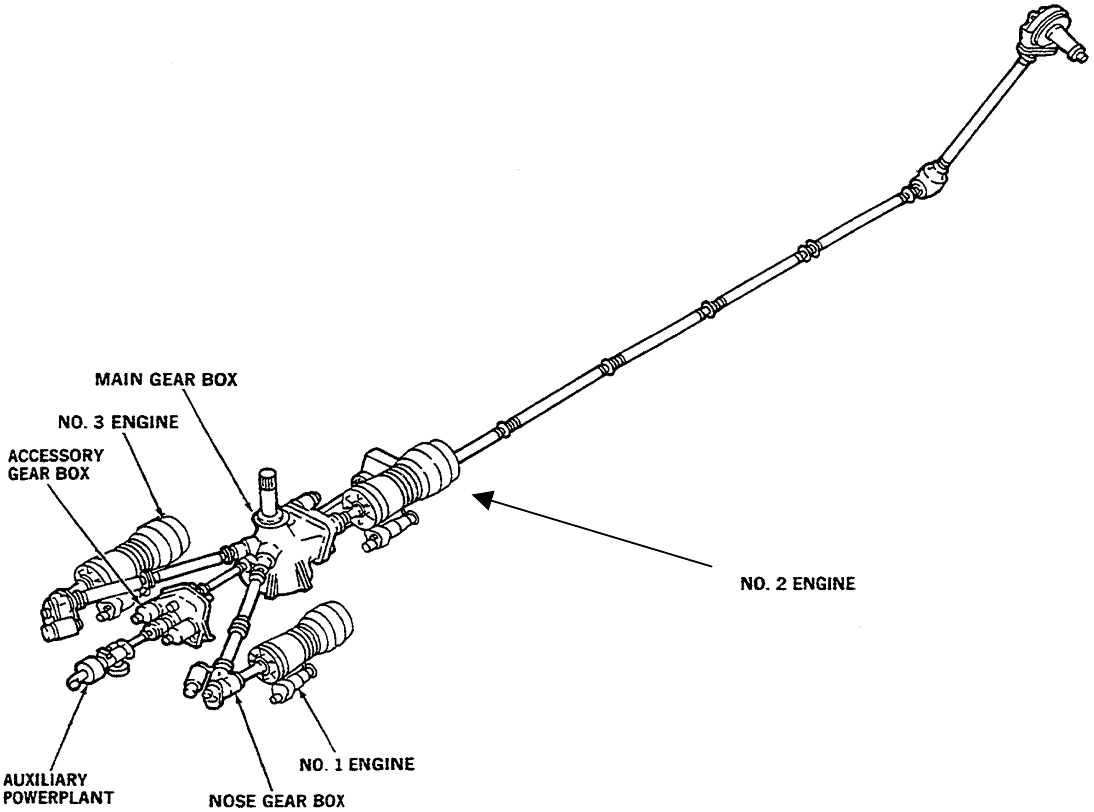


Figure 3
Auxiliary Power Plant/Accessory Gearbox/Main Gearbox Installation

(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

1.3.2.1 APP Turbine Engine. The P-7-2 gas turbine aircraft APP, illustrated in figure 4, incorporates a single stage centrifugal compressor and a single stage radial inflow turbine wheel mounted on a high speed rotor shaft. Compressed air is mixed with fuel and burned in an annular combustor can (NAVAIR, 1971).

1.3.2.2 Reduction Drive Assembly. The reduction drive assembly, rated for a continuously applied load of 110 SHP, is housed in a magnesium casing, incorporates a series of ball bearing supported planetary, ring, and Zerol® bevel gears to reduce APP output RPM from 61,248 to 8,216 on the axial output drive pad. The reduction drive assembly is presented in figure 5. An oil pump, fuel pump, and electrical generator are mounted on the reduction drive assembly (NAVAIR, 1971).

1.3.2.3 APP Oil System. A pressure-type oil system, incorporating a 10 micron by-passable filter, lubricates the APP and reduction drive assembly. Five jets provide pressurized oil, regulated between 15 and 40 psi, to the planetary gear/high speed pinion input point. The two remaining jets direct oil at the Zerol bevel gear: one aimed at the pinion/gear mesh point while the other is aimed at the end of the gear shaft and allows oil to lubricate the aft rotor shaft roller bearing. What can be best described as a splash type lubrication system provides oil to the rest of the bearings and gears. An air/oil mist is generated by the interaction of the rotating planetary gear/pinion and jet-directed pressurized oil. This mist covers the gears and bearings, cooling and lubricating them (NAVAIR, 1971).

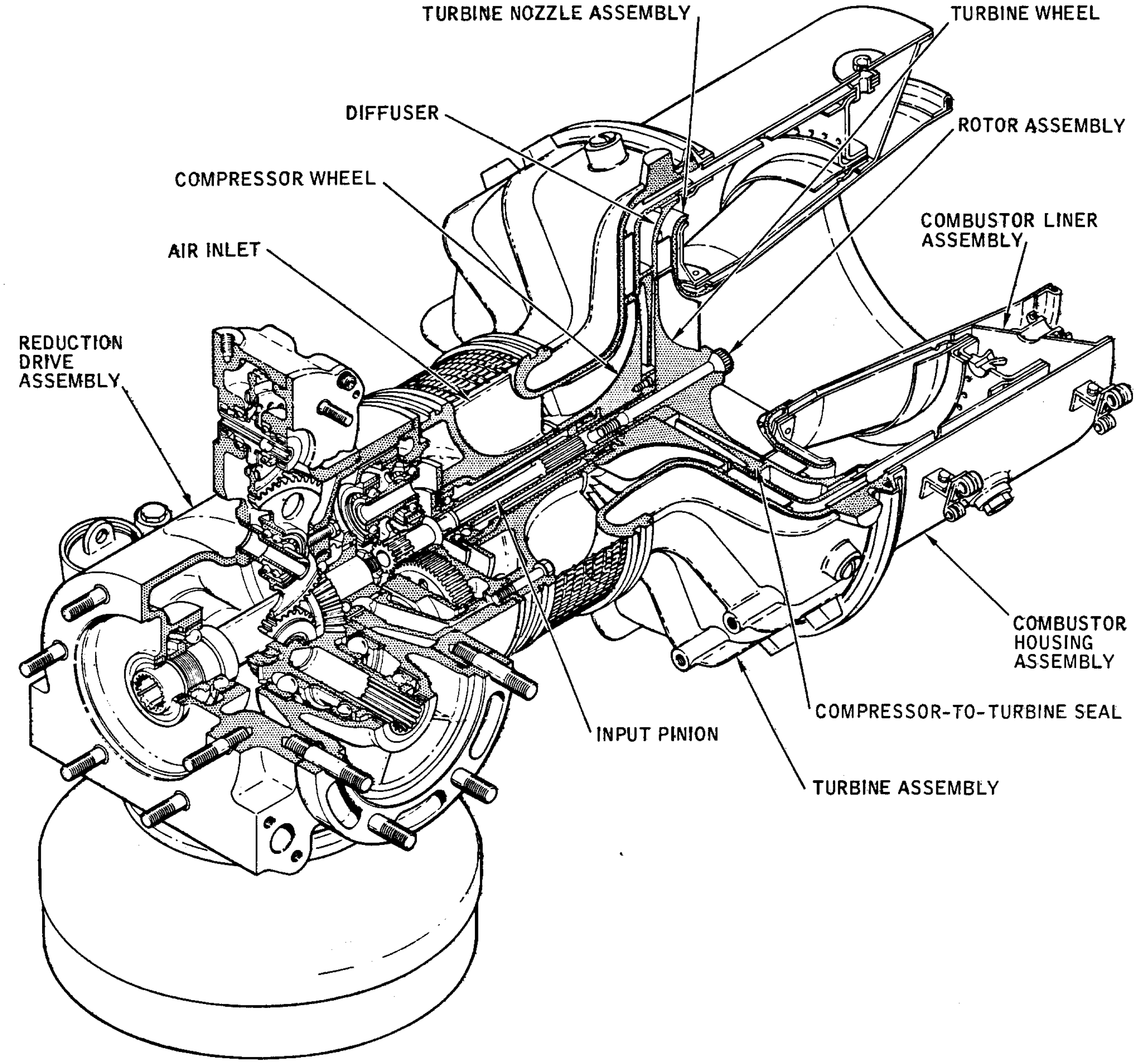


Figure 4
Auxiliary Power Plant

(Naval Air Systems Command, *Handbook and Maintenance Instructions, Gas Turbine Auxiliary Power Plant, Solar Model T-62T-27, NAVAIR Model P-7-2, Part No. 42100-0, NAVAIR 19-105B-39*, Naval Air Technical Services Facility, Philadelphia, PA, February 1971)

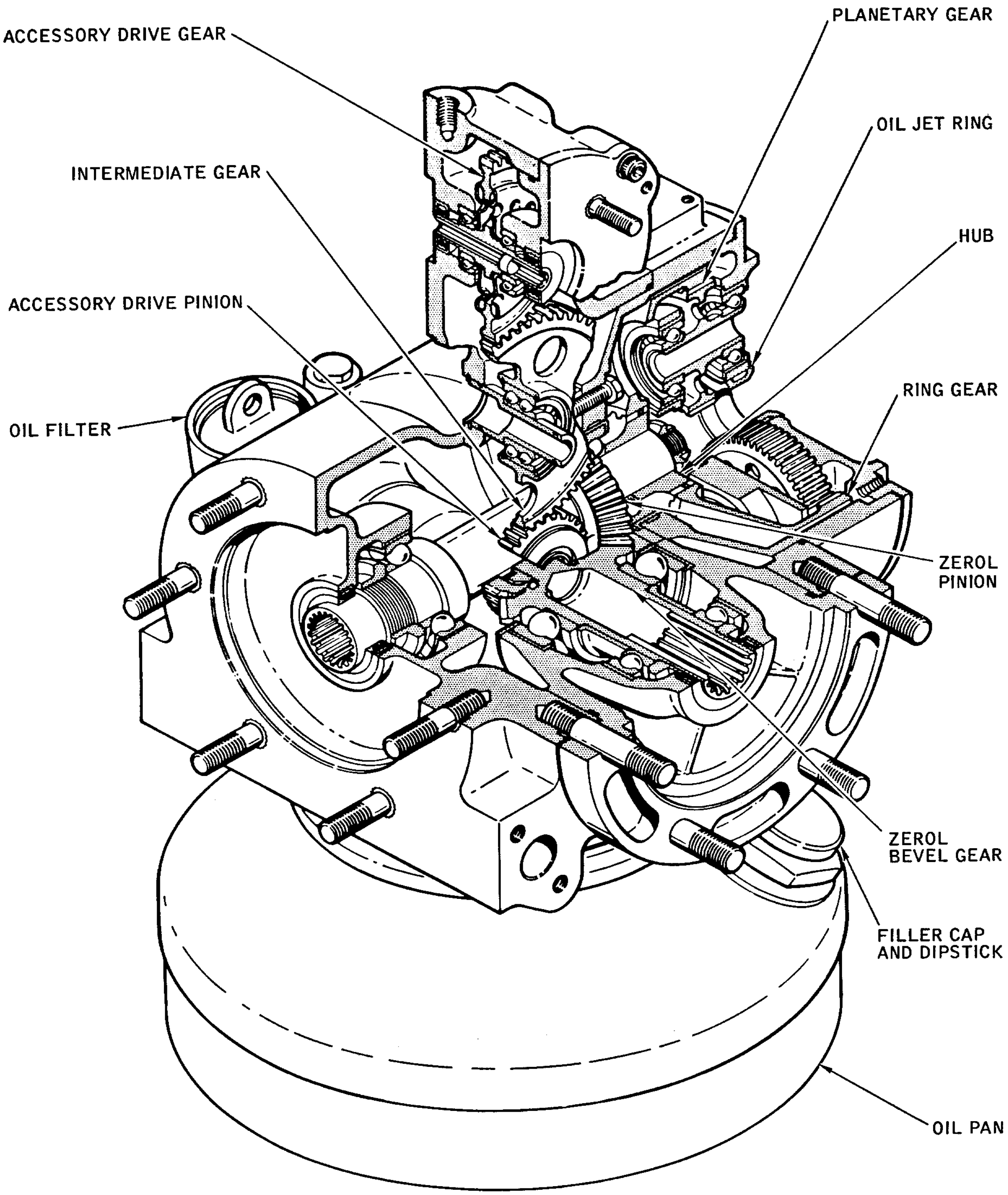


Figure 5
Reduction Drive Assembly

(Naval Air Systems Command, *Handbook and Maintenance Instructions, Gas Turbine Auxiliary Power Plant, Solar Model T-62T-27, NAVAIR Model P-7-2, Part No. 42100-0, NAVAIR 19-105B-39*, Naval Air Technical Services Facility, Philadelphia, PA, February 1971)

1.3.2.4 APP Clutch. A pneumatically operated clutch, using APP compressor bleed air, is mounted to the reduction drive assembly and connects the APP to the AGB via a drive shaft, as depicted in figures 3 and 6 (NAMTRAGRU, 1988).

1.3.2.5 APP Control/Indicator Panel. The APP control/indicator panel, shown in figure 7, is located in the cockpit on the overhead control panel. It includes a control lever to initiate the start sequence, allow continuous operation, and initiate the shutdown sequence; three protective circuit breakers; a protective circuit breaker on/off switch; gauges to indicate turbine speed in percent RPM and exhaust gas temperature (EGT) in degrees Celsius; and a T-shaped fire-indicating handle which, when moved aft, secures the APP and cabin heater and simultaneously discharges a fire retardant in the APP compartment. The protective circuit breakers automatically shut the APP down for operations as indicated in table 2. Certain protective features are bypassed during main engine start and when the APP start switch, located on the emergency control panel, is moved from “NORM” to “EMER”, as indicated in table 2 (NAMTRAGRU, 1988).

1.3.2.6 APP Operation. Prior to initiating the APP start sequence, the cockpit flight crew completes the pre-start checklist. In essence, this ensures that all electrical, and to the maximum extent possible, hydraulic draw is secured and that the APP start switch is in the “NORM” position. The pre-start checklist directs the crew to ensure that the fire indicating handle is forward, that the protective circuit breakers are set, and that the protective circuit breaker control switch is in the “ON” position prior to moving the APP

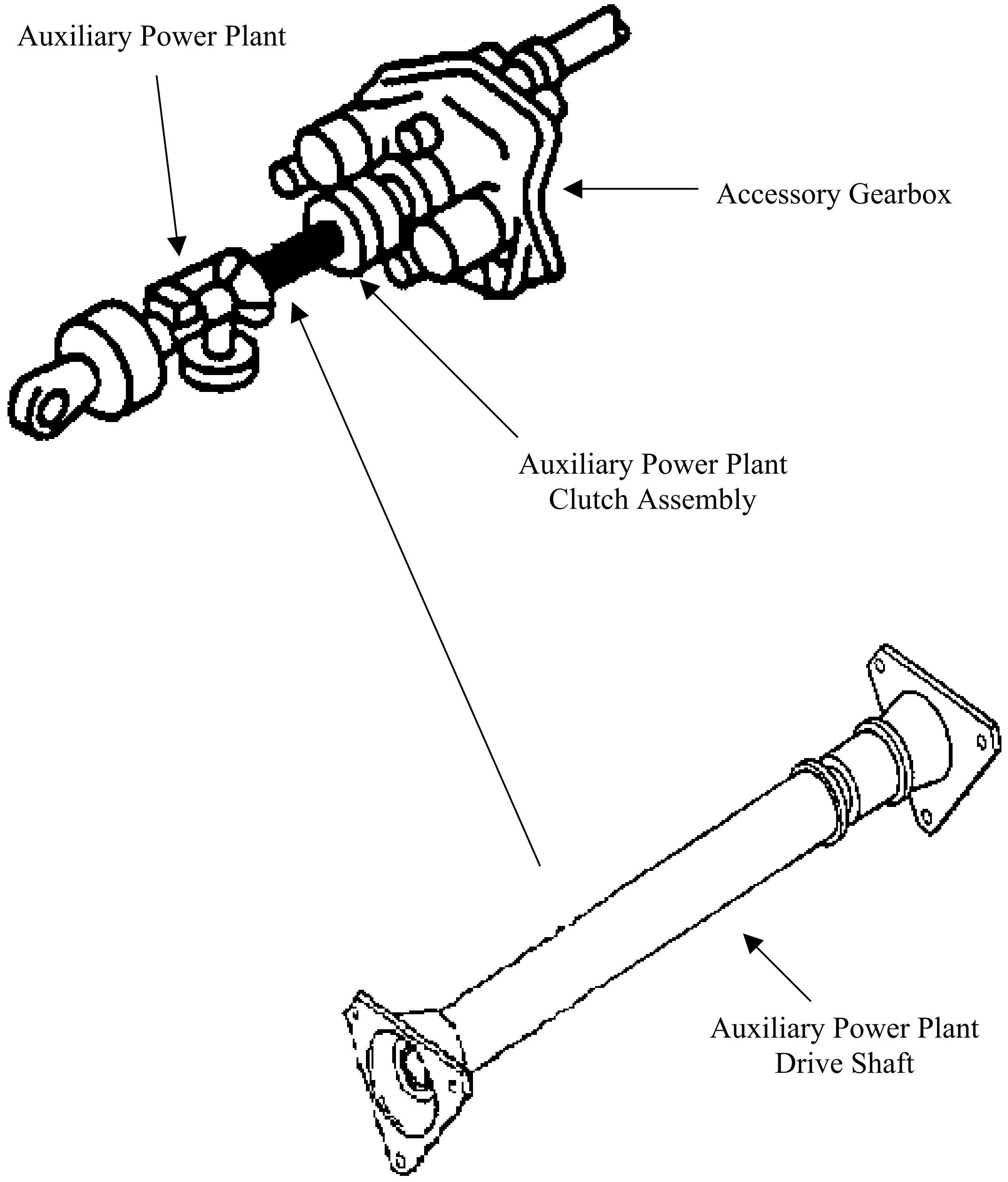


Figure 6
Auxiliary Power Plant Driveshaft

(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

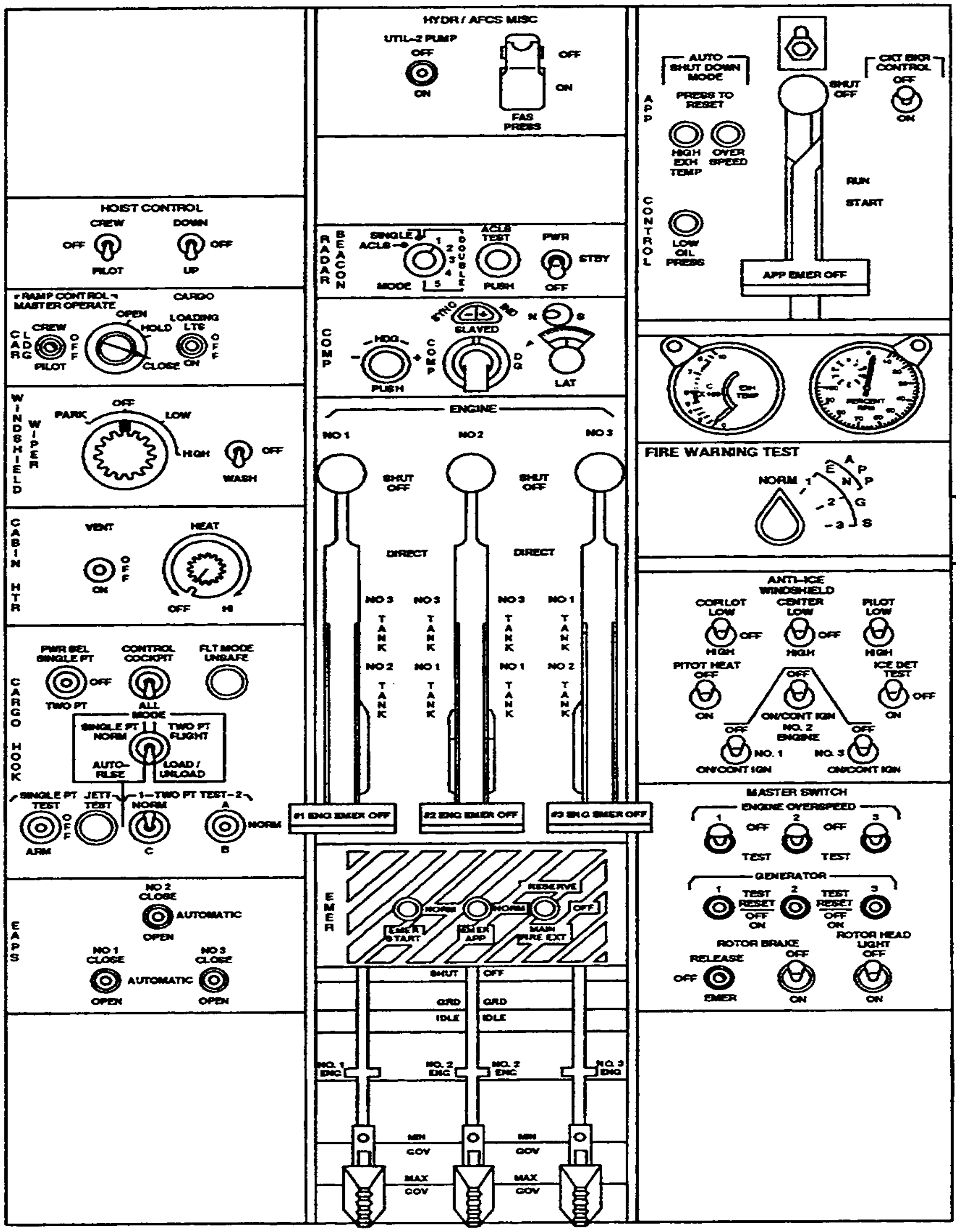


Figure 7
Auxiliary Power Plant Control/Indicator Panel

(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

Table 2
APP Protective Circuit Breaker Functions

		Bypassed During:	
Title[1]	Condition[2]	Main Engine Start Sequence	APP Start Switch in "Emergency Start"
High EGT	EGT>621° Celsius	Yes	Yes
Turbine Overspeed	Turbine RPM>110%	No	No
Low Oil Pressure	Oil pressure<6±1 psi	Yes	Yes

Notes: (1) Turbine overspeed protection and low oil pressure protection are not available until the turbine achieves 92% operating RPM.
(2) Operation outside of these parameters will result in APP shutdown, except as noted otherwise.

(Source: Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

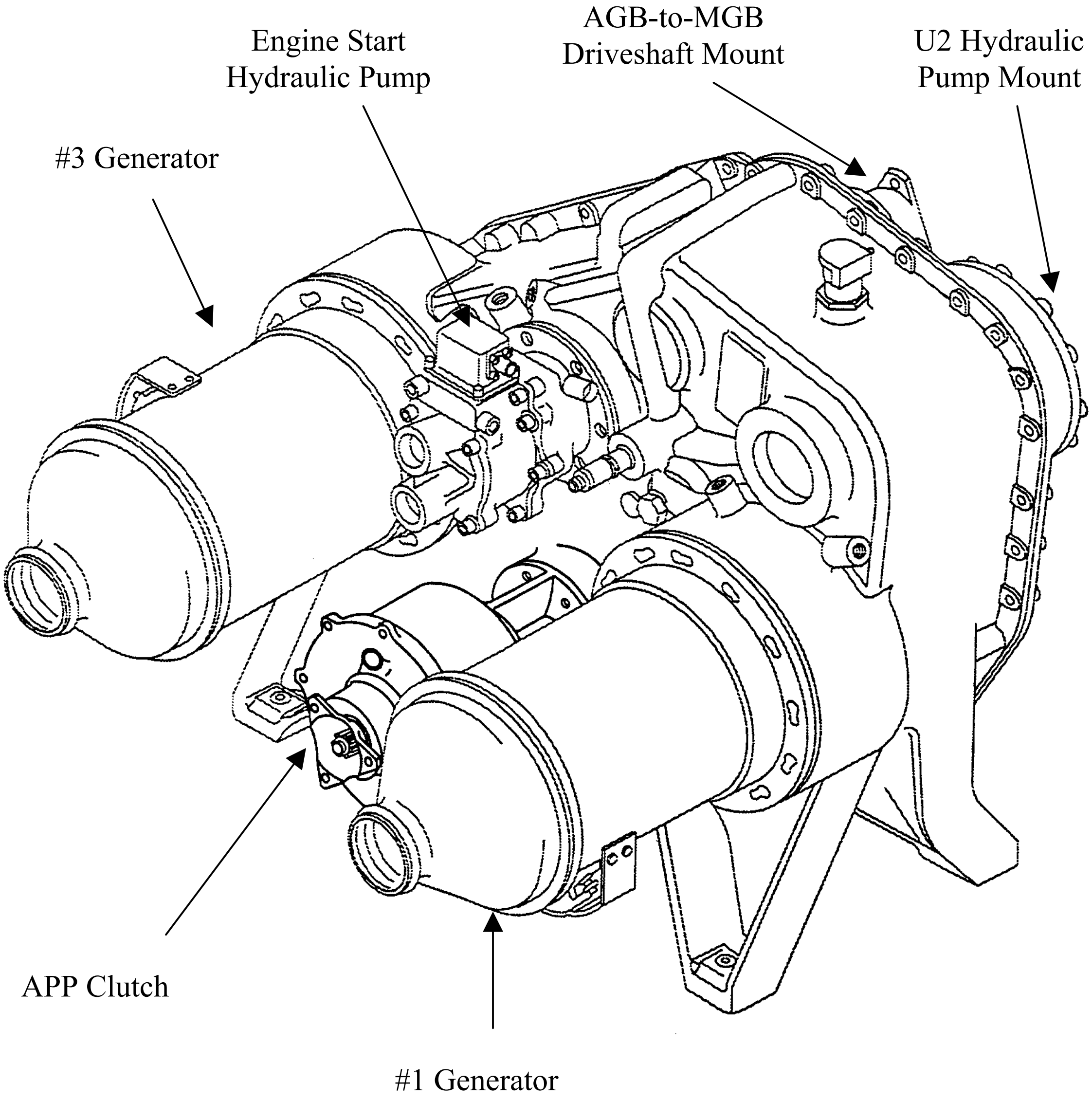
control lever forward to the "START" position. When held in the "START" position, hydraulic fluid, stored under pressure in an accumulator, is routed to the APP start motor, causing the turbine to spin. The fuel pump, bolted to the reduction drive assembly, draws fuel from the aircraft fuel system and routes it to the fuel nozzles where it is mixed with compressed air. This mixture continues into the combustion chamber, where it is ignited by a spark plug. When turbine RPM exceeds starter speed, a starter clutch assembly disengages the starter and allows the turbine to freely accelerate. When the turbine reaches 92% operating RPM and EGT reaches 204 degrees Celsius, bleed air from the compressor is released to the APP clutch, causing it to engage. Full engagement is indicated when the #1 GEN, #3 GEN, #1 RECT, and #2 RECT lights on the caution/warning/advisory are lit. At this point, the cockpit flight crew return the APP control lever to the "RUN" position (NAMTRAGRU, 1988).

1.3.3 Accessory Gearbox.

A series of hydraulic pumps and electrical generators are mounted on the AGB and are designed to provide necessary hydraulic and electrical power for ground operations and unassisted engine starting, as presented in figure 8 and as noted in table 3. The AGB is powered by the APP through the APP reduction drive and clutch assemblies or by the MGB through the MGB-to-AGB drive shaft, depending on main rotor rotational speed (N_r). During ground operations with the APP operating and N_r below 97%, the AGB is designed to be powered by the APP. An overrunning clutch is designed to prevent the MGB-to-AGB drive shaft from turning and back-driving the MGB. After rotor engagement, the APP is typically secured when 97% N_r has been achieved, thus disengaging the APP clutch and allowing the MGB to power the AGB.

The AGB incorporates two magnetic chip detectors whose purpose is to detect and warn of an excessive build-up of metallic particles in the lubricating oil. The chip detectors feature a system dubbed “fuzz burn”, designed to burn away insignificant accumulations of metal resulting from normal wear through an electric discharge. When enough significant particles have accumulated, an electrical gap is bridged, illuminating the MASTER CAUTION light, the CHIP DETECTED caution light, and the ACCESS GB light on the chip locator panel, as depicted in figures 9 and 10 (PMA-261, 1991, 1993).

1.3.3.1 #1 and #3 Generators. The helicopter incorporates three identical generators to supply electrical power to the aircraft. Each generator is capable of supplying 40 kVA,



(Not shown: 1st Stage and U1 Hydraulic Pumps)

Figure 8
Accessory Gearbox

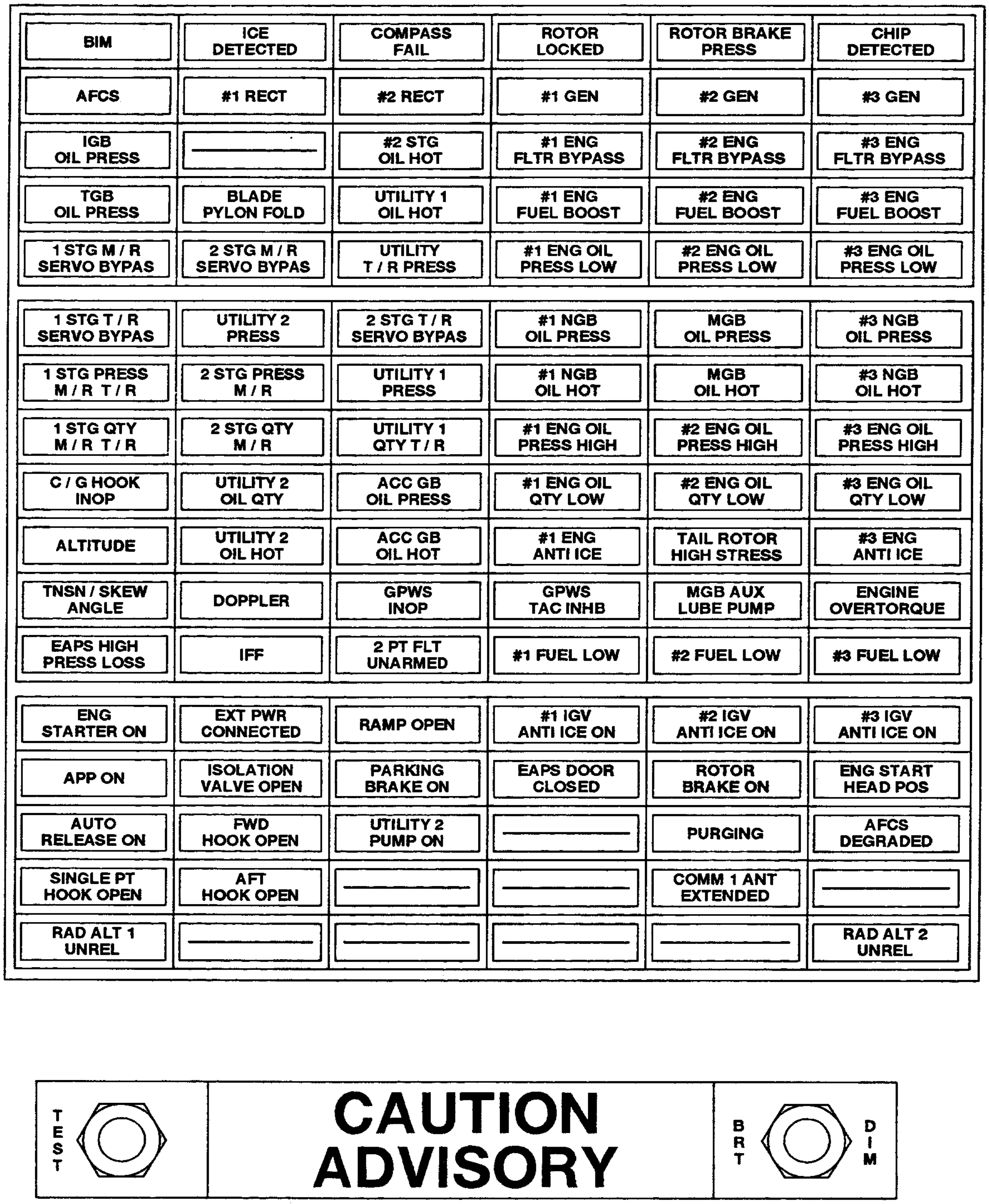
(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

Table 3
H-53E Accessory Gearbox Accessories

Aircraft Model	#1 Generator	#3 Generator	2nd Stage Hydraulic Pump	Utility 1 Hydraulic Pump	Utility 2 Hydraulic Pump	Engine Start Hydraulic Pump
CH-53E	Yes	Yes	Yes	Yes	No[1]	Yes
MH-53E	Yes	Yes	Yes	Yes	Yes	Yes

Note: As the CH-53E does not perform AMCM, it is not equipped with any AMCM mission-specific equipment, to include the utility 2 hydraulic pump.

(Sources: Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988. Janes, 1997)



BIM	ICE DETECTED	COMPASS FAIL	ROTOR LOCKED	ROTOR BRAKE PRESS	CHIP DETECTED
AFCS	#1 RECT	#2 RECT	#1 GEN	#2 GEN	#3 GEN
IGB OIL PRESS	————	#2 STG OIL HOT	#1 ENG FLTR BYPASS	#2 ENG FLTR BYPASS	#3 ENG FLTR BYPASS
TGB OIL PRESS	BLADE PYLON FOLD	UTILITY 1 OIL HOT	#1 ENG FUEL BOOST	#2 ENG FUEL BOOST	#3 ENG FUEL BOOST
1 STG M / R SERVO BYPAS	2 STG M / R SERVO BYPAS	UTILITY T / R PRESS	#1 ENG OIL PRESS LOW	#2 ENG OIL PRESS LOW	#3 ENG OIL PRESS LOW
1 STG T / R SERVO BYPAS	UTILITY 2 PRESS	2 STG T / R SERVO BYPAS	#1 NGB OIL PRESS	MGB OIL PRESS	#3 NGB OIL PRESS
1 STG PRESS M / R T / R	2 STG PRESS M / R	UTILITY 1 PRESS	#1 NGB OIL HOT	MGB OIL HOT	#3 NGB OIL HOT
1 STG QTY M / R T / R	2 STG QTY M / R	UTILITY 1 QTY T / R	#1 ENG OIL PRESS HIGH	#2 ENG OIL PRESS HIGH	#3 ENG OIL PRESS HIGH
C / G HOOK INOP	UTILITY 2 OIL QTY	ACC GB OIL PRESS	#1 ENG OIL QTY LOW	#2 ENG OIL QTY LOW	#3 ENG OIL QTY LOW
ALTITUDE	UTILITY 2 OIL HOT	ACC GB OIL HOT	#1 ENG ANTI ICE	TAIL ROTOR HIGH STRESS	#3 ENG ANTI ICE
TNSN / SKEW ANGLE	DOPPLER	GPWS INOP	GPWS TAC INHB	MGB AUX LUBE PUMP	ENGINE OVERTORQUE
EAPS HIGH PRESS LOSS	IFF	2 PT FLT UNARMED	#1 FUEL LOW	#2 FUEL LOW	#3 FUEL LOW
ENG STARTER ON	EXT PWR CONNECTED	RAMP OPEN	#1 IGV ANTI ICE ON	#2 IGV ANTI ICE ON	#3 IGV ANTI ICE ON
APP ON	ISOLATION VALVE OPEN	PARKING BRAKE ON	EAPS DOOR CLOSED	ROTOR BRAKE ON	ENG START HEAD POS
AUTO RELEASE ON	FWD HOOK OPEN	UTILITY 2 PUMP ON	————	PURGING	AFCS DEGRADED
SINGLE PT HOOK OPEN	AFT HOOK OPEN	————	————	COMM 1 ANT EXTENDED	————
RAD ALT 1 UNREL	————	————	————	————	RAD ALT 2 UNREL

Figure 9
Caution/Advisory Panel

(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

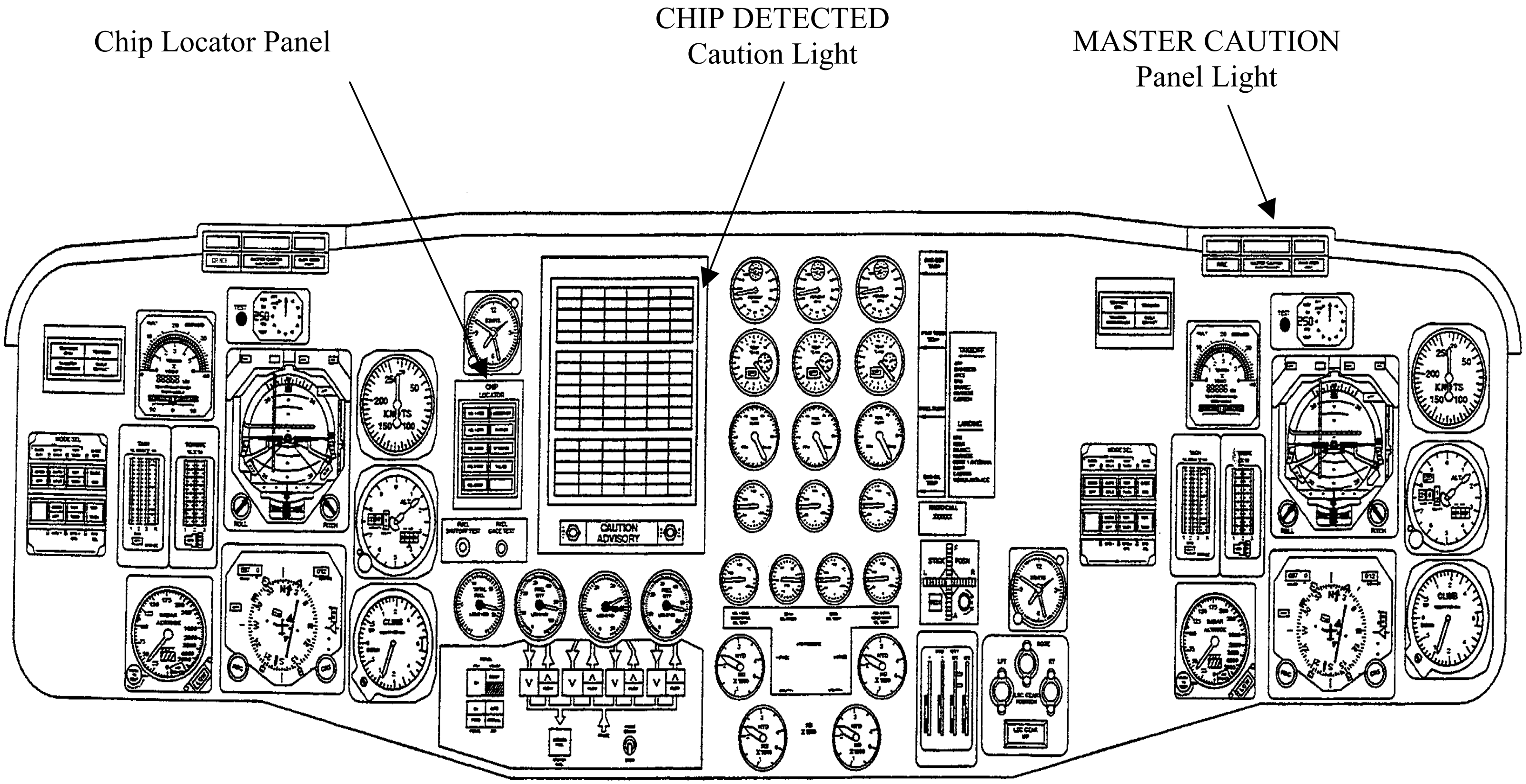


Figure 10
Instrument Panel

(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

115/200 volts, 400 Hz, three phase power to its dedicated supervisory panel, whereupon it is routed to the various alternating current (AC) buses, rectifiers, and direct current(DC) buses. Power supply requirements for the different configurations of #1 and #3 generator employment are shown in table 4 (PMA-261, 1991, 1993).

1.3.3.2 Second Stage Hydraulic Pump. The second stage hydraulic pump generates 3,000 pounds per square inch (psi) hydraulic pressure and supplies it to various portions of the primary and automatic flight control systems, as illustrated in figure 11. These systems include the second stage of the main rotor and tail rotor primary flight control tandem servos[2]. Additionally, if servo 1 of the automatic flight control system (AFCS) is selected on the AFCS control panel, second stage hydraulic power is routed to all four AFCS servos as well as the force augmentation system (FAS) actuator, after being reduced to 1,000 psi through a pressure reducer (PMA-261, 1991, 1993).

1.3.3.3 Utility 1 Hydraulic Pump. The utility 1 hydraulic pump generates 3,000 psi hydraulic pressure and supplies it to various flight control and non-flight control systems, as shown in figure 12. Flight control systems receiving hydraulic power from the utility 1 system include the second stage of the tail rotor primary flight control tandem servo and all four of the AFCS servos, as well as the FAS actuator, if servo 2 of the AFCS is

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[2] The 1st stage hydraulic pump is mounted on the accessory section of the MGB. With the main rotor static, 1st hydraulic pressure is not available to the 1st stage of the main rotor primary flight control tandem servos.

Table 4

Power Supply Requirements for Differing Configurations of Generator Employment

AC Power Sources	AC Buses[1, 2]							DC Power Sources[1, 2]		DC Buses[2, 3]				
Condition	#1 PRI AC Bus	#3 PRI AC Bus	#2A PRI AC Bus	#2B PRI AC Bus	EMER AC Bus	#1 MON AC Bus	#3 MON AC Bus	#1 RECT	#2 RECT	#1 PRI DC Bus	#2 PRI DC Bus	#3 PRI DC Bus	EMER DC Bus	#1 MON DC Bus
#1 Gen	1		1		1			1		1	1	1	1	
#3 Gen		3		3	3				3	2	2	2	2	
#1 + #3 Gen	1	3	1	3	3			1	3	1	2	2	2	1

Notes: (1) Numbers indicate generator supplying power to the indicated bus.
(2) Empty columns indicate that the bus or rectifier is unpowered.
(3) Numbers indicate rectifier supplying power to the indicated bus.

(Source: Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

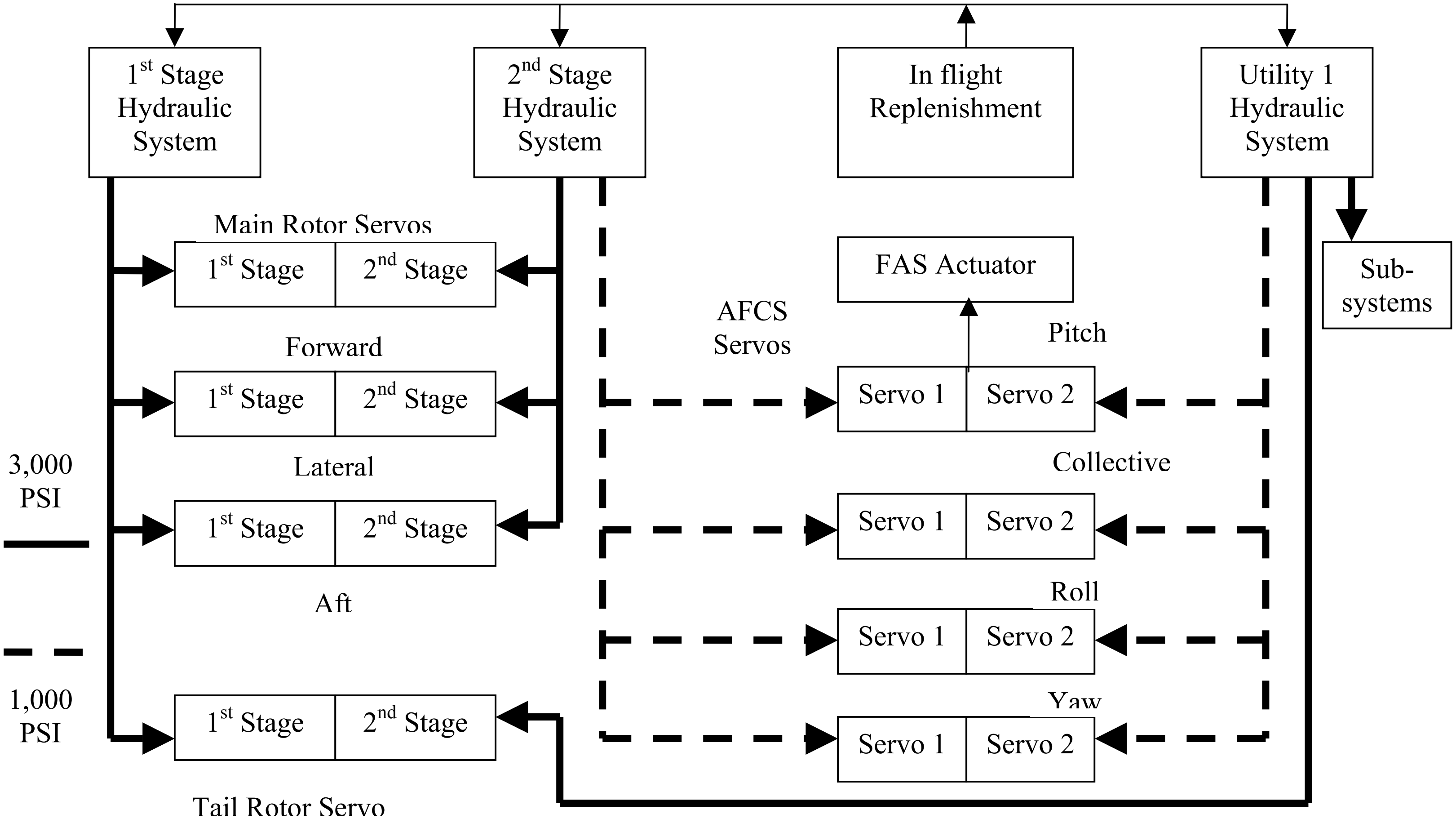

Figure 11
Simplified Flight Control System Hydraulics

(Source: Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

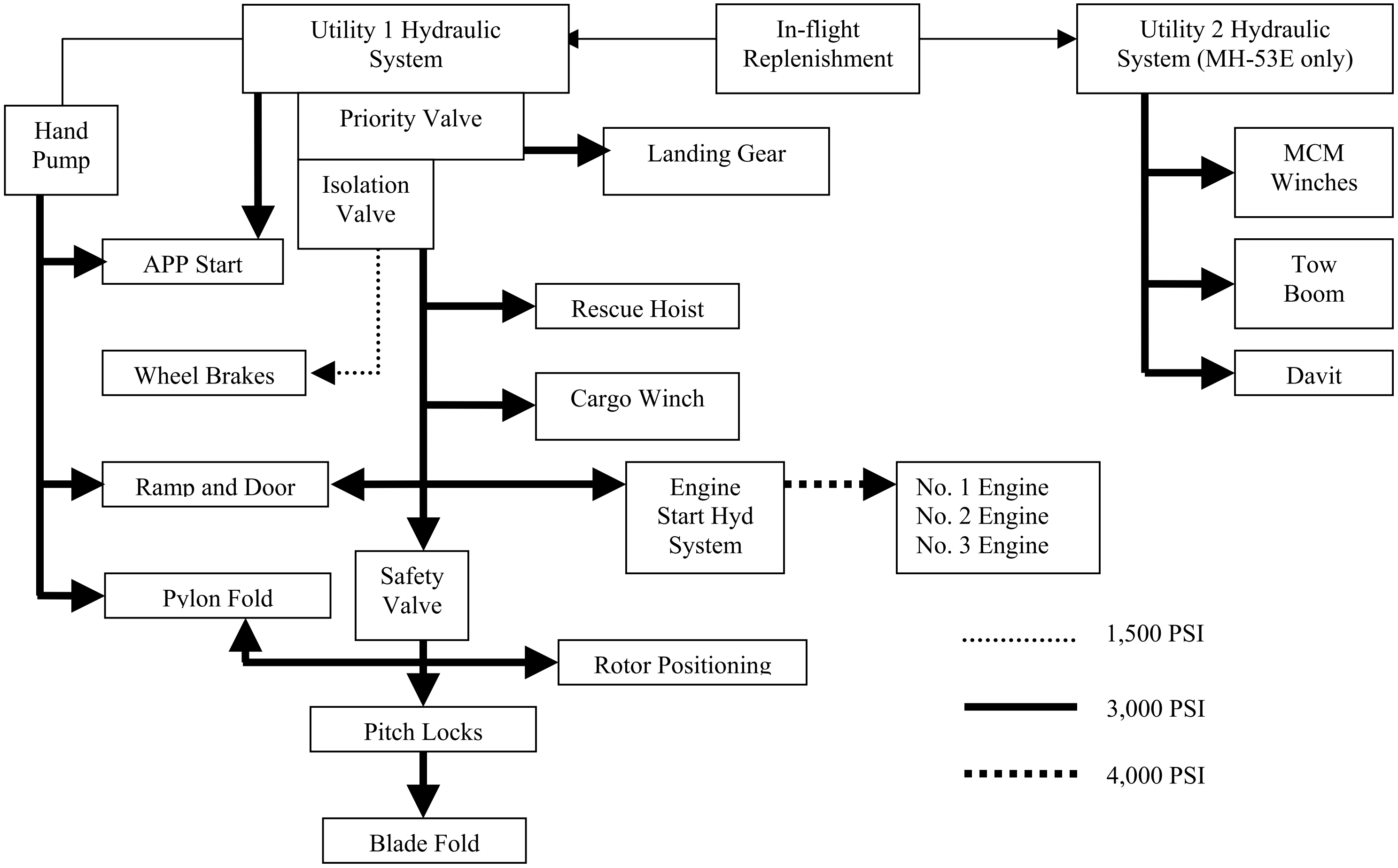

Figure 12
Simplified Utility 1 Hydraulic System Subsystems

(Source: Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

selected on the AFCS control panel. As in the case of second stage hydraulics, utility 1 pressure is reduced to 1,000 psi before being routed to the AFCS servos and the FAS actuator. Non-flight control systems receiving hydraulic power from the utility 1 system include the APP start accumulators, cargo door and ramp actuators, cargo winch, engine start system, landing gear extension and retraction system, main rotor blade/tail pylon fold/spread system, main wheel power brakes, and utility hoist. In the case of the engine start system, utility 1 hydraulic fluid, pressurized to 3,000 psi, is routed through the engine start pump and is boosted to an overall pressure of 4,000 psi. A brief statement of purpose for these systems follows (PMA-261, 1991, 1993):

a. The APP start accumulators store hydraulic fluid under pressure for the APP start sequence.

b. The cargo door and ramp actuators are used to allow the flight crew to open and close the cargo door or cargo ramp found in the rear area of the aircraft cabin.

c. The cargo winch is mounted in the forward part of the cabin and is used to aid the flight crew in loading heavy objects.

d. The engine start system allows the main engine to achieve sufficient gas generator turbine speed for start.

e. The landing gear extension and retraction system function to allow the tricycle landing gear to be lowered and raised.

f. The main rotor blade/tail pylon fold/spread system function to allow the main rotor blades and tail pylon to be folded and spread to reduce area footprint.

g. The main wheel power brakes allow the flight crew to reduce aircraft speed during ground operations.

h. The utility hoist allows the flight crew to lower and raise up to 600 pounds from the hoist mounted just outside and above the personnel door.

1.3.3.4 Utility 2 Hydraulic Pump. The utility 2 hydraulic system is dedicated to providing hydraulic pressure to AMCM-specific mission equipment. This equipment includes the davit, dual- and single-winch pallets, and the tow boom. The hydraulic pump is designed to operate at 3,000 psi, although a now deactivated 3,000 psi-to-1,000 psi pressure reducer is found on the pump (Powell, 1995). A brief statement of purpose for these items follows (PMA-261, 1991):

a. The davit is a hydraulically-positioned A-frame and pulley used in the stream and recovery of mine hunting devices.

b. The dual- and single-winch pallets are used to lower and raise AMCM gear from the helicopter to the water and vice versa.

c. The tow boom is the pivoting, hydraulically damped point at which AMCM towed devices are connected to the helicopter.

1.3.4 Flight Controls.

1.3.4.1 Mechanical Linkages. The aircraft is equipped with dual conventional cyclic, collective, and pedal flight controls. Cyclic, collective, and yaw pedal inputs are transferred to the main and tail rotor heads via the lower flight control section, AFCS servos, mixing unit, and main and tail rotor primary flight control tandem servos, as depicted in figure 13. Movement of the main rotor primary flight control tandem servos translates into swashplate assembly displacement. Swashplate assembly displacement is transferred to the main rotor blades by the main rotor pitch change rods, resulting in main rotor blade pitch changes. Tail rotor blade pitch change results from tail rotor pitch beam extension and retraction by the tail rotor primary flight control tandem servo which translates into tail rotor pitch change by way of pitch links connecting the tail rotor pitch beam and pitch change horns (PMA-261, 1991, 1993).

1.3.4.2 Main and Tail Rotor Primary Flight Control Servos. Three main rotor primary flight control tandem servos are connected to the main rotor swashplate and provide the required power to cause swashplate assembly displacement. Each is identical, containing a first and second stage piston. While each stage is capable of controlling the main rotor by itself, in most cases both stages are pressurized and work in tandem. The first and second stage hydraulic systems provide power to the first and second stages of these servos, respectively. A single primary flight control tandem servo is used to extend and retract the tail rotor pitch beam and has the same capabilities as a main rotor primary flight control tandem servo in that a single stage is capable of providing the requisite power to change tail rotor blade pitch angle, although normally both stages are pressurized. Unlike the main rotor primary flight control tandem servos, hydraulic power is available to both stages of the tail rotor primary flight control tandem servo whenever the AGB is active as the first stage of the servo receives hydraulic power

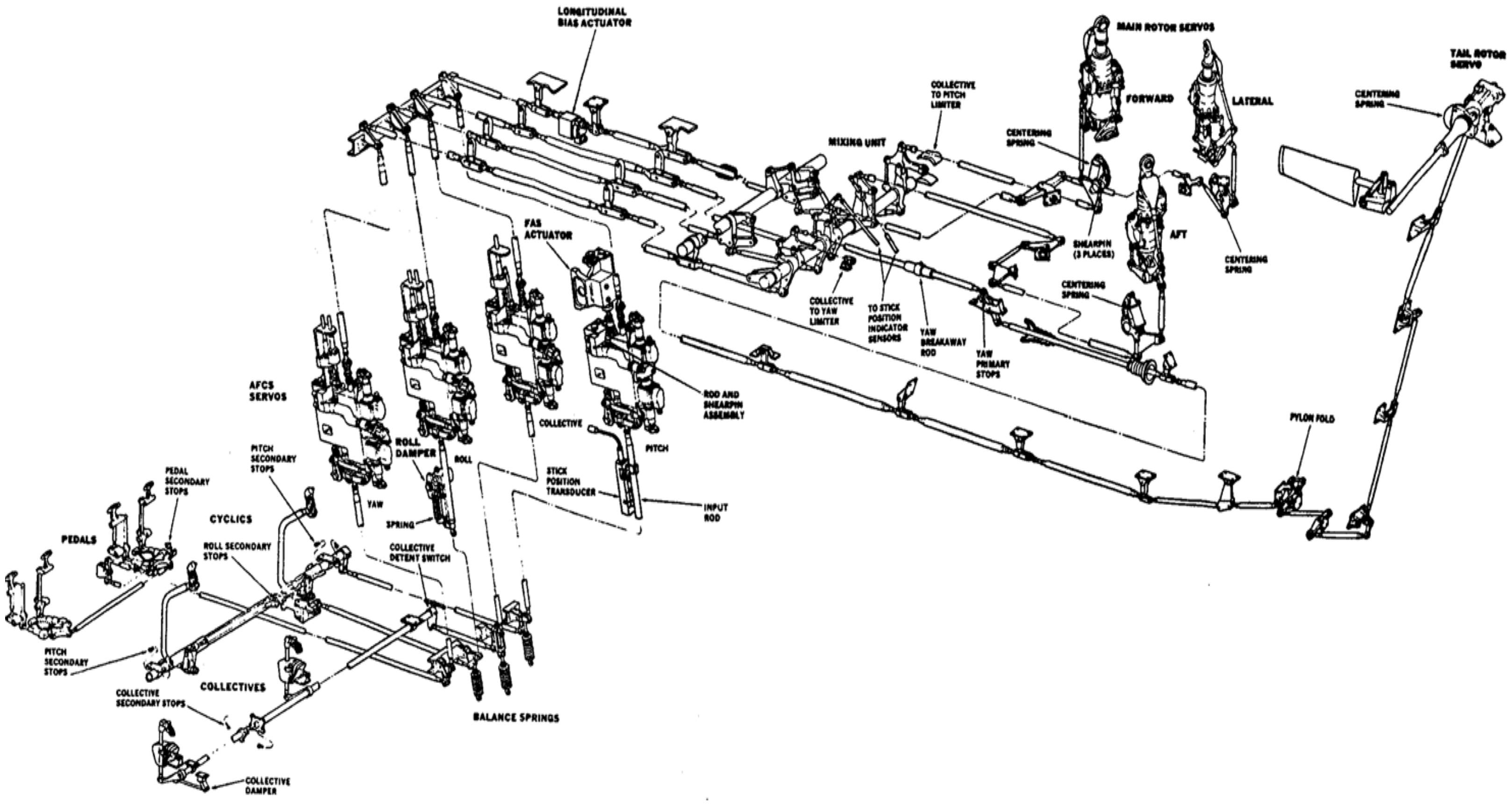

Figure 13
Flight Control System

(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

from the second stage hydraulic system while the second stage of the servo receives hydraulic power from the utility 1 hydraulic system (PMA-261, 1991, 1993).

1.3.4.3 AFCS Servos. Four AFCS servos are installed in the aircraft, one each for pitch channel, roll channel, altitude (or collective) channel, and yaw channel. Each has two stages, only one of which can be pressurized at a time. When hydraulic power is removed from the AFCS servos, they act as a simple mechanical linkage. When the AFCS servos are pressurized, they ease cockpit flight control movement in that cockpit flight control forces are reduced. The FAS actuator is part of the longitudinal, or pitch, flight control run and functions to provide pitch-related AFCS functions. As discussed earlier, the first stage of the AFCS servos are powered by the second stage hydraulic system while the second stage of the AFCS servos are powered by the utility one hydraulic system (PMA-261, 1991, 1993).

1.3.5 Caution/Advisory Panel.

A caution and advisory panel is mounted on the instrument panel and is designed to warn or advise the cockpit flight crew of system failures or unsafe conditions, or certain operating conditions, respectively. The caution/advisory panel is presented in figure 9 (NAMTRAGRU, 1988).

1.3.6 Main Landing Gear Scissors Switches.

The H-53E is equipped with tricycle landing gear comprised of a nose gear and two main landing gear. The main landing gear extend and compress on a fluid- and gas-damped shock strut. Each of the main landing gear incorporates a scissors switch, also known as a weight on wheels switch. One side of the weight on wheels switch is mounted to the shock strut housing while the other side is mounted to shock strut. The switch opens and closes with extension and compression of the main landing gear, respectively, and functions to engage and disengage certain features of the aircraft’s systems, based on whether the aircraft is flying or has landed (NAMTRAGRU, 1988).

SECTION II

METHODOLOGY

2.1 TEST METHODS AND PROCEDURES.

As discussed, NRWATS was initially tasked with defining the rotors-static operating conditions of the APP. Interestingly, USN units flying the MH-53E in the AMCM role experienced a statistically higher percentage of failures when compared to USMC units. The CH-53E and MH-53E Naval Air Training and Operating Procedures Standardization Program (NATOPS) flight manuals were used to determine a logical series of fleet representative ground checks that would be performed by the flight crew prior to rotor head engagement to replicate APP loading as experienced during day-to-day fleet operations. These series of checks fell into two categories: CH/MH-53E common tests and MH-53E unique tests, and are presented in the Appendix. The common checks consisted of motoring engines one at a time, folding and spreading the tail rotor pylon, spreading and folding the main rotor blades, operating the utility hoist, operating the cargo ramp and door, and conducting flight control checks with and without the AFCS servos pressurized with hydraulics. MH-53E unique tests added the requirement for AMCM dual winch pallet operations. Initially, these checks were conducted as solitary, finite events. Where feasible and logical, they were combined to determine the effect that multiple, simultaneous checks had on the system.

To gather data, the APP driveshaft was instrumented to measure torque and drive shaft speed, and the exhaust was instrumented to measure EGT. Data were recorded on strip charts. Testing was conducted at NRWATS by an H-53 engineering test pilot and two mechanical engineers during two separate periods totaling approximately 4.5 hours from March 1995 to December 1995. Initial testing was conducted on MH-53E bureau number (BuNo) 162497. The second set of tests were conducted on MH-53E BuNo 163054.

2.2 TEST CONFIGURATIONS.

Although the tests were conducted on two different aircraft, the test team did not feel that it presented significant differences in data. MH-53E BuNo 162497 was configured with three T64-GE-419 engines and one AMCM dual winch pallet while MH-53E BuNo 163054 was configured with two T64-GE 416A, one T64-GE-416 engine, and one AMCM dual winch pallet (a single winch pallet was not available during the test period). The most significant difference between the –416/A and –419 engines is a change in turbine and combustion section casing material to allow higher operating temperatures, a change in fuel control, and a change in the method of cooling engine oil. It was felt that these differences would not significantly affect the torque required to accelerate the gas generator turbine to sufficient operating speed to introduce fuel for engine start. As a result of the first series of tests, MH-53E BuNo 163054 was configured with a switch and wire harness assembly that allowed selection and de-selection of the 3,000 psi to 1,000 psi depressurization valve located in the utility 2 hydraulic pump in order to measure loading differences at lower utility 2 hydraulic system operating pressures.

SECTION III

RESULTS

3.1 DATA.

The results of all phases of testing are presented in the Appendix.

3.1.1 Non-AMCM Checks.

A comparison of results from similar checks conducted during phases 1 and 2 is presented in table 5. As can be seen with the checks that did not require the flight controls to be moved, results between phase 1 and phase 2 were close in terms of measured horsepower. The variations in those checks involving the movement of flight controls is reasonable given the difficulty in replicating flight control movement exactly from event to event.

Table 5
Non-AMCM Check SHP Comparison

Initial Load	Concurrent Loads	SHP	
		Phase 1(1)	Phase 2(2)
Motor #1 Engine	AFCS Servo 1 pressurized	93.7	87.7
Motor #1 Engine	AFCS Servo 2 pressurized	96.3	99.4
Motor #1 Engine	Pedal doublet	89.0	96.7
Motor #1 Engine	Cyclic stir	99.5	98.0
Motor #1 Engine	Collective doublet	117.1	126.1
Motor #1 Engine	All flight controls	104.1	114.8

Notes: (1) MH-53E BuNo 162497
(2) MH-53E BuNo 163054

3.1.2 AMCM Checks.

A comparison of results from similar checks conducted during phases 1 and 2 is presented in table 6 and the Appendix. The differences in loading between phase 1 testing and phase 2 testing with the utility 2 pump operating at 3,000 psi are fairly significant, but remain fairly consistent.

The AMCM dual winch pallet reeling speed is variable. Maintenance settings for maximum reel-out speeds range from 24 to 30 RPM while maximum reel-in speeds range from 30 to 36 RPM. Once installed in the aircraft, the degree of lever deflection on the AMCM winch control pendant determines reeling speed, from zero to its maximum setting. The utility 2 pump will function to meet this hydraulic demand.

NRWATS did not possess AMCM equipment at the time of the tests, requiring the test team to borrow dual winch pallets from an operational unit. Different pallets were used during each phase. As the power required to operate the desired loads remained fairly consistent in those checks not requiring flight control movement, it seems reasonable to assume that a difference in utility 2 system operating pressures between MH-53E BuNo 162497 and 163054 as well as differences in power required to operate the phase 1 winch pallet and the phase 2 winch pallet would account for the noted SHP disparities.

Table 6
AMCM Check SHP Comparison

Initial Load	Concurrent Loads		Phase $1^{(1)}$	Phase $2^{(2)}$
	First	Second		
Utility 2 system on	None	None	95.4	77.3
AMCM Winch Pallet$^{(3)}$	None	None	83.1	61.3
AMCM Winch Pallet$^{(3)}$	Utility hoist	None	89.0	58.6
AMCM Winch Pallet$^{(3)}$	Cargo ramp	None	91.1	-$^{(4)}$
AMCM Winch Pallet$^{(3)}$	AFCS Servo 1 pressurized	None	93.7	61.3
AMCM Winch Pallet$^{(3)}$	AFCS Servo 1 pressurized	Pedal doublet	117.1	84.8
AMCM Winch Pallet$^{(3)}$	AFCS Servo 1 pressurized	Cyclic stir	114.5	87.4
AMCM Winch Pallet$^{(3)}$	AFCS Servo 1 pressurized	Collective doublet	140.5	105.4
AMCM Winch Pallet$^{(3)}$	AFCS Servo 1 pressurized	All flight controls	142.2	105.4

Notes:(1) MH-53E BuNo 162497.
(2) MH-53E BuNo 163054.
(3) Utility 2 system operating pressure was 3,000 psi.
(4) The minimum measurable SHP value at 102% operating RPM was 53.2.

3.2 AUXILIARY POWER PLANT OVERLOADS.

Certain simultaneous ground checks applied loads in the APP reduction gearbox which exceeded the 110 SHP limit, as presented in table 7 and the Appendix. The applied loads were sinusoidal and in phase with the movement of the flight controls and varied from a minimum of 112.3 SHP to a maximum of 142.2 SHP. Additionally, loads generated during flight control checks varied with the rate at which the controls were moved (i.e., faster movement equated to higher loading and vice versa).

Table 7
APP Overloads

Event	Initial Load	Concurrent Loads		Utility 2 (3K psi)	SHP
		First	Second		
1-8	Motor #1 Engine	Collective doublet	None	Off	117.1
2-6	Motor #1 Engine	Collective doublet	None	Off	126.1
2-7	Motor #1 Engine	Move all flight controls	None	Off	114.8
2-13	Motor #1 Engine	Collective doublet	None	On	128.7
1-41	AMCM Winch Pallet	AFCS Servo 1 pressurized	Pedal doublet	Off	117.1
1-42	AMCM Winch Pallet	AFCS Servo 1 pressurized	Cyclic stir	Off	114.5
1-43	AMCM Winch Pallet	AFCS Servo 1 pressurized	Collective doublet	Off	140.5
1-44	AMCM Winch Pallet	AFCS Servo 1 pressurized	All flight controls	Off	142.2

3.3 AUXILIARY POWER PLANT TRANSIENT LOADS.

Various applied loads in the APP reduction gearbox exhibited spike characteristics (infinite slope on time history), with some exceeding 110 SHP. The applied loads spiked from the 53.2 SHP minimum measurable threshold to the values outlined in table 8 and the Appendix, and then immediately fell below the minimum measurable threshold.

Table 8
APP Transient Loads

Event	Initial Load	Concurrent Loads		SHP
		First	Utility 2	
2-1	APP Clutch Engagement	None	Off	122.0
2-10	Motor #1 Engine	AFCS Servo 2 pressurized	On/3K psi	109.6
2-3	Motor #1 Engine	AFCS Servo 2 pressurized	Off	99.4
1-5	Motor #1 Engine	AFCS Servo 2 pressurized	Off	96.3
1-36	Utility 2 System on	None	On/3K psi	95.4
1-4	Motor #1 Engine	AFCS Servo 1 pressurized	Off	93.7
2-16	AMCM Winch Pallet	None	On/1K psi	80.6
2-24	Utility 2 System on	None	On/3K psi	77.3

SECTION IV

DISCUSSION

4.1 OVERLOAD AND TRANSIENT LOAD REDUCTION TECHNIQUES.

Upon completion of each of the test phases, the data were reviewed. Two things were readily evident from the data collected. First, the power required by the AGB during certain operating conditions exceeded the continuous power rating of the APP. Second, certain operating conditions caused an immediate increase in power required which the APP met, sometimes in excess of the continuous power rating. Methods to reduce or eliminate these conditions were examined using administrative restrictions. Additionally, engineering changes were examined and/or instituted to mitigate the failure potential.

4.1.1. Administrative Restrictions.

The NATOPS program includes the publication of flight manuals for each aircraft that is part of the Navy's inventory. The program allows end users to recommend changes, allowing the manual to be updated to "enhance safety and combat effectiveness (OPNAV, 2001)." These changes may modify procedures; may include wording to indicate whether a procedure is to be considered mandatory, recommended, or optional[3]; or may highlight critical information through warnings, cautions, or notes. The definition of these is as follows (OPNAV, 2001):

---

[3] These terms are shall, should, or may, respectively.

a. Warning: An operating procedure, practice, or condition, etc., that may result in injury or death if not carefully observed or followed.

b. Caution: An operating procedure, practice, or condition, etc., that may result in damage to equipment if not carefully observed or followed.

c. Note: An operating procedure, practice, or condition, etc., that is essential to emphasize.

4.1.1.1 Procedural Changes. Procedural changes generally seek to add, delete, or modify standardized checklist items or specific steps in other standardized operations. Several options to reduce APP loading through procedural modification were examined.

4.1.1.1.1 Single Generator Operations. As noted earlier, two generators are located on the AGB. Unlike the hydraulic pumps, generator operation can be controlled from the cockpit using an ON and OFF/RESET switch. Rather than utilizing both the number 1 and number 3 generators, it might be possible to reduce AGB power required by conducting pre-rotor engagement checks using only one of the two generators available. This change could be implemented by simply revising the pre-start checklists. However, single generator operations result in the loss of several electrical buses, some of which power items required to execute steps called for in the various checklists or which are required to safely operate required subsystems. These systems are listed in tables 9 and 10. As such, single generator operations were discarded as a practical alternative.

Table 9

Single Generator Operations Critical Component Loss (#1 Generator Only)

#1 Generator Operating		
Lost Bus	Lost Component	Impact
#2B PRI AC	#2 Engine Fuel Flow Gage	Loss of initial indication of possible main engine hot start.
#2B PRI AC	2nd Stage Heat Exchanger Power	Potential overheating of 2nd stage hydraulic fluid.
#2B PRI AC	2nd Stage Hydraulic Pressure Gage	Inability to ensure that the 2nd stage hydraulic system is operating within normal limits.
#2B PRI AC	Utility 1 Hydraulic Pressure Gage	Inability to ensure that the utility 1 hydraulic system is operating within normal limits.
#2B PRI AC	Hydraulic Quantity Indicator	Inability to ensure that hydraulic systems are serviced with the proper fluid quantity. Unable to monitor hydraulic systems for leaks from the cockpit.

(Source: Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

Table 10

Single Generator Operations Critical Component Loss (#3 Generator Only)

#3 Generator Operating		
Lost Bus	Lost Component	Impact
#1 PRI AC	Doppler Fan	Possible overheating of Doppler compartment.
#1 PRI AC	#1, #2, and #3 Engine T_5 Gages	Inability to monitor engine for possible hot start. After engine start, unable to monitor engine operating temperatures.
#1 PRI AC	#1 Engine Fuel Flow Gage	Loss of initial indication of possible main engine hot start.
#1 PRI AC	Utility 1 Heat Exchanger Power	Potential overheating of utility 1 hydraulic fluid.
#2A PRI AC	Utility 2 Heat Exchanger Power	Potential overheating of utility 2 hydraulic fluid.

(Source: Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

4.1.1.1.2 *Modified Utility 2 Operations*. As noted in table 11 and the Appendix, selection of the utility 2 pump during phase 1 and phase 2 testing caused spikes measured at 95.4 SHP and 77.3 SHP, respectively. It was thought that a slower run-up of the utility 2 pump might lessen this impact and was evaluated during phase 2. The APP was shut down with the utility 2 pump left in the "ON" position. The APP was then started, allowing the utility 2 pump to begin to build pressure at the onset of APP clutch engagement. As can be seen, not only was this method ineffective, it substantially increased the SHP spike in comparison with values noted in which the utility 2 pump was activated after the APP clutch engagement cycle was complete. Consequently, a procedural change ensuring that the utility 2 pump switch would be placed in the "ON" position prior to APP shutdown was discarded.

4.1.1.1.3 *Information Highlight*. As noted in table 7 and the Appendix, overload conditions were noted with certain combinations of simultaneous ground checks. As such, the author submitted a NATOPS change that was accepted and has been

Table 11
Procedural Change Load Comparison

Event	Initial Load	Utility 2	SHP	Comments
1-36	Utility 2 System on(1)	3K psi	95.4	Spike
2-24	Utility 2 System on(1)	3K psi	77.3	Spike
2-1	APP Clutch Engagement	Off	122.0	Spike
2-8	APP Clutch Engagement(2)	3K psi	156.9	Spike

Note: (1) The APP clutch was completely engaged and the utility 2 switch advanced from "OFF" to "ON".
(2) The utility 2 switch was left in the "ON" position, allowing the system to build pressure while the clutch engaged.

incorporated in the MH-53E NATOPS flight manual. It is restated as follows (Twomey, 1995):

> **CAUTION**
>
> With the utility 2 system on prior to 100% N_r, APP maximum operating thresholds can be exceeded when combined AGB loads (rapid control inputs, engine starter engagement, cargo winch use, etc.) are encountered. Use of the utility 2 system prior to 100% N_r shall be minimized and combined AGB loads avoided.

4.1.2 Engineering Changes.

Administrative changes offer many advantages. These include the ability to rapidly incorporate the desired change, the ability to execute these changes at a minimal cost, resulting in the ability to incorporate changes with a minimal short-term impact. However, administrative changes are difficult to enforce and standardize, and impose changes that have a long-term impact in that the restrictions imposed generally will remain in-place until the problem is tackled using a different type of solution. While potentially expensive and slow to incorporate, engineering changes offer the ability to address the root cause.

As discussed in paragraphs 1.2 through 1.2.8, gear failure modes can be categorized by type and by class, with manifestations grouped as either progressive or catastrophic in nature. The engineering changes discussed focus on ways to mitigate these manifestations through load reduction techniques, pre-failure identification, or load capacity enhancement.

4.1.2.1 Load Reduction Techniques. The nature of the failures noted lend credence to the assertion that excessive loads may be a major contributor, especially given that the MH-53E, with its higher AGB power required, has statistically been subject to a higher percentage of problems. While these loads have not caused widespread catastrophic failures, they may contribute to premature wear and subsequent breakdown.

4.1.2.1.1 Utility 2 System Pressure Reduction. As discussed in paragraph 1.3.3.4, the utility 2 hydraulic pump incorporates a 3,000 psi to 1,000 psi pressure reducer. To evaluate the effect that this pressure reduction might have on applied loads, an ON/OFF toggle switch and harness assembly was installed on the phase 2 test aircraft that allowed the pressure reduction valve to be engaged or disengaged. The permanent installation, if incorporated, would have discarded the toggle switch and instead routed the switching mechanism through the weight-on-wheels switch, automatically depressurizing the utility 2 system upon landing without any further intervention by the cockpit flight crew. Upon takeoff, the utility 2 system would be fully pressurized to 3,000 psi, providing the requisite hydraulic power to conduct AMCM operations. Test results are presented in tables 12 and A-2. As can be seen, APP reduction gearbox loading at 1,000 psi was significantly less than at 3,000 psi.

4.1.2.1.2 Overtorque Protection. A possible engineering change that could be instituted would be the installation of a system that would shut the APP down or limit reduction gearbox loading in the event that the power required to meet AGB demands

Table 12
Utility 2 Pressure Reduction SHP Comparison

Initial Load	Concurrent Loads		Phase 1(1)	Phase 2(1)		
	First	Second	U2/3K psi	U2/3K psi	U2/1K psi	Reduction(2)
Utility 2 system on(3)	None	None	95.4	77.3	-	24.1(4)
AMCM Winch Pallet	None	None	83.1	61.3	80.6	-19.3(5)
AMCM Winch Pallet	Utility hoist	None	89.0	58.6	-	5.4(4)
AMCM Winch Pallet	Cargo ramp	None	91.1	-	-	Unknown
AMCM Winch Pallet	AFCS Servo 1 pressurized	None	93.7	61.3	-	8.1(4)
AMCM Winch Pallet	AFCS Servo 1 pressurized	Pedal doublet	117.1	84.8	-	31.6(4)
AMCM Winch Pallet	AFCS Servo 1 pressurized	Cyclic stir	114.5	87.4	-	34.2(4)
AMCM Winch Pallet	AFCS Servo 1 pressurized	Collective doublet	140.5	105.4	64.0	41.4
AMCM Winch Pallet	AFCS Servo 1 pressurized	All flight controls	142.2	105.4	61.3	44.1

Notes: (1) Loading values are peak SHP, unless noted specifically as spike SHP values.
(2) Loading reduction computations use the phase two testing values, only.
(3) Activation of the utility 2 pump resulted in SHP spikes to the values noted.
(4) The minimum measurable shaft horsepower value at 102% rotational speed was 53.2. The values shown indicate the minimum reduction as the actual on the shaft could not be measured by the test equipment in use.
(5) As noted in table 9, the measured value exhibited came in the form of a spike. This is believed to have been caused by a momentary malfunction of the data gathering equipment.

exceeded a pre-determined limit, given that the aircraft was on the ground supported by the landing gear. The installation envisioned is one that would provide automatic protection in the event of a continuous overtorque condition. Two types of protection could be provided and include automatic shutdown or torque limiting through intentional clutch slippage or fuel flow limitation. The installation, depending on the type of protection provided, would include a re-designed APP-to-AGB driveshaft, speed sensor, logic circuitry, an advisory and caution light, associated wiring, and either a circuit breaker, revised clutch design, or a fully automated digital engine control (FADEC). A proposed logic flow is presented in figure 14.

A real-time monitor would provide a driveshaft torque and rotational speed indication. These values would be processed and converted to a SHP value. If the aircraft was airborne, the system would essentially be inactive. As discussed previously, the APP is normally shut down after N_r is sufficient to drive the AGB at its proper speed. In general, the only time that the APP would be started in flight would be in the event that a problem had developed in the MGB-to-AGB drive train. The only corrective action taken in this instance is to start the APP, thus providing power to the AGB in order to regain critical subsystem features. Allowing the system to monitor AGB power required, with the subsequent possibility of APP shutdown while in flight, would be inappropriate.

If the aircraft was on deck, the SHP value would then be compared to three different thresholds. Exceeding the lowest of these values would result in the illumination of an advisory light, letting the cockpit flight crew know that they were approaching potentially

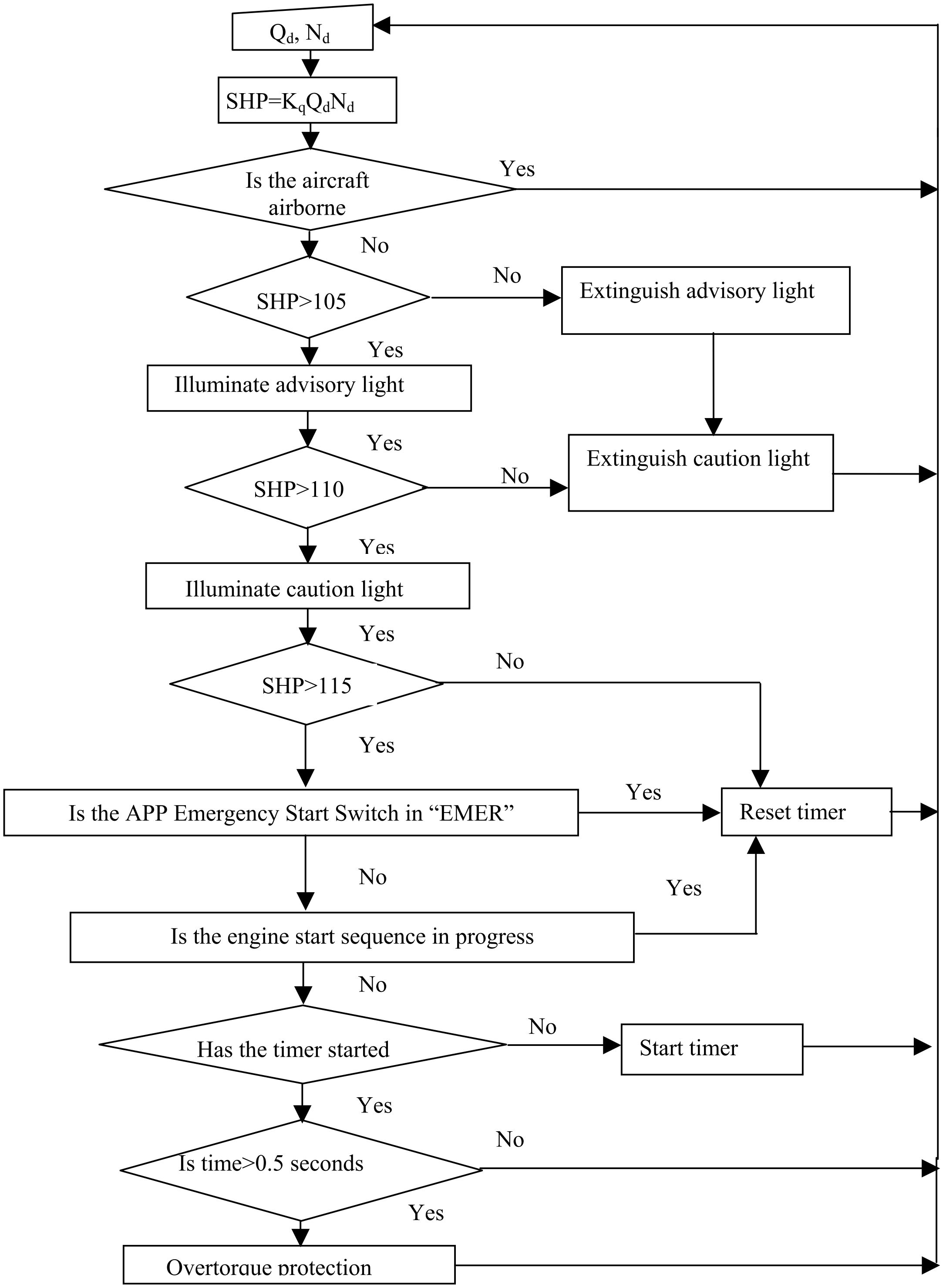

Figure 14
Overtorque Protection Logic Diagram

damaging reduction gearbox loading. Exceeding the middle value would result in the illumination of a caution light, warning the cockpit flight crew that they were applying damaging loads to the reduction gearbox. Exceeding the highest value for a short period of time would result in overtorque protection, given that the engine start cycle was not in progress nor was the APP start switch in the emergency, or EMER, position. The time delay was incorporated to account for transient overloads, such as APP clutch engagement.

The overtorque protection while the emergency start switch is in the EMER position is based on the fact that this is a conscious act and assumes that there was a justifiable impetus behind it. Bypassing the protection during engine start is necessary to preclude premature interruption of engine start system hydraulic pressure, which could result in a damaging main engine hot start. Regardless, the stepped indications would still be given in the event that a pre-determined threshold had been exceeded.

Overtorque protection, if initiated, could be manifested through shutdown or torque limiting. Automatic shutdown would be accomplished in the same manner as experienced during overspeed, low oil pressure, or high exhaust temperature conditions. Torque limiting could be used to limit the applied load to the reduction gearbox. Inducing APP clutch slippage could be initiated and controlled through a re-design of the clutch mechanism. This method, when used in other applications, generally results in excessive heat build-up and reduced clutch life (Cameron, 2000). Additionally, power production could be controlled by replacing the APP fuel control with a fully automated digital engine control, or FADEC. Exceeding the preset values would result in fuel flow limiting, thus limiting horsepower production.

4.1.2.2. Pre-failure Identification. Pre-failure identification is not a method that attempts to extend the life of the APP. Rather, it is a way to alert personnel that something potentially catastrophic might occur so that they can initiate corrective action before equipment is damaged or personnel sustain injury. Examples of this process include periodic and real-time monitoring.

4.1.2.2.1 Chip Lights and Oil Monitoring. As gears and bearings wear, metallic particles become suspended in the lubricating oil. Drago notes, in reference to metallic contamination monitoring, that "critical systems should always incorporate such devices". These devices might include chip detectors and magnetic drain plugs (Drago, 1988).

With the exception of the APP, all engines and transmissions on the H-53E incorporate magnetic chip detectors (NAMTRAGRU, 1988). The installation of chip detecting system would require the addition of a magnetic chip detector in the bottom of the oil sump; a power source routed to the caution/advisory panel and chip locator panel; an APP SUMP light on the chip locator panel; and associated wiring. Bridging the electrical gap would cause the MASTER CAUTION, CHIP DETECTED, and APP SUMP lights to illuminate, as depicted in figure 15, providing an early indication of potential problems

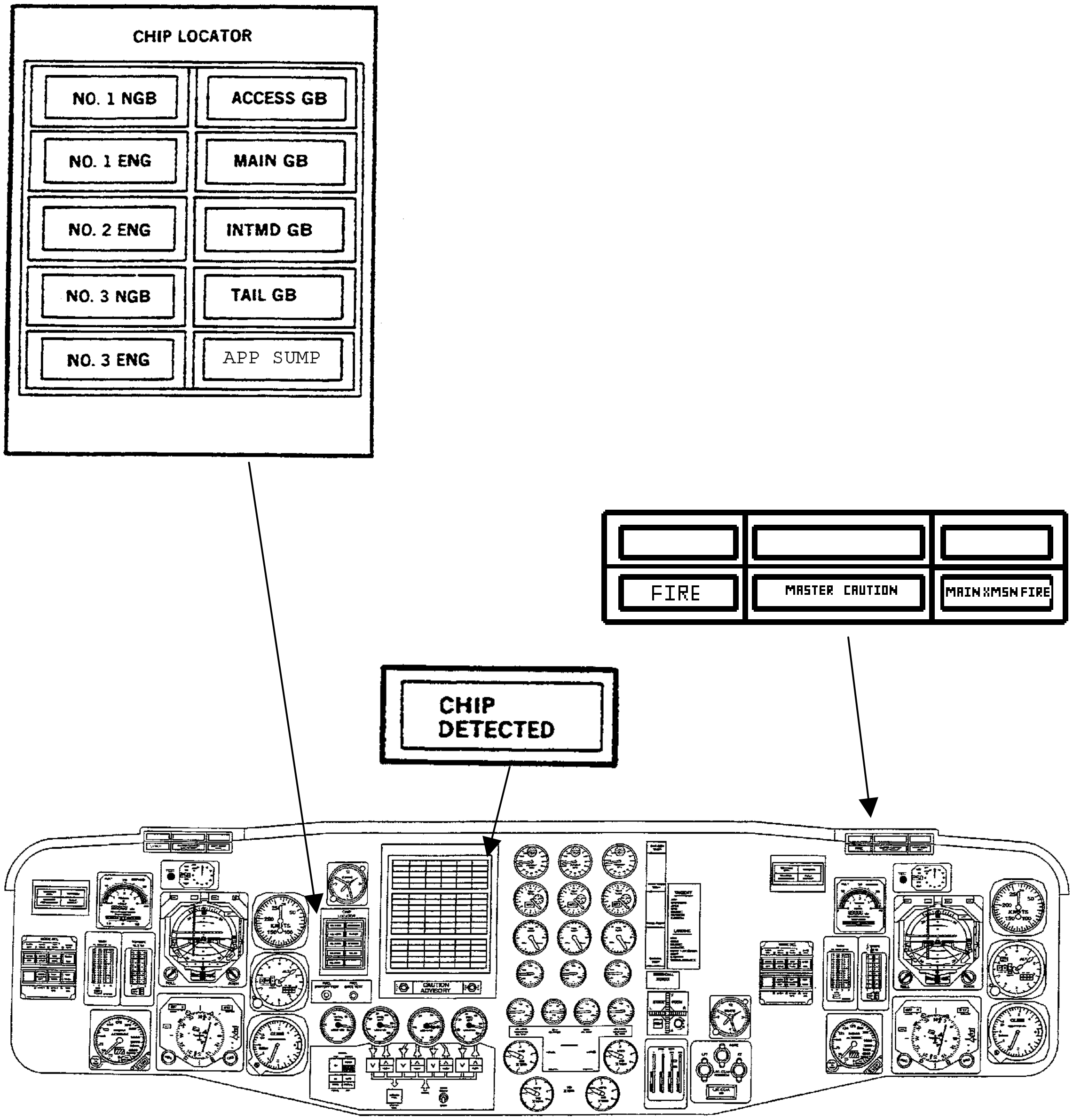

Figure 15
APP Chip Detection Warning

(Naval Air Maintenance Training Group, *Student Guide for MH-53E Pilot Systems Familiarization Course, C-2C-3443, Section IV Diagrams*, Naval Air Maintenance Training Group, Norfolk, VA, August 1988)

within the APP. Given the impact of such an indication, the added expense and complexity of a fuzz burn capability to preclude false indications of impending failure as a result of the gap being bridged does not seem warranted.

Additionally, all transmissions and engines have their respective oils sampled and analyzed at 50 or 100 hour intervals, again, with the exception of the APP. Samples are taken after the specific systems have been run long enough to bring the oil up to operating temperature. They are then shut down, the reservoirs are opened, a tube is inserted, and a small portion of the lubricant is extracted. The extraction is sent off to a lab for analysis. The analysis results are then sent back to the squadron. Maintenance action is taken, if necessary, based on the results of the analysis.

4.1.2.2.2 Health and Usage Monitoring System. Zakrajsek, Handschuh, and Decker note that one of the few options available to reliably monitor dynamic components is through the use of an on-line Health and Usage Monitoring System (HUMS) (Zakrajsek, Handschuh, and Decker, 1994). In their study, a spiral bevel gear and pinion set, seen commonly in helicopters, was instrumented with an accelerometer feeding data into a real-time computer monitor, which in turn processed the frequency data for fault detection and progression. Interestingly, small variations in load and speed had a noticeable affect on the system's ability to reliably process the measured data. As such, they recommend that the two most promising fault detection algorithms be modified to reliably process data in spite of these fluctuations.

The incorporation of such a system on the H-53E to monitor the APP would have to include the same items noted in Zakrajsek, Handschuh, and Decker's study. Additionally, the requirement to be able to download and analyze the health data at the squadron level using existing computing capabilities would have to be ensured. Lastly, a reliable database to determine APP health would have to be established to preclude unnecessary maintenance action[4].

4.1.2.3 Upgraded Reduction Gearbox Assembly. Upgrading the reduction gearbox assembly to meet the power demands of the AGB subsystems is another option available to avoid future failures. Redesigning the gear faces to a design that betters handles applied loads is one potential solution. For example, Townsend notes that like-sized spiral bevel gears are generally better suited to high loads than either straight bevel or Zerol® bevel gears (Townsend, 1962). Additionally, altering gear material, altering gear hardness, altering post-production inspection criteria, or a combination thereof are all methods available to avoid gearbox failure.

4.2 RECOMMENDATIONS.

The H-53E model helicopter is "mature", meaning that it has been through all its developmental and operational test phases and all the planned airframe purchases have been completed. Deficiencies noted during testing have been categorized from major to

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[4] The H-53E was chosen as the airframe to "lead the fleet" for HUMS integration. As of this writing, testing is still ongoing.

minor. Funding to address these deficiencies is generally allocated along these same lines. This fact was a major factor in choosing which alternatives are best suited to address the problem.

a. As has been noted, the caution discussed in paragraph 4.1.1.1.3 has been incorporated into the MH-53E NATOPS manual as an initial measure. It was the most expeditious and most cost effective way to alert units operating the MH-53E of the potential causal factors behind APP failures and to potentially preclude them from overloading the reduction gearbox. To date, it has been the only fleet-wide action taken.

b. In examining the loading conditions, it is apparent that the simultaneous operation of utility 2 and other systems can result in overloads. The decrease in APP reduction gearbox loading while operating the utility 2 system at 1,000 psi, if incorporated, would allow flight crews to conduct simultaneous ground checks, resulting in reduced on-deck time and greater mission flexibility. Additionally, one would expect an increase in APP life due to the reduced exposure to loads above its design limit. The cost of such a system should be minimal, given that the majority of the installation piggy-backs on installed equipment, specifically the depressurization valve and the weight-on-wheels switch, and the fact that only MH-53E aircraft would be subject to this installation[5]. Due to the simplicity, one would expect the incorporation to be quickly accomplished and straightforward. It is, therefore, a recommended solution.

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[5] There are nearly 4 times as many Super Stallions as Sea Dragons.

c. Overtorque protection offers several advantages over reduced utility 2 pressure operations. It would provide an indication of and protection from overload conditions during all ground operations, regardless of aircraft type/model/series, be it MH-53E or CH-53E. However, it is a more complex system and would in all likelihood be expensive. Additionally, it would result in the temporarily loss of the aircraft while the installation was completed, would temporarily result in a non-standard mix of aircraft at the squadron level, and would increase the level of required maintenance. The increased long-term maintenance impact might be mitigated by the reduction in APP and AGB repairs. Still, it is not a practical solution given today's fiscal environment and is therefore not recommended.

d. APP oil sampling and analysis is a simple way to identify the build-up of metal in the lubricating system, providing a means of predicting gearbox failure. It should be incorporated into the oil monitoring program.

e. Installing a magnetic drain plug or a chip detector system is not considered necessary. As noted, the H-53E fleet has been chosen for the installation of HUMS. This system should be adequate, given the development of an accurate failure detection and progression database, to warn of impending problems. The modification of the APP to include a magnetic drain plug and chip detection system is therefore not recommended. If HUMS is not procured, the chip detector system, as previously described, should be reconsidered.

f. Given the long-lead nature of the procurement and upgrade process, limited resources, competing engineering issues, and the life of the H-53[6] program, upgrading the reduction gearbox with new or improved gearing is seen as the least viable alternative. In view of the aforementioned recommendations and in light of the planned procurement of HUMS, it is not recommended.

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[6] The last H-53E was delivered to HMX-1 in 1996. The assembly line has since been closed down.

SECTION V

CONCLUSION

The purpose of this report was to investigate possible causal factors behind failures in the APP reduction gearbox. Testing was conducted to define the operating environment of the APP while it was the sole source of power for the AGB. Test methods were derived by examining CH-53E and MH-53E NATOPS flight manuals to determine a logical series of fleet representative ground checks that would be performed by the flight crew prior to rotor head engagement to replicate APP loading as experienced during day-to-day fleet operations. Two categories of tests were identified, specifically CH/MH-53E common tests and MH-53E unique tests. The test aircraft were configured with an instrumented APP driveshaft to measure torque and drive shaft speed, and an instrumented exhaust to measure EGT. Data were recorded on strip charts. Data were reduced and examined to identify solutions to overload and detrimental transient load conditions noted. Finally, a series of changes designed to preclude future APP reduction gearbox failures were examined.

The changes identified fell into two categories: administrative and engineering. While administrative changes offer advantages in terms of lower expense and quick introduction, they can be difficult to enforce and standardize, and have a long-term impact on fleet operations. Engineering changes, on the other hand, would allow the fleet pilot to conduct “business as usual”, but tend to incur added expense and can take longer to introduce.

Of the changes identified, the two most viable options are a combination of administrative and engineering changes. First, the caution statement recommended by the author, as noted in paragraph 4.1.1, was chosen by NAVAIR as the first step in correcting the identified deficiency. Second, the simplicity and low cost of the utility 2 pressure reduction switch, especially in view of it's beneficial impact on gearbox loading as identified during the test program, made it the next choice. Additionally, APP oil sampling and analysis was recommended by the author for incorporation with current items included in the H-53E oil analysis program. Lastly, with the planned procurement by NAVAIR of a HUMS, the other oil monitoring items as well as upgrading the reduction gearbox redesigned internal components were not recommended.

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APPENDIX

Table A-1 (1 of 4)
Phase 1 Test Results (MH-53E BuNo 162497)

Event	Initial Load	Concurrent Loads		Torque	Speed		SHP	EGT	Comments
		First	Second		RPM	%			
1	Motor Engine #1	None	None	610	8,250	100.4	79.8	776	Peak
2	Motor Engine #2	None	None	610	8,250	100.4	79.8	742	Peak
3	Motor Engine #3	None	None	605	8,250	100.4	79.2	742	Peak
4	Motor Engine #1	AFCS Servo 1 pressurized	None	720	8,200	99.8	93.7	742	Spike
5	Motor Engine #1	AFCS Servo 2 pressurized	None	740	8,200	99.8	96.3	742	Spike
6	Motor Engine #1	Pedal doublet	None	680	8,250	100.4	89.0	742	Peak
7	Motor Engine #1	Cyclic stir	None	760	8,250	100.4	99.5	776	Peak
8	Motor Engine #1	Collective doublet	None	900	8,200	99.8	117.1	809	Peak
9	Motor Engine #1	All flight controls	None	800	8,200	99.8	104.1	809	Peak
10	Pylon Fold/Spread	None	None	-	8,450	102.8	-	675	Note (5)
11	Pylon Fold/Spread	Cargo ramp	None	-	8,400	102.2	-	675	Note (5)
12	Pylon Fold/Spread	Utility hoist	None	-	8,400	102.2	-	675	Note (5)
13	Pylon Fold/Spread	Cargo ramp	Utility hoist	-	8,450	102.8	-	641	Note (5)
14	Blade Fold/Spread	None	None	-	8,400	102.2	-	641	Note (5)
15	Blade Fold/Spread	Cargo ramp	None	-	8,500	103.5	-	641	Note (5)
16	Blade Fold/Spread	Utility hoist	None	480	8,250	100.4	62.8	708	Peak

Notes:
(1) Conditions: 28 March 1995; OAT: +1 C; Hp: -30 ft.
(2) APP Specifications: SN: S424620; model: T-62-T-27; type: 42100-0; time since new: 819 hrs; time since overhaul: 241 hrs; overhaul: May 1992; installed: 26 June 1992; starts: 3,076.
(3) SHP limit was 110.
(4) EGT limit was 1149.8° F.
(5) Torque for this event was below the 400 in.-lb MMT.

Table A-1 (2 of 4), continued

Event	Initial Load	Concurrent Loads		Torque	Speed		SHP	EGT	Comments
		First	Second		RPM	%			
17	Blade Fold/Spread	Cargo ramp	Utility hoist	-	8,400	102.2	-	641	Note (5)
18	Utility Hoist	None	None	-	8,400	102.2	-	675	Note (5)
19	Cargo Ramp	None	None	-	8,500	103.5	-	641	Note (5)
20	Cargo Ramp	Utility hoist	None	-	8,450	102.8	-	641	Note (5)
21	Cargo Ramp	AFCS Servo 1 pressurized	None	-	8,400	102.2	-	641	Note (5)
22	Cargo Ramp	AFCS Servo 2 pressurized	None	-	8,400	102.2	-	641	Note (5)
23	Cargo Ramp	Motor #1 engine	None	640	8,250	100.4	83.8	776	Peak
24	Cargo Ramp	Pedal doublet	None	-	8,400	102.2	-	641	Note (5)
25	Cargo Ramp	Cyclic stir	None	-	8,350	101.6	-	641	Note (5)
26	Cargo Ramp	Collective doublet	None	460	8,300	101.0	60.6	675	Peak
27	Cargo Ramp	All flight controls	None	-	8,300	101.0	-	641	Note (5)
28	Cargo Ramp	Pedal doublet	AFCS Servo 1 pressurized	420	8,400	102.2	56.0	641	Peak
29	Cargo Ramp	Cyclic stir	AFCS Servo 1 pressurized	-	8,300	101.0	-	641	Note (5)
30	Cargo Ramp	Collective doublet	AFCS Servo 1 pressurized	480	8,250	100.4	62.8	675	Peak

Notes: (1) Conditions: 28 March 1995; OAT: +1 C; Hp: -30 ft.

(2) APP Specifications: SN: S424620; model: T-62-T-27; type: 42100-0; time since new: 819 hrs; time since overhaul: 241 hrs; overhaul: May 1992; installed: 26 June 1992; starts: 3,076.

(3) SHP limit was 110.

(4) EGT limit was 1149.8° F.

(5) Torque for this event was below the 400 in.-lb MMT.

Table A-1 (3 of 4), continued

		Concurrent Loads			Speed				
Event	Initial Load	First	Second	Torque	RPM	%	SHP	EGT	Comments
31	Cargo Ramp	All flight controls	AFCS Servo 1 pressurized	460	8,300	101.0	60.6	675	Peak
32	Cargo Winch	All flight controls	AFCS Servo 1 pressurized	460	8,300	101.0	60.6	675	Peak
33	Utility Hoist	AFCS Servo 1 pressurized	None		8,450	102.8		641	Note (5)
34	Utility Hoist	Motor #2 engine	AFCS Servo 1 pressurized	620	8,200	99.8	80.7	742	Peak
35	Utility Hoist	All flight controls	AFCS Servo 1 pressurized	460	8,300	101.0	60.6	641	Peak
36	Utility 2 System on	None	None	720	8,350	101.6	95.4	641	Spike
37	AMCM Winch Pallet	None	None	620	8,450	102.8	83.1	641	Peak
38	AMCM Winch Pallet	Utility hoist	None	680	8,250	100.4	89.0	776	Peak
39	AMCM Winch Pallet	Cargo ramp	None	700	8,200	99.8	91.1	809	Peak
40	AMCM Winch Pallet	AFCS Servo 1 pressurized	None	720	8,200	99.8	93.7	809	Peak
41	AMCM Winch Pallet	AFCS Servo 1 pressurized	Pedal doublet	900	8,200	99.8	117.1	843	Peak

Notes: (1) Conditions: 28 March 1995; OAT: +1 C; Hp: -30 ft.

(2) APP Specifications: SN: S424620; model: T-62-T-27; type: 42100-0; time since new: 819 hrs; time since overhaul: 241 hrs; overhaul: May 1992; installed: 26 June 1992; starts: 3,076.

(3) SHP limit was 110.

(4) EGT limit was 1149.8° F.

(5) Torque for this event was below the 400 in.-lb MMT.

Table A-1 (4 of 4), continued

Event	Initial Load	Concurrent Loads		Torque	Speed		SHP	EGT	Comments
		First	Second		RPM	%			
42	AMCM Winch Pallet	AFCS Servo 1 pressurized	Cyclic stir	880	8,200	99.8	114.5	843	Peak
43	AMCM Winch Pallet	AFCS Servo 1 pressurized	Collective doublet	1,080	8,200	99.8	140.5	944	Peak
44	AMCM Winch Pallet	AFCS Servo 1 pressurized	Move all flight controls	1,100	8,150	99.2	142.2	944	Peak

Notes: (1) Conditions: 28 March 1995; OAT: +1 C; Hp: -30 ft.

(2) APP Specifications: SN: S424620; model: T-62-T-27; type: 42100-0; time since new: 819 hrs; time since overhaul: 241 hrs; overhaul: May 1992; installed: 26 June 1992; starts: 3,076.

(3) SHP limit was 110.

(4) EGT limit was 1149.8° F.

(5) Torque for this event was below the 400 in.-lb MMT.

Table A-2 (1 of 4)
Phase 2 Test Results (MH-53E BuNo 163054)

Event	Initial Load	Concurrent Loads			Torque	Speed		SHP	EGT	Comments
		First	Second	Utility 2 System		RPM	%			
1	APP Clutch Engagement	None	None	Off	910	8,450	102.8	122.0	826	Spike
2	Motor #1 Engine	AFCS Servo 1 pressurized	None	Off	660	8,370	101.9	87.7	859	Peak
3	Motor #1 Engine	AFCS Servo 2 pressurized	None	Off	750	8,350	101.6	99.4	876	Spike
4	Motor #1 Engine	Pedal doublet	None	Off	730	8,350	101.6	96.7	910	Peak
5	Motor #1 Engine	Cyclic stir	None	Off	740	8,350	101.6	98.0	944	Peak
6	Motor #1 Engine	Collective doublet	None	Off	960	8,280	100.8	126.1	960	Peak
7	Motor #1 Engine	Move all flight controls	None	Off	870	8,320	101.3	114.8	960	Peak
8	APP Clutch Engagement	None	None	On/ 3,000 psi	1,170	8,450	102.8	156.9	977	Spike
9	Motor #1 Engine	AFCS Servo 1 pressurized	None	On/ 3,000 psi	710	8,350	101.6	94.1	876	Peak

Notes: (1) Conditions: 30 November 1995; OAT: +6C; Hp: -200 ft.
(2) APP Specifications: SN: 834809; model: T-62-T-27; type: 42100-0; time since new: unknown; time since overhaul: 82.8 hrs; overhaul: 6 September 1994; installed: 6 September 1994; starts: 233 since overhaul.
(3) SHP limit was 110.
(4) EGT limit was 1149.8° F.
(5) Torque for this event was below the 400 in.-lb MMT.

Table A-2 (2 of 4), continued

Event	Initial Load	Concurrent Loads			Torque	Speed		SHP	EGT	Comments
		First	Second	Utility 2 System		RPM	%			
10	Motor #1 Engine	AFCS Servo 2 pressurized	None	On/ 3,000 psi	830	8,325	101.3	109.6	910	Spike
11	Motor #1 Engine	Pedal doublet	None	On/ 3,000 psi	750	8,350	101.6	99.4	927	Peak
12	Motor #1 Engine	Cyclic stir	None	On/ 3,000 psi	580	8,350	101.6	76.8	960	Peak
13	Motor #1 Engine	Collective doublet	None	On/ 3,000 psi	980	8,280	100.8	128.7	1,011	Peak
14	Motor #1 Engine	All flight controls	None	On/ 3,000 psi	850	8,325	101.3	112.3	994	Peak
15	Utility 2 system On	None	None	On/ 1,000 psi	-	8,450	102.8	-	744	Note (5)
16	AMCM Winch Pallet	None	None	On/ 1,000 psi	605	8,400	102.2	80.6	778	Spike
17	AMCM Winch Pallet	Utility hoist	None	On/ 1,000 psi	-	8,450	102.8	-	743	Note (5)
18	AMCM Winch Pallet	Cargo ramp	None	On/ 1,000 psi	-	8,450	102.8	-	777	Note (5)

Notes: (1) Conditions: 30 November 1995; OAT: +6C; Hp: -200 ft.

(2) APP Specifications: SN: 834809; model: T-62-T-27; type: 42100-0; time since new: unknown; time since overhaul: 82.8 hrs; overhaul: 6 September 1994; installed: 6 September 1994; starts: 233 since overhaul.

(3) SHP limit was 110.

(4) EGT limit was 1149.8° F.

(5) Torque for this event was below the 400 in.-lb MMT.

Table A-2 (3 of 4), continued

Event	Initial Load	Concurrent Loads			Torque	Speed		SHP	EGT	Comments
		First	Second	Utility 2 System		RPM	%			
19	AMCM Winch Pallet	AFCS Servo 1 pressurized	None	On/ 1,000 psi	-	8,400	102.2	-	777	Note (5)
20	AMCM Winch Pallet	AFCS Servo 1 pressurized	Pedal doublet	On/ 1,000 psi	-	8,400	102.2	-	777	Note (5)
21	AMCM Winch Pallet	AFCS Servo 1 pressurized	Cyclic stir	On/ 1,000 psi	-	8,450	102.8	-	777	Note (5)
22	AMCM Winch Pallet	AFCS Servo 1 pressurized	Collective doublet	On/ 1,000 psi	480	8,400	102.2	64.0	811	Peak
23	AMCM Winch Pallet	AFCS Servo 1 pressurized	All flight controls	On/ 1,000 psi	460	8,400	102.2	61.3	811	Peak
24	Utility 2 System On	None	None	On/ 3,000 psi	580	8,400	102.2	77.3	777	Spike
25	AMCM Winch Pallet	None	None	On/ 3,000 psi	460	8,400	102.2	61.3	811	Peak
26	AMCM Winch Pallet	Utility hoist	None	On/ 3,000 psi	440	8,400	102.2	58.6	844	Peak
27	AMCM Winch Pallet	Cargo ramp	None	On/ 3,000 psi	-	8,450	102.8	-	811	Note (5)

Notes: (1) Conditions: 30 November 1995; OAT: +6C; Hp: -200 ft.

(2) APP Specifications: SN: 834809; model: T-62-T-27; type: 42100-0; time since new: unknown; time since overhaul: 82.8 hrs; overhaul: 6 September 1994; installed: 6 September 1994; starts: 233 since overhaul.

(3) SHP limit was 110.

(4) EGT limit was 1149.8° F.

(5) Torque for this event was below the 400 in.-lb MMT.

Table A-2 (4 of 4), continued

Event	Initial Load	Concurrent Loads			Torque	Speed		SHP	EGT	Comments
		First	Second	Utility 2 System		RPM	%			
28	AMCM Winch Pallet	AFCS Servo 1 pressurized	None	On/ 3,000 psi	460	8,400	102.2	61.3	811	Peak
29	AMCM Winch Pallet	AFCS Servo 1 pressurized	Pedal doublet	On/ 3,000 psi	640	8,350	101.6	84.8	878	Peak
30	AMCM Winch Pallet	AFCS Servo 1 pressurized	Cyclic stir	On/ 3,000 psi	660	8,350	101.6	87.4	878	Peak
31	AMCM Winch Pallet	AFCS Servo 1 pressurized	Collective doublet	On/ 3,000 psi	800	8,300	101.0	105.4	946	Peak
32	AMCM Winch Pallet	AFCS Servo 1 pressurized	All flight controls	On/ 3,000 psi	800	8,300	101.0	105.4	946	Peak

Notes: (1) Conditions: 30 November 1995; OAT: +6C; Hp: -200 ft.

(2) APP Specifications: SN: 834809; model: T-62-T-27; type: 42100-0; time since new: unknown; time since overhaul: 82.8 hrs; overhaul: 6 September 1994; installed: 6 September 1994; starts: 233 since overhaul.

(3) SHP limit was 110.

(4) EGT limit was 1149.8° F.

(5) Torque for this event was below the 400 in.-lb MMT.

VITA

Patrick J. Twomey was born in Minneapolis, MN, on January 19, 1966. After graduation from Seattle University in 1988, he was commissioned an Ensign in the U.S. Navy. He graduated from MH-53E Fleet Replacement Squadron training at Helicopter Mine Countermeasures Squadron 12 (HM-12) in 1991 and reported to HM-15 shortly afterward. In October 1993, he was selected for Test Pilot Training at the U.S. Naval Test Pilot School (USNTPS) and graduated from the Rotary Wing curriculum in December, 1994. He then served at the Naval Rotary Wing Aircraft Test Squadron from December, 1994, to February, 1997, testing and evaluating various Navy and Marine Corps helicopters, including the MH-53E and CH-53E. From February 1997 through January 2004, he was the Air Plans Officer at Mine Countermeasures Squadron One; Executive Officer at the Airborne Mine Countermeasures Weapon Systems Training School; Detachment One Officer-in-charge and Operations Officer at HM-14; and the Senior Rotary Wing Instructor Pilot at USNTPS. He is currently assigned to Air Test and Evaluation Squadron 21 (HX-21, formerly known as the Naval Rotary Wing Aircraft Test Squadron) as an Engineering Test Pilot on the MH-60S and H-53 programs.