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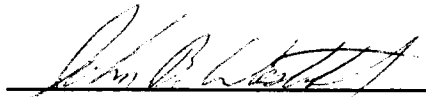
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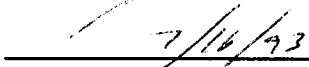
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AN INVESTIGATION INTO HOT GAS INGESTION
BY AN HH-65A HELICOPTER

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

John Bradley Westerbeke
August 1993

DEDICATION

This thesis is dedicated to my parents
Mr. John H. Westerbeke, Jr. and
Mrs. Frances K. Westerbeke
who have encouraged me despite
the hazards I invite,
and to my fiancée Cindy
who demonstrated superb
patience throughout

ACKNOWLEDGMENTS

I would like to thank my major professor, Dr. Frank Collins, for his support. I would also like to thank the committee members, Mr. Robert Richards and Dr. Ted Paludan for their comments and assistance over the past year. I would like to express my thanks to Mr. Kurt Long who was my lead engineer for the test project and who *really* understood what was going on.

ABSTRACT

This thesis presents the methodology developed to determine if the HH-65A helicopter could be subject to the ingestion of a ship's hot exhaust gases into its engine intakes while operating from the flight deck of that ship. The research and development was conducted in response to a request by the United States Coast Guard for the United States Navy to determine the answer to the question presented above. The two major areas of preparation included an analysis of the effects of hot gas ingestion and the aerodynamic flow mechanisms by which the hot gases could travel, and the development of a method to determine if hot gases can be ingested by the helicopter. Although not the sole method of data collection and analysis, the use of infrared thermography was identified as the most practical and conclusive method available for this effort. The data were collected by conducting hover maneuvers to determine baseline helicopter power requirements, then conducting actual shipboard landings and launches at sea under various relative wind conditions while recording applicable data. The infrared thermography images were recorded on video tape and digitally on a computer. The results of the data analysis revealed that although there was some interaction of the ship's exhaust gases with the helicopter, they never actually reached the engine inlets.

It was concluded that the ingestion of hot gases into the helicopter engine inlets did not occur and should not be a concern during routine helicopter operations aboard this ship. Additionally, the infrared thermography video provided the definitive evidence required to support this conclusion.

TABLE OF CONTENTS

CHAPTER	PAGE
1. INTRODUCTION	1
2. BACKGROUND	4
3. LITERATURE REVIEW	9
4. METHODOLOGY	17
General	17
The Test Assets	18
210 ft Medium Endurance Cutter	18
HH-65A Helicopter	21
Hot Gas Ingestion	25
Aerodynamic Circulation Patterns	33
General	33
The Ground Vortex	34
Wingtip Vortex	37
Inner Wake Reflection	38
Hub Wake	41
Main Rotor Tip Vortex	42
Instrumentation	43
General	43
HH-65A Helicopter	43
WMEC 615 Cutter	46
Common	50
Qualitative Assessment	53
General	53
Dynamic Interface Pilot Rating Scale	54
Cooper Harper Handling Qualities Rating Scale	59
Turbulence Scale	61
Vibration Assessment Rating Scale	63
Test Conduct	64
General	64
Land-Based Flight Tests	64
Pierside IR Thermography	66
Shipboard Flight Tests	66
5. RESULTS AND DISCUSSION	71
General	71
Hover Ladder	72
Land-Based	72
Shipboard	74
Shipboard Verses Land-Based	77
Main Transmission Torque	82
Engine Condition Monitoring System	86

Rating Scales	87
Infrared Thermography	89
Flight Deck Thermocouples	98
6. CONCLUSION	101
BIBLIOGRAPHY	106
VITA	110

LIST OF TABLES

TABLE	PAGE
1. Helicopter Characteristics Comparison	25
2. The Pilot Rating Scale (PRS)	55
3. HH-65A Main Transmission Torque And Main Rotor Speed Values Which Determine Specific PRS Values	57
4. Turbulence Scale	62
5. Vibration Assessment Rating (VAR) Scale	63
6. Hover Ladder Test Matrix	65
7. Flight Test Condition Summary	71
8. Events With High Peak Main Transmission Torque Values	83
9. Main Transmission Torque Values Recorded By The Helicopter's ECMS	87

LIST OF FIGURES

FIGURE	PAGE
1. Profiles of the (a) CG-47, (b) DD-963, and (c) DDG-993 class ships	11
2. The SH-2F "Seasprite" Helicopter	12
3. The SH-3H "Sea King" Helicopter	15
4. The CH-46E "Sea Knight" Helicopter	16
5. Pre-MMA 210 Foot Coast Guard Medium Endurance Cutter (WMEC 615 Class)	20
6. Post-MMA 210 Foot Coast Guard Medium Endurance Cutter (WMEC 615 Class)	20
7. The HH-65A "Dolphin" Helicopter	22
8. The CH-53 "Sea Stallion" Helicopter	26
9. Thrust Loss Due To Temperature Rise Of Ingested Air For A Typical Turbofan Or Turboshaft Engine.	29
10. Typical Shipboard Approach Profile	31
11. Effect Of Rotor Height Above The Ground On Inlet Concentration.	31
12. The Formation and Destruction of the Ground Vortex	36
13. The Wingtip Vortex	38
14. Inner Wake Reflection	40
15. Variation Of Rotor Inner Wake Boundaries.	40
16. Hub Wake Circulation Patterns	41
17. Main Rotor Tip Vortex	42
18. ECMS Monitored Parameters List	44
19. HH-65A Main Transmission Torque Values	58
20. Cooper-Harper Handling Qualities Rating Scale	60
21. DI General Launch/Recovery Envelope	67
22. HH-65A Flight Manual Hover Torque Comparison With Land-Based Hover Ladder Test Torques	73
23. HH-65A Flight Manual Hover Torque Comparison With Shipboard Hover Ladder Test Torques	75
24. The HH-65A Conducting A Shipboard Hover Ladder	76
25. Comparison Of Land-Based Hover Ladder Test Torques With Shipboard Hover Ladder Test Torques, Using Land-Based Torque As Reference	78
26. Exhaust Stack Thermocouple Installation	80
27. Temperatures Recorded By Exhaust Stack Mounted Thermocouples	81
28. Flight Manual Hover In Ground Effect Torque Comparison With Shipboard Test Torques	85
29. Flight Manual Hover Out Of Ground Effect Torque Comparison With Shipboard Test Torques	86
30. Pilot Rating Scale (PRS) Data	88
31. Photographic Presentation Of The IR Camera's Field Of View	91

32.	IR Thermography Image Of Exhaust Gas During Final Approach To Landing Evolution With Relative Winds 000 degrees at 22 knots	92
33.	IR Thermography Image Of Exhaust Gas During Hover Prior To Landing With Relative Winds 000 degrees at 22 knots	93
34.	IR Thermography Image Of Exhaust Gas With Helicopter On Deck After Landing With Relative Winds 000 degrees at 22 knots	94
35.	IR Thermography Image Of Exhaust Gas With Helicopter On Deck Prior To Launching With Relative Winds 000 degrees at 22 knots	95
36.	IR Thermography Image Of Exhaust Gas With Helicopter On Deck Prior To Launching With Relative Winds 000 degrees at 22 knots	96
37.	IR Thermography Image Of Exhaust Gas During Launching Evolution With Relative Winds 000 degrees at 22 knots	97
38.	Flight Deck Thermocouple Locations	99
39.	A Sample Of The Flight Deck Thermocouple Data .	100

LIST OF ABBREVIATIONS

DI - Dynamic Interface
DMA - Defense Mapping Agency
DTIC - Defense Technical Information Center
ECMS - Engine Condition Monitoring System
FAA - Federal Aviation Administration
GTG - Gas Turbine Generator (also known as SSG)
HOGE - Hover Out of Ground Effect
HQR - Cooper Harper Handling Qualities Rating
IR - Infrared
MGB - Main Gearbox (also known as Main Transmission)
MMA - Major Maintenance Availability
NASA - National Aeronautics and Space Administration
NTIS - National Technical Information Service
OAT - Outside Air Temperature
PRS - Pilot Rating Scale
RWATD - Rotary Wing Aircraft Test Directorate
SMP - Ship Motion Package
SSG - Ships Service Generator
SSGTG 3 - Ships Service Gas Turbine Generator Number 3
VAR - Vibration Assessment Rating

LIST OF SYMBOLS

A_D = main rotor disk area (feet²)

v_i = airflow velocity induced by the main rotor system at the rotor disk (feet/second)

v_w = ultimate airflow velocity induced by the main rotor system (feet/second)

T = thrust generated by the main rotor system (pounds)

W = gross weight (pounds)

ρ = density of air (slugs/feet³)

D_L = main rotor disk loading (pounds/feet²)

CHAPTER 1

INTRODUCTION

The multi-faceted capability of the modern day helicopter has provided man with a tool uniquely suited to a number of tasks. Although its most notable reputation may be as a weapon system, both defensive and offensive, used by armed forces throughout the world, the helicopter has become an indispensable part of everyday life. A few of the tasks accomplished by helicopters include transporting the injured, logistics support of offshore working platforms, assisting loggers in removing timber from remote locations, supporting law enforcement activities, herding livestock, providing commercial transportation, and providing a flexible search and rescue platform. Any situation which requires rapid airborne transportation while maintaining the capability to operate from remote areas not easily approached by ground transportation, or to locations that are otherwise confined or inaccessible are situations in which the helicopter excels. (Fay, 1976)

With the ever expanding roles in which the helicopter participates come an increased exposure to hazards, old and new, that may impede or catastrophically end the mission of a flight crew. These hazards come in numerous forms including

atmospheric phenomena, natural and man made surface obstacles, mid-air collision, or the ingestion of some foreign matter into the engine intake. This last hazard has the obvious impact of partial or total destruction of the engine, but if the ingested material is some form of hot gas, either from recirculation of the helicopters own exhaust or exhaust from some external source, the result can be reduced engine power output which may not be sufficient for the aircraft to operate in its present environment or possibly engine surges, thrust fluctuations, or engine compressor stalls (AGARD, 1968).

Arguably, the most challenging environment for a helicopter and the pilot to operate in is at sea from the flight deck of a small ship. This environment includes many of the hazards previously mentioned as well as the difficulties associated with launching from and landing onto a platform which is in motion. The research conducted in this thesis develops a method to explore the impact of operating a helicopter from and to the flight deck of a ship which has engine exhausts that discharge in the vicinity of that flight deck.

The hot gas ingestion problem has attracted significant attention in other areas of aviation, but relatively little attention for helicopters, particularly in the shipboard environment. The purpose of Chapter 2 is to present the background information leading to this investigation of potential hot gas ingestion by an HH-65A helicopter while

operating from a 615 class U. S. Coast Guard Medium Endurance Cutter (WMEC 615), as requested by the U. S. Coast Guard.

Part of the preparation for this flight test program included a review of similar investigations previously conducted. Chapter 3 is included to provide an overview of other investigations into the area of hot gas ingestion.

Preparation for the flight test program included a theoretical analysis of the operating environment with its potential impact on the performance of the helicopter. Beyond the theoretical analysis, an analysis of various methods of collecting the appropriate data was conducted. In Chapter 4, an in-depth review of the test planning process is completed followed by a summary of the events leading to final preparation for the actual test flights.

The data collected, along with a discussion of the results, are presented in Chapter 5, and the author's conclusions, which do not necessarily reflect the conclusions reached by the U. S. Navy, are included in Chapter 6.

CHAPTER 2

BACKGROUND

Before the background of this specific hot gas ingestion investigation can be discussed, it is important to have a general understanding of the effects of hot gas ingestion on the performance of a helicopter, and of the various aerodynamic flow mechanisms which may contribute to this phenomena. Hot gas ingestion problems are not unique to rotorcraft only, so much of the following discussion, particularly in regard to the performance effects, can be applicable to fixed wing aircraft which use some form of turbine engine.

The effects of hot gas ingestion on aircraft performance can be divided into both short term and long term effects. The importance or applicability of either is dependent on the aircraft's operating environment, the amount of time the aircraft operates within that particular environment, and the nature or composition of the hot gas which may be ingested by the aircraft.

Short term effects include those that are observable or measurable for the period of time that the aircraft is physically operating within the hot gas environment and while hot gas is being ingested by the engine(s). The short term

effects dissipate immediately after the hot gas ingestion flow into the engine is terminated. The primary relevance is not dependent on the type of gas being ingested, but rather the increase in engine inlet temperature above ambient temperature associated with the hot gas. This is discussed by several sources, including Bevan and Hodder (1986). In an example taken from Bevan and Hodder (1986), a typical modern engine operating at 4000 feet and 95°F which experiences an inlet temperature rise of 14.5°C was shown to have a power decrease from 830 to 759 shaft horsepower, or a 15 percent power loss. This corresponded to a 10 percent reduction in thrust. In many cases, a 15 percent power loss, although noticeable, would not present an unnecessary risk to the aircraft. However, if an aircraft is operating near the limits of its engine(s) capability, in close proximity to some obstacle such as the ground, or is attempting a maneuver that requires precise aircraft control such as landing and such a power loss is experienced, the results could be catastrophic.

Long term effects are those which are present even after the aircraft has exited the hot gas ingestion environment and do not diminish with time. Repeated exposure to the hot gas ingestion environment generally cause the long term effects to worsen with time. The long term effects are attributed to coating of the engine compressor by contaminants present in the ingested gas. As reported by Altobelli (1982), this type of hot gas ingestion resulted in a nominal 7.6 percent to 12.7

percent power loss in the CH-53D helicopter. In most cases, this deterioration in performance would become apparent to a flight crew while performing routine power available checks and does not present the risks associated with a sudden power loss. However, the impact can still be dramatic if the long term power loss limits the aircraft from performing maneuvers or flying in atmospheric conditions which require total power near the normal operating limits of its engine(s). As an example, in the case of a helicopter, this power loss may mean, in some situations, the difference between being able to hover or not. If a helicopter cannot hover, then it has lost the capability that separates it from most other forms of rapid airborne transportation and significantly reduces its flexibility.

The Rotary Wing Aircraft Test Directorate (RWATD), located in Patuxent River, Maryland, is a United States Navy organization responsible for all aspects of rotary wing test and evaluation for the Navy and Marine Corps and additionally assists other government agencies in support of rotary wing related projects. The Dynamic Interface (DI) Department of the RWATD is primarily tasked with conducting shipboard dynamic interface testing of various helicopter and ship combinations. This tasking includes but is not limited to the development of safe helicopter landing and launching wind and ship motion envelopes for use in the shipboard environment, the test and evaluation of systems used to facilitate shipboard landings

and launches, and the investigation of any potential hazards within this shipboard environment that may unnecessarily place the helicopter and ship at risk (Kolwey, 1977). In June of 1992, the United States Coast Guard tasked the DI Department of the RWATD to evaluate the combination of an HH-65A helicopter and a 210 foot Medium Endurance Cutter which had undergone Major Maintenance Availability (MMA) structural modifications.

The Coast Guard tasking included three major goals. The first goal was to evaluate the validity of using the pre-MMA launch and recovery wind and ship motion envelopes that were already in existence for this helicopter and ship combination for use aboard the post-MMA cutter. This validation was necessary because one of the structural modifications incorporated into the post-MMA configuration resulted in a reduction in the useable surface area of the flight deck by approximately 22 percent. This structural modification was the construction of an exhaust stack structure located at the forward end of the flight deck just aft of the cutter's superstructure. The pre-MMA cutter had all of it's exhaust sources discharged below the water line. In addition to the reduction in flight deck size, this exhaust stack structure presented a second potential hazard. The post-MMA cutter's exhausts discharged just forward and approximately 25 feet above the flight deck. The second goal of this test program was to determine if this exhaust gas stack could create an

environment which would make the HH-65A helicopter a potential victim of hot gas ingestion. The third goal was to evaluate the Talon securing system which was designed to rapidly secure the helicopter to the flight deck at touch down and to secure the helicopter to the deck prior to launching (Heinz, 1990). Information concerning the first and third goals is provided so that the reader has a complete understanding of the scope of this flight testing evolution but they are not a subject of this thesis.

CHAPTER 3

LITERATURE REVIEW

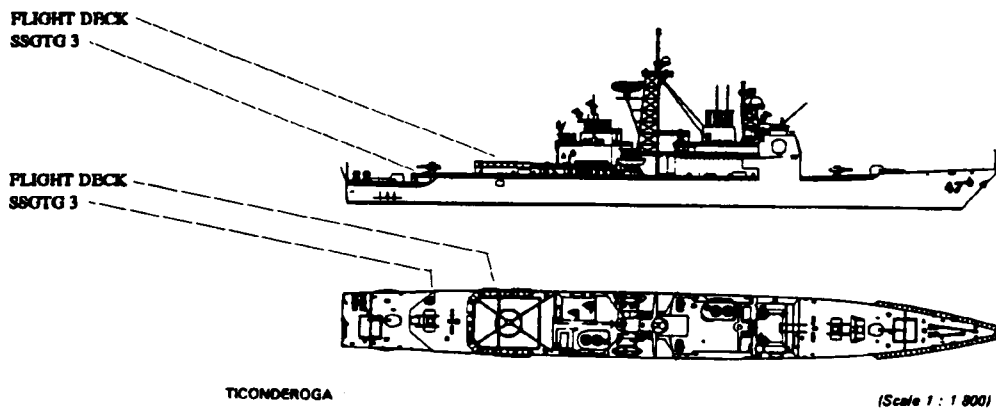
A comprehensive literature search was conducted to identify any previous investigations into the area of hot gas ingestion by helicopters operating in the shipboard environment. Three different computerized literature searches were completed by the Patuxent River Naval Air Station Base Library located in Patuxent River, Maryland. The data bases interrogated included a local data base maintained by this library, the Defense Technical Information Center (DTIC) data base, and the National Technical Information Service (NTIS) data base.

With such a narrow search topic, there was little expectation that very much would be generated, and in fact not one document of any type was uncovered directly related to hot gas ingestion by a helicopter in the shipboard environment. The search topic was later expanded beyond the shipboard environment and beyond simply helicopters. Because the DI Department of RWATD is the focal point for all helicopter-ship dynamic interface testing for the United States Armed Forces, an informal search of local files was also conducted. This search revealed that no formal reports had ever been published directly relating to this topic, but that some limited testing

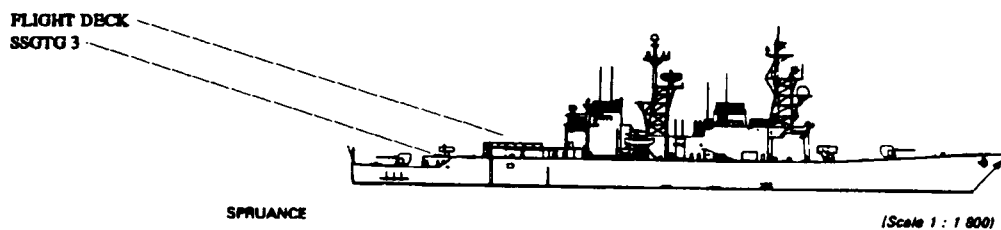
had been conducted with helicopter-ship combinations other than that being addressed in this thesis and that some informal reporting had been completed.

All documented testing previously conducted by the DI Department centered around one particular ship configuration, but included several different types of helicopters. This ship configuration was common to three specific classes of ships, the Ticonderoga Class Guided Missile Cruiser (CG-47 class), the Spruance Class Destroyer (DD-963 class), and the Kidd Class Guided Missile Destroyer (DDG-993 class) (Moore, 1984). Because these three classes of ships were built upon identical hulls and the portion of the ship's design that was important to this investigation was virtually identical between all three, either type ship would have been suitable for the test effort. As it turned out, due to ship and aircraft availability issues, two distinct testing periods were identified and both the CG-47 and the DD-963 classes of ships were used. (Long, 1993) Profiles of these ship classes are presented in figure 1.

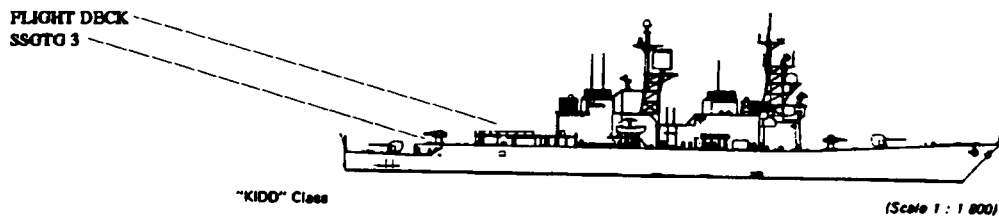
The issue at hand for these two test periods was the Ships Service Gas Turbine Generator Number Three (SSGTG 3) exhaust stack located just aft of, to the left side of, and one deck below the flight deck.



(a)



(b)



(c)

Figure 1. Profiles of the (a) CG-47, (b) DD-963, and (c) DDG-993 class ships.

Source: Moore, John. Jane's Fighting Ships, 1984-1985. New York, New York: Jane's Publishing, Incorporated.

The concern was that helicopters which had to fly through these exhaust gases in order to land on the flight deck may encounter a short term hot gas ingestion problem in the critical shipboard landing phase of a flight.

The first test period was conducted in June of 1988 and evaluated the effects of SSGTG 3 onboard a DDG-963 class ship in combination with an SH-2F helicopter. A diagram of the SH-2F is presented in figure 2.

Prior to actual flight testing, the SSGTG 3 exhaust temperatures were measured at two locations using point source thermocouples with the SSGTG 3 under full load. The temperature measurements were made at the exhaust outlet located 5.3 ft below the flight deck level and at the flight deck level directly above the exhaust outlet.

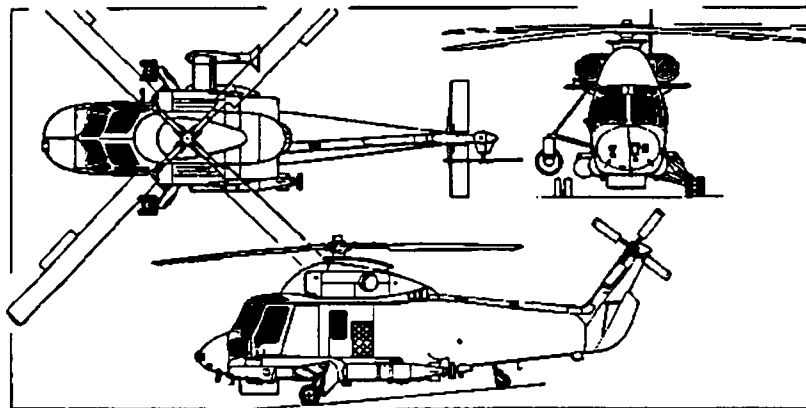


Figure 2. The SH-2F "Seasprite" Helicopter.

Source: Taylor, John. 1983. Jane's All The World's Aircraft, 1983-1984. New York, NY: Jane's Publishing, Incorporated.

The maximum recorded temperatures were 464 degrees F and 200 degrees F respectively with an ambient air temperature of 65 degrees F. The SH-2F aircraft used was representative of a normally configured aircraft with the exception that the right hand engine inlet was instrumented to record inlet temperature. It was noted that the aircraft was flown at an average gross weight of 10,995 lbs, a gross weight relatively low in comparison to it's maximum gross weight of 13,500 lbs.

The test team summarized that using a lighter gross weight would minimize exhaust plume dispersion and/or exhaust mixing caused by the rotor downwash and thus provide the maximum opportunity to validate any exhaust gas ingestion. In addition, emphasis was placed on low relative wind conditions in expectation that this would also help to minimize exhaust plume dispersion (Smith, 1988). At this point, it is important to note that not only are true winds important to consider in a shipboard landing evolution, but because a ship is usually in motion, the winds relative to the moving flight deck, which is a vector sum of the true winds and the ship's course and speed, are of paramount importance. These relative winds are in essence what the aircraft must contend with as it lands onto, hovers over, or launches from a moving platform. This feature also has some advantages in that the relative winds can be controlled to a large extent by adjusting the course and speed of the ship.

During over four hours of flight testing with the SSGTG

3 under full load, two relative wind conditions were identified that resulted in an engine inlet temperature rise indicating that hot gas ingestion was occurring. With relative winds over the flight deck of 210 degrees to 240 degrees at 5 knots, there was a 10 degree F inlet temperature rise over ambient temperature. With relative winds 190 degrees to 210 degrees at 2 knots, an inlet temperature rise of 5 degrees F above ambient temperature was recorded. In both cases, this event occurred just as the helicopter transitioned over the edge of the flight deck. Under both of these conditions, the exhaust plume from the SSGTG 3 would be expected to travel forward and to the right in relation to the ship which would place it directly over the flight deck and not only in the direct path of the helicopter, but to a large degree traveling along with the helicopter, during the final phase of the landing. The test team calculated that for this aircraft at the test day conditions, a 10 degree F inlet temperature rise reduced power available by approximately 3 percent. It was further stated that during conditions of marginal excess power and relative winds as indicated previously, SSGTG 3 exhaust effects *will* reduce the hover capability of the SH-2F helicopter. A restriction in the relative wind landing envelope was recommended based on these results (Smith, 1988).

The second test period occurred in January of 1989 onboard a CG-47 class ship using both an SH-3H and a CH-46E helicopter. The SH-3H and the CH-46E are presented in figures

3 and 4, respectively. The approach to this test was identical to the first test period. Again, light aircraft gross weights and low relative wind speeds were emphasized in order to minimized exhaust gas dispersion and mixing. It is important to note that the average gross weights of the SH-3H and the CH-46E, which were 17,500 lbs and 19,000 lbs respectively, were significantly higher than that of the SH-2F of the first test period. No notable inlet temperature rise was identified in either aircraft that could be attributed to ingestion of the SSGTG 3 exhaust. It was recommended that relative wind restrictions for shipboard landings and launches not be established for either type aircraft (Baty, 1989).

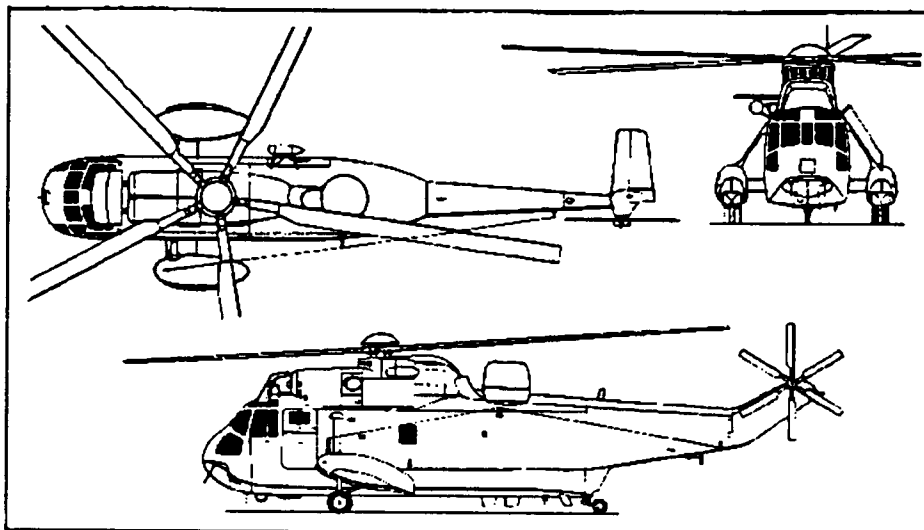


Figure 3. The SH-3H "Sea King" Helicopter.

Source: Lambert, Mark. 1991. Jane's All The World's Aircraft, 1991-1992. New York, NY: Jane's Publishing, Incorporated.

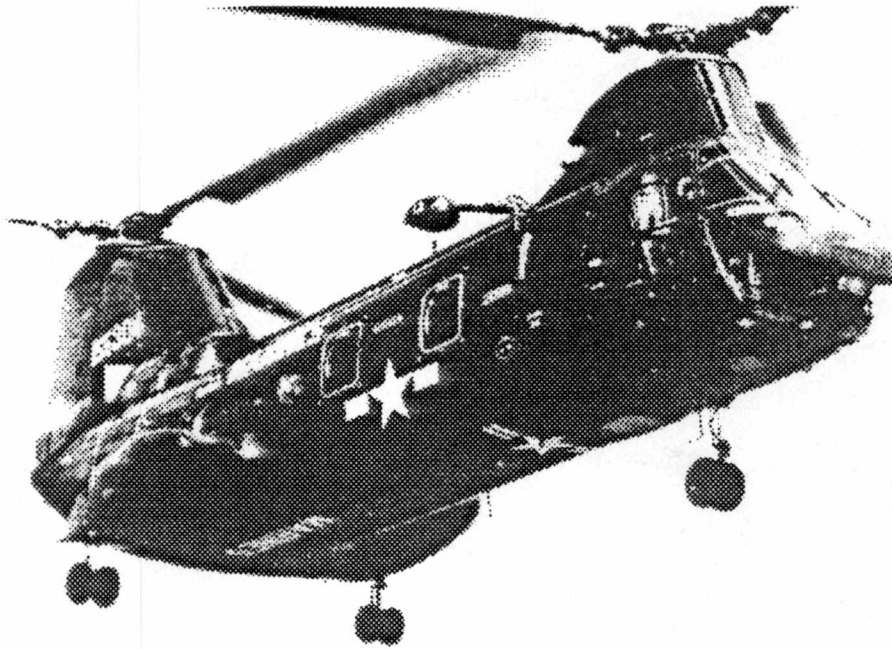


Figure 4. The CH-46E "Sea Knight" Helicopter.

Source: Taylor, John. 1983. Jane's All The World's Aircraft, 1983-1984. New York, NY: Jane's Publishing, Incorporated.

As part of the investigation and preparation for the flight test program at hand, additional research was conducted concentrating on two particular goals. The first was to gain a more complete understanding of the detriments of experiencing hot gas ingestion as was discussed in chapter 2. The second was to gain a knowledge of the aerodynamic circulation patterns that can be generated by a helicopter as it operates in close proximity to the ground. This will be discussed in greater detail in chapter 4. These research efforts were also supported by computerized searches of both the DTIC and NTIS data bases.

CHAPTER 4

METHODOLOGY

General

A testing effort of this magnitude requires a significant amount of preparation and planning. Because this test effort was in support of the U. S. Coast Guard and the RWATD is primarily tasked with supporting U. S. Navy and Marine Corp rotary wing test and evaluation, there was no dedicated test aircraft available. Both an aircraft and a cutter suitable to complete this test had to be provided by the Coast Guard and because of limited asset availability, both helicopter and cutter, there was a very small window of opportunity available. This in itself necessitated thorough planning and preparation. In addition, the expense in terms of monetary costs were very high and may have prevented any attempts to repeat the test if the original test period did not produce the desired results.

In order to satisfactorily address all aspects of the test during the planning process, each major element was evaluated individually and the results were combined to provide a comprehensive test plan. Each of these elements are discussed in the following paragraphs and although they are

presented in a specific sequence, in actuality, research into each area coincided and overlapped with other areas. The author was selected as the project coordinator because of his previous experience flying this model helicopter, because of his extensive experience flying helicopters from ships with a single landing area, and because of past experience working with the Coast Guard on other projects.

The Test Assets

The first step in the planning process was to gain a complete understanding of the environment in which the test will occur. This included evaluating the capabilities and limitations of both the helicopter and the cutter. Without this initial understanding, it would not be possible to adequately design a suitable test program.

210 ft Medium Endurance Cutter

The 210 ft Medium Endurance Cutter, abbreviated WMEC 615, is 210.5 feet long, has a width of 34 feet at it's widest point, has a 10.5 foot draft, and displaces approximately 1,129 tons. The cutter is propelled by two Alco 16V-251 turbocharged diesel engines which can deliver a combined 5,000 horsepower and can propel the cutter to speeds of up to 18 knots. The WMEC 615 cutter has a single helicopter flight deck

located immediately aft of the it's superstructure, approximately 16 feet above the waterline.

All of the cutters in this class have or will undergo a refit or modernization period known as a Major Maintenance Availability (MMA). Specific MMA structural modifications which have an impact on helicopter operations include a relocation of the cutter's two engines, boiler, and two 250 kilowatt ship service generators (SSGs) exhausts to a single vertical stack located aft of the cutter's superstructure and just forward of the flight deck. The exhaust stack discharge point is approximately 25 feet above the flight deck and 45 feet ahead of the center of the landing area. This single structural modification presented three potential difficulties in conducting helicopter operations. The location of the stack reduced the useable size of the landing area from 2,372 to 1,860 square feet. The stack structure itself, as well as the exhaust, may create turbulent wind conditions in the vicinity of the flight deck that could limit the useable wind envelope allowable to conduct helicopter operations. Lastly, the ship's exhaust discharge location created the potential for ingestion of those exhausts by the helicopters engines. A diagram of a pre-MMA WMEC 615 is shown in figure 5 (Moore,1984), and a photograph of a post-MMA WMEC 615 is shown in figure 6. Note the addition of the exhaust stack just aft of the cutter's superstructure in figure 6.

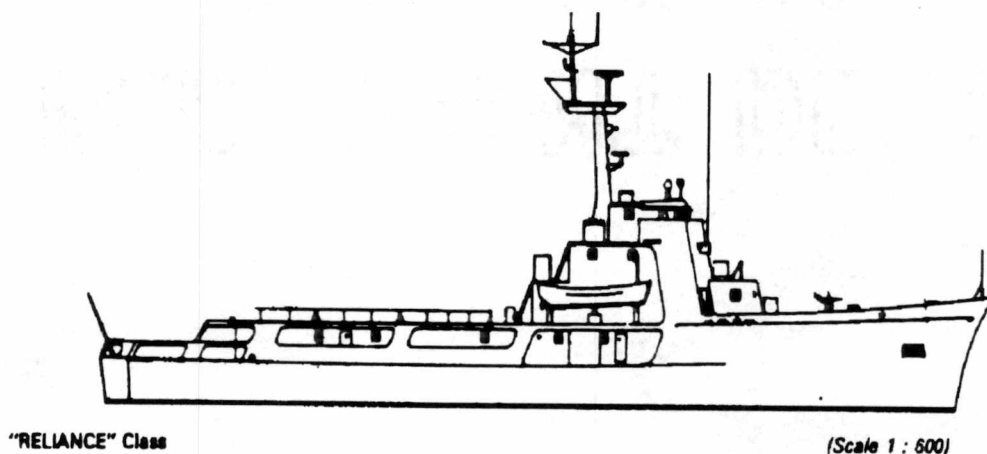


Figure 5. Pre-MMA 210 Foot Coast Guard Medium Endurance Cutter (WMEC 615 Class).

Source: Moore, John. Jane's Fighting Ships, 1984-1985. New York, New York: Jane's Publishing, Incorporated.

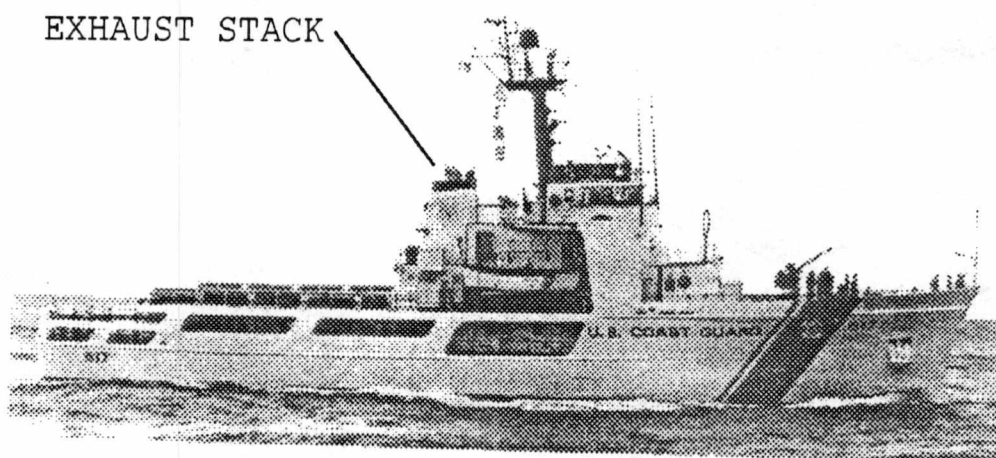


Figure 6. Post-MMA 210 Foot Coast Guard Medium Endurance Cutter (WMEC 615 Class).

Source: Prezelin, Bernard. Combat Fleets Of The World, 1993. Annapolis, MD: Naval Institute Press House.

A closer examination of the ship's exhaust characteristics revealed that at a minimum, the ship required one main engine, one SSG, and the boiler operating to meet propulsion and basic power requirements. In a worst case scenario, all five exhaust sources would be operating simultaneously at full power.

HH-65A Helicopter

The HH-65A helicopter is used by the Coast Guard primarily for search and rescue operations originating from both shore based locations as well as from ships. This helicopter is configured with a four blade single main rotor and a single tail rotor for anti-torque control. It's maximum gross weight is 8,900 pounds, it has a maximum forward airspeed limit of 165 knots and a maximum sideward and rearward airspeed limit of 35 knots. The HH-65A is powered by two Lycoming LTS-101 gas turbine engines which produce a total output of 1,360 shaft horsepower. The main rotor diameter is 39.2 feet which results in a disk area of 1,204.8 square feet. Subtracting out the center portion of the main rotor disk where the blades are attached to the hub and in which no useful lift is produced, the main rotor disk area (A_D) becomes 1,197 square feet. A diagram of the HH-65A is presented in figure 7. (HH-65A, 1992)

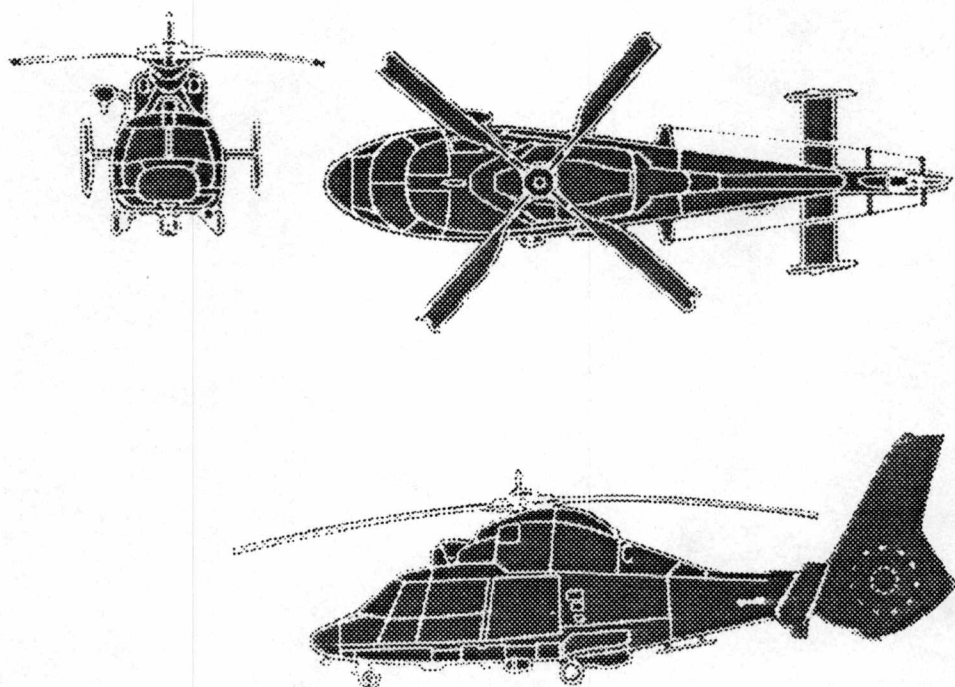


Figure 7. The HH-65A "Dolphin" Helicopter.

Source: HH-65A. 1992. Flight Manual: Series HH-65A Helicopter. Revision 1. Washington, DC: U.S. Coast Guard.

In order to gain a more complete picture of the environment created by this helicopter, additional calculations were performed assuming a standard day at sea level and maximum gross weight. Additionally, the assumption was made that if the helicopter is maintaining a stationary hover, the thrust (T) generated by the main rotor system is equal to the gross weight (W) of the helicopter. Using equation 1, in which ρ is air density, the average velocity (v_i) of the airflow created by the main rotor is 40 feet per second in a hover. This estimation is the average airflow velocity at the rotor disk. The ultimate wake velocity (v_w) is approximately double the velocity seen at the rotor disk and usually reaches this velocity between one and two rotor radii below the helicopter main rotor. Using equation 2, the average main rotor disk loading is 7.44 pounds per square feet. Using equation 3, the main rotor average induced flow rate is 47,400 cubic feet per second.

$$v_i = \sqrt{\frac{T}{2\rho A_D}} = \sqrt{\frac{W}{2\rho A_D}} \quad (1)$$

$$D_L = \frac{T}{A_D} = \frac{W}{A_D} \quad (2)$$

$$\text{Induced Flow Rate} = A_D \times v_i \quad (3)$$

All of these calculations were completed using equations developed from the Momentum Theory (Richards, 1968). Although the Momentum Theory is generally not as precise as some other calculation methods, for the purposes of this investigation, exact numbers are not as important as gaining a general appreciation for the characteristics of the helicopter. The Momentum Theory allows for this without requiring extensive calculations. For comparison purposes, table 1 provides the results of completing the same calculations for both the SH-2F and the SH-3H helicopters. The CH-46E was not included in table 1 because it is a tandem rotor design which would make a direct comparison with the HH-65A less credible. The HH-65A is the lightest of the three helicopters and although its disk loading and main rotor induced velocity are comparable to the SH-3H, it also has the smallest induced flow rate of the three. Based on these characteristics and the fact that only the SH-2F, the lightest helicopter with the smallest induced flow rate from the previous flight tests, exhibited any signs of hot gas ingestion, it can be conservatively assumed that the HH-65A has the potential to be subject to hot gas ingestion.

Table 1. Helicopter Characteristics Comparison.

Helicopter	Gross Weight (pounds)	Main Rotor Disk Area (feet ²)	Main Rotor Average Induced Velocity (feet/second)	Main Rotor Average Disk Loading (pounds/feet ²)	Main Rotor Average Induced Flow Rate (1000 feet ³ / second)
HH-65A	6080/8900	1197	33/40	5.08/7.44	39.1/47.3
SH-2F	11600/13500	1469	41/44	7.90/9.19	59.9/64.6
SH-3H	15300/21000	3010	33/38	5.08/6.98	98.4/115.3

- Notes:
1. Calculations presented represent the minimum and maximum value possible based on helicopter minimum and maximum gross weight values.
 2. Calculations based on standard atmospheric conditions at sea level.
 3. Center portion of main rotor disk in which no useful lift is produced has been subtracted out.

Hot Gas Ingestion

In chapter 2, the problems associated with the ingestion of hot gas by an aircraft engine were discussed. For the purpose of this test, the primary concern was with the possibility of experiencing the short term effects of hot gas ingestion. If it was determined that hot gas ingestion was in fact occurring, but the short term effects were not severe enough to warrant any restrictions in flight operations, then the long term effects would have to be addressed.

As it turns out, the long term effects of hot gas ingestion are relatively easy to deal with. As reported by Altobelli (1982), any long term power loss resulting from the

coating of the engine compressor by contaminants contained in the ingested gases can be erased by performing a periodic engine wash. In his investigation of hot gas reingestion by a CH-53D helicopter, Altobelli determined that in as few as 20 flights hours in an environment conducive to hot gas ingestion, a measurable degradation in available power had occurred. This was immediately corrected by washing the engines. A variant of the CH-53 is presented in figure 8. The HH-65A helicopter is equipped with the hardware and connection points required to support engine washing and the current practice is to wash the engines after the last flight each day following over-water and shipboard flights (Shipboard, 1991). Because of this practice, the long term effects of hot gas ingestion were not considered to be a significant concern.

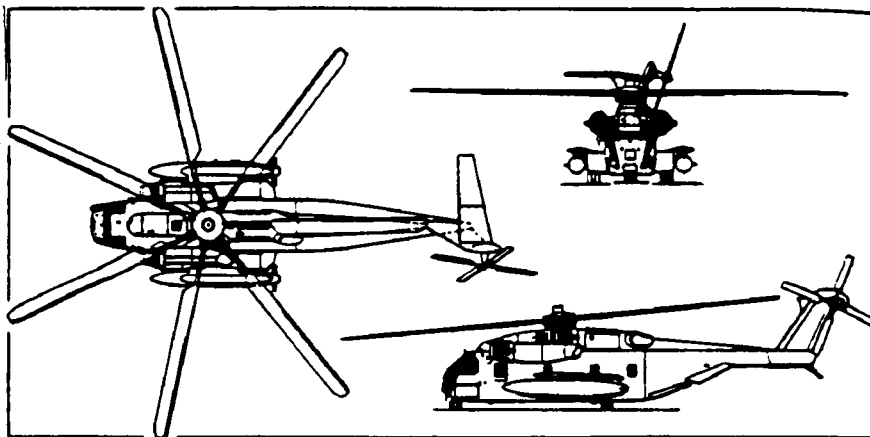


Figure 8. The CH-53 "Sea Stallion" Helicopter.

Source: Taylor, John. 1983. Jane's All The World's Aircraft, 1983-1984. New York, NY: Jane's Publishing, Incorporated.

Additional research into hot gas ingestion was conducted and revealed that an extensive amount of research has been done. A large portion of the documents uncovered dealt with fixed wing military aircraft being subject to hot gas ingestion by the exhaust from missiles, guns, and rockets being fired from the subject aircraft. Some examples include the firing of the Sidewinder missile from an S-3 airplane as reported by Benn, Remick, Pratt and McCune (1987), the firing of the Sidewinder missile from an F-14A airplane (F-14A, 1975), and the firing of Zuni rockets from an S-3 aircraft as reported by Rich (1974). As well as the specific examples given above, similar tests have been conducted, but of a more generic nature, assessing the general effects of hot gas ingestion by gas turbine engines at various altitudes, ingestion rates, flight speeds, and by various hot gas sources (Felderman, 1971)(Rich, 1971, 1970, 1969). Although test reports confirmed the necessary concern with short term hot gas ingestion problems, the nature of these occurrences were not very similar to what the HH-65A helicopter would be subject to. As an example, the temperatures associated with rocket exhaust were generally several times higher than that associated with the WMEC 615 exhausts, but the length of time of ingestion associated with rocket firings was generally less than one second whereas the WMEC 615 exhaust had the potential to be ingested by the HH-65A helicopter in a more continuous manner.

A literature search limited to hot gas ingestion by helicopters and jet aircraft that have the ability to hover revealed that all of the documented research found by the author was devoted to the ingestion of the aircraft's own exhaust back into it's own engine intake(s). From this point forward, "ingestion" will refer to the ingestion of exhaust gases from a source other than the aircraft, and "reingestion" will refer to the ingestion of the aircraft's own exhaust gases. The CH-53D hot gas reingestion investigation conducted by Altobelli (1982) discussed previously was one example. A significant majority of the documentation uncovered was devoted to hover capable jet aircraft rather than helicopters. The most likely reason for this emphasis is that historically hot gas reingestion in helicopters has not been a very serious problem because the exhaust temperatures and downwash velocities are relatively low in comparison to hover capable jet aircraft (AGARD, 1968)(Jackson, 1981). Green and Zanine (1979) presented a figure which shows the loss in thrust for a typical turbofan or turboshaft engine. This is presented in figure 9. Two curves are presented, one for intermediate rated power which is a power setting that can be maintained for usually about 30 minutes, and one for contingency power which provides for additional power, but for a shorter period of time, usually only several minutes. Although these curves were presented in support of research into hot gas ingestion by hovering jet aircraft, they are also applicable to helicopters.

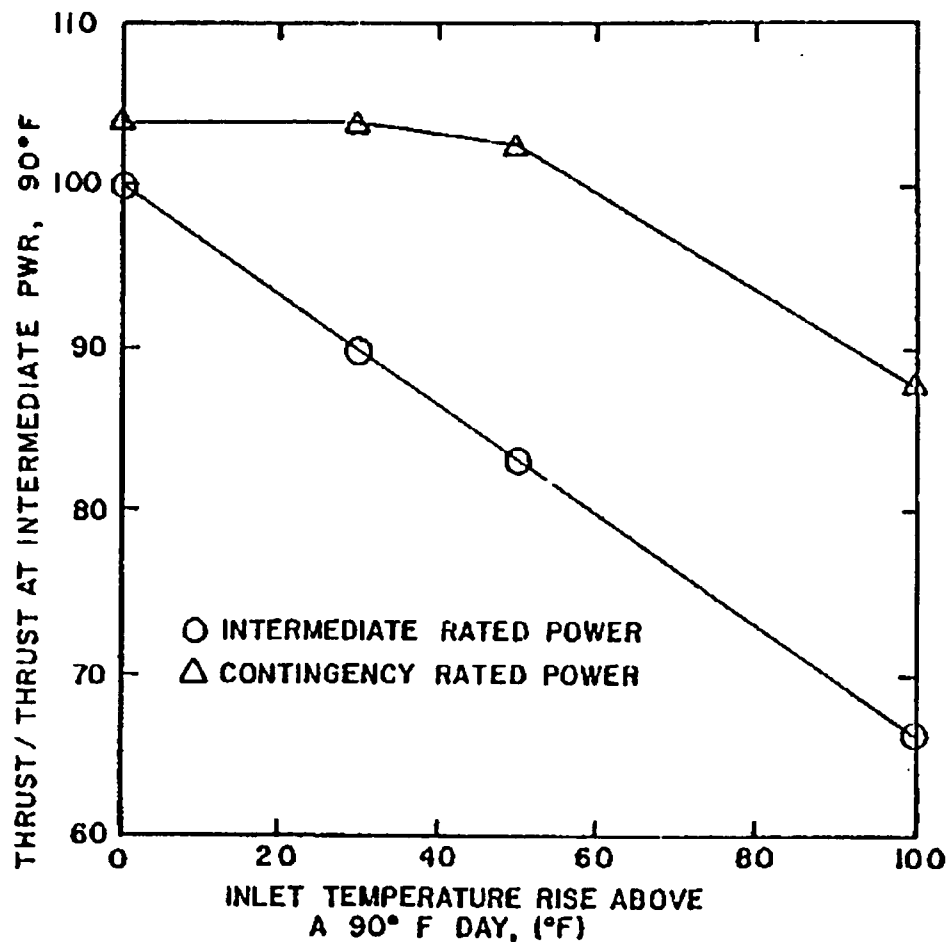


Figure 9. Thrust Loss Due To Temperature Rise Of Ingested Air For A Typical Turbofan Or Turboshift Engine.

Source: Green, K. and J. Zanine. 1979. "Computerized Method For An Estimation Of Hot Gas Reingestion For A VTOL Aircraft At The Conceptual Design Phase." NADC-78256-60, Final Report. Warminster, PA: Naval Air Development Center.

Turczeniuk of Boeing Vertol Company investigated hot gas reingestion of both the YUH-61A and the CH-47C helicopters. In the case of the YUH-61A, the engine inlets were instrumented with high response thermocouples. During deceleration maneuvers beginning from 50 knots at altitudes between 3 and 10 feet, temperature transients as high as 80 degrees C above ambient temperature at a rate of temperature rise of up to 120 degrees per second were recorded. This flight profile would closely match the profile flown while approaching and landing onto the WMEC 615 cutter with the exception that higher altitudes would be flown further from the flight deck. A typical approach profile for shipboard landings is presented in figure 10.

Turczeniuk also determined two important points; that engine power setting had very little effect on the maximum temperature rise at the engine inlet, and that "helicopter height had a major effect, with greater heights showing lesser temperature" (Turczeniuk, 1979). Figure 11 shows the effect of relative height above the ground on inlet concentration.

The test program using the CH-47C helicopter was expanded to include more maneuvers and maneuvers both in and out of ground effect. For helicopters, ground effect is an aerodynamic phenomenon in which the power required to maintain a hover or low airspeed flight is usually reduced as the height above the ground is reduced.

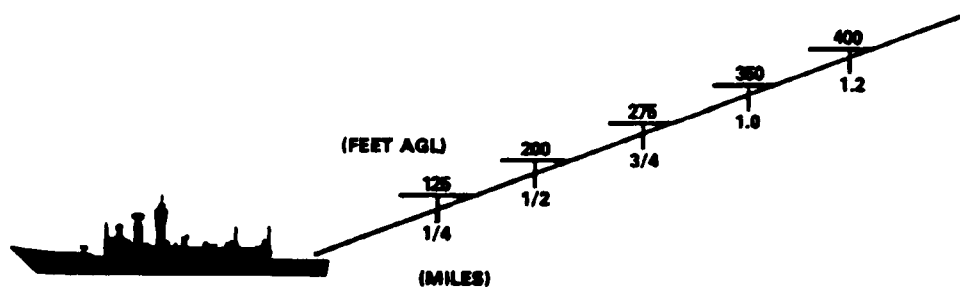


Figure 10. Typical Shipboard Approach Profile.

Source: SH-60B. 1990. NATOPS Flight Manual Navy Model SH-60B Aircraft. Change 1. Washington, DC: Naval Air Systems Command.

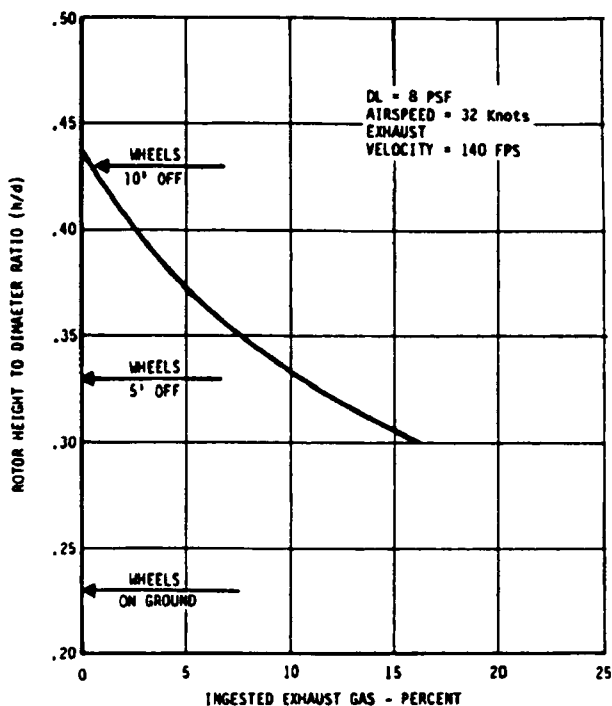


Figure 11. Effect Of Rotor Height Above The Ground On Inlet Concentration.

Source: Turczeniuk, Bohdan. 1979. "Exhaust Gas Reingestion Measurements." American Helicopter Society. Washington, DC: American Helicopter Society.

As height above the ground is increased, the power required to maintain a specific height increases until the helicopter is "out of ground effect." Once out of ground effect, the power required to maintain a specific height above the ground is constant and no longer affected by height above the ground. The specific altitude in which a helicopter transitions from in ground effect to out of ground effect varies slightly, but a height above the ground equal to one rotor diameter is an approximate value (McCue, 1990). Hot gas reingestion was recorded both in ground effect and out of ground effect during lateral acceleration, maximum yaw rate hovering turns, sideward flight, and rearward flight. Typical results included engine inlet temperature rises of 35 degrees C above ambient temperature at rates as high as 200 degrees C per second. Correcting the temperature rise data for lag in the high response thermocouples resulted in a peak corrected temperature rise of 41 degrees C. Using figure 9, this would result in a loss of thrust of 14% at intermediate rated power. In the worst case, the reingestion duration was as long as 6 seconds (Turczeniuk, 1979). Typical shipboard approaches and landings would require maneuvers both in ground effect and out of ground effect including sideward flight, which results in sideward acceleration, and rearward flight. This is true because the relative winds during landings can be from any direction. As an example, if relative winds are from the left and the helicopter is not moving in relation to the ground, as

far as the helicopter is concerned, that would be aerodynamically equivalent to sideward flight to the left.

Summarizing this section, it was shown that hot gas reingestion is a documented phenomenon and that maneuvering typical of a shipboard landing has generated varying degrees of hot gas reingestion. In addition, Turczeniuk (1979) determined that the degree of reingestion decreased with altitude and that the power setting of the helicopter had little effect on the degree of reingestion.

Aerodynamic Circulation Patterns

General

The next and final phase of general research included a determination of the various circulation patterns that exist around a helicopter. There was no attempt to accept or reject the existence or validity of any particular flow pattern or to fully explain their existence, but instead to gain an understanding of the various aerodynamic forces that may be at work and which may then be a path for hot gas to be ingested by a helicopter.

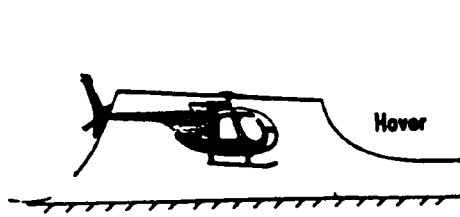
The Ground Vortex

Sheridan and Wiesner (1977) of Boeing Vertol Company conducted a wind tunnel evaluation to investigate the ground vortex largely in response to the complex flow patterns seen during the YUH-61A testing conducted by Turczeniuk (1979). In addition, military application of helicopter use began to see an increase in the amount of time each flight spent in altitude regimes below 125 feet above the ground and airspeed regimes below 50 knots, including sideward and rearward flight (Sheridan, 1977). Again, these flight profiles are typical of what would be experienced during shipboard operations. The results presented here were based on extensive wind tunnel testing using smoke in order to visualize the generated flow patterns.

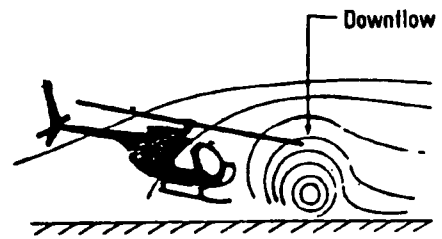
The mechanisms for ground vortex generation were not understood completely, but appeared to be the result of the interaction of the helicopter main rotor downwash with the velocity of forward translation or the presence of a relative wind from ahead of the helicopter. It did not appear to be present from a hover to 5 knots, but at about 5 knots, it began to form. This formation is depicted pictorially in figure 12. Figures 12b and 12c show the ground vortex as it exists between 5 and 10 knots. Oncoming air travels over the vortex, then can be drawn back toward and down through the forward portion of the main rotor disk. Some of this negative

inflow would be directed aft and under the aircraft while the rest would be directed forward to feed the ground vortex itself. Meanwhile, the ground vortex approaches the rotor disk as the aircraft (or relative wind) increases from 5 to 15 knots. As the vortex approaches and moves under the rotor disk, it appears to gain strength. This is depicted in figure 12d. As the vortex moves under the rotor disk between 18 and 20 knots, the flow near the leading edge of the rotor disk changes from a high downflow (negative inflow) to a high upflow, as shown in figure 12e. As the helicopter accelerates up toward 30 to 35 knots, the ground vortex appears to diminish in strength and deteriorate, as shown in figure 12f. This sequence of events was essentially reversed during a deceleration maneuver with the ground vortex finally vanishing forward of the helicopter. Sheridan and Wiesner also verified the steady state existence of the ground vortex when the aircraft was neither accelerating or decelerating.

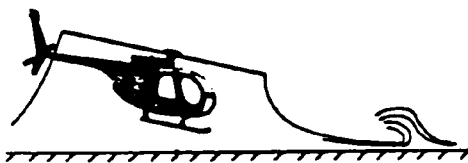
Some additional observations made by Sheridan and Wiesner (1977) include that the vortex center maintained it's vertical position regardless of rotor disk height above the ground, that the vortex center tends to moves aft as rotor height is increased, and that the existence of the ground vortex was not dependent on rotor type or the number of rotor blades. The final conclusion was that the ground vortex resulted from an interaction of the ground, the velocity of translation or helicopter movement, and the main rotor downwash.



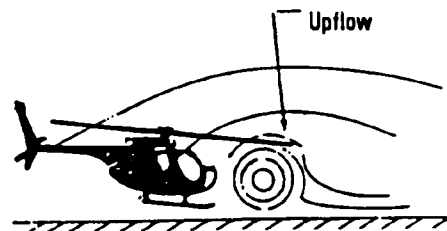
(a) Ground Vortex
in a Hover



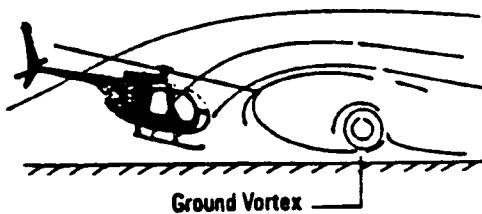
(d) Ground Vortex
at 15 Knots



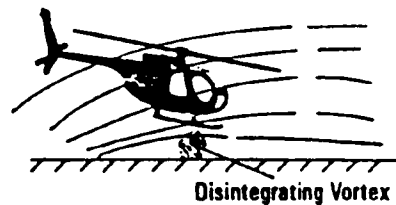
(b) Ground Vortex
at 5 Knots



(e) Ground Vortex
at 20 Knots



(c) Ground Vortex
at 10 Knots



(f) Ground Vortex
at 30 Knots

Figure 12. The Formation and Destruction of the Ground Vortex.

Source: Prouty, R. 1979. "Falling Off The Cushion..." Rotor And Wing International. Peoria, IL: Philips Publishing, Inc.

It was also emphasized that the flow was very unsteady and reached a violence peak as the vortex moved under the rotor disk and was compressed between the ground and the rotor.

Prouty (1979) presents a discussion of the ground vortex phenomenon which tends to confirm the results of Sheridan and Wiesner.

Wingtip Vortex

The wingtip vortex is essentially identical to that which is generated about the wingtips of fixed wing aircraft. In the case of the helicopter, this vortex is formed at the left and right outboard edge of the rotor disk. Wiesner and Kohler (1974) indicate that formation of this vortex is evident beginning about 20 knots and is fully developed by 35 knots. Figure 13 (Wiesner, 1974) pictorially displays the wingtip vortex pattern. This pattern can be view by watching an airplane or helicopter as it flies through smoke or agricultural dust. Sheridan and Wiesner (1977) discussed the wingtip vortex as the phenomenon in which the deteriorated ground vortex is drawn into at approximately 30 knots.

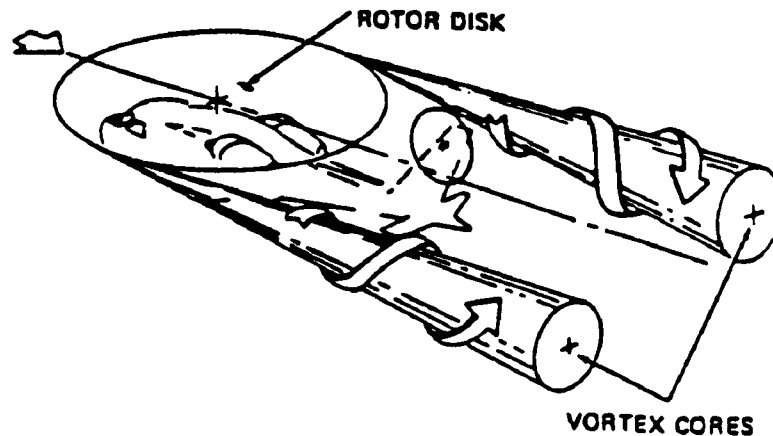


Figure 13. The Wingtip Vortex.

Source: Weisner, W. and G. Kohler. 1974. "Tail Rotor Performance In Presence Of Main Rotor, Ground, And Winds." Journal Of The American Helicopter Society. American Helicopter Society, 29th Annual National Forum. Washington, DC: American Helicopter Society

Inner Wake Reflection

Much of the understanding of inner wake reflection, otherwise known as the *fountain*, is credited to the development of the CH-53E helicopter. During its development, extensive wind tunnel testing was completed, much of which was verified with actual flight test data, documenting inner wake reflection. This phenomenon primarily exists in a hover or at slow airspeeds and is the result of the reflection of rotor downwash into the zone located beneath the center of the main rotor. The inner wake zone is not directly affected by

downwash because the helicopter fuselage blocks the downwash in this location and because the rotor blades are attached to the rotor hub at the center and no useful lift is produced there. Once in the inner wake core, the air mass is free to circulate up through the rotor hub. (Jackson, 1981)

The specific purpose of this testing was to evaluate hot gas reingestion during hovering in ground effect because of the addition of a third engine, designated number 2, behind the main rotor center. Figure 14 (Jackson, 1981) presents a schematic of this circulation pattern. Figure 15 (Jackson, 1981) depicts the inner wake reflection boundaries as affected by hover altitude. As evident from figure 15, the higher the altitude, the smaller the inner wake reflection zone becomes. In addition, as the altitude decreases, more of the recirculation region appears above the rotor disk.

Jackson and House concluded that inner wake reflection was primarily influenced by rotor height above the ground, but that it was also affected by distortions in wind speed, wind direction, and airframe interference. They also concluded that larger helicopters were more prone to hot gas reingestion as a result of the inner wake reflection in that the inner wake core was larger with larger helicopters. (Jackson, 1981)

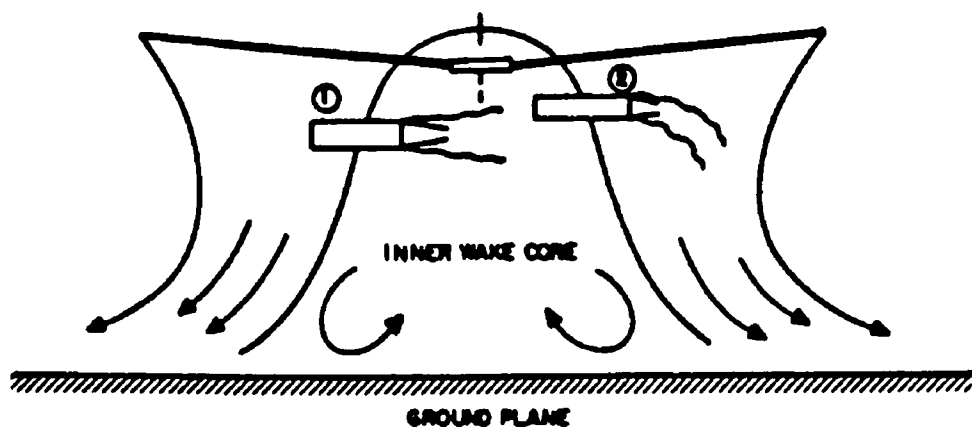


Figure 14. Inner Wake Reflection.

Source: Jackson, Micheal and Richard House. 1981. "Exhaust Gas Reingestion During Hover In-Ground-Effect." American Helicopter Society, 37th Annual Forum. Washington, DC: American Helicopter Society.

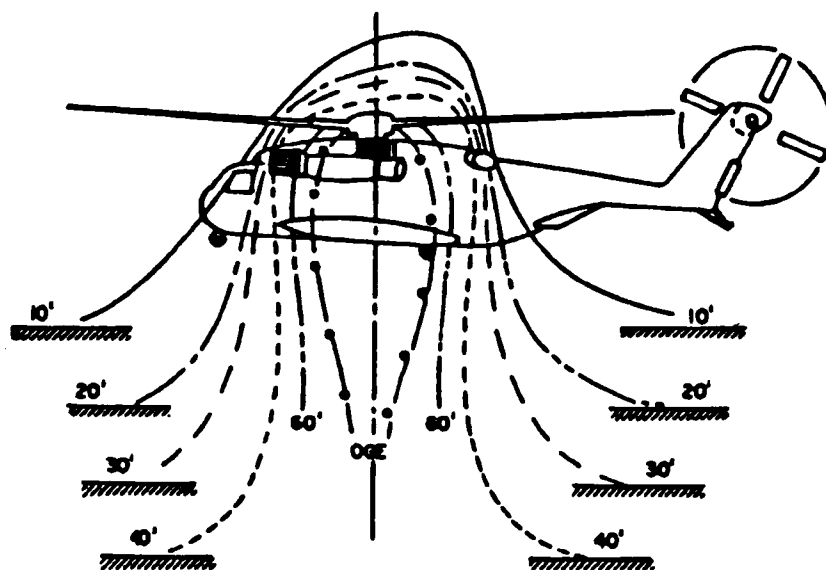


Figure 15. Variation Of Rotor Inner Wake Boundaries.

Source: Jackson, Micheal and Richard House. 1981. "Exhaust Gas Reingestion During Hover In-Ground-Effect." American Helicopter Society, 37th Annual Forum. Washington, DC: American Helicopter Society.

Hub Wake

Bevan and Hodder (1986) discussed the existence of a wake zone behind the main rotor hub. This hub wake, or region of separated flow, was created whenever there was a relative wind from the nose of the helicopter. This wake would be similar to one created if one drags their hand through a tub of water. This region was an area of low pressure which created a pocket in which any trapped gases could actually migrate forward towards the engine inlets. In some cases, the flow could travel up through the rotor behind the rotor hub, then forward over the top of the rotor hub, and finally back down through the rotor forward of the rotor hub. A diagram taken from Bevan and Hodder (1986) of these two flow paths is presented in figure 16.

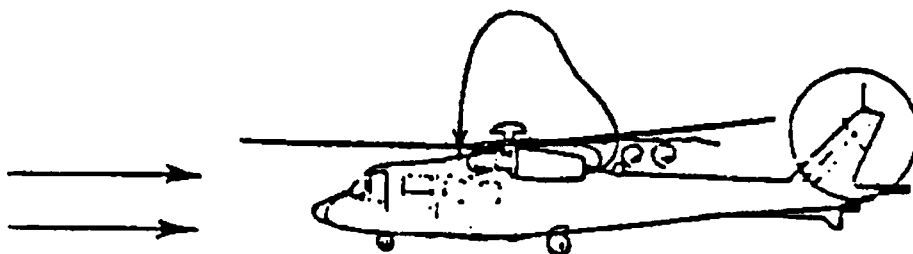


Figure 16. Hub Wake Circulation Patterns.

Source: Bevan, David and David Hodder. 1986. "Investigation Into Helicopter Main Rotor/Exhaust Gas Flow Interactions." Fort Eustis, VA: Aviation Applied Technology Directorate.

Main Rotor Tip Vortex

Main rotor tip vortex is the recirculation of the main rotor downwash near the rotor tip upward and outboard of the main rotor, then back down through the rotor. Figure 17 depicts this flow pattern. If the recirculation pattern were large enough, hot gas could be carried from the exhaust, around the rotor tip, and back down through the main rotor in the vicinity of the engine intake(s). This flow path is considered to be very unsteady and not likely to be able to support high gas temperatures for any significant period of time. In addition, the path described would be very lengthy and also not likely to support high gas temperatures for very long (Hanker, 1983).

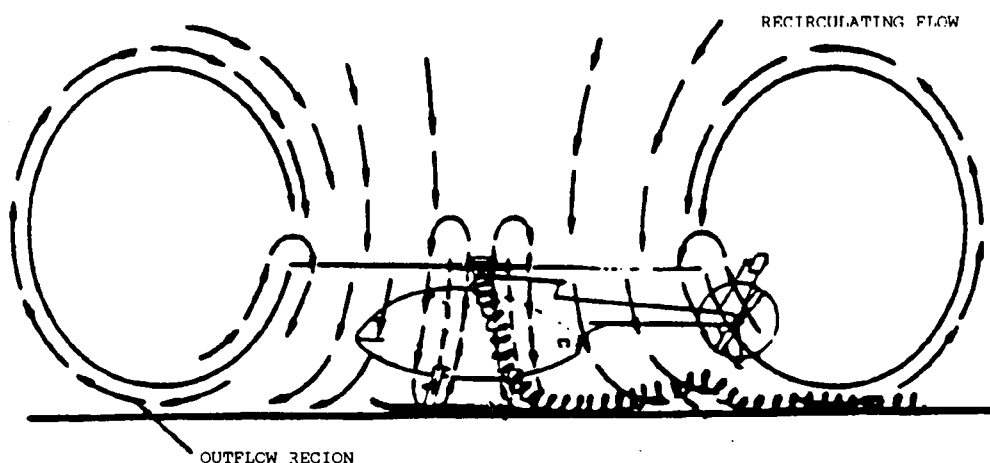


Figure 17. Main Rotor Tip Vortex.

Source: Prouty, R. 1979. "Falling Off The Cushion..." Rotor And Wing International. Peoria, IL: Philips Publishing, Inc.

Instrumentation

General

Armed with a familiarity of the test assets, an understanding of the effects of hot gas ingestion, and an understanding of some of the potential aerodynamic mechanisms by which hot gas could be introduced into the helicopter inlets, the next issue to be addressed was how to instrument the WMEC 615 cutter and the HH-65A helicopter to provide the information desired.

HH-65A Helicopter

The HH-65A helicopter is somewhat unique in relation to military helicopters in that it has an Engine Condition Monitoring System (ECMS) built into it's onboard systems. The ECMS monitors selected parameters of both engines and of the main rotor transmission and provides the aircrew with a visual warning whenever a monitored parameter exceeds acceptable limits. A list of the monitored parameters is presented in figure 18 (HH-65A, 1992). Once a limit is exceeded, the aircrew can enter the ECMS data base to determine exactly which parameters were exceeded, and to what degree. A more complete description of the ECMS can be found in the HH-65A Flight Manual (HH-65A, 1992).

Parameter	Exceedance Conditions
Gas Generator Speed (NG)	NG Overspeed
Power Turbine Speed (NP)	NP Overspeed
Fuel Pressure (FP)	Low Fuel Pressure
Engine Torque (Q)	Over Torque
Total Torque (QT) (Calculated)	Over Torque
Main Rotor RPM (NR)	Rotor Overspeed
Measured Gas Temperature (MGT)	Time at High MGT
Main Gearbox Temperature (GBT)	High MGB Oil Temperature
Main Gearbox Pressure (GBP)	Low MGB Oil Pressure
Engine Oil Pressure (EOP)	High/Low Oil Pressure
Engine Oil Temperature (EOT)	High Oil Temperature Versus OAT

NOTE: The above listed parameters are monitored for exceedance conditions (i.e., out of prescribed limits) and displayed on the top two lines of the engine exceedance page. If multiple exceedances occur simultaneously, each exceedance is recorded and monitored individually as a single exceedance.

MGB - Main Gearbox (Main Transmission)

OAT - Outside Air Temperature

Figure 18. ECMS Monitored Parameters List.

Source: HH-65A. 1992. Flight Manual: Series HH-65A Helicopter. Revision 1. Washington, DC: U.S. Coast Guard.

This system provides a basic instrumentation package that could retain extremely useful information that would ordinarily be lost if the parameter exceeded was of such a short duration as to not be observed by the aircrew. One major disadvantage to the ECMS is that only exceeded parameters are recorded. If the aircraft experiences hot gas ingestion of sufficient magnitude to cause engine parameters to change, but not enough to exceed the limits of those parameters, there would be no recorded indication. The only possibility of recording any parameter change would be if the aircrew happened to see it and could record it manually. Although this would be an acceptable source of information, it could not be solely relied on because the pilots would be involved in

flying the aircraft in a situation which requires a great deal of attention looking outside of the cockpit.

One possible solution to being able to continually record the engine instruments would be to install a video camera inside the aircraft. This is a common technique used for flight testing in this type of application. Unfortunately, the data that would be recorded on video would only be as accurate as the installed instrumentation is capable of providing. As was indicated previously, high response thermocouples were usually used to monitor inlet temperature conditions because of the potentially erratic nature of the ingestion. Production instrumentation generally does not have a fast enough response rate to detect rapidly changing conditions and would not be adequate for this type of application.

Another desirable option would be to instrument one or both engine inlets with high response thermocouples and a recording capability, as was done in many of the investigations discussed previously. This method has the advantage of providing a positive indication of inlet temperature change, but would not provide any information on the path in which the hot gas traveled to the engine inlet.

As was mentioned previously, because this test was in support of Coast Guard tasking and an HH-65A helicopter was not part of the RWATD stable of aircraft, the actual test aircraft would be a normally configured production asset. There would not be an opportunity to perform any

instrumentation other than what could be accomplished at the testing location and within the available time allocated, largely because the aircraft could not be released from it's normal duties for more than the time available to actually conduct the test flights. Because of stringent requirements associated with most airborne instrumentation, including installation, inspection, and flight certification, it was not feasible to do this on site. As a result, the helicopter was not instrumented in any significant fashion. The onboard ECMS was available and would be used to record any engine parameters that were exceeded. In addition, a voice tape recorder would be used to record internal aircraft communications and pilot comments.

WMEC 615 Cutter

The maneuverability of a ship is one of it's greatest assets while conducting helicopter operations. This capability will allow the test team to explore a variety of relative wind conditions simply by adjusting the course and speed of the cutter. With relatively constant true winds and wave characteristics, each different course and speed combination results in different relative winds (which are the vector sum of the true wind direction and speed and the cutter's course and speed), and different pitch, roll, yaw, and heave characteristics of the cutter. Pitch is the rotation of the

cutter about an imaginary axis running laterally through it's center of gravity. Roll is the rotation of the cutter about an imaginary axis running longitudinally through it's center of gravity. Yaw is the rotation of the cutter about an imaginary axis running vertically through it's center of gravity. Heave is the purely vertical motion of the cutter which results as the cutter moves up and down with the waves.

Of prime importance for the hot gas ingestion investigation would be the true wind, relative wind, and cutter course and speed information. The hot gases from the cutter will initially travel with the relative winds when exiting the exhaust stack, then eventually be influenced purely by the true winds as the momentum from the cutter dissipates. The cutter's course and speed and the relative wind information can be recorded manually from indicators available as part of the cutter's normal equipment. The true winds can then be computed using vector analysis.

The Dynamic Interface (DI) Department has also developed a device named the Ship Motion Package (SMP). This device includes a COMPAQ 386 portable computer, a ship motion instrumentation box, assorted interface cables, and SMP data collection and analysis software. The SMP has the capability to measure and record displacements, rates, and accelerations for ship motion in all three axes at a rate of 3 hertz. In addition, the SMP also will record ship's course and speed, and ship's anemometer, or relative wind data. Although the

pitch, roll, yaw, and heave data generated by the SMP would not be directly relatable to the hot gas ingestion investigation, it will provide useful data to develop safe helicopter landing and launching wind and ship motion envelopes, and can also provide ship motion data that can be used to update aircraft simulator motion software.

Documentation of the cutter's exhaust stack gas temperature is also important if in fact hot gas ingestion were to occur. In addition, measurement of the exhaust gas temperature at some distance away from the stack exit point would provide at least a rough estimate of the rate at which the exhaust gas was being dispersed into the atmosphere and how quickly the gas temperature would decrease. Thermocouples would provide this type of data, but in this application, the thermocouple would not need to have the high response capability required at the helicopter engine inlet. This is because the cutter exhaust characteristics would not be expected to vary significantly with the cutter's engines, boiler, and ship's service generators (SSGs) under a constant load. For the purposes of this test, it is desirable to determine the worst possible situation, in other words the highest possible exhaust temperature at the highest possible flow rate, therefore all of the cutter's engines, boiler, and SSGs should be operating under the maximum load whenever possible. In reality, the total exhaust output is largely a function of the cutter's speed. The only way to get the

maximum output from the propulsion engines is to drive the ship at maximum speed; therefore, the exhaust output will be a function of the cutter's speed.

Locating thermocouples at the exhaust stack discharge point would be relatively simple because the stack structure should provide suitable anchor points. Locating thermocouples at some distance downstream of the discharge point presents a more difficult challenge because there are no anchor points available. A thermocouple could be suspended into the exhaust stream or some support structure could be created to project the thermocouple into the exhaust stream, but this presents several problems. First, any extension system may prove to be an obstacle to the helicopter, especially at night when it could not be seen, and second, the exhaust flow path will vary significantly depending upon the changing relative winds as the cutter is maneuvered for different data points and because of rotor wash influences as the helicopter approaches.

Based on the discussion presented above, the decision was made to install the SMP, manually record the cutter's course, speed, and anemometer information as a backup to the SMP, and to install thermocouples at the discharge points of the cutter's exhaust stack. The exhaust of each engine, the boiler, and each SSG exited through individual pipes at the top of the exhaust stack. It was decided to instrument both engine exhausts and one SSG exhaust. The idea to incorporate thermocouples downstream of the exhaust discharge point was

abandoned because of the complexities mentioned earlier and because time constraints imposed on the project would not allow for the installation of a system to accomplish this. In addition to the three thermocouples mentioned above, it was decided to also install two additional thermocouples vertically along the rear wall of the exhaust stack to monitor temperatures in the vicinity of the flight deck. They would provide ambient temperature data as well as indicate possible exhaust gas circulation at the forward portion of the landing area when the helicopter was operating in the vicinity.

Common

The instrumentation methods accepted at this point would provide some basic information, but there was still a major concern that during times of actual hot gas ingestion conditions, the only reliable documentation would be when some helicopter engine parameter was exceeded and recorded by its ECMS. Even in that situation, there would be no guarantee that the cause of engine parameter being exceeded was in fact related to hot gas ingestion. It could as easily be caused by the pilot, or by wind conditions which require high levels of power to maintain controlled flight. A second but less critical concern was that there would be no capability to document the path in which the hot gas travels to reach the helicopter engine inlets.

One solution which had the potential to provide both an indication of hot gas ingestion as well as provide some information concerning the travel mechanism of the hot gas to the engine inlets was the use of an imaging system sensitive to some of the components contained in the exhaust gases. In this case, a system sensitive to carbon dioxide (CO_2), a major compound found in the exhaust of internal combustion engines which use fossil fuels, would satisfy this requirement. A system called the AGEMA 780 Thermovision, which was locally available, was appropriate for this task.

The AGEMA 780 Thermovision is a video camera which detects thermal signatures in the 3 to 5 micron wave length infrared (IR) portion of the electromagnetic spectrum. This system is used for flow visualization only. The IR image temperature scale which is generated is based on a blackbody emission (emissivity equal to 1.0) and assumes no atmospheric attenuation (transmissivity equal to 1.0). The emissivity of a hot gas is generally a function of carbon dioxide concentration, temperature and thickness. Because all three of these characteristics change rapidly as the exhaust dissipates, the emissivity is very dynamic, therefore, the generated temperature scale becomes grossly inaccurate. The temperature scale does provide some reasonable accuracy for solid objects whose emissivity does not significantly change and the temperature readings can be corrected based on an objects known emissivity. The IR images can be recorded both

on analog video tape and digitally using a personal computer. The analog presentation is more useful for visualizing the flow characteristics whereas the digitally processed data provides still images which are most useful for temperature analysis. In order to provide temperature data, thermocouples are used to determine the actual temperature of certain location(s) within the field of view of the AGEMA 780 Thermovision. The thermocouple data is used in the digital processing procedure and provides the reference data from which the complete temperature scale is determined. The thermocouples discussed in the previous section would be used.

The only difficulty in using the AGEMA 780 Thermovision would be to determine a suitable location to mount the camera. The 40 degree field of view of the lens and the width of the cutter were the two limiting factors. Positioning the camera out to the left or the right side of the landing area so that as a minimum, the exhaust stack and the entire landing area was in the field of view would be optimum. This would provide excellent flow path visualization in the longitudinal and vertical directions. If the camera were positioned forward of the exhaust stack looking aft to the landing area, it would not be possible to determine the exhaust flow path in the longitudinal direction because only two dimensional information is provided. The longitudinal and vertical flow path information is most important. Unfortunately, the physical limits of the cutter would not allow for the optimum

mounting location. The best that could be accomplished would be to locate the camera as far out to the outboard edge of the cutter as possible, looking aft so as to include the exhaust stack and the landing area. This location would limit the longitudinal flow path visualization ability, but improve the lateral. Actual location for the AGEMA 780 Thermovision would be determined after arrival at the cutter.

In order to provide standard video documentation of the test evolutions, several video cameras would be mounted onboard the ship. One camera would be co-located with the AGEMA 780 Thermovision camera to provide simultaneous documentation of the test evolutions from an equivalent perspective. Because the AGEMA 780 Thermovision presents IR imagery which can be difficult to visualize, the standard video documentation would help clarify the IR images.

Qualitative Assessment

General

The collection of data to support any conclusions or recommendations is vital to a proper and credible engineering investigation. However, the most important information that can be collected is based on the pilot's opinion of the difficulty in completing the assigned maneuver, in this case a shipboard takeoff and landing. If such a maneuver is

determined by a test pilot to be more difficult than should be permitted for an average pilot to attempt, but there is no additional data available to support that conclusion, then the final decision will be based on the test pilot's input. In order to provide the test pilot with the tools necessary to qualitatively assess the relative ease or difficulty in performing a task, several rating scales have been developed. Additional rating scales also exist for pilots to qualitatively assess environmental factors which may influence the ability to complete a task.

Dynamic Interface Pilot Rating Scale

The DI Department of the RWATD developed the Pilot Rating Scale (PRS) so that test pilots could quantify their qualitative assessment of the relative ease or difficulty of completing a flying task. This scale was specifically developed to assess those tasks associated with helicopter operations in the shipboard environment which include, but are not limited to, takeoffs and landings. The PRS is presented in table 2.

Typically the PRS values assigned by a pilot are based on the degree of task difficulty which is primarily driven by wind direction and velocity, and ship motion. Some of the other factors which can influence the assignment of a PRS value include ship generated turbulence, excessive power

requirements, proximity of obstacles, day verses night luminance levels, and excessive hovering attitudes. In that the goals of this test evolution include developing a safe helicopter landing and launching wind and ship motion envelope, the PRS will play a significant role. The PRS may also play a role in evaluating hot gas ingestion in that conditions created by the hot gas may influence the PRS value assigned to a specific task.

Table 2. The Pilot Rating Scale (PRS).

PRS Number	Pilot Effort	Rating Description
1	Slight	No problems; minimal pilot effort required to conduct consistently safe shipboard evolutions under these conditions
2	Moderate	Consistently safe shipboard evolutions are possible under these conditions. These points define the fleet limits recommended by NAVAIRWARCENACDIV PAX RIVER
3	Maximum	Evolutions are successfully conducted only through maximum effort of experienced test pilots using proven test methods under controlled test conditions. Successful evolutions could not be consistently repeated by fleet pilots under typical operational conditions. Loss of aircraft or ship system is likely to raise pilot effort beyond capabilities of average fleet pilot
4	Unsatisfactory	Pilot effort and/or controllability reach critical levels; repeated safe evolutions by experienced test pilots are not probable, even under controlled test conditions

The most likely area in which hot gas ingestion could influence the PRS value is in the power required to conduct a task. If a particular task requires power in excess of that available, an PRS value indicating unsatisfactory performance should be assigned. For a helicopter, power output is usually determined by measuring the torque being produced by the engine(s), or by measuring the torque being transmitted from the main transmission to the main rotor. In the case of the HH-65A, both systems are used. It was decided that the main transmission torque value would be used as the gauge in which to measure power required. This would require monitoring a single parameter rather than having to average the torque values of both engines. Table 3 presents HH-65A main transmission torque values and main rotor speed conditions which were determined to be limiting factors in assigning PRS values. These torque limits were based on information available in the HH-65A Flight Manual (HH-65A, 1992) which is presented in figure 19. The flight profiles required for shipboard landings and launches include both the "TRANSITION" and "HOVER" portion of figure 19. "TRANSITION" refers to the change in flight profile from a hover to forward flight or from forward flight to a hover. Because the "TRANSITION" branch presented the more restrictive limits, they were chosen to develop table 3.

Table 3. HH-65A Main Transmission Torque And Main Rotor Speed Values Which Determine Specific PRS Values.

Potential Limiting Parameter	PRS-1 or PRS-2 Value	PRS-3 Value	PRS-4 Value
Main Transmission Torque	- $\leq 100\%$ continuous - $\leq 100\%$ transient	- $\leq 106\%$ continuous - $\leq 106\%$ transient	- $> 106\%$ continuous - $> 106\%$ transient
Main Rotor Speed	- $= 100\%$ continuous - $\pm 1\%$ transient	- $= 100\%$ continuous - $\pm 3\%$ transient	- $= 100\%$ continuous - $\pm 5\%$ transient

- Notes: 1. Transient values defined as those lasting less than 5 seconds.
2. All values generated for aircraft speeds of less than 75 knots indicated airspeed.
3. Values determined based on information contained in figure 19.

A second area in which the exhaust gases may influence the PRS is if the gases create turbulence which is detected by the pilot. The pilot may evaluate this as turbulence or as an airframe vibration. In addition to influencing the PRS values, turbulence can be qualitatively evaluated using the Turbulence Scale or the Vibration Assessment Rating Scale which will be discussed shortly.

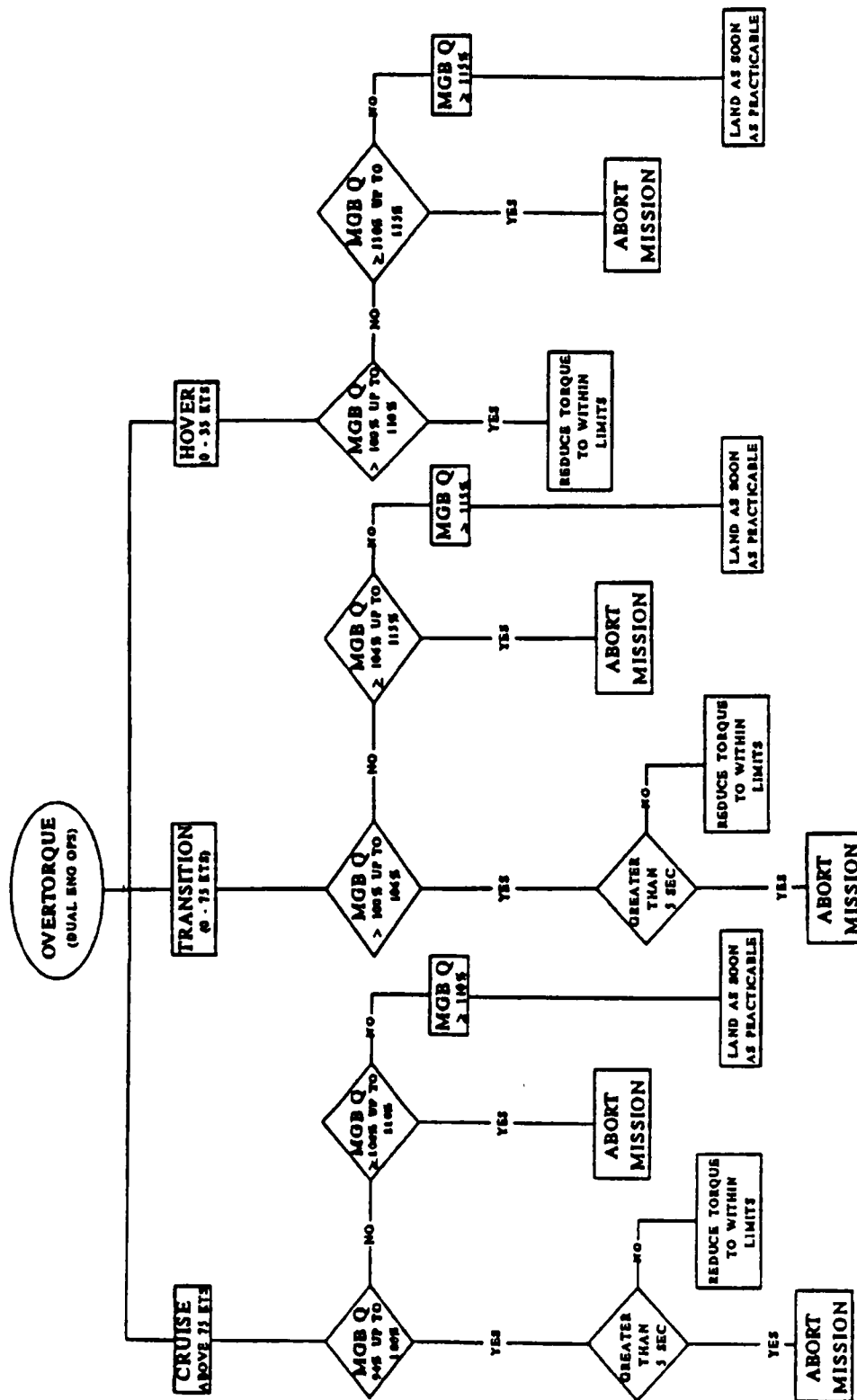


Figure 19. HH-65A Main Transmission Torque Values.

Source: HH-65A. 1992. Flight Manual: Series HH-65A Helicopter.
Revision 1. Washington, DC: U.S. Coast Guard.

Cooper Harper Handling Qualities Rating Scale

The Cooper Harper Handling Qualities Rating (HQR) scale (Naval, 1983) was developed by the National Aeronautics and Space Administration (NASA) so that test pilots could qualitatively assess an aircraft while performing a particular task. This scale is presented in figure 20.

Whereas the PRS was developed to evaluate helicopter flying qualities in the shipboard environment, the HQR scale was developed to evaluate any flying task by fixed wing or rotary wing aircraft. Although there is no specific intention to use this scale during the test evolution, it is included in the planning process so that the pilots will have an additional method to assess any characteristic that they determine is warranted.

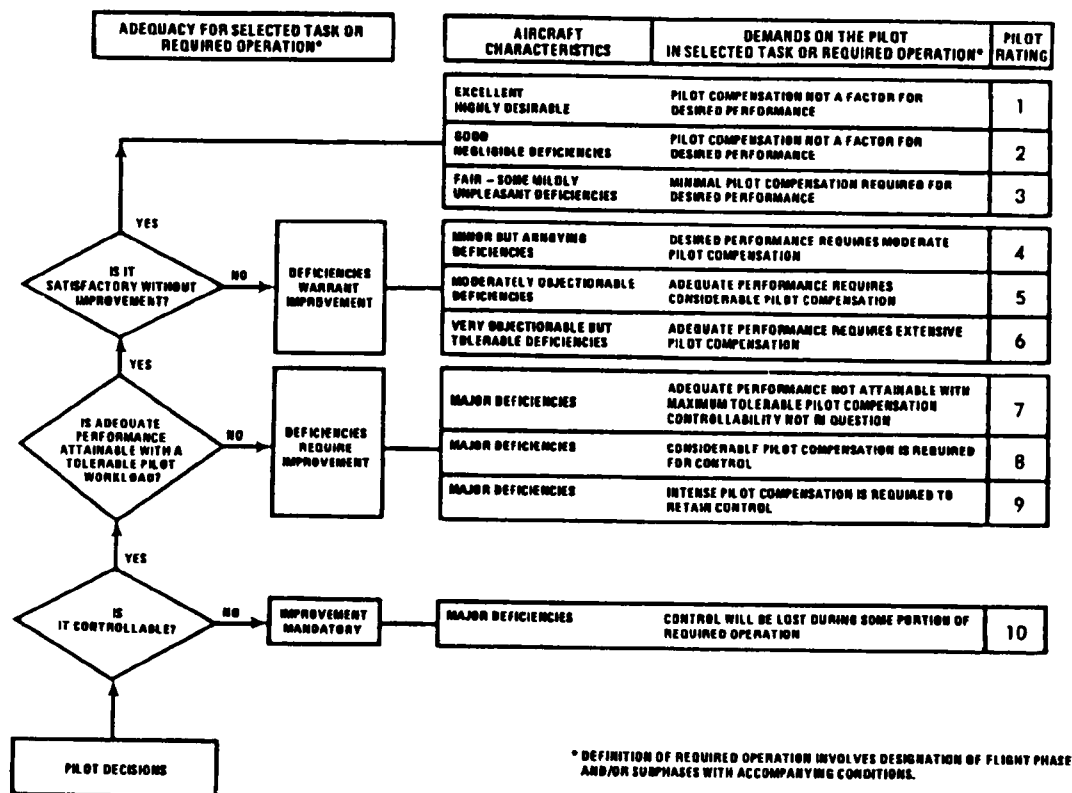


Figure 20. Cooper-Harper Handling Qualities Rating Scale.

Source: NAVAL. 1983. Naval Test Pilot School Flight Test Manual: Helicopter Stability And Control. USNTPS-FTM-NO. 105. Patuxent River, MD: Naval Air Test Center.

Turbulence Scale

The Turbulence Scale can be found in the Flight Information Handbook (Flight, 1992), which is published by the Defense Mapping Agency (DMA). A reproduction of the Turbulence Scale is presented in table 4. This scale is used by the Federal Aviation Administration (FAA) to provide a qualitative assessment of turbulent conditions to aircrews for flight planning purposes. In addition, if an aircrew encounters unexpected turbulence, this information can be passed to a ground controller who can then pass the information along to other aircrews entering the area.

The Turbulence Scale may be useful if turbulence is encountered during the testing, but the source of the turbulence may not be easily identified. The author's experience in conducting DI testing is that some form of turbulence generated by the ship's superstructure is almost always present and any turbulence generated by the cutter's exhaust may not be distinguishable.

Table 4. Turbulence Scale.

Source: Flight. 1992. Flight Information Handbook. St. Louis, MO: Defense Mapping Agency Aerospace Center.

Intensity	Aircraft Reaction	Reaction Inside Aircraft
Light	<u>TURBULENCE</u>: The aircraft momentarily experiences slight, erratic changes in altitude or attitude. <u>CHOP</u>: The aircraft experiences slight, rapid, and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude.	Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly.
Moderate	<u>TURBULENCE</u>: The aircraft experiences changes in altitude or attitude, but remains in positive control at all times. The aircraft also usually experiences variations in indicated airspeed. <u>CHOP</u>: The aircraft experiences rapid bumps or jolts without appreciable changes in altitude and/or attitude.	Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are displaced.
Severe	The aircraft experiences large, abrupt changes in altitude and/or attitude. The aircraft also usually experiences large variations in indicated airspeed. Aircraft may be momentarily out of control.	Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about.
Extreme	The aircraft is violently tossed about and is practically impossible to control. It may cause structural damage.	

Vibration Assessment Rating Scale

The Vibration Assessment Rating (VAR) Scale, presented in table 5, is based on the Subjective Vibration Assessment Scale developed by the Aeroplane and Armament Experimental Establishment located in Boscombe Down, England. This scale would be used to characterize some type of vibration detected by the aircrew on a scale from 1 to 10. (Report, 1984) As with the HQR scale, there is no specific intent to use this scale, but it is made available to the pilots if some vibration is encountered and needs to be documented.

Table 5. Vibration Assessment Rating (VAR) Scale.

Source: Report. 1984. Report Writing Handbook. NATCINST 5213.3F. Patuxent River, MD: Naval Air Test Center.

Degree Of Vibration	Description	Pilot Rating
None		0
Slight	Not apparent to experienced aircrew fully occupied by their tasks, but noticeable if their attention is directed to it or if not otherwise occupied.	1
		2
		3
Moderate	Experienced aircrew are aware of the vibration, but it does not affect their work, at least over a short period.	4
		5
		6
Severe	Vibration is immediately apparent to experienced aircrew even when fully occupied. Performance of primary task is affected, or tasks can only be done with difficulty.	7
		8
		9
Intolerable	Sole preoccupation of aircrew is to reduce vibration level.	10

Test Conduct

General

The actual testing is comprised of several phases, some of which occur prior to the shipboard testing. Some of the planning presented follows that of a typical DI test, and some is unique in support of the hot gas ingestion investigation.

Before any form of testing can begin, the pilots involved need to complete refresher flight training which includes an emphasis on day and night shipboard procedures and a review of aircraft emergency procedures, especially those unique to shipboard operations. For this DI test, the refresher training is particularly important because the HH-65A is not an asset held by RWATD and the pilots selected had not flown this helicopter in over one year. The refresher training was completed at the U. S. Coast Guard Aviation Training Facility located in Mobile, Alabama.

Land-Based Flight Tests

The land-based flight testing consists of a series of hovers in which the main transmission torque required to maintain that hover is recorded. The hover points are varied by changing altitude and changing the wind direction relative to the nose of the helicopter. The torque values recorded are

then compared to the torque values predicted by the hover performance charts contained in the HH-65A Flight Manual (HH-65A, 1992). This test series is known as a "hover ladder" and the test matrix is presented in table 6. The data collected will serve as baseline information with which to compare with data collected during shipboard operations.

Table 6. Hover Ladder Test Matrix.

Event Number	Hover Height ² (feet)	Wind Direction ³ (degrees)	Condition
A1 A2 A3 A4 A5	5	000 045 090 315 270	In Ground Effect
B1 B2 B3 B4 B5	15	000 045 090 315 270	In Ground Effect
C1 C2 C3 C4 C5	25	000 045 090 315 270	In Ground Effect
D1 D2 D3 D4 D5	40 or above	000 045 090 315 270	Out Of Ground Effect

- Notes: 1. Wind magnitude will be determined based on the aircraft hovering stationary with respect to the ground or the ship flight deck.
2. Hover height relative to the ground or the ship flight deck.
3. Wind direction is relative to the aircraft nose.

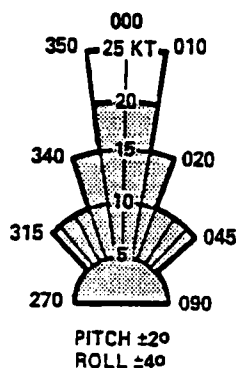
Pierside IR Thermography

Prior to getting underway, IR Thermography documentation of the cutter's exhaust would provide some baseline information on SSG exhaust temperature. The main engines would not be included because they could not be placed under any load with the cutter tied to the pier. This test period would also serve to determine a suitable mounting location for the IR camera and verify it's operational status before the arrival of the helicopter.

Shipboard Flight Tests

The shipboard flight tests would begin with a shipboard landing qualification period. This would provide each pilot with an opportunity to reacclimate to the shipboard environment without having to concentrate on data gathering. Although this qualification period is primarily designed for the pilots, every event conducted would provide data in support of the test.

In order to minimize the workload on the pilots during the qualification period, all landings and launches would be conducted within the "DI General Launch/Recovery Envelope." This envelope is presented in figure 21 and represents a starting point to begin envelope expansion testing.



NOTES:

Helicopter aligned with ship's lineup line and wind shown relative to aircraft nose. Wind over deck shall be sufficient to provide 10% margin over HOGE torque requirements.

Entire Envelope - Day Operations

Shaded Envelope - Night Operations

HOGE - Hover Out of Ground Effect

Figure 21. DI General Launch/Recovery Envelope.

This envelope was developed by the DI department based on years of DI testing and provides the pilot with wind and ship motion conditions which generally are relatively benign.

It was decided to include an additional relative wind restriction for the qualification period to minimize the potential for hot gas ingestion. With the exhaust stack located just forward of landing area and centered laterally, relative winds close to 0 degrees would carry the hot gases directly into the flight path of the helicopter. It was decided that relative winds offset 30 degrees would be sufficient to avoid hot gas ingestion by the helicopter. The IR Thermography would be monitored closely in case the 30 degree offset proved to be insufficient. It was also decided

to orient the relative winds 30 degrees to the left of the cutter's heading to compensate for a specific hovering characteristic of the HH-65A. This helicopter normally hovers with an attitude in which the right side is lower than the left side, oriented approximately 3 degrees from vertical. A helicopter's hovering attitude is influenced by the direction from which the relative winds are coming. The helicopter's hover attitude will rotate along the longitudinal axis into the relative winds. From the pilot's perspective, relative winds from the left will cause the helicopter to hover with more of a counterclockwise attitude. In the case of the HH-65A, relative winds from the left will help to lessen it's off vertical hovering attitude.

The next phase of testing would include the simultaneous efforts of validating a safe relative wind and ship motion envelope for conducting HH-65A launches and landings, and determining whether and under what conditions hot gas ingestion is a concern. Using the DI General Launch/Recovery Envelope, figure 21, as a starting point, relative wind speed and direction are adjusted in increments of approximately 5 knots and 15 degrees, respectively. Ship motion is generally not a controllable factor so whatever motion is generated at each test point is simply documented. This expansion continues until the envelope is complete. The edges of the envelope are determined based on the PRS values assigned to each test point. A PRS value of 1 or 2 will be acceptable to include in

the final launch and recovery envelope. A PRS value of 3 or 4 will not be acceptable in the final envelope, however, any test point assigned a PRS value of 3 can be reflown for further evaluation and can be adjusted accordingly. Any test point which generates a PRS value of 4 will not be reflown.

As a reminder, the PRS values assigned to a specific test point can be assigned based on one or a combination of several factors including relative winds, ship motion, excessive power requirements, turbulence, or, in this case, the detrimental effects of hot gas ingestion.

The hover ladders which are conducted prior to shipboard testing will be repeated over the landing area of the cutter. The helicopter will be limited to conducting the hover ladder with the direction of the helicopter within ± 90 degrees of the direction of the cutter. This will limit the risk of striking the cutter's superstructure with the tail of the helicopter. The data collected can then be compared with the land based data as well as the predicted values obtained from the HH-65A flight manual (HH-65A, 1992). Generally speaking, the power required to conduct shipboard operations is higher than that required to conduct similar operations on land. This has been attributed to the continuous power adjustments required to maintain position relative to a landing area which is in motion, and to turbulence created by a ship's superstructure. In this investigation, higher than anticipated required torque could also be an indication of hot gas ingestion.

The final phase of testing will be conducted provided time allows. This phase is designed to actually induce hot gas ingestion, rather than to simply observe the IR Thermography as the helicopter conducts launches and landings. In this phase, the aircraft will lift off the deck into a low hover (5-10 feet). The pilots will check for any exhaust related anomalies such as excessive torque, excessive turbulence, elevated ambient temperatures, or exhaust odors. If there are no indications of hot gas ingestion, the pilot will maneuver the helicopter to each side and vertically looking for any exhaust related anomalies. If there are still no indications of hot gas ingestion, the test sequence will be repeated after adjusting the cutter's course and speed to generate new relative winds. At any point in which hot gas ingestion is detected, the helicopter will land and the cutter's course and speed will be adjusted and the test sequence will be repeated.

CHAPTER 5

RESULTS AND DISCUSSION

General

The actual flight testing evolutions occurred from August 30 to September 2, 1992 in the vicinity of New Castle, New Hampshire. A total of 9 at-sea test periods were completed which included 16.7 hours of day and 8.5 hours of night flight hours. The events completed included 143 day landings and 73 night landings as well as 4 hover ladder sequences. An additional 3 hover ladder evolutions were conducted over land. A summary of the test conditions is presented in table 7.

Table 7. Flight Test Condition Summary.

PARAMETER	MINIMUM VALUE	MAXIMUM VALUE
Aircraft Gross Weight (pounds)	7,745	8,555
True Wind Speed (knots)	4	16
Pressure Altitude (feet)	-250	145
Ambient Air Temperature (degrees celsius)	10	19
Ship Pitch (degrees)	0	3
Ship Roll (degrees)	1	4

Hover Ladder

Land-Based

Using the helicopter main transmission torque data collected during the land-based hover ladders, a comparison was made with predicted torque values obtained from the HH-65A Flight Manual (HH-65A, 1992) for hovering at several in ground effect altitudes and at one out of ground effect altitude. Figure 22 displays this comparison by plotting the torque difference between the actual value and the predicted value obtained from the HH-65A Flight Manual. Negative values indicate that the actual torque required exceeded the predicted torque. On average, the actual torque required to execute the hover ladders was slightly higher than the value predicted by the flight manual. This was true for most altitude and relative wind conditions tested with the exception that both the 15 foot and the out of ground effect hover with the helicopter heading 315 degrees relative to the windline required less torque than predicted by the flight manual. A second point of interest was that with the aircraft heading 90 degrees relative to the windline, the actual torque required was notably higher than both the predicted value and the actual values at the other relative wind conditions with the exception of the 5 foot hover.

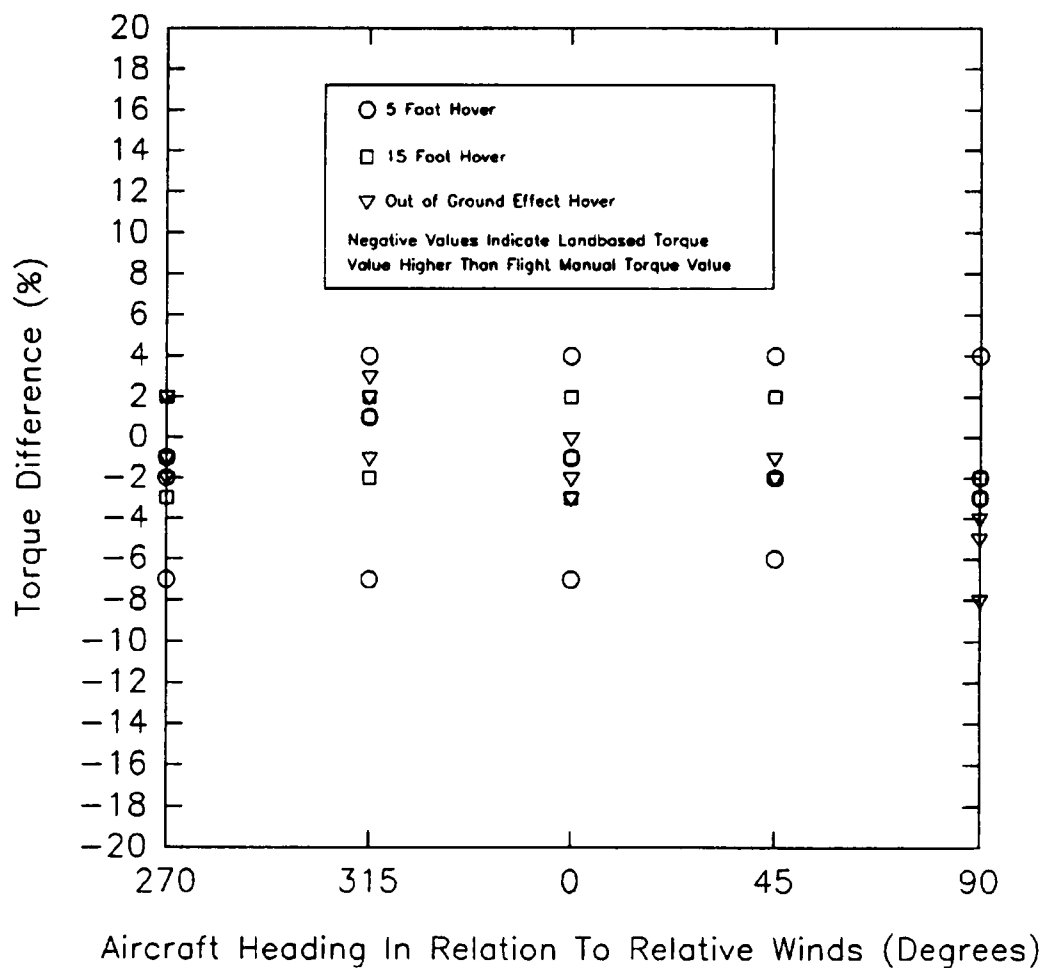


Figure 22. HH-65A Flight Manual Hover Torque Comparison With Land-Based Hover Ladder Test Torques.

Shipboard

Shipboard hover ladder main transmission torque data was compared to the HH-65A Flight Manual predicted values in a manner identical to that of the previous section. The results are presented in figure 23. Again, the results show that in general, the flight manual tends to underpredict the actual torque required to perform the hovers. The same trends that existed in figure 22 are present in the shipboard environment with one important exception. On average, the flight manual would underpredict the actual torque required to a greater degree than occurred during the land based hovers. The only two situations in which the flight manual significantly overpredicted the actual torque was during the out of ground effect hover with the helicopter heading 0 degrees and 315 degrees relative to the windline. A photograph of the HH-65A conducting a shipboard hover ladder is presented in figure 24.

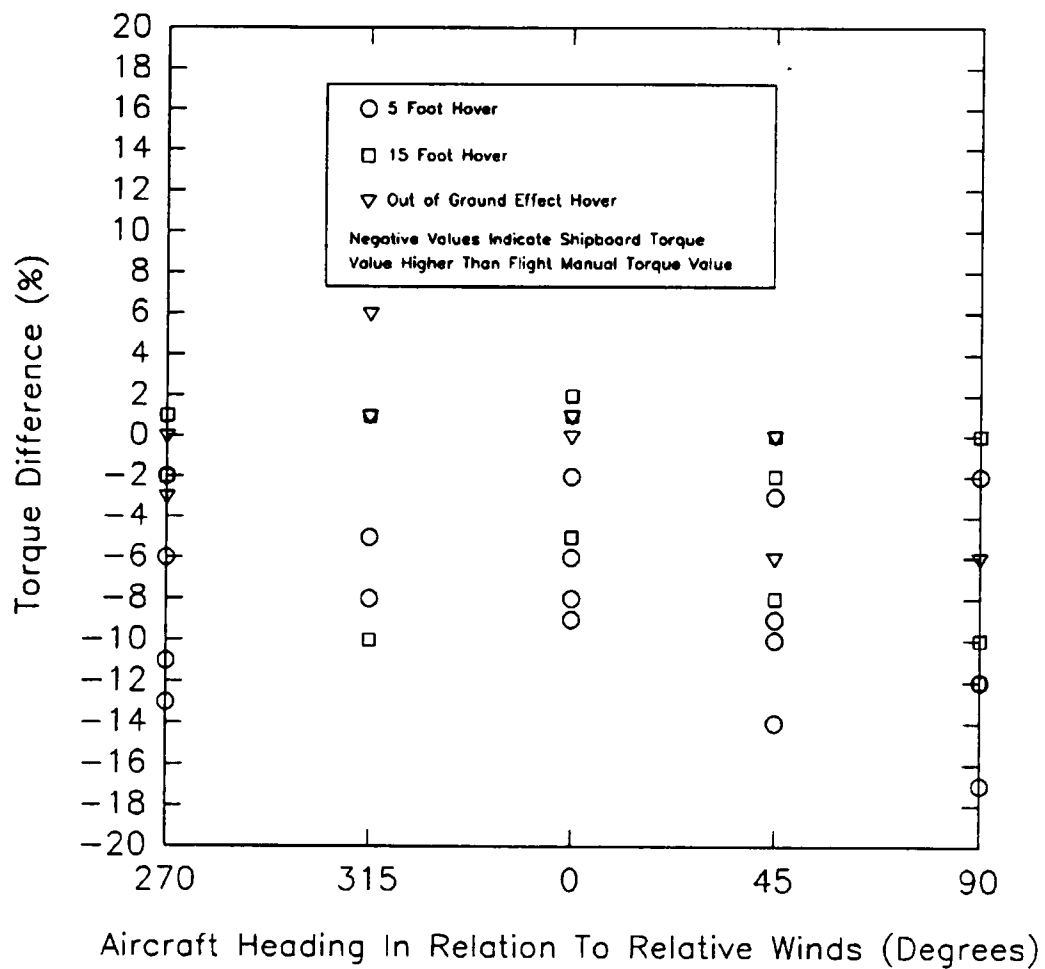


Figure 23. HH-65A Flight Manual Hover Torque Comparison With Shipboard Hover Ladder Test Torques.



Figure 24. The HH-65A Conducting A Shipboard Hover Ladder.

Shipboard Verses Land-Based

Although the previous two sections provide valuable data in order to validate the accuracy of the HH-65A Flight Manual with regard to its torque prediction capability, those comparisons provide little insight into the difference in torque required as a result of operating in a shipboard environment. By comparing the land-based hover ladder data with the shipboard hover ladder data, this comparison is possible. Figure 25 shows this comparison for two in ground effect and one out of ground effect hover altitudes. This figure was developed by using the land-based hover ladder data as a baseline and comparing that average value to the average torque value obtained during the shipboard hover ladders. Negatively plotted points indicate that the shipboard hover torque was higher than the land-based hover torque. These data show that for the 5 and 15 foot hovers, the shipboard environment does appear to require additional torque to perform comparable maneuvers, and that for the out of ground effect hovers, although there were both positive and negative torque differences, on average, the shipboard and land-based torque values were about equal.

This comparison is valid under the conditions in which the testing occurred. Unfortunately, it is very difficult to extrapolate this data to other wind and ship motion conditions.

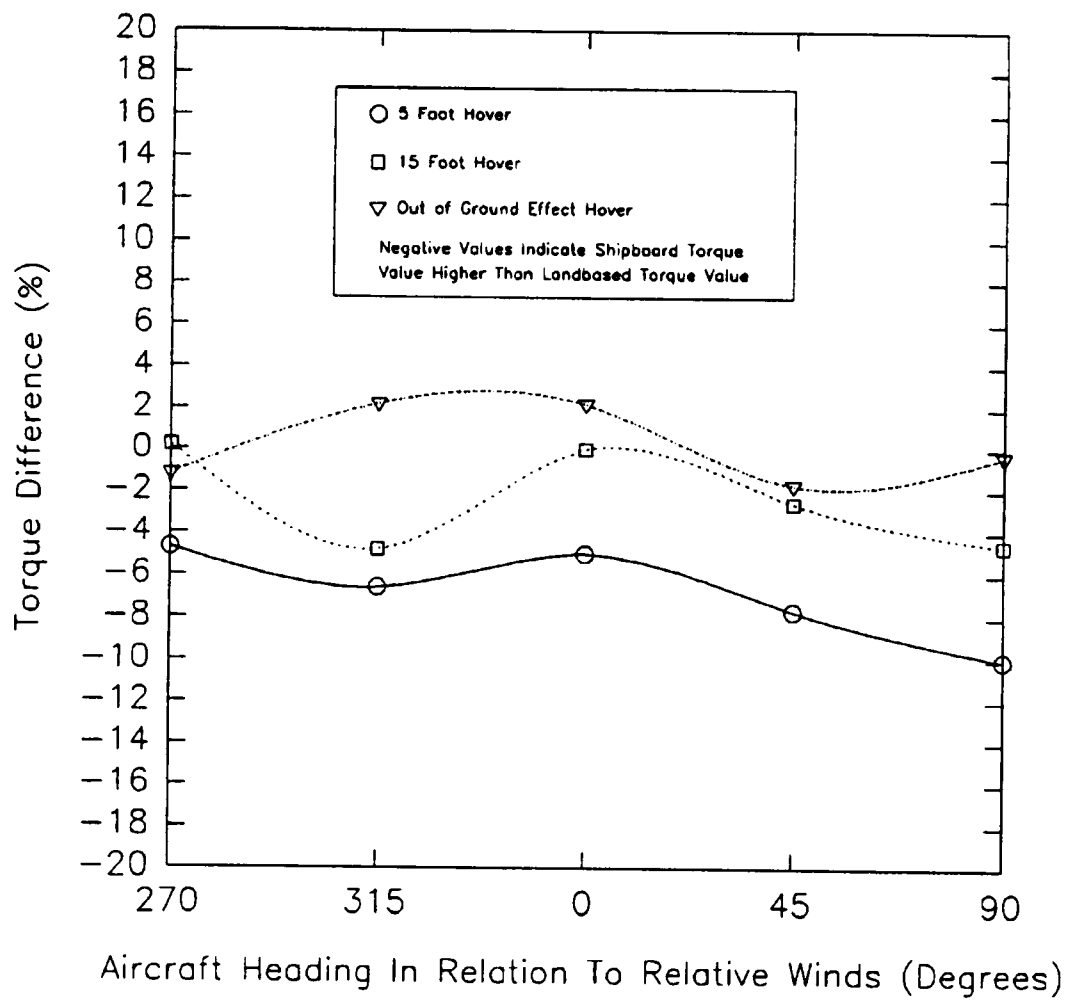


Figure 25. Comparison Of Land-Based Hover Ladder Test Torques With Shipboard Hover Ladder Test Torques, Using Land-Based Torque As Reference.

As table 7 indicated, the winds and ship motion encountered throughout the test period were relatively benign. The trend towards higher torque required to conduct shipboard operations could be explained by the ingestion of hot gas, however, experience in previous shipboard testing has generally shown that as winds and ship motion increase, so does the average torque required to conduct comparable maneuvers, with or without a hot gas source in the vicinity. Although the hover ladder in itself is not a maneuver that a pilot would conduct, it does provide a method to gather torque data under somewhat controlled and repeatable conditions.

Exhaust Temperatures

The exhaust stack thermocouples were mounted using "C" clamps which were safety wired to prevent them from falling if they should become loose. A photograph of the installation is presented in figure 26.

Selected portions of the cutter's exhaust temperatures were recorded throughout the testing period and the results are presented in figure 27. As was predicted, the starboard GTG exhaust maintained a relatively constant exhaust temperature of approximately 490 °F. Although the port GTG was not instrumented with a thermocouple, it is assumed that the port GTG exhaust exhibited similar characteristics.

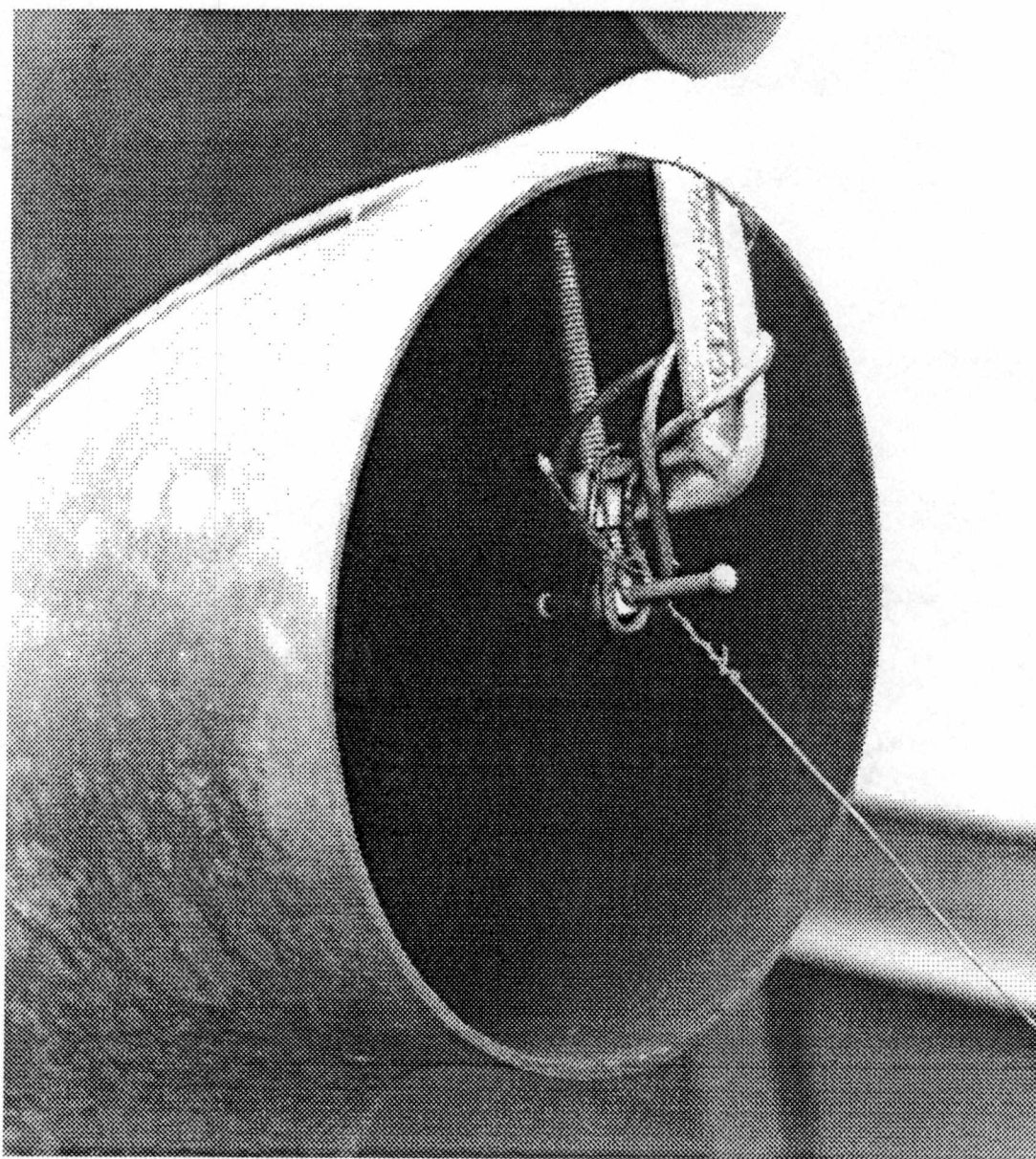
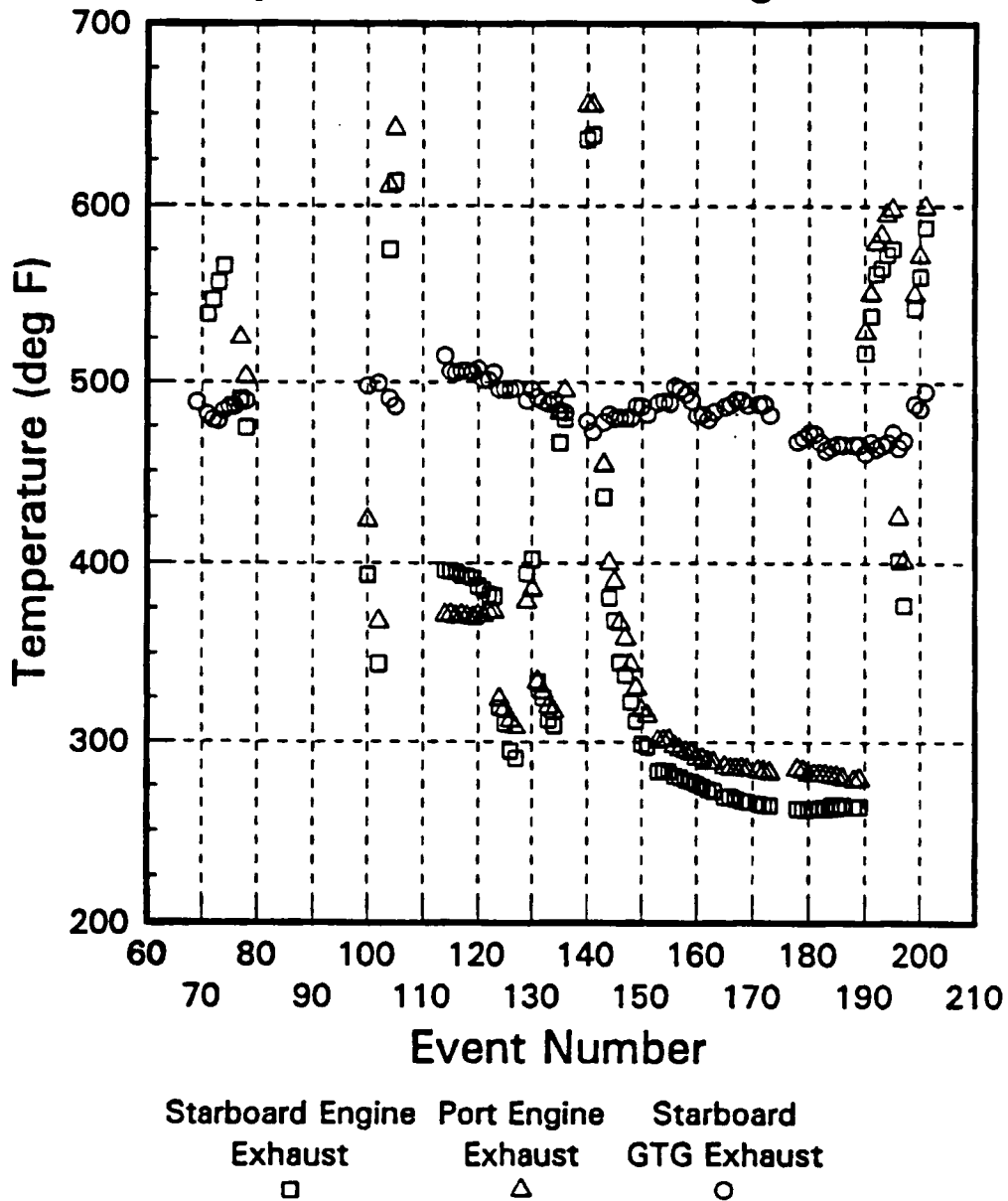


Figure 26. Exhaust Stack Thermocouple Installation.

USCGC RELIANCE

Dynamic Interface Testing



NOTE: GTG - Gas Turbine Generator, otherwise known as the SSG (Ships Service Generator)

Figure 27. Temperatures Recorded By Exhaust Stack Mounted Thermocouples.

Both the port and the starboard engine exhaust temperatures varied between approximately 260 °F and 660 °F, but remained within about 40 degrees of each other when both were operating simultaneously. The wide range of engine exhaust temperatures was directly related to the speed at which the cutter was traveling, the higher the exhaust temperatures, the faster the cutter was moving.

Main Transmission Torque

A qualitative and subjective analysis of the main transmission torque readings recorded during each landing and launching evolution was conducted by isolating events in which the peak torque value recorded was notably higher than the average torque value on an individual basis. Table 8 presents these specific data points.

A majority of these events had relative winds coming from the left side of the helicopter. In a helicopter in which the main rotor rotates clockwise as viewed looking down from above, the power required by the tail rotor assembly to provide anti-torque control is higher with relative winds from the left. Although certainly not conclusive, it can be reasonably assumed that the events with left relative winds had higher torque values because of this aerodynamic feature. The data presented previously based on the hover ladder testing also showed this trend.

Table 8. Events With High Peak Main Transmission Torque Values.

EVENT NUMBER	RELATIVE WIND DIRECTION (degrees)	RELATIVE WIND SPEED (knots)	AVERAGE TORQUE VALUE (percent)	PEAK TORQUE VALUE (percent)	GROSS WEIGHT (pounds)
103	130	1	80	98	8445
131	280	16	75	96	8245
132	285	16	75	96	8215
133	290	18	75	98	8195
189	315	12	80	97	8325
199	285	6	UNKNOWN	100.1	8355
215	090	6	75	97	7895
220	000	0	80	96	8355

Although relatively few, there were some cases of high torque values with relative winds from the right and one case with relative winds from the nose of the helicopter. In the later case, the cause may be attributed to the lack of any appreciable wind. Without going into a lengthy explanation, generally speaking, the power required by a helicopter to hover is less with some relative wind. In this case there was no wind and that coupled with a relatively high gross weight would result in higher torque values. As far as the two events with relative winds from the right are concerned, there is no simple explanation except possibly high gross weight or poor pilot technique.

A more quantitative analysis was conducted in which each of the main transmission torques recorded during the hover

portion of the landing evolution were compared with values obtained from both the in and out of ground effect hover charts of the HH-65A Flight Manual. The actual altitude was usually between 8 and 12 feet. This comparison is presented in figures 28 and 29. Negative values indicate situations in which the actual torque exceeded the value predicted by the Flight Manual.

The HH-65A Flight Manual would underpredict the actual required torque about 50% of the time and by as much as 18% using the in ground effect hover chart as shown in figure 28. Using the out of ground effect hover charts, the HH-65A Flight Manual would underpredict the actual required torque by up to 8% as shown in figure 29, but in a vast majority of the cases, the HH-65A Flight Manual actually overpredicted the required torque. This resulted in a built in safety margin. Based on these results, it would be more appropriate for aircrew to use the out of ground effect hover data contained in the HH-65A Flight Manual in order to calculate predicted torque values required for shipboard operations, regardless of actual altitude. Of the eleven points indicating a negative value in figure 29, only three were more than 5% less than the HH-65A Flight Manual predicted value. Of those final three, all were associated with left relative winds which, as discussed previously, result in higher than average torque values. The flight manual charts do not account for relative wind conditions other than for winds from 000 degrees, therefore,

any changes in torque required resulting from cross or tail winds can not be predicted using the flight manual.

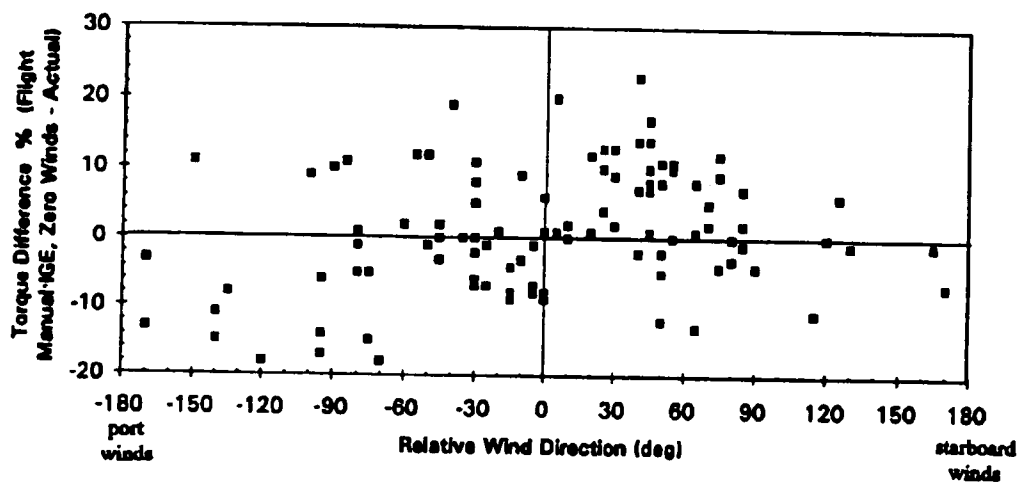


Figure 28. Flight Manual Hover In Ground Effect Torque Comparison With Shipboard Test Torques.

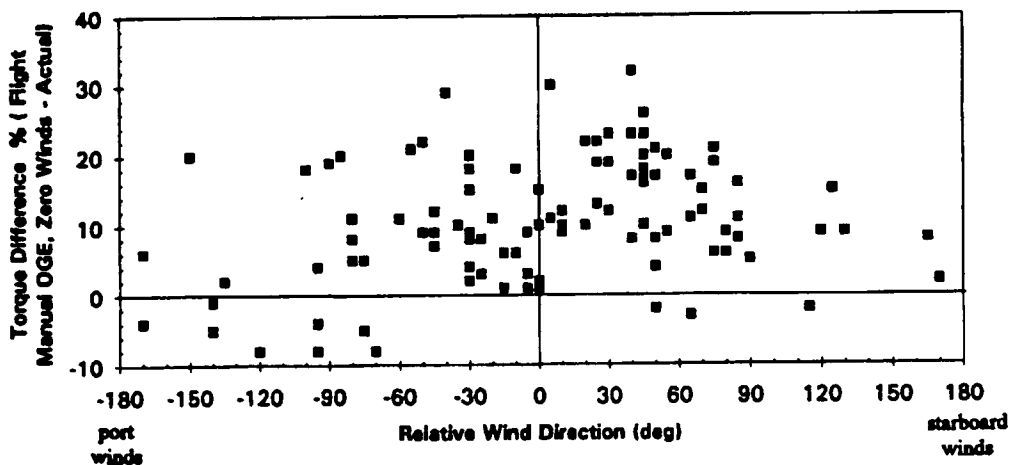


Figure 29. Flight Manual Hover Out Of Ground Effect Torque Comparison With Shipboard Test Torques.

Engine Condition Monitoring System

The helicopter's ECMS recorded only two occurrences in which the main transmission torque exceeded the preset threshold of 100%. These data points are presented in table 9. These two points are very similar in that both occurred under conditions of relatively high gross weight and with relative winds from the left, conditions which are characteristic of situations requiring high power levels.

Table 9. Main Transmission Torque Values Recorded By The Helicopter's ECMS.

EVENT NUMBER	ECMS TORQUE READING (%)	RELATIVE WIND DIRECTION (Degrees)	RELATIVE WIND SPEED (Knots)	AIRCRAFT GROSS WEIGHT (Pounds)
198	101.4	240	8	8,475
199	100.1	285	6	8,355

Rating Scales

Of all the rating scales available, only the Pilot Rating Scale (PRS) was used to quantify each landing evolution. None of the conditions encountered warranted use of the other scales. The data collected is presented in figure 30.

Of the 134 test points flown, only one resulted in a PRS rating of more than 2. As a reminder, any data points which result in a PRS rating above 2 are not considered to be suitable for the average pilot to safely fly and will not be included in the final landing envelope. This particular data point was flown at night with relative winds of 240 degrees at 8 knots and resulted in a PRS 3 rating. The rating was primarily attributed to a high degree of pilot workload associated with the lack of visual cues in the night environment coupled with relative winds from the left rear quadrant of the helicopter. This data point, number 198, was also one in which the ECMS recorded a main transmission torque of 101.4%.

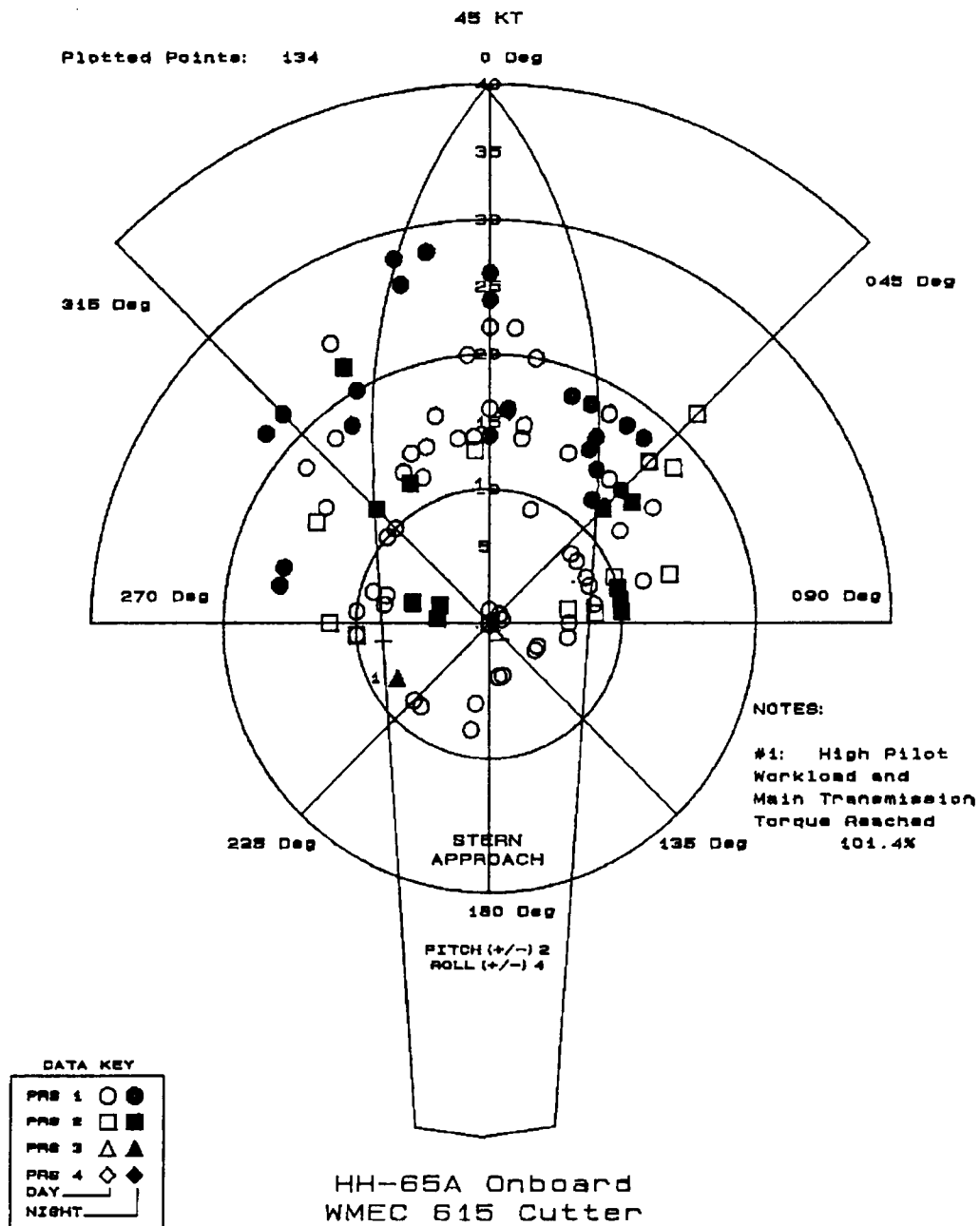


Figure 30. Pilot Rating Scale (PRS) Data.

From the pilot's perspective, none of the PRS values assigned were influenced to any degree by suspected hot gas ingestion.

Infrared Thermography

The IR thermography video and still images provided the most conclusive evidence in regard to the hot gas ingestion issue. As anticipated, relative winds beyond ± 30 degrees from the ship's heading resulted in the exhaust gases being carried clear of the flight deck environment and posed no hazard for the helicopter. One potential difficulty would exist if during a launching evolution the helicopter departed the flight deck in a direction which would cause it to enter the exhaust trail. Although this could pose a problem, the standard procedure for launching evolutions is to depart to the side of the ship in which the relative wind is approaching from. This procedure would ensure that the path of the helicopter and the ship's exhaust trail would not cross.

With relative winds within ± 30 degrees of the ship's heading, it was apparent that the helicopter's approach and departure paths were underneath the ship's exhaust trail, indicating that the height of the exhaust stack was sufficient, under most conditions, to keep the exhaust clear of the helicopter. Under only one set of relative wind conditions was there any indication of the exhaust gases traveling towards the helicopter. With relative winds of 000

degrees at 22 knots, there was positive evidence that the exhaust trail was being influenced by the presence of the helicopter. This was evident both during the landing and during the departure. Figure 31 shows a black and white presentation of the IR camera's field of view and figures 32 through 37 are sequential IR thermography images of the transitory redirection of the exhaust path towards the helicopter during a landing and launching evolution with relative winds of 000 degrees at 22 knots. The path of travel of the exhaust trail was essentially direct from the exhaust stack towards the top forward portion of the helicopter's main rotor disk. It is surmised that the region of relatively low pressure created above the main rotor disk by the flow of air through the disk was of sufficient magnitude to draw the exhaust trail towards it. Although the exhaust flow was directed toward the main rotor disk, figures 32-37 also show that even before the exhaust trail reached the main rotor disk, all of it's heat content above ambient temperature had essentially dissipated into the atmosphere. Based on the IR thermography, there was absolutely no indication that the helicopter engine inlets were subject to any significant degree of hot gas ingestion.



Figure 31. Photographic Presentation Of The IR Camera's Field Of View.

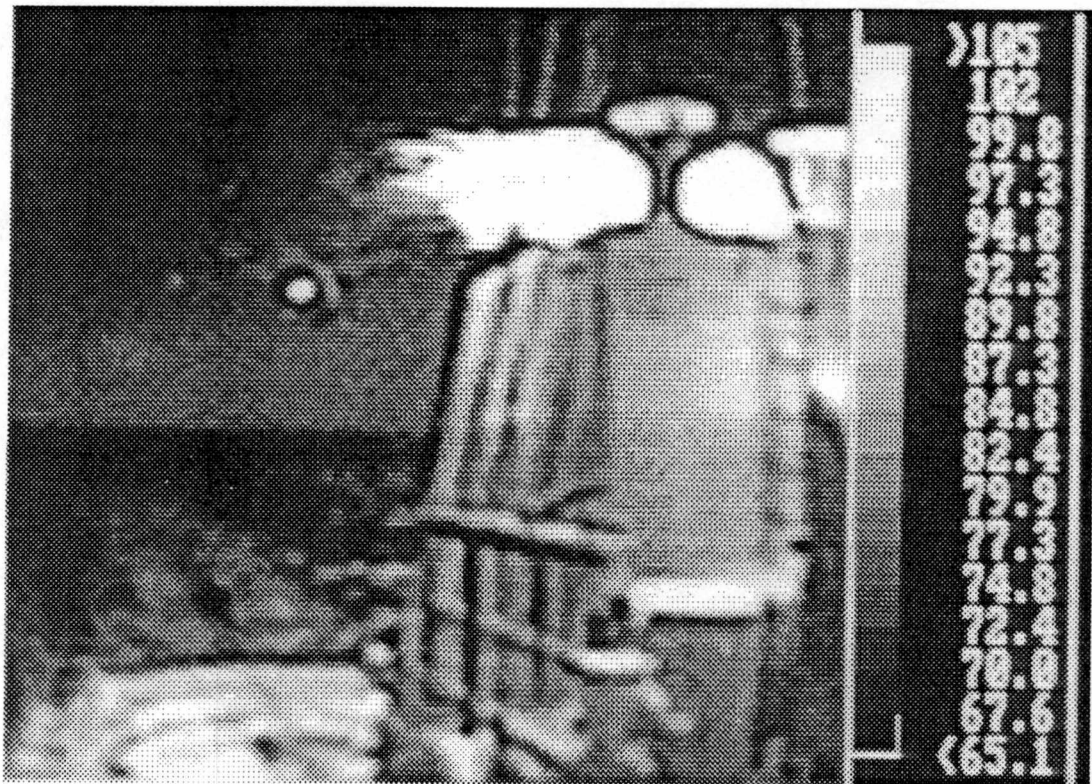


Figure 32. IR Thermography Image Of Exhaust Gas During Final Approach To Landing Evolution With Relative Winds 000 degrees at 22 knots.

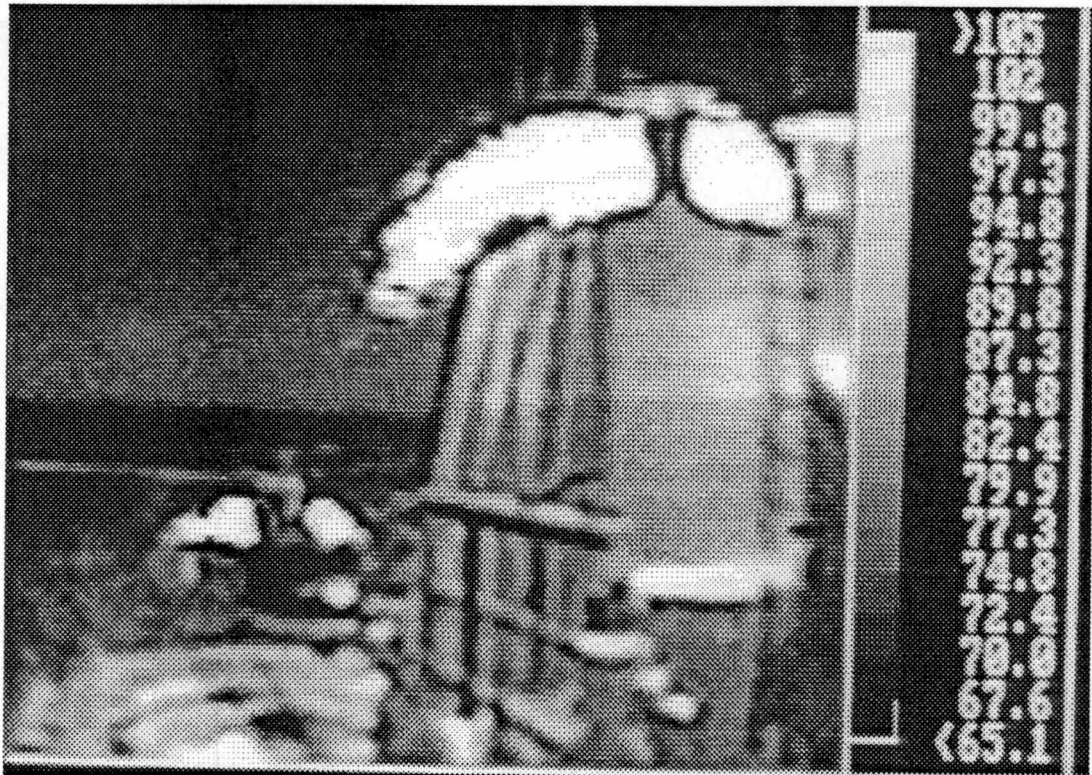


Figure 33. IR Thermography Image Of Exhaust Gas During Hover Prior To Landing With Relative Winds 000 degrees at 22 knots.



Figure 34. IR Thermography Image Of Exhaust Gas With Helicopter On Deck After Landing With Relative Winds 000 degrees at 22 knots.

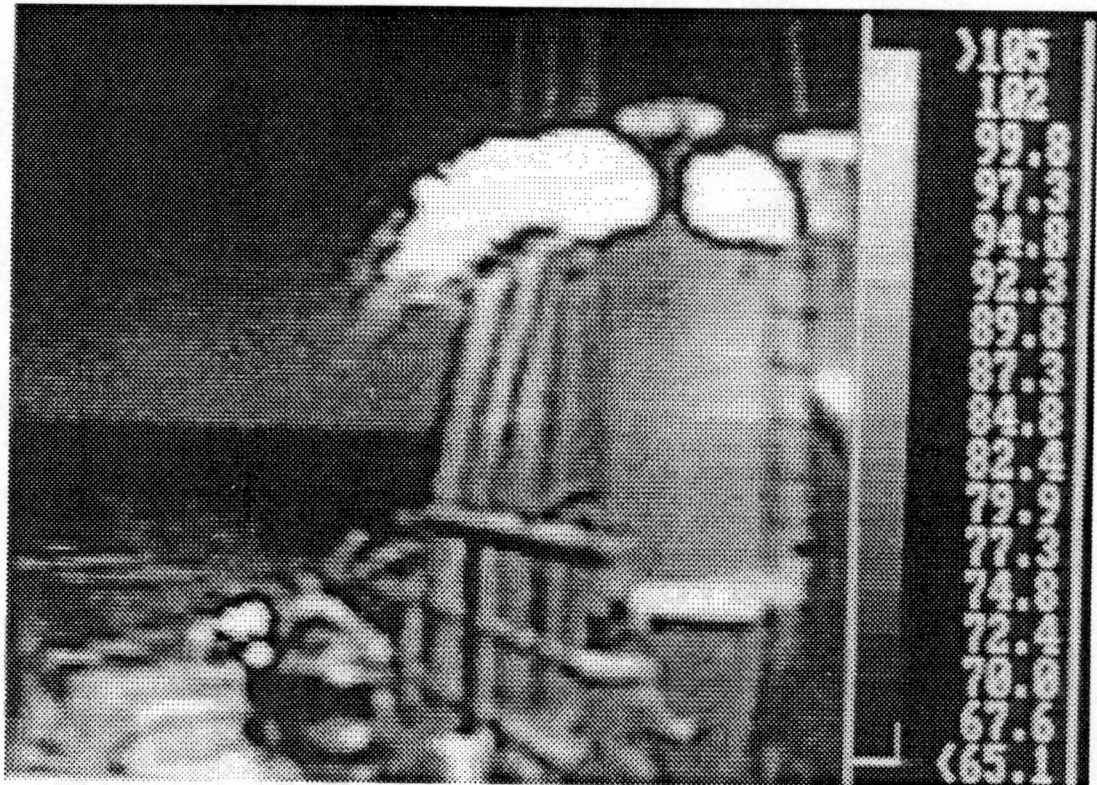


Figure 35. IR Thermography Image Of Exhaust Gas With Helicopter On Deck Prior To Launching With Relative Winds 000 degrees at 22 knots.



Figure 36. IR Thermography Image Of Exhaust Gas With Helicopter On Deck Prior To Launching With Relative Winds 000 degrees at 22 knots.



Figure 37. IR Thermography Image Of Exhaust Gas During Launching Evolution With Relative Winds 000 degrees at 22 knots.

Analysis of the IR thermography video at each of the wind conditions discussed earlier in this chapter in which a high main transmission torque condition existed was conducted in order to eliminate hot gas ingestion as a possible cause in those cases. The video tape did not reveal any indication that hot gas ingestion was occurring, in fact, the exhaust trail did not even appear to be significantly influenced by the helicopter.

Flight Deck Thermocouples

The last data to present is the thermocouple data generated by the two thermocouples mounted along the aft face of the exhaust stack. These two thermocouples were included to help and identify situations in which hot gases were being circulated around the flight deck. Figure 38 shows the location of the two thermocouples. The data generated did not show any significant rise in temperature in the flight deck environment when the helicopter was in the vicinity under any relative wind conditions. In fact, under conditions of light relative winds or winds from the nose of the ship, the thermocouples actually recorded a noticeable decrease in temperature. This is attributed to the airflow created by the helicopter cooling the flight deck area which had been heated by solar radiation. The flight deck itself is surfaced by a black tar-like material which is conducive to solar heating.

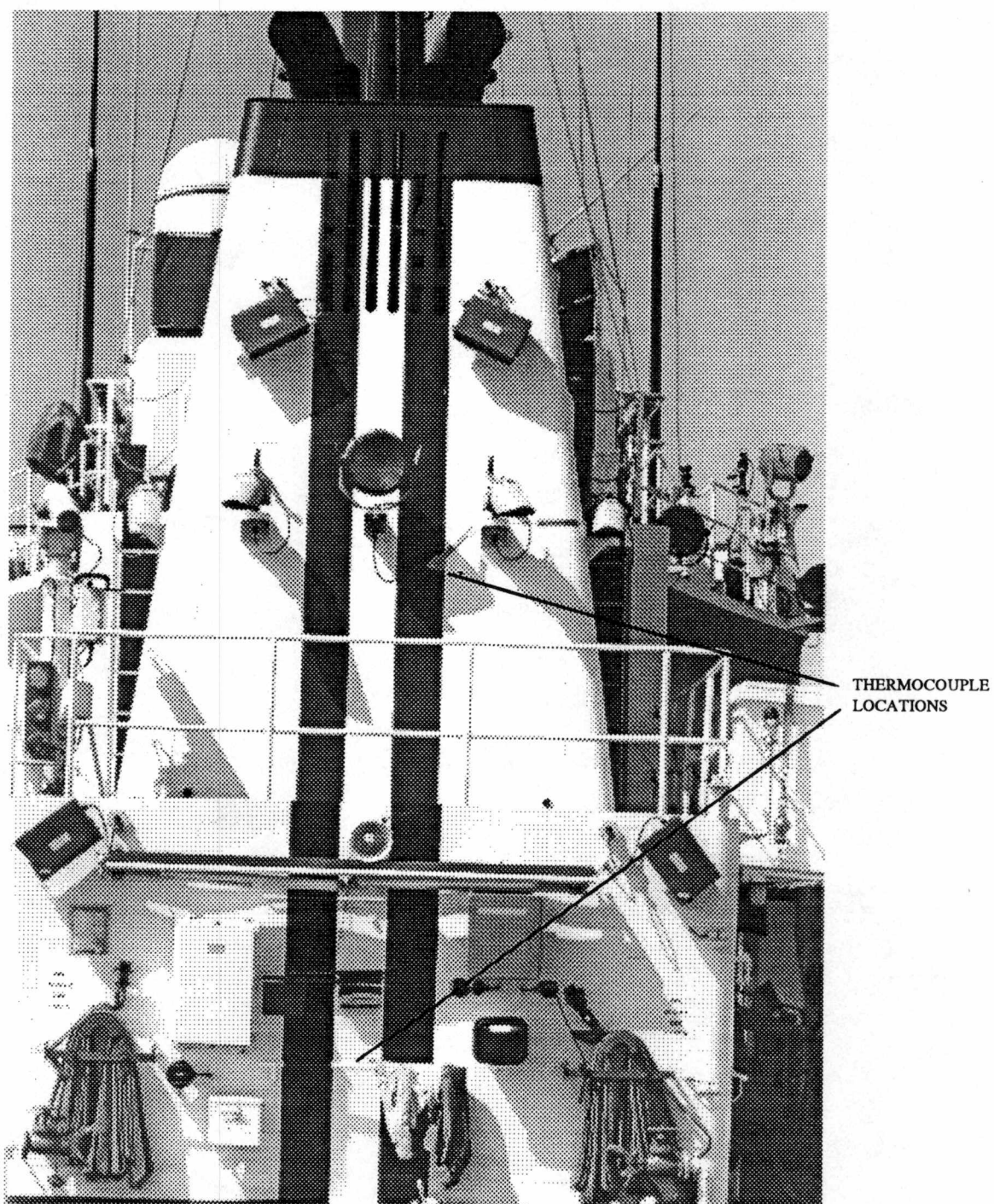


Figure 38. Flight Deck Thermocouple Locations.

Figure 39 presents an example of this data. One deficiency identified with the thermocouples was that they were capable of an update rate of only 0.25 hertz. If any circulation of hot gases had occurred, they may have been of short enough a duration to have not been detected by the thermocouples. In any event, the IR Thermography should have identified any such occurrences, and none were noted.

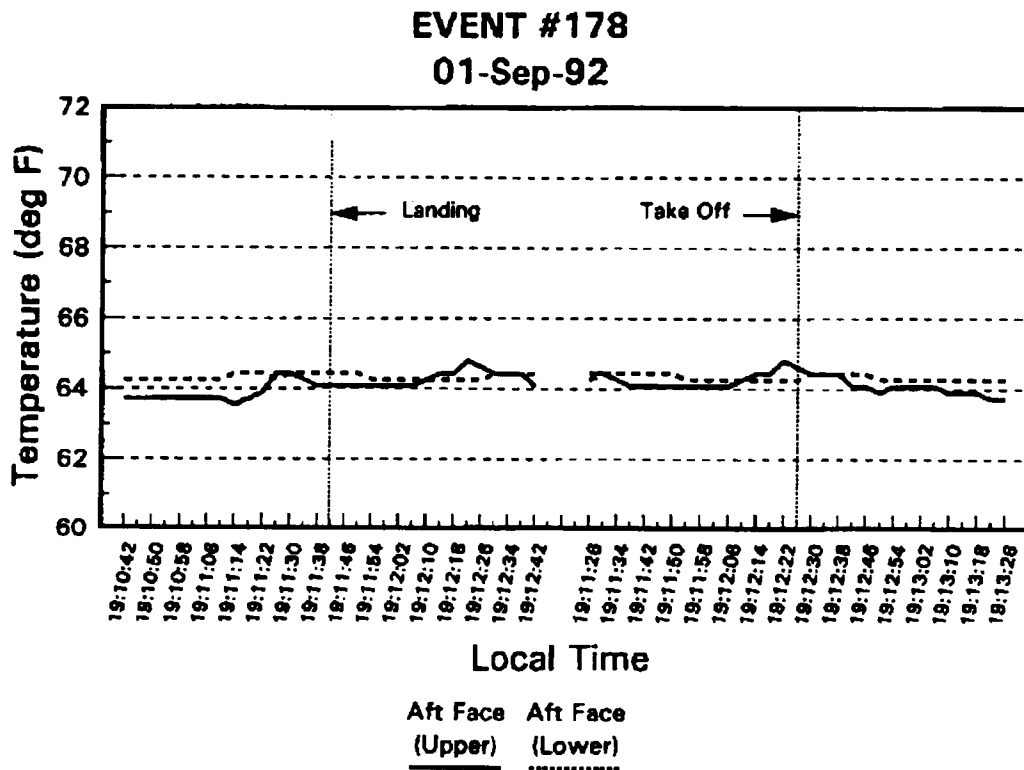


Figure 39. A Sample Of The Flight Deck Thermocouple Data.

CHAPTER 6

CONCLUSION

The data collected can be divided into three major groups, each providing some information with which conclusions concerning hot gas ingestion can be developed. The first group was the HH-65A main transmission torque data. The land-based hover ladder data provided baseline information in order to validate the accuracy of the HH-65A flight manual hover charts and to compare with the shipboard hover ladder data. The conclusions developed included that the flight manual hover charts generally underpredicted the actual main transmission torque required to execute the maneuvers by up to 8 percent, and that in the in ground effect environment up to 10 percent more main transmission torque was required in the shipboard environment than in the land-based environment. Once the helicopter elevated out of ground effect, the average main transmission torque difference between the shipboard and land-based data was less than 2 percent and not very significant. Based on these results alone, the reason additional torque was required to conduct shipboard operations could not be definitively determined, however, hot gas ingestion had to be included as one of the possible causes. Based on the authors extensive experience conducting Dynamic Interface evaluations,

the additional torque required is typical of shipboard operations in the absence of exhaust stack gases and in this case, the shipboard environment may be the only cause.

Additional main transmission torque data collected during the actual landing and launching evolutions included the average torque required during the hover portion of each landing, the peak torque observed throughout each evolution, and any situations in which the helicopters ECMS recorded any engine or main transmission exceedance conditions. The conclusions reached based on these results indicated that the actual torque required could be as much as 18 percent higher than the values predicted by the HH-65A Flight Manual in ground effect hover charts, that the actual torque required would exceed the flight manual in ground effect value approximately 50 percent of the time, and that the out of ground effect hover charts actually overpredicted the main transmission torque required in a significant majority of the cases. Additionally, in a majority of the situations in which a high peak torque value was recorded, there were plausible aerodynamic explanations. Based on this data, there was not sufficient evidence to exclude hot gas ingestion as a cause of any high main transmission torque observations.

The second group of data included information collected using the various rating scales. In this test, only the PRS was utilized. The data collected generated only one situation in which an unsatisfactory rating was assigned and that rating

was based on elements not associated with hot gas ingestion. None of the pilot's comments made throughout the testing period indicated a concern with hot gas ingestion.

The third and last group of data included the infrared thermography and thermocouple data. The thermocouples attached to the exhaust outlets provided excellent exhaust temperature data that could be used for further analysis in situations where hot gas ingestion was confirmed or suspected. The flight deck mounted thermocouples provided no evidence that hot gases were being circulated around the flight deck, but because of the relatively slow response rate of the thermocouples, hot gas circulation of a relatively short duration, less than several seconds, may not have been detected.

The IR thermography provided the most conclusive evidence regarding hot gas ingestion. After a thorough review of the IR thermography video tapes, with particular attention being made to data points identified by previous methods as being at least possibly associated with hot gas ingestion, it was determined that there were no situations in which hot gases actually reached the helicopter engine inlets. One wind condition, relative winds from 000 degrees at 22 knots, was identified in which the hot gas path was influenced by the helicopter. The hot gas path was direct from the exhaust source towards the top forward portion of the rotor disk, an area of relatively low pressure created by the airflow through the main rotor system. The exhaust's heat content essentially

dissipated prior to reaching the rotor disk.

In comparison to the test conducted in which the SH-2F helicopter was confirmed to be subject to hot gas ingestion, there were several notable differences. In the SH-2F investigation, the relative wind strength was less than 6 knots, but in a direction which placed the hot gases on a path directly over and rising above the flight deck. With the HH-65A, the wind strength was significantly higher, but also placed the exhaust gases directly over the flight deck. During analysis of the IR thermography video, it was noted that the exhaust gas path was above the path of the approaching helicopter. This was more so as the wind strength decreased. With the relative wind strength at 22 knots, it appears that the horizontal velocity component of the hot gas was of sufficient magnitude to allow the hot gas to enter the low pressure region created by the main rotor induced flow. With a relative wind strength above 22 knots, the region of low pressure may not have been strong enough to redirect the exhaust flow path. With a relative wind strength less than 22 knots, the vertical velocity component of the hot gas was enough to ensure the hot gases remained clear of the low pressure region.

If the hot gases had been able to sustain some degree of increased temperature, the author surmises that one of two situations could have occurred based on the aerodynamic circulation patterns discussed in chapter 4. The exhaust gases

could have traveled down through the main rotor system and become entrained within the main rotor tip vortex. They would not likely reach the helicopter engine inlets before the increased temperature had dissipated. A second scenario could occur if the horizontal velocity component of the hot gases was strong enough for the gases to reach the main rotor hub. If there were some degree of hub wake circulation occurring above the rotor disk, the exhaust gases could become entrained and be delivered to the vicinity of the engine inlets.

Without the use of the IR thermography system, conclusive evidence supporting the determination that under the conditions tested hot gas ingestion did not occur would not have been available. There were several situations in which hot gas ingestion could have been the cause of some atypical data, but the IR thermography video provided the conclusive evidence eliminating that possibility.

BIBLIOGRAPHY

BIBLIOGRAPHY

- AGARD. 1968. Helicopter Propulsion Systems. Advisory Group For Aerospace Research And Development, AGARD Conference Proceedings No. 31. London, England: Technical Editing and Reproduction Limited.
- Altobelli, Donald. 1982. "CH-53D Helicopter Investigation Of Power Loss Due To Exhaust Ingestion." NAPC-PE-64. Trenton, NJ: Naval Air Propulsion Center.
- Baty, Roger, Kurt Long and A. Vanaria. 1989. "Tech Eval Of No. 3 Ship's Service Gas Turbine Generator (SSGTG 3) Exhaust Effects On SH-3H And CH-46E Aircraft." RW-13R-89, Final Report. Patuxent River, MD: Naval Air Test Center.
- Benn, A., B. Remick, J. Pratt and J. McCune. 1987. "Evaluation Of AIM-9 Sidewinder Missile Compatibility With The S-3 Airplane." NATC-FW-41R-87, Final Report. Patuxent River, MD: Naval Air Test Center.
- Bevan, David and David Hodder. 1986. "Investigation Into Helicopter Main Rotor/Exhaust Gas Flow Interactions." Fort Eustis, VA: Aviation Applied Technology Directorate.
- F-14A. 1975. "F-14A/AIM-9 Missile Firing Incident Investigation." NATC-WST-19R-75. Patuxent River, MD: Naval Air Test Center.
- Fay, John. 1976. The Helicopter: History, Piloting And How It Flies. Third Edition. North Pomfret, VT: David and Charles Incorporated.
- Felderman, E. and M. High. 1971. "Missile Exhaust Gas Ingestion Simulation." AEDC-TR-71-252. Arnold, TN: Arnold Engineering Development Center.
- Green, K. and J. Zanine. 1979. "Computerized Method For An Estimation Of Hot Gas Reingestion For A VTOL Aircraft At The Conceptual Design Phase." NADC-78256-60, Final Report. Warminster, PA: Naval Air Development Center.
- Hanker, Edward J. and Robert P. Smith. 1983. "Parameters Affecting Helicopter Interactional Aerodynamics In Ground Effect." 39th Annual National Forum. Washington, DC: American Helicopter Society.
- Heinz, J. 1990. "Talon Deployment Plan." Washington, DC: U.S. Department Of Transportation.

- HH-65A. 1992. Flight Manual: Series HH-65A Helicopter. Revision 1. Washington, DC: U.S. Coast Guard.
- Jackson, Micheal and Richard House. 1981. "Exhaust Gas Reingestion During Hover In-Ground-Effect." American Helicopter Society, 37th Annual Forum. Washington, DC: American Helicopter Society.
- Kolwey, Herman G. 1977. "Summary Of Helicopter Airframe Testing In The Shipboard Environment." TM 77-2 RW, Technical Memorandum. Patuxent River, MD: Naval Air Test Center.
- Lambert, Mark. 1991. Jane's Fighting Ships, 1991-1992. Coulsden, Surrey, United Kingdom: Jane's Information Group, Sentinal House.
- Long, Kurt. 1993. Interview In Person.
- McCue, James J. 1990. "Power Required to Hover (In Ground Effect)." Class notes from *Helicopter Performance* class held at the U.S. Naval Test Pilot School, Patuxent River, MD.
- Moore, John. 1984. Jane's Fighting Ships, 1984-1985. New York, New York: Jane's Publishing, Incorporated.
- NASA. 1969. "The Use Of Pilot Ratings In The Evaluation Of Aircraft Qualities (HQR Scale)." NASA TN-D-5153. Washington, DC: National Aeronautics And Space Administration.
- NAVAL. 1983. Naval Test Pilot School Flight Test Manual: Helicopter Stability And Control. USNTPS-FTM-NO. 105. Patuxent River, MD: Naval Air Test Center.
- Prezelin, Bernard. 1993. Combat Fleets Of The World 1993. Annapolis, MD: Naval Institute Press.
- Prouty, R. 1979. "Falling Off The Cushion..." Rotor and Wing International. Peoria, IL: Philips Publishing, Inc.
- Prouty, R. 1985. "Ground Effect And The Helicopter--A Summary." AIAA/AHS/ASEE Aircraft Design Systems And Operations Meeting. AIAA-85-4034. New York, NY: American Institute Of Aeronautics and Astronautics.
- Report. 1984. Report Writing Handbook. NATCINST 5213.3F. Patuxent River, MD: Naval Air Test Center.

- Rich, William and Robert Reale. 1969. "J52-P-6A Engine, Sea Level Missile Exhaust Gas Ingestion Tests." NAPTC-ATD-162. Trenton, NJ: Naval Air Propulsion Test Center.
- Rich, William and Robert Reale. 1970. "J52-P-8A Engine, Altitude Missile Exhaust Gas Ingestion Tests." NAPTC-ATD-195. Trenton, NJ: Naval Air Propulsion Test Center.
- Rich, William and Robert Reale. 1971. "Specification Rocket Test For Turbojet/Turbofan Missile Gas Ingestion." NAPTC-ATD-197. Trenton, NJ: Naval Air Propulsion Test Center.
- Rich, William. 1974. "TF34-GE-2 Rocket Gas Ingestion Test." NAPTC-PE-36. Trenton, NJ: Naval Air Propulsion Test Center.
- Richards, Robert B. 1968. Principals of Helicopter Performance. USNTPS-T-No. 1. Patuxent River, MD: U.S. Test Pilot School, Naval Air Test Center.
- SH-60B. 1990. NATOPS Flight Manual Navy Model SH-60B Aircraft. Change 1. Washington, DC: Naval Air Systems Command.
- Sheridan, Philip and Wayne Wiesner. 1977. "Aerodynamics Of Helicopter Flight Near The Ground." American Helicopter Society, 33rd Annual National Forum. Washington, DC: American Helicopter Society.
- Shipboard. 1992. Shipboard Aviation Facilities Resume. NAEC-ENG-7576. Lakehurst, NJ: Naval Air Warfare Center, Aircraft Division.
- Shipboard. 1991. Shipboard-Helicopter Operational Procedures Manual. Washington, DC: US Department Of Transportation.
- Smith, Patrick and Kurt Long. 1988. "Technical Evaluation Of Ships Service Gas Turbine Generator No.3 (SSGTG 3) Exhaust Effects On The SH-2F Helo." RW-60R-88, Final Report. Patuxent River, MD: Naval Air Test Center.
- Taylor, John. 1983. Jane's All The World's Aircraft, 1983-1984. New York, NY: Jane's Publishing Incorporated.
- Turczeniuk, Bohdan. 1979. "Exhaust Gas Reingestion Measurements." American Helicopter Society. Washington, DC: American Helicopter Society.
- Weisner, W. and G. Kohler. 1974. "Tail Rotor Performance In Presence Of Main Rotor, Ground, And Winds." Journal Of The American Helicopter Society. American Helicopter Society, 29th Annual National Forum. Washington, DC: American Helicopter Society.

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