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STOCHASTIC MODELING OF NAVAL UNMANNED AERIAL VEHICLE MISHAPS: ASSESSMENT OF POTENTIAL INTERVENTION STRATEGIES

by
Michael G. Ferguson

September 1999

Thesis Advisor:	John K. Schmidt
Thesis Co-Advisor	Lyn R. Whitaker
Second Reader:	Robert R. Read

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The employment of unmanned aerial vehicles (UAVs) in combat operations has demonstrated that UAVs can effectively provide surveillance, reconnaissance, and target acquisition support in place of manned aircraft. However, the Pioneer UAV, currently employed by the U.S. Navy and Marine Corps, has an unacceptable mishap rate. Half of the UAV mishaps are attributable in part to human factors causes. This points to a requirement for developing tailored intervention strategies. This study develops a stochastic simulation model of UAV mishaps to be used for the evaluation of human factor initiatives in terms of budgetary cost and mission readiness. It determines that electro-mechanically caused mishaps cost approximately the same as human factors mishaps. However, in comparison, human factors mishaps degrade mission readiness significantly. Intervention strategies need to address unsafe acts by the operator, unsafe conditions for flight operations, and unsafe supervision. The study recommends the following intervention measures: the use of system simulators; the implementation of improved aircrew coordination training; and the stabilization of personnel assignments.

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Michael G. Ferguson
Major, United States Marine Corps
B.A., Villanova University, 1989

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September 1999

Author: Michael G. Ferguson

Approved by: John K. Schmidt, Thesis Advisor

Lyn R. Whitaker, Thesis Co-Advisor

Robert R. Read, Second Reader

Richard E. Rosenthal, Department Chairman

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LIST OF ACRONYMS

AAA	Anti-Aircraft Artillery
ACT	Aircrew Coordination Training
ATC	Air Traffic Control
BDA	Battle Damage Assessment
BUMED	Bureau of Medicine
COMINT	Communications Intelligence
CRM	Crew Resource Management
DoD	Department of Defense
ECM	Electronic Countermeasures
ELINT	Electronic Intelligence
EMI	Electro-Mechanical Interference
E-O	Electro-Optical
EP	External Pilot
FLIR	Forward Looking Infrared
FY	Fiscal Year
GCS	Ground Control Station
HFACS	Human Factors Accident and Classification System
HMI	Human-Machine Interface
HMMWV	High Mobility Multi Wheeled Vehicle
IAI	Israeli Aircraft Industries
ICAO	International Civil Aviation Organization

ICS	Intercom System
IDF	Israeli Defense Forces
IP	Internal Pilot
KS g.o.f.	Kolomogorov-Smirnov goodness of fit (test)
KTO	Kuwait Theater of Operations
LAV	Light Armored Vehicle
MC	Mission Commander
MEF	Marine Expeditionary Force
MIR	Mishap Investigation Report
MOS	Military Occupational Specialty
NAI	Named Area of Interest
NATOPS	Naval Aviation Training Operations Procedures & Standardization
NCCA	Naval Center for Cost Analysis
NSC	Naval Safety Center
NTSB	National Transportation Safety Board
OMFTS	Operational Maneuver from the Sea
OOTW	Operations Other Than War
OPTEMPO	Operational Tempo
PCS	Portable Control Station
PO	Payload Operator
PSYOPS	Psychological Operations
RATO	Rocket Assisted Take-off

RRS	Remote Receiver Station
RSTA	Reconnaissance, Surveillance, Target Acquisition
SAM	Surface to Air Missile
SHEL	Software, Hardware, Environment, Liveware
SOP	Standard Operating Procedure
T & R	Training and Readiness (Manual)
TCS	Tactical Control System
UAV	Unmanned Aerial Vehicle

EXECUTIVE SUMMARY

The employment of unmanned aerial vehicles (UAVs) by the Israeli Defense Forces during the *Peace for Galilee* campaign in 1982, and by United States forces during Operations *Desert Shield* and *Desert Storm* in 1990-91, provides a proof of concept that relatively low cost UAVs can provide effective surveillance, reconnaissance, target acquisition and fire support adjustment missions. The United States has employed UAVs subsequently in operations in Somalia, Haiti, Bosnia, and most recently in Kosovo. The Department of the Navy's doctrine of Operational Maneuver from the Sea will place greater reliance on aerial battlefield surveillance from "over the horizon" or expeditionary sites ashore in order to control a greater operational area with less force concentration. However, the current Naval UAV platform, the Pioneer, is beset by an unacceptable mishap rate. Since its fielding in operational units in 1986, the Pioneer Class A flight mishap rate is 385 mishaps per 100,000 flight hours. This stands in stark contrast to that of manned Naval Aviation where the rate is approximately two Class A flight mishaps per 100,000 flight hours.

Schmidt & Parker (1995), while working at the Naval Safety Center in Norfolk, Virginia, have identified that human factors related issues cause half of the Naval UAV mishaps. Seagle (1997) applies the Human Factors Analysis and Classification System (HFACS) taxonomy to UAV mishap reports in order to improve human factors mishap investigation, reporting and analysis. The HFACS taxonomy, based upon the Reason (1990) "Swiss Cheese" model of accident causation, captures the latent conditions that "set the stage" for active failures that lead to mishaps.

This study refines the coding of UAV mishaps in accordance with the HFACS taxonomy. Once the mishaps are parsed, the factors influencing the mishap rate and their resultant costs are computed. These results are used to conduct a stochastic model simulation of annual UAV flight operations in order to isolate those categories of mishaps that contribute most to increased budgetary costs and decreased mission readiness. The study places UAV mishap reports from FY86 to FY98 into categories using the HFACS taxonomy. Particular emphasis is placed on the FY93 to FY98 period when Naval UAVs first came under the cognizance of the Naval Aviation Safety Program. Then, mishap rates and probabilities are estimated for the various categories. Thereupon, these probability distributions are used as the input to a stochastic model for the simulation of annual flight operations. The model output is the annual mishap costs associated with a particular category, and a resulting mission readiness index.

Intervention strategies are assigned to associated category of mishap causation. Comparing the annual mishap cost, readiness index, and the feasibility associated with a particular intervention strategy, Fleet users and program managers can determine what intervention strategies are most appropriate. Some strategies are specific to the Pioneer system, for example, an engine remanufacturing or upgrading, or an electronic weatherproofing modification. Other strategies, such as improved aircrew coordination training and personnel assignment stabilization, transcend the Pioneer system, and are applicable to all follow-on UAV configurations.

The mishap categorization phase of this study, data coding and classification, was conducted independently of previous studies (Schmidt & Parker, 1995; Seagle, 1997).

The relative frequency of mishap causes agrees with the previous classifications, and validates their findings. Even though mishap reports remain vague, and lack granularity at identifying lower, root causes, there is general agreement in the classification of the mishap in each independent analysis.

The second phase of the study, stochastic model simulation of annual flight operations, finds that electro-mechanical causes have a low impact on mission readiness although they account for approximately one-quarter of UAV mishaps. On the other hand, unsafe acts, unsafe conditions for flight operations, and unsafe supervision have a more significant impact on equipment repair and replacement costs, and mission readiness. The study concludes that addressing the human factors related issues through increased aircrew coordination training, the use of simulators for mission rehearsal, personnel stabilization, and the development of a UAV career path, will have a greater impact on controlling cost and improving readiness. The study also generates the budgetary costs of selected mishap categories. These costs can be compared to the cost of implementing a particular intervention strategy. Thereupon, the program manager can chose the most appropriate strategies for implementation. While in isolation, no single intervention strategy will eliminate mishap occurrences; their implementation will increase the density of the "safety net" surrounding UAV operations.

I. INTRODUCTION

A. OVERVIEW

From the advent of modern military operations through the present day, successful commanders have relied on knowledge of the battlefield and intelligence of the enemy's disposition in order to employ their force to achieve victory (Marine Aviation Weapons and Tactics Squadron One [MAWTS-1], 1997). During the 19th century, in the American Civil War and the Franco-Prussian War, hot air balloons were employed in order to get a bird's eye view of the battlefield. They added a third dimension to the intelligence collecting effort. Early in the 20th century, the invention of the airplane replaced the restrictive and vulnerable use of balloons. During the First World War, manned aircraft were employed as airborne intelligence collectors. Later, in the 1960's in response to increasingly lethal air defense networks and enormously developing technology, reconnaissance satellites have taken over the role of aerial surveillance at the strategic and operational levels of warfare. Presently, Unmanned Aerial Vehicles (UAVs) are used to augment satellite systems by providing near real-time, tactical aerial reconnaissance. However, the current Naval UAV, the Pioneer, is beset by an unacceptable mishap rate. This thesis addresses several potential intervention strategies designed to mitigate these mishaps, lower their budgetary cost and improve operational readiness.

B. AERIAL RECONNAISSANCE

The U-2 "spy plane" was developed during the early 1950s in order to monitor Soviet ICBM development and deployment (Jones, 1997). The U.S. conducted U-2 over flights of the Soviet Union since 1955. On 2 May 1960, Francis Gary Powers was shot down in a U-2 over the Soviet Union by an SA-2 "Guideline" missile. The shoot down of Powers, and the failed attempt at covering up the mission, proved to be a devastating blow to the U.S.'s international prestige. A second U-2 was shot down over Cuba during the Missile Crisis on 27 October 1962, while attempting to determine the status of Soviet nuclear missiles. Consequently, the nation became increasingly wary of manned reconnaissance. However, the only reconnaissance systems in development were the SR-71 Blackbird and the CORONA spy-satellite. Both of these systems were designed for strategic level reconnaissance only.

The U.S. made an initial serious attempt at an airborne tactical reconnaissance UAV during the Vietnam War (Jones, 1997). The U.S. Air Force experimented with launching the Teledyne-Ryan developed *Lightning Bug* UAV from MC-130's in order to conduct aerial reconnaissance. By the end of the war, the *Lightning Bug* UAV had grown into a vehicle for providing real-time video, electronic intelligence (ELINT) collection, electronic countermeasures (ECM), communications intelligence (COMINT) and psychological operations (PSYOPS) leaflet dropping. However interest in UAVs waned as the war wound down, and the Department of Defense (DoD) trimmed budgets and force structure.

Nevertheless, U.S. lessons learned in Vietnam did not go unheeded. During that same period, Israel Aircraft Industries (IAI) began the successful development UAVs for the Israeli Defense Forces (IDF) (Kumar, 1997). These Israeli developed and manufactured UAVs were first employed in combat in 1982 during the *Peace for Galilee* campaign in Lebanon. During an attack against Syrian forces in the Bekaa Valley, the Israeli Air Force (IAF) launched decoy missiles to stimulate the Syrian air defense system. As the Syrians responded to this perceived attack, Israeli *Mastiff* and *Scout* UAVs with electro-optical and radar-detecting payloads were able to locate and target Syrian missile sites. Once target locations were confirmed, and during the Syrian missile reload cycle, the IAF launched A-4, F-4 and KFIR aircraft to attack these targets. The Israelis destroyed 19 SAM batteries and 86 MiG aircraft while only losing one aircraft of their own, effectively dismembering the entire Syrian air defense network.

The early 1980s saw a resurgence in enthusiasm for UAVs within DoD as a result of the Israeli's successful UAV employment in Lebanon. U.S. peacekeeping operations in Beirut (1982-3), Operation *Urgent Fury* (Grenada, 1983), Operation *Eldorado Canyon* (Libya, 1986) all highlighted a requirement for an inexpensive, over the horizon, unmanned reconnaissance capability for the on-scene tactical commander. In July 1985, the Secretary of the Navy, John Lehman directed the expeditious acquisition of UAVs for fleet operations. By December 1985, the U.S. Navy procured the Pioneer UAV system developed by IAI. The Pioneer UAV is the next generation UAV following the *Mastiff* that was employed in the *Peace for Galilee* campaign. The U.S. Navy and Marine Corps began establishing UAV units in 1986. The first Pioneer overseas deployment occurred in December 1986, aboard the U.S.S. Iowa (Pioneer UAV Inc., 1999).

The first time the Pioneer UAV saw combat action was in Operations *Desert Shield* and *Desert Storm* (Melson, Englander & Dawson, 1992). During that conflict, six UAV units were deployed to the Kuwaiti Theater of Operations (KTO) - two Navy, three

Marine Corps and one Army. Together, the units flew 336 missions, accruing 985 flight hours. Only three UAVs were hit by enemy anti-aircraft artillery (AAA), resulting in the loss of only one UAV from enemy action. General Walter Boomer, USMC (ret.) who commanded the Marine Expeditionary Force (MEF) in the Kuwaiti theater summed up the effect of UAV employment during the war when he said, "The Pioneer UAV was the most significant intelligence collection source within I MEF."

Pioneer UAV units were later deployed for Operations *Restore* and *Continue Hope* in Somalia, Operation *Uphold Democracy* in Haiti, and Operation *Joint Endeavor* in Bosnia. Their successful mission performance reinforced the potential of exploiting this technology to support future combat operations and operations other than war (OOTW) (Jenkins, 1998). The Department of the Navy's doctrine of "Operational Maneuver from the Sea" (OMFTS) will place greater reliance on battlefield surveillance from "over the horizon" and expeditionary sites ashore in order to control a greater operational area with less force concentration. Relatively inexpensive reconnaissance UAVs with the ability to conduct missions in hostile airspace, without putting pilots into harm's way is a key element of OMFTS (Marine Corps Combat Development Command [MCCDC], 1999).

C. THE PIONEER UAV SYSTEM

A Pioneer UAV system consists of five Pioneer air vehicles, a ground control station (GCS), a portable control station (PCS), a tracking communications unit (TCU), a data link, two remote receiver stations (RRS) and a reconnaissance payload. The system can be operated aboard specially configured U.S.S. Austin Class Landing Platform Dock

(LPD-4) ships or from prepared airstrips ashore. While UAVs do not carry any ordnance, they can perform as forward observers of indirect fire support assets – offensive attack aviation, artillery and naval surface fire support. Figure 1 is a representation of how UAVs can be deployed during an amphibious operation.

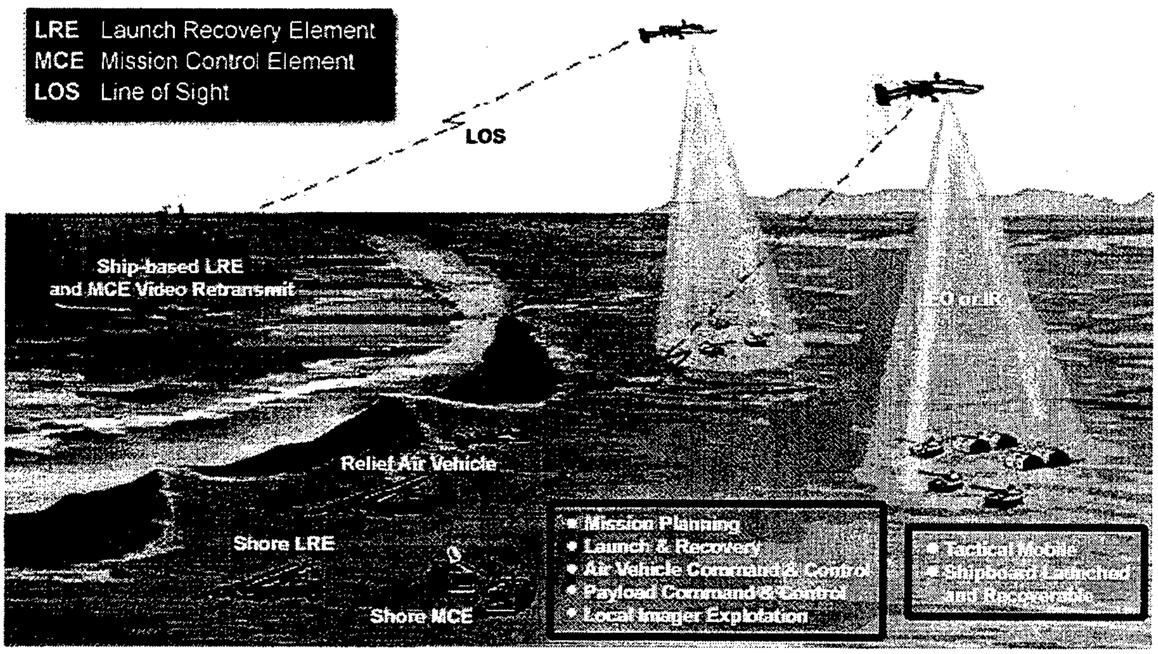

FIGURE 1: PIONEER UAV CONCEPT OF OPERATIONS

Within DoD, only the U.S. Navy, Marine Corps and the Defense UAV Training Command (DUTC) operate the Pioneer UAV (MAWTS-1, 1997). The Navy's UAV unit is VC-6, headquartered in Norfolk, Virginia; however, the UAV elements are located at Webster Field, Patuxet River, Maryland. From there, they deploy as detachments with a complete Pioneer system aboard ship. There are two Marine Corps UAV units. VMU-1 is located in Twenty-Nine Palms, California, and VMU-2 is headquartered at MCAS Cherry Point, North Carolina. The training command, DUTC, is located in Fort Huachuca, Arizona. The U.S. Army deactivated their Pioneer UAV units in anticipation of procuring the Hunter (IAI) or Outrider (Alliant Techsystems) UAV system. However, both programs were cancelled because they failed to meet desired size, weight and corrosion control specifications (Sherman, 1998).

Pioneer UAV units are currently tasked to provide the following missions:

a) Reconnaissance, surveillance and target acquisition (RSTA).

b) Adjusting indirect fire (Artillery, Naval Surface Fire Support).

c) Collect Battle Damage Assessment (BDA).

d) Support security operations (e.g., convoy escort, monitor enemy avenues of approach and named areas of interest (NAIs).

The term "unmanned" is a misnomer when applied to the Unmanned Aerial Vehicle system because UAV operations involve many remote participants. The essential members of a UAV crew include a Mission Commander, an Internal Pilot, a Payload Operator and an External Pilot. Additionally launch and recovery teams and maintenance personnel will be involved in flight operations (Joint UAV Training Operations Procedures & Standardization [JUAVTOPS], 1997). A detailed description of the Pioneer UAV system, capabilities and crew responsibilities is attached as Appendix A.

D. PIONEER UAV SAFETY RECORD

Schmidt & Parker (1995), of the Naval Safety Center (NSC), begin the initial effort at improving UAV operational readiness by focusing on mishap prevention. Their study examines the 107 mishaps that occurred between 1986 and 1993. The breakdown of causal factors is illustrated in Figure 2. This research indicates a significant number (approximately 59%) of mishaps occur as a result of electromechanical problems.

Human error accounts for nearly one-third of these mishaps. Their research indicates the following factors present significant safety concerns: crew selection and training; aeromedical readiness; pilot proficiency/currency; personnel shortages; operational tempo (OPTEMPO); human error in teamwork and aircraft control.

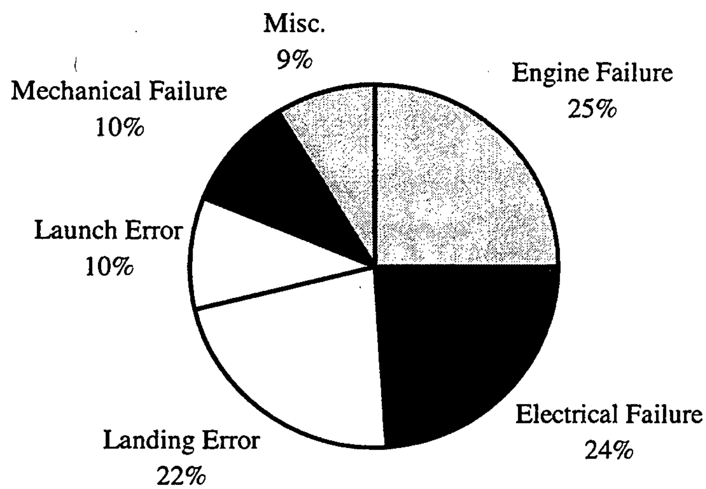

FIGURE 2: FY 86 – FY 94 NAVAL PIONEER UAV MISHAP CAUSAL FACTORS (SCHMIDT & PARKER, 1995)

Schmidt & Parker (1995) recommend the following corrective actions be taken to decrease the mishap rate: aeromedical screening and monitoring; criteria based selection process; UAV crew coordination training; take off, landing and external pilot (EP) simulators; inclusion into OPNAVINST 3710.7P NATOPS oversight and improved human systems integration. These recommendations have been implemented with varying degrees of success. Aeromedical screening is conducted prior to being assigned to the UAV community. In addition, aptitude testing is conducted to assess the flight potential of incoming aircrew. Aircrew coordination training (ACT) is currently in progress and constantly evolving. A take off and landing drone was developed to enable

EPs to fly an air vehicle without having the entire system activated. In FY 94, UAV flight operations were included in the Naval Aviation Safety Program (OPNAVINST 3750.6Q).

These improvements have marginally decreased the mishap rate. However, improvement is still required. Initially, aeromedical screening takes place but a flight surgeon is not assigned to UAV units to continue aeromedical education and crew monitoring. The lack of operational experience and personnel stability in UAV units limits ACT because lessons learned are difficult to capture and implement. Additionally, emergency action simulation drills are not possible because there is no crew simulator. Air vehicle drones, called MiGs by their crews, do not have the same aerodynamic characteristics of the Pioneer air vehicle. Thus, while the MiG training is effective in training the EPs in basic flight controls and procedures, the discrepancies between its response and that of the real Pioneer vehicle may reinforce improper handling and result in a negative learning experience.

Seagle (1997) continues the work of Schmidt & Parker. He applies the Human Factors Mishap Classification System (HFACS) to analyze UAV mishaps from 1986 to 1997. His research studies the 203 mishap investigation reports from 1986 through 1997, determining that 88 include human related causal factors. His categorization of mishaps is illustrated in Table 1. His work provides insight into the cause of human factors related mishaps and clarifies the broad, generalized "human error" labels. Seagle goes further by demonstrating that although the primary cause of an accident may have been electro-mechanical in nature, a latent cause was due potentially to human factors, either contributing to the mishap, or failing to correct a condition that led to the accident.

CAUSAL FACTOR		CODE	#	FREQ
Unsafe Act		UA	52	59.1%
	Intended	UAI	6	6.8%
	Mistake	UAIM	34	38.6%
	Violation	UAIV	6	6.8%
	Unintended	UAU	46	52.3%
	Slip	UAUS	2	2.2%
	Lapse	UAUL	14	15.9%
Unsafe Condition		UC	40	45.5%
	Aeromedical	UCA	18	20.4%
	CRM	UCC	24	27.2%
	Readiness	UCV	6	6.8%
Unsafe Supervision		US	54	61.4
	Unforeseen	USU	30	34.1%
	Foreseen	USF	41	46.5%
Human Factors		HF	88	

TABLE 1: FY86 – FY97 UAV MISHAPS PARSED BY CAUSAL CATEGORY (SEAGLE, 1997)

Seagle confirms Schmidt & Parker's recommendations for a full crew simulator to enhance the rehearsal of ACT and flight emergency drills. He also reports a trend in the following categories: loss of situational awareness, lack or loss of depth perception, visual illusions, self-medication and fatigue. In 1996, the Navy's Bureau of Medicine (BUMED) incorporated medical standards for UAV aircrew to address these factors. Seagle also proposes an automatic, "hands off" landing system for runway arrestment and embarked net recoveries with an override capability for the EP or IP in the case of degraded operations. He attributes the lack of urgency in implementation of these efforts to the UAV community having no "champion" at the flag officer level. The relatively inexperienced and young officers who serve in the UAV community have not reached (or may never reach) the rank where they can affect change, unlike officers in manned aviation careers.

E. RESEARCH OBJECTIVE

The objective of this study is to further identify the causal factors resulting in the unacceptable number of UAV mishaps. Particular emphasis is placed on human factors related mishaps. Once identified the study constructs a stochastic model to evaluate mishap intervention initiatives with the goal of mishap reduction in terms of cost and mission readiness. The results of the model are presented to allow decision-makers to focus on specific accident causation categories and to choose the most efficient and effective intervention strategies for further development.

F. STATEMENT OF THE PROBLEM

Since its fielding in 1986, the Pioneer has accumulated a Class A mishap rate of 385 mishaps per 100,000 flight hours. When this is compared to the manned aviation Class A mishap rate of approximately two mishaps per 100,000 flight hours, one sees the Homeric proportions of this unacceptable situation. The excessive UAV mishap rate translates into significant budgetary cost, degradation in mission readiness, and a perception of unreliability by fleet users and those whom they support. Steps must be taken to bridge the gap between conceptual capability and actual performance. The bottom line is to achieve a dramatic reduction in the UAV mishap rate to an acceptable level, to sustain mission readiness, and to minimize mishap costs. Specific research goals include the following:

1. The classification of UAV mishaps under the current aviation mishap taxonomy. Additionally, the identification the human factors characteristics that significantly impact the UAV mishap rate.

2. The development of a stochastic model of UAV mishaps which can be used to accurately represent mishap occurrences.

3. The use of the model to analyze the effects of mishap reduction intervention strategies.

4. The identification of the impact of a particular intervention strategy on cost savings and mission readiness improvement.

G. DEFINITIONS

Mishap. A naval mishap is an unplanned event or series of events directly involving naval aircraft, which results in $10,000 or greater cumulative damage to naval aircraft or personnel injury. Aviation flight mishaps are divided into one of three categories based on the severity of the damage, and the cost incurred by the mishap. The definitions governing each class of mishap is given in Naval Publication OPNAVINST 3750.6Q.

Class A Mishap: A class A mishap occurs when the total amount of damage exceeds $1,000,000 or if the air vehicle is destroyed. Because the total cost of a Pioneer UAV is approximately $1.1 million, a class A mishap will only occur if the UAV is damaged beyond repair or lost. Class A mishaps include being lost at sea, or destruction of the air vehicle if it forcefully impacts terrain. Loss of a UAV during a combat mission is not classified as a class A mishap, but rather, a combat loss.

Class B Mishap: This category is used when the total cost of damage is at least $200,000 but less than $1,000,000. Usually, a UAV class B mishap occurs when there is serious damage to the air vehicle, or if the payload is damaged. The cost of the surveillance camera alone ranges from $300,000 to $800,000 depending on whether it is the day EO or night FLIR camera. The variance of the cost depends upon whether the payload is repairable or permanently damaged.

Class C Mishap: This category is used when the total cost of damage is at least $10,000 but less than $200,000. For UAV mishaps, this situation occurs when there is a small amount of damage to the air vehicle possibly from a hard landing, or striking another object. Usually, swapping out or remanufacturing parts can repair these types of mishaps, keeping costs low.

H. SCOPE AND LIMITATIONS

The scope of this research is limited to the Defense UAV Training Command, and U.S. Navy and Marine Corps fleet Pioneer UAV squadrons. However, the results of this analysis will be pertinent to all UAV operations of current and future systems that integrate a human component to conduct the mission. Detailed mishap analysis is conducted from FY93 through FY98. In FY93, UAVs were incorporated into the Naval Aviation Safety system, and mishap reporting procedures were standardized. Prior to FY93, UAV mishap reports contained limited descriptive information, rendering detailed analysis nearly impossible. Mishap causes were typically described as pilot error, electrical or mechanical failure with little amplifying information.

The contents of the thesis are presented in the following order: Chapter Two is a literature review of three human error causation models. They serve to provide background to the HFACS model used by the NSC, which in turn is discussed in detail with specific examples of UAV applications. Chapter Two also discusses accident investigations and analysis, mishap intervention strategies, and stochastic modeling. Chapter Three describes the methods used to estimate statistical parameters, which are inputs to the stochastic model. Further, the simulation methodology is developed. Chapter Four includes the mishap database construction, parameter estimates and the output of the stochastic model simulation. Conclusions and recommended courses of action are presented in Chapter Five.

II. LITERATURE REVIEW

A. ACCIDENT CAUSATION THEORIES

The Asia-Pacific Safety Magazine (March, 1995), published by the Australian Bureau of Air Safety Investigations, reports "between 70% and 80% of [mishap] occurrences contain a human factors element." The article continues, "Indeed it can be argued that human factors are involved in all occurrences." In a system designed, built, maintained and operated by humans, only a fraction of one percent of the mishaps can be attributed to factors beyond human control (Bruggink, 1996).

Because of society's obvious goal to reduce the number of aviation mishaps and eventually their overall prevention, much research has been dedicated to determining accident causation, and developing a safe environment where the probability of having an accident is minimized (Harle, 1993). Nevertheless, the results of aviation accident investigations often limit conclusions to phrases such as "pilot error," "failure to see and avoid," "improper use of controls," or "failure to observe and adhere to established standard operating procedures (SOPs).

"However, effective accident intervention and prevention requires more than identifying who is culpable. In order to implement a safety conscious program, a better understanding of the context in which these individuals faced accident conducive circumstances is required.

Within the last thirty years, three accident causation theories stand out for their merits in dissecting the myriad of contributing causal factors that create the context of an incident. These three theories are Edward's (1977) "SHEL" model; Helmreich's (1990) model; and the Reason's (1990) "Swiss Cheese" model. Each of the three theories attempts to explore the latent or removed factors that influence the mishap. The main focus is on the "chain of events" and surrounding circumstances that lead to an accident.

1. The SHEL Model

The "SHEL" (Software, Hardware, Environment and Liveware) model is first introduced by Edwards (1972) and later modified by Hawkins (1984). The SHEL model places emphasis on the human being and its interfaces with the other components of the man-machine-environment system. Each component of the SHEL model represents the components of a modern technological system as depicted in Figure 3.

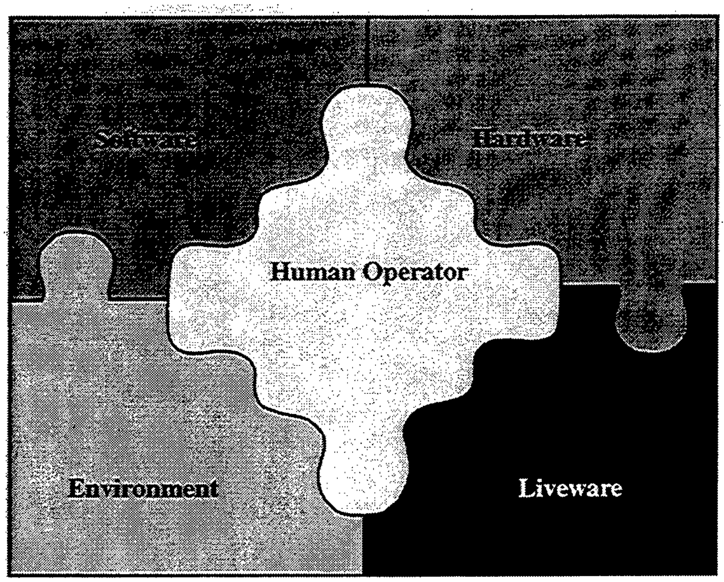

FIGURE 3: THE SHEL MODEL

The human operator is set at the center of the model, and must interact with each of the four external components. The edges of the blocks are not simple or straight, indicating that the human must be matched with each component in order to function properly. A mismatch between blocks, or an improper fit is a potential cause for human error. In order to analyze the human factors aspects of an environment, one must look at both the individual component blocks, and also their interface (Harle, 1993). The following is a brief description of each component of the model:

a) Human Operator

The human operator is the hub of the SHEL model. As such, analysis of the individual must incorporate four categories: physical, physiological, psychological, and psychosocial. Physically, one must determine if the individual is capable of performing the required task, and if there are any impediments or limitations to successful task performance. Physiologically, an individual must be prepared to conduct the task. This category includes the items of proper nutrition, alcohol or drug use, tobacco use, stress and fatigue, and the effect these have on an individual or crew's ability to perform and make appropriate decisions. Psychologically, an individual must be capable of mentally executing the task. Knowledge of what is required, and the confidence to perform the task must be established. Moreover, the workload must be appropriate to an individual's information processing and attention capabilities. Finally, psychosocial factors impact human performance. Stress, pressure from a supervisor, the workplace climate and personal issues all influence one's reaction in a potentially dangerous situation.

b) Liveware

The liveware interface is the operator's relationship to the other individuals in the workplace. In aviation, this is often referred to as crew resource management

(CRM) and is addressed later. Liveware also relates to teamwork, morale and the overall command climate. Obviously, healthy interpersonal relationships among a crew, or between individuals and their supervisors are essential for a safe and effective work environment.

c) Hardware

The hardware interface addresses the human machine interface (HMI). The HMI includes workspace configuration, displays, controls, seat design and configuration, visibility and climatic conditions. The physical work environment impacts crew orientation, information processing, cognition and execution of the task. Similarities of component design and their physical layout can affect effective scan patterns, and facilitate correlation of input data. The hardware interface is the focus of ergonomic and anthropometrical study.

d) Software

The software interface is the relationship between the individual and all supporting systems found in the workplace. This category includes not only computer software design, but also regulations, manuals, checklists, and SOPs. These items must be user friendly and understandable to the human operator. Automation is also a significant contributor to the software human interface. An entirely automated system may have the tendency to breed complacency and boredom for an operator resulting in decreased vigilance. On the other hand, the lack of automation can cause task saturation for an operator in extreme situations, also resulting in an unsafe environment.

e) Environment

The environmental interface is the relationship between the operator and the internal and external environment. The internal environment includes temperature, lighting, noise, vibration and air quality. The external environment includes visibility, weather and terrain. For military applications, the external environment includes the combat situation during which operations must be executed. The surrounding environment has significant impact on individual and crew motivation, attention, judgment and performance.

2. The Helmreich Model

Helmreich advised the International Civil Aviation Organization (ICAO) Commission of Inquiry on the human factors aspects of an Air Ontario flight accident that took place in Dryden, Ontario in 1990 (Zotov, 1996). The advantage of his theory is that it eliminates an opportunity for regulators and organizations to argue that their actions should not be discussed in the accident report. It is frequently argued that an accident is the end result of a chain of events: if a causal factor can be removed and the accident could still have occurred, then *ipso facto* that factor can not be causal. The Helmreich model illustrates that an accident is the accumulation of factors, rather than their chaining together, which affects a crew's performance.

The Helmreich model can be envisioned as a series of concentric circles surrounding an operator or crew. Each ring potentially influences the crew and may cause a degradation of performance. The four levels of influence are the regulatory environment, the organizational environment, the physical environment, and the crew environment (see figure 4). Accidents occur as the result actions taken within the context of this crew environment.

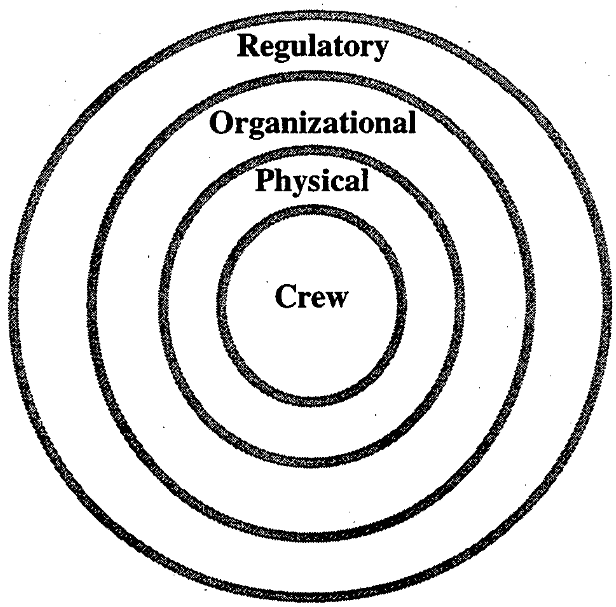

FIGURE 4: HELMREICH MODEL OF ACCIDENT CAUSATION

a) Regulatory Environment

The regulatory environment is the guidance for conducting operations. Within Naval aviation, this includes NATOPS procedures, the Training and Readiness (T&R) manual, unit SOPs, operations orders and commanders guidance. These regulations guide supervisors on how to conduct mission planning and execution within certain limitations. Examples of these regulations are proficiency and currency requirements, crew rest and approved flight profiles.

b) Organizational Environment

The organizational environment includes crew composition and its performance. Consistent training, personnel stability, OPTEMPO and leadership contribute to the organizational environment. On the micro level, the interface between operations and maintenance personnel, and on the macro level between a unit and is higher and adjacent units within the command and control structure greatly influence the organizational environment and the niche into which a crew fits.

c) Physical Environment

The physical environment is consistent with the internal and external environments of the SHEL model. It also includes the physical condition of equipment at the time of an incident, and what affect that had on mission performance. The model recognizes that the surroundings of an individual or crew have a significant impact on the vigilance and responsiveness of the operator.

d) The Crew Environment

The crew environment comprises the interpersonal coordination and communication within a crew. The model also extends the crew definition to include its interfaces with external control, such as air traffic (ATC) and enroute controllers. Anyone associated with the conduct of a mission is *de facto* part of the extended crew. The crew environment is also influenced by CRM. Finally, the crew is further broken down into individual components. Individuals possess their own performance strengths, weaknesses and vulnerabilities.

The Helmreich model of accident causation is crew centered. However, instead of "blaming" the crew or individuals on the crew, it looks at the context of the accident that arises from the faulty actions or decisions by external agencies. These contributing factors, although potentially missing from the "chain of events" are equally influential in an accident occurrence (Zotov, 1996).

3. *The "Swiss Cheese" Model*

The "Swiss Cheese" model is the outgrowth of research examining human error by Reason (1990). The model discusses the layers of defense used to protect against accident occurrences. Reason's model identifies four layers that potentially contribute to an accident: organizational influences, unsafe supervision, unsafe conditions and individuals performing unsafe acts (see Figure 5).

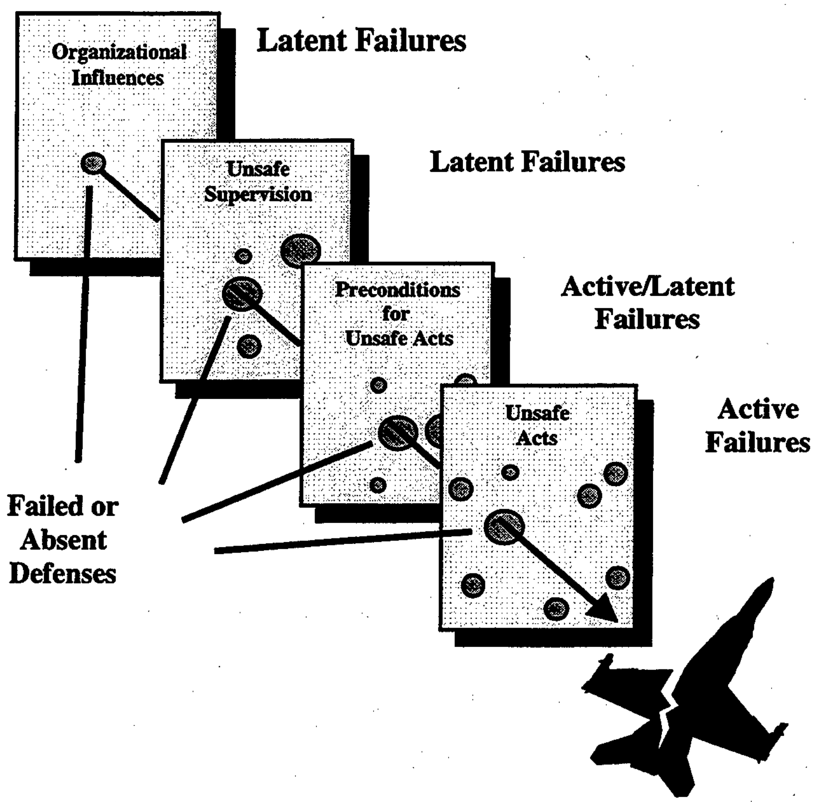

FIGURE 5: REASON'S SWISS CHEESE MODEL

In an ideal world, the defensive layers would be intact, preventing the "accident trajectory," as depicted in the diagram by the arrow, from passing through to the accident event. However, each layer has weaknesses and gaps that are revealed by the holes. In the real world, these holes are not fixed and static, otherwise they could be identified and repaired. Reason (1998) describes the holes as dynamic and in a constant state of flux. Local conditions drive which defensive layer comes in and out of the frame at a particular time.

Reason (1998) attributes the holes as either active failures, or latent conditions. Active failures are either violations or errors that occur in the immediate vicinity of the accident occurrence. They are performed by the operators – pilots, air traffic controllers, police officers, control room operators, maintenance personnel, and so on. The discovery and mitigation of this active failure immediately prior to the accident would most likely prevent the accident from happening. Twenty years ago, the discovery of this unsafe act would have ended an accident investigation. However in today's climate, unsafe acts are seen more as consequences than principle causes. It is recognized that people working in complex systems make errors or violate procedures for reasons that go beyond an individual. These causes are called latent conditions.

Latent conditions can be present for many years before they combine with local circumstances and active failures to penetrate they systems layers of defense. Examples of latent conditions include poor design, improper training and supervision, undetected manufacturing defects or poor design, unworkable procedures, or improper automation. At the macro level, government, regulator or corporate policy shapes the organizational culture, creating the error producing factors within an individual environment.

Latent conditions are present in all systems and are an inevitable part of the organizational culture. Latent conditions are not bad policy decisions, but can result from the demands of a limited budget or manpower management constraints. These latent conditions can lie dormant for years and have no impact until they become manifested at a time where particular weaknesses in the defense become exposed. In contrast to active failures, which tend to be unique to a specific event, latent conditions can go unrecognized and can contribute to a number of different accidents. Latent conditions increase the likelihood of active failures through the creation of local factors allowing error and violations to occur (Reason, 1998).

B. HUMAN FACTORS ANALYSIS AND CLASSIFICATION SYSTEM

The Human Factors Analysis and Classification System (HFACS) taxonomy as developed by Shappell & Wiegmann (1997) at the Naval Safety Center (NSC), is based on Reason's concept of human error in accident causation. HFACS also incorporates, albeit to a lesser extent, components of the SHEL and Helmreich model to define the context surrounding an accident. The HFACS taxonomy will be added to the next publication of OPNAVINST 3750 and become the standardized methodology adopted by the Naval Aviation Safety Program for human factors mishap investigation. HFACS attempts to capture the context in which an accident occurs by categorized failures into four separate tiers depicted in Figure 6. These tiers are organizational influences, unsafe supervision, unsafe conditions, and unsafe acts. For the purposes of this discussion, each tier is viewed through the context of naval UAV operations.

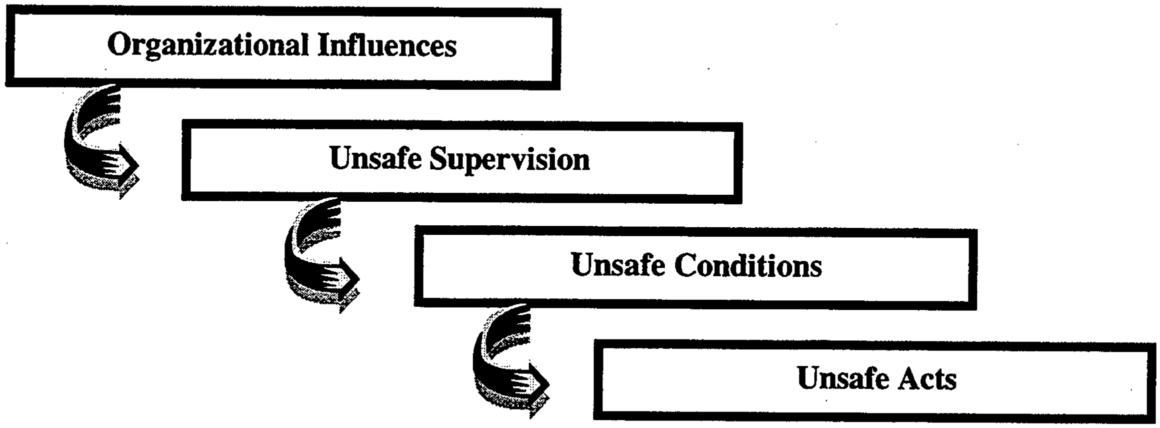

FIGURE 6: HFACS MISHAP CAUSATION CATEGORIES

1. *Organizational Influences*

The first HFACS tier of mishap causation is organizational influences. Organizational influences are often difficult to quantify and can rarely be tied as a specific cause to an accident. However, their existence certainly contributes to the circumstances surrounding an accident. The author discussed these influences with UAV crewmembers at VMU-1, VMU-2 and VC-6. Among aviators, there is a perception that a UAV tour shows a lack of competitiveness with one's peers who are in a flying billet in their primary airframe. Being assigned to the UAV unit relegates them to the status of a second-class citizen. In contrast, several see the UAV field as an opportunity to excel in a challenging and developing community. As such, they channel their drive and energy to guarantee success.

Another organizational influence is the lack of a UAV specialty and career path. Until 1996, UAV enlisted personnel did not have a specific rating or military operational specialty (MOS). As a result, personnel were assigned to a UAV unit with no previous background, underwent training and left the unit three years later, never to return again. Initial accessions to UAV units were recruited by advertising for individuals whose hobby was remote control airplanes. Initially, a unit could be made up of truck drivers, mechanics, yeomen, or any combination of backgrounds. The establishment of enlisted specialties has improved the situation. Nevertheless, there are no officer specialties or career paths. It is still the case that an officer will only serve one tour in a UAV unit before leaving the community. Typically, all officers in a UAV unit, including the commanding officer, will be new to the community upon assignment (MAWTS-1, 1997).

A third organizational influence within the UAV community is the perception by others in the aviation field. Besides the normal rivalries that exist among communities, aviators typically relegate UAV crews to being the lowest on the totem pole. Often, their inclusion in aviation planning and operations in regarded as a nuisance by those who do not understand the unique integration requirements that UAV operations must address. These organizational conditions, unhealthy at times, can create an environment susceptible to unsafe operations and potentially lead to mishap causation.

2. *Unsafe Supervision*

Unsafe supervision is the second HFACS tier that contributes to an actual mishap occurrence. Unsafe supervision can be both unforeseen and foreseen. Unforeseen unsafe supervision includes unrecognized unsafe operations, inadequate documentation and inadequate design. Unrecognized unsafe operations result from a supervisor not recognizing an unsafe act or condition. For example, a supervisor may not be aware of accumulated fatigue among aircrew or maintenance personnel in a unit. Instead of taking corrective action, the situation is ignored. Also, by not being aware of influences on individuals, crew assignments and personnel management suffer. An example is the supervisor who is not aware that a crewmember has a sick spouse or child, a recent death in the family, or marital difficulty. As a result, the supervisor does not know to take these adverse mental conditions into account when making crew assignments.

Inadequate documentation refers to unknown "bugs" in the system. Designed for combat, the Pioneer was not fully tested until Operation *Desert Storm*. Operational testing and training are designed to closely resemble combat, but cannot replicate it. During Operation *Desert Storm*, the Marine Pioneer units operated as part of a full scale Marine Expeditionary Force (MEF). A microwave antenna/transmitter was located at the UAV airstrip for communications. The microwave signal caused electro-mechanical interference (EMI) with the UAV uplink and downlink causing loss of vehicle control resulting in crashes on several occasions. Because the Pioneer had not previously operated in close proximity to this specific communications equipment, this condition was neither realized nor documented.

Inadequate design is an extension of inadequate documentation in that an inadequate condition exists that is unintentional. The engineers who designed the equipment may not have anticipated requirements for certain performance characteristics or capabilities. Although it may seem inconceivable for a naval UAV, the Pioneer was not built to fly through rain or visible moisture. It was designed by the Israeli Aircraft Industries (IAI) for operations in arid areas around Israel. It has a laminated wooden propeller that delaminates in moisture, and the electronic components on the air vehicle are not waterproof. This inadequate design has been the cause of several UAV mishaps.

Foreseen unsafe supervision is the mismanagement of individuals at the personal level. It includes the lack of or inadequate supervision, the failure to correct a known problem, or a supervisory violation. Foreseen unsafe supervision is a lack of leadership and guidance in a crew or in the entire unit that creates an unsafe situation for flight operations. Within a unit, this can be an underlying condition that is reflected in lack of discipline, operational focus or morale. Unsafe supervision is rarely an isolated instance, but is symptomatic of underlying conditions, which can all lead to a mishap.

3. Unsafe Conditions

Reason (1990) addresses the category of unsafe conditions in accident causation, however Shappell & Wiegmann's (1997) HFACS taxonomy further subdivides these conditions into aeromedical, crew resource management and readiness violations. The following paragraphs characterize each of these subdivisions. Additionally, each subdivision is discussed within the context of UAV community issues.

a) Aeromedical Conditions

Aeromedical conditions include the physiological and mental condition of individuals, and their physical and mental limitations. The physiological condition of an individual includes the functioning of their sensory system and physical condition. A UAV crewmember may experience spatial disorientation or visual illusions caused by the remote controls of the air vehicle. Unlike manned aviation where pilots incorporate vestibular inputs with visual cues to perceive the attitude and motion of the aircraft, a

UAV operator does not have those inputs. In order to operate effectively as a crewmember, there are required sensory thresholds that must be maintained. In addition to the senses, other physical conditions can affect the crewmember. Though not exhaustive, medications, fatigue, change in circadian rhythm, hypoglycemia, use of alcohol, or vitamin deficiencies can cause a person to be physically unqualified to conduct a mission (Edwards, 1990).

The adverse mental condition of a crewmember is also an aeromedical condition that can adversely affect mission performance. The effects of stress and mental workload on human performance are widely documented. Both can cause a loss of situational awareness, mental fatigue and task saturation. Additionally, personality traits and attitudes such as overconfidence, complacency, misplaced motivation, or a desire to please, cause an adverse mental state. Increased OPTEMPO, and associated family separations, financial concerns, operational or combat fatigue and competition among members of a crew, all potentially combine to create the adverse mental conditions that can cause an accident (Hawkins, 1987). The final aeromedical contribution to unsafe conditions is the physical and mental limitations of the crewmember. Individuals must be physically and mentally screened for selection as UAV aircrew in order to prevent the environment for the previously discussed conditions to occur.

b) Crew Resource Management

Jensen (1995) defines crew resource management (CRM) as the effective use of all resources (hardware, software, and liveware) to achieve safe and efficient flight operations. The resources that a crew manages are people (other crewmembers), equipment (instruments and controls) and other items such as charts, checklists and operational manuals. UAV operations, as stated earlier, involve a crew of at least four, and normally more crewmembers. The competency and experience of these individuals, their supervision, their interpersonal communication and the remote aspect of the air vehicle from the operational control site combine to make unique CRM demands on a UAV crew. The crew must communicate via an intercom system (ICS) and crewmembers often cannot establish eye contact with one another. Additionally, not all crewmembers have access to flight instrument information. As the number of crewmembers goes up, the potential for conflicting interpretations of information also increases, potentially causing confusion and indecisive actions.

c) Readiness

Readiness violations refer to violations of standard operating procedures (SOPs), rules, and instructions designed to provide a safe operating environment for flight operations. Among other things, NATOPS defines regulations on crew rest, self-medication and alcohol consumption. In the Marine Corps, the Training and Readiness (T&R) Manuals (MCO 3500.21: Volumes I and VI), define crew proficiency and currency requirements for an individual conducting a specified mission. Violations of any of these regulations can create unsafe conditions for a mission.

4. Unsafe Acts

The fourth HFACS tier is unsafe acts, which can be classified as either intended or unintended. Intended acts are either mistakes or violations, whereas, unintended acts are either slips or lapses. The following paragraphs characterize each of these subdivisions. Additionally, each subdivision is discussed within the context of UAV community issues.

a) *Intended Acts*

Mistakes are failures to formulate the correct intentions, and can result from shortcomings of perception, memory and cognition. In these cases, the intended action is wrong. Knowledge based mistakes are caused by failures to understand the situation and arriving at an incorrect course of action. In this situation a UAV operator may be saturated with raw information, and may not be able to process the data to formulate the correct actions. Also, because of inexperience, an operator does not have the capacity to assimilate the information given to formulate a correct response.

In contrast, someone with more experience who misapplies a rule under certain conditions usually makes a rule-based error. A rule-based decision can be likened to *if...then* logic. These mistakes normally occur in one of three ways. The first is that a rule is followed, but exceptions to the situation are not noted. An example is a UAV operator who has been operating from a shore location and is now operating at sea. Emergency procedures that are learned and reinforced through training ashore may not be applicable or desirable at sea. A mistake occurs when the operator applies a land-based procedure at sea and an accident occurs. The second type of rule based mistake is when the *if...* part of the situation is misinterpreted, and the *...then* action is inappropriately applied. And finally, the third type of rule based mistake is when the *if...* observation is correct and the *...then* action is incorrectly applied. (Wickens, 1992)

In contrast to mistakes, violations are the willful breaking of rules or procedures. Violations can be categorized into routine or exceptional violations. A routine violation tends to be habitual in nature and is typical of an individual's behavioral repertoire. An example of a UAV related routine violation is when a crewmember habitually fails to follow the unit SOP or NATOPS procedures. This can be as harmless as failing to brief a certain emergency procedure during a pre-flight brief. Lack of supervision and correction action acerbates the violation by passively reinforcing incorrect procedures. On the other hand, an exceptional violation is an isolated departure from authority, neither typical of the individual nor condoned by supervisors. The deliberate decision to ignore directions from an air controller is an example of an exceptional violation.

b) Unintended Actions

A slip is an unintended error in which the correct intention is incorrectly carried out, as opposed to a mistake where the incorrect intention is correctly carried out. For example, the internal pilot (IP) uses dials to control the speed and altitude of the air vehicle. Intending to adjust the UAV airspeed and inadvertently changing the altitude dial is an example of a slip. According to Wickens (1992), slips occur for three reasons: (1) the intended action involves a slight departure from the routine, frequently performed action; (2) some characteristics of the stimulus environment or action sequence closely relate to the inappropriate, but more frequent action; and (3) the action sequence is automated and therefore, not monitored closely by attention.

Finally, a lapse is the failure to carry out an action. Memory failure, memory overload, or interruption can cause a lapse. Prior to every UAV mission, all members of the UAV crew perform various tasks as outlined in a preflight checklist. If that sequence of events is interrupted unexpectantly, requiring the crew or an individual to divert attention and then come back to the pre-flight sequence, a particular step may be skipped. This momentary distraction can cause a lapse to occur with unknown consequences.

C. ACCIDENT INVESTIGATIONS, ANALYSIS, AND REPORTS

Bruggink's (1996) research in civil aviation points out that accident reporting is too preoccupied with reactive, formal responses to stated accident causes. Typical investigations focus on the black and white elements of accident causes. Since the role of human factors is often a gray area, it can seldom be accommodated by the rules of evidence favored by investigating authorities. Emphasis is placed upon direct cause-effect relationships, and causal statements become official designators of blame. The inclusion of contributing factors to causal statements perpetuates a distinction between primary causes and contributing factors that has the effect of lessening their relationship to the accident. McAdams, a senior and respected member of the National Transportation and Safety Board (NTSB) commented after a 1978 mid-air collision investigation that: "A contributing factor is not a primary cause; it is more remote and does not carry the same weight or implications as that of a probable cause." (Bruggink, 1996) As a result, the context of the situation is dismissed easier than the individual acts themselves.

Zotov (1996) also concludes that there exists reluctance to closely analysis human factors related causal factors. Often investigations lead to personal attacks, legal obstruction and corporate pressure on the investigating authority if the entire "system" is under investigation. A corporation will attempt a legal response that frees them from culpability by using the "chain of causation" approach to accident occurrences. Additionally, the legal concept of "remoteness of damage" can make it difficult to present the concept of a complex network of interacting events that caused an accident.

Mayer & Ellingstad (1992) state that accident databases frequently describe attributes of the physical environment and equipment, but that detailed analysis of accident causes, including human factors information, are frequently not represented because they are too difficult to obtain and code. Engineers and front-line operators design most accident reporting systems with limited backgrounds in human factors. This results in a lack of suitability for addressing human factors issues. Naval Aviation is continuing to attempt addressing this shortcoming through the Naval Aviation Safety Program.

The purpose of the Naval Aviation safety program is to preserve both human and material resources in order to enhance operational readiness. In order to accomplish this goal, damage and injury must be addressed to mitigate the hazards inherent in flight operations (OPNAVINST 3750.6Q, 1997). The use of HFACS in mishap reporting is designed to improve the quality of mishap reports, which will in turn improve the data available for analysis. With a higher quality database available, mishap analysts can isolate recurring causal factors and recommend suitable strategies to eliminate or reduce the frequency of these accidents. These intervention strategies can then be evaluated for their effectiveness in improving operational readiness and reducing budgetary losses.

D. MISHAP INTERVENTION STRATEGIES

Mishap intervention strategies are designed to address common mishap causes and decrease the probability of their occurring. Typically, these strategies fall into one of three categories: engineering controls, policy and procedures and individual protection measures. Engineering controls deal with a physical reconfiguration of the system. It may be ergonomic, or mechanical in nature. The result of the change is improved system performance. Policy and procedures address the circumstances surrounding operations. Within the HFACS model, these strategies reflect mishaps in the unsafe conditions and unsafe supervision. Changes in flight prerequisites and improved time to train are examples of policy modifications. Individual protection refers to the equipment a person may use to decrease the possibility of physical injury due to operations. This study addresses seven mishap intervention strategies.

1. Aeromedical Screening and Education

Among the recommendations made by Schmidt & Parker (1995) several are associated with aeromedical screening and monitoring. Currently, this is taking place prior to assignment to UAV training. However once initial training is complete, a flight surgeon is not assigned to each UAV unit. There still exists a perception that UAV crewmembers are just like any other ground community, where crew rest and other requirements are perceived as a luxury and not a requirement. Additionally, ongoing training is not routinely conducted to address the affects of nutrition, alcohol and tobacco use, stress and psychological readiness on mission performance. The first intervention strategy addressed is continuing and increasing the education and follow up attention to aeromedical issues and their effect on readiness. This intervention strategy is a policy and procedure change and is modeled by the unsafe condition (UC) causation category.

2. Aircrew Coordination Training / Crew Resource Management

The policy and procedural recommendation for mishap intervention is increased aircrew coordination training (ACT)/CRM. This is being conducted in UAV units; however, the lack of experience among crewmembers limits its effectiveness. Because UAV operators are cyclically new to the community, there is no senior leadership that can speak with a voice of experience to situations that may occur during a flight. Aviators on the crew bring a generic ACT background to a unit, but lack specific UAV applications. This results in a reactive rather than deliberate approach to an emergency situation. Improved, standardized training will impact mishaps caused by unsafe acts (UA) and unsafe conditions (UC).

3. UAV Flight Simulator

A UAV mission simulator can further enhance mission performance skills and mitigate unsafe actions during the conduct of a flight. Schmidt & Parker (1995) find that 59% of mishaps occurred as a result of electrical, mechanical or engine failure. If these situations can be replicated via simulation, a crew can rehearse procedures to correct the problem, or put the aircraft in an attitude where damage is minimized. Currently the Pioneer does not have a simulation capability where an instructor can induce such an emergency, observe the crew response, and then debrief the crew on their performance.

The only time the entire crew can operate as a team to address an emergency is during an actual flight. A replacement to the GCS is under development as the Tactical Control System (TCS). The TCS is designed to be a universal ground control and communications shelter that has the ability to interface with all follow-on DoD UAV systems. One of the TCS's requirements is the ability to conduct simulator training without conducting an actual mission. The model addresses unit training procedures and is modeled in the unsafe act (UA) category.

4. Automated Take off and Landing System

Schmidt & Parker attribute 32% of mishaps to take-off and landing error. Although not currently a requirement for future UAV systems, several contractors are developing an automated take-off and landing system. Their concept is to fly the UAV to a predetermined handover point where it flies into a radio beacon. The beacon then takes over sending navigational information to the UAV until it is safely on deck. There would also be a manual override system. This engineering control will lower the incidents of unsafe acts (UA) during the takeoff and landing phase of the flight.

5. Personnel Stabilization

In order to lessen the effects of unsafe supervision as well as unsafe acts. The UAV community can establish officer specialty codes and career progression possibilities. The current situation of constantly rotating first time supervisors into UAV units causes instability and limits the "corporate knowledge" of squadron members. If implemented, supervisory and performance skills will dramatically improve. The policy change is modeled by the unsafe acts (UA) and unsafe supervision (US) categories.

6. *Engine Replacement*

Although not human factors related, engine failure has been attributed to one quarter of UAV mishaps (Schmidt & Parker, 1995). Engineering modifications replacing the current engine with a more reliable engine is modeled in the analysis section.

7. *Electronic Waterproofing*

Like engine failures, electronic failures account for another quarter of UAV mishaps. Although not originally designed as a naval UAV, the Pioneer is operated by the U.S. naval services and would benefit by environmental shielding. The affect of engineering modifications such as water proofing system components for operation at sea, in the littorals, and in foul weather is addressed.

E. STOCHASIC MODELING

Ross (1997) states that in making a mathematical model for a real world phenomenon, it is always necessary to make simplifying assumptions so as to make the mathematics tractable. However, making too many simplifying assumptions can make our conclusions not applicable to the real world. Therefore, the stochastic model must strike a balance between simplicity and realism.

Law & Kelton (1991) state that mathematic model simulation is one of the most widely used techniques in operations research. The mathematical model is used to represent a system in terms of logical and quantitative relationships that can be manipulated to see how the model reacts. A stochastic process is the collection of random variables ordered over time, which are defined on a common sample space. A stochastic simulation model takes random variable input components and repeats the simulation multiple times in order to achieve a random, although converging solution. The output of a stochastic model is itself random, but the number of repetitions can decrease the variance in the results.

In order to create a stochastic simulation model, probability distributions and parameters must be identified. In lieu of using the empirical distribution that may contain some "irregularities," particularly if the sample size is small, a theoretical, parametric distribution is used to smooth out the data (Law & Kelton, 1997). Mintz (1954a) models taxi cab accidents in order to determine whether they could be modeled by a specific, known distribution. In order to accomplish this simplification, Mintz makes two assumptions: (1) accident liability (or proneness) of people is not changed by accidents in which they are involved and do not vary over time; and (2) accident liability is distributed in some known manner. Through his study of over 1200 taxi cab accidents, Mintz (1954b) concludes that accident rates closely approximate a Poisson Process because (1) they do display a "memory less" property; and (2) they are distributed as an exponential random variable. For the purpose of the UAV mishap model, parameterized distributions are tested to determine their suitability as model inputs.

The goal of the stochastic model is to probabilistically simulate annual Pioneer UAV flight operations for the Navy and Marine Corps to approximate mishap events, their cost, and effect on readiness. The model simulates these mishaps as a Poisson Process. The model is designed with an open architecture to model any durations of flight operations, or quantify other measures of performance (MOPs). While it may not be feasible or desirable to modify the Pioneer UAV with these results, they are applicable for addressing the next generation replacement system.

In order to model intervention strategies, this model isolates causal factor categories. Although, none of these intervention measures can be totally successful when employed in isolation within a mishap category. For example, ACT relies on experience, which is tied to specific UAV occupational fields and career progression within the community. Simulators also enhance training and readiness. Aeromedical readiness is tied to standardization and supervision. All aspects of mishap prevention are interdependent.

Stochastic modeling is used effectively in previous studies to effectively model accidents and their effects on cost and missed working hours. Schmorrow (1998) uses the HFACS taxonomy to code aviation maintenance mishaps, and stochastic modeling to predict cost and readiness. Sciretta (1999) uses a similar methodology to stochastically model U.S. Navy shipboard electrical shock mishaps. Teeters (1999), applying HFACS, studies the distribution of major and minor aviation maintenance mishaps for Fleet Logistic Support (VR) Wing aircraft. This study applies a similar framework to stochastically model UAV mishaps.

F. SUMMARY

In order to effectively analyze mishap intervention techniques, effective coding and documentation is required. The Naval Aviation Safety program provides the framework and resources to collect this data. HFACS is the most recent improvement to aid in accident investigation, reporting and analysis. HFACS is based upon accepted accident causation theories. Using HFACS coding, mishaps can be categorized, and mishap probabilities determined. To analyze these categories, a stochastic model can be used to simulate mishap occurrences over a defined period of time. While random in themselves, the results are used to weigh the various options available to reduce mishap cost and increase mission readiness.

Applying the HFACS taxonomy, accidents happen as a result of a confluence of weaknesses in all four tiers of the model. Intervention strategies are designed to reinforce the cohesion of the tiers and decrease the probability of a window of accident opportunity. Intervention strategies are designed to strengthen safety environment at each of the four levels.

III. METHODOLOGY

A. RESEARCH DATA

The goal of this research is to use a stochastic model simulation to predict the effects of mishap intervention strategies on both operational readiness and budgetary costs. The data inputs must be determined in order to conduct the simulation. First, a database is constructed from the mishap reports, and causal factors are coded and parsed from the data. Analysis of the data leads to the statistical determination of the model inputs: inter-event times for mishaps; the mishap rate parameters; the probability of mishaps by class (A, B or C); the mishap cost distribution; and the annual UAV flight hours. Once calculated, these statistics are used in a stochastic model simulation of annual UAV flight operations. The output of the model is expressed as a mission readiness factor, and annual mishap costs. Detailed description of each phase is discussed below.

1. Mishap Records

The Naval Safety Center (NSC) is responsible for maintaining aviation mishap records for the Navy and Marine Corps. The foundation of the mishap record is the mishap investigation report (MIR). MIRs are required for all Class A, B and C mishaps in accordance with OPNAVINST 3750.6Q. The following items are described in the MIR: the events leading up to a mishap, the location and type of operations involved in the mishap, causal factors and recommendations for reducing the risk of similar type accidents occurring. Prior to FY93, UAV mishaps were not incorporated into the

Aviation Safety Program. As a result, the MIRs are not complete and normally point only to one causal factor, usually mechanical, electrical or human error. MIRs submitted since October 1992 have improved mishap records significantly. Primary and contributing factors are reported with greater detail.

2. *Data Base*

The database for this thesis is constructed from the UAV MIRs maintained by the NSC, and formatted into an EXCEL spreadsheet. Each mishap event contains the following categories: mishap date; air vehicle number; unit; mishap summary; aircraft equipment and damage; repair cost; time, location, altitude, and weather at the mishap occurrence; causal factors; and recommendations. All repair costs are converted into FY98 dollars using the aviation price inflation indices provided by the Naval Center for Cost Analysis (NCCA).

This study addresses mishap rates from the entire database (FY86-FY98). When detailed analysis of causal factors is required, it limits its scope to the FY93–FY98 MIRs that are standardized by the Aviation Safety Program. Additionally, this partition helps to focus analysis on recent steady state UAV operations. Initial mishaps caused by the introduction of the air vehicle into the Fleet inventory or by the aberrations to normal operations such as those occurring during Operations *Desert Shield* and *Desert Storm* do not confound the data.

3. *Causal Factors*

A single mishap typically has several codes associated with it. This analysis goes beyond the primary causal factor, and addresses known contributing factors. Also of note, mishap coding is done at the lowest level possible given the data provided. For example, a UAI (unsafe act: intended) is a subset of UA (unsafe act). However, if the MIR provides limited information, coding is done at the highest level discernable. The UAV mishaps are coded by causal factor in accordance with the Human Factors Mishap Classification System (HFACS) (Shappell & Wiegmann, 1997). Material failures are recorded by causal factor. Table 2 contains the codes used in the database:

CAUSAL FACTOR				CODE
Human Factors				HF
	Unsafe Act			UA
		Intended		UAI
			Mistake	UAIM
			Violation	UAIV
		Unintended		UAU
			Slip	UAUS
			Lapse	UAUL
	Unsafe Condition			UC
		Aeromedical		UCA
		CRM		UCC
		Readiness		UCV
	Unsafe Supervision			US
		Unforeseen		USU
		Foreseen		USF
Electro - Mechanical				EM
		Engine		ENG
		Electrical		ELEC
		Launcher Failure		LNCHR
		Net Recovery Failure		NET
		Software		SOFT
		Other		OTHER
Unknown or unspecified				UNK

TABLE 2: MISHAP DATABASE CAUSAL FACTOR CODES

B. DATA ANALYSIS

1. Inter-event Times

The computation of mishap inter-event times requires that a transformation be made from inter-event days, as recorded by the MIR, to inter-event flight hours, for use by the model. In order to accomplish this transformation, annual flight hours are assumed to be uniformly distributed throughout the fiscal year. An estimate is made of daily flight hours using annual flight hours flown information. This daily flight hour rate is multiplied by inter-event days to transform inter-event times from days to flight hours flown.

2. Mean, Variance, and Rate Parameters

Unbiased estimators for the mean and variance of inter-event times are determined for each mishap category that is modeled by the simulation. The mishap rate (λ) is calculated by taking the inverse of the mean inter-event time (Ross, 1997). The Kolmogorov-Smirnov goodness of fit (KS g.o.f.) test is used to decide whether an exponential distribution with parameter (λ) is an appropriate model for the inter-event data, and thus whether the occurrence of mishaps could be modeled as a Poisson Process (Conover, 1999). The mishap rate for the entire data set and the mishap rates by causal factor are the components of the stochastic counting process, which is being modeled.

3. Probability of Mishap by Class

The number of mishaps by class (A, B, C) is recorded for each mishap category. The probability of Class A, B and C mishaps is estimated by the number of mishaps in each class divided by the total number of mishaps in that category. A vector of Class A, Class B and Class C probabilities is used as a multinomial input to the model simulation.

4. *Cost Distribution*

A cost distribution of each mishap class is determined by estimating the mean and variance, and then performing a K-S g.o.f. test to confirm their suitability. The combined mishap rates, probability of accident severity and cost distributions are used to describe the model in terms of a compound Poisson Process.

5. *Determining Annual Flight Hours*

A regression analysis of annual flight hours by fiscal year is used to predict annual flight hours for the stochastic model. The model uses the FY99 flight hour prediction as the input. The time is the bound in the simulation for the mishap generation period.

C. SIMULATING THE EFFECTS OF MISHAP INTERVENTION

The mishap simulation model inputs are the number of simulation repetitions, the mishap rate parameter, the multinomial probability vector of the mishap categories (A, B and C), and the time period to be simulated. The program instantiates two vectors to store the mission readiness factor, and the budgetary cost value. Each simulation run goes from time zero to the end time period input value. Time steps are made as a mishap is generated using the exponential distribution with the appropriate input rate parameter. Once a mishap is encountered, its class is determined randomly, using the input probability vector. Mishap cost is calculated using the predetermined cost distribution data for that particular mishap class which is "hardwired" into the code.

The simulation run ends when the time clock exceeds the input time period. The mission readiness factor is calculated by multiplying the number of class A mishaps by three, multiplying the number of class B mishaps by two, and adding in the number of class C mishaps. If this readiness factor exceeds 21 for the time period, the mission readiness is stored as a zero; otherwise, the simulation returns a one – mission ready. Both the cost and mission readiness factor are stored in their respective vectors. Once the simulation has completed the required number of runs, the simulation returns the mean and standard deviation of budgetary cost (FY98$M), and the average of the readiness factor. The mishap intervention model code, MishapSim() is programmed in S-Plus 4.0 and is attached as Appendix B.

For each mishap intervention strategy, the model is run one thousand repetitions and through a total of four simulations. The first simulation is baseline simulation using the current mishap rate. A reduction of the mishap rate by 10%, 30% and 50% for each intervention strategy is hypothesized for the next three simulation runs. If two or more mishap categories are being modeled together, for example, unsafe acts and unsafe supervision, the rate parameters are determined as described above. However, all replicated mishaps are removed from the composite mishap category. These calculations will enable fleet users and program managers to weigh the effectiveness of a proposed change with the resulting cost and readiness savings.

IV. RESULTS

A. OVERVIEW

This chapter presents a database summary for annual flight operations by mishap class, and flight hours flown. Mishap causal frequencies are summarized for operations going back to 1986, and for the period of the study, 1993-98. Mishap coding results are presented by both number and frequency. All simulation model input parameters are then estimated and presented. Simulation results for the each mishap intervention strategy are presented for the existing baseline and for mishap frequency reductions of 10 percent, 30 percent and 50 percent. The chapter concludes with a graphic comparison of cost and readiness results for all intervention categories.

B. BACKGROUND UAV FLIGHT DATA

Figure 7 is a graph of flight hours flown and the number of mishaps versus time. Table 3 contains a summary of the UAV annual flight hours, mishaps and associated rates for the period since the fielding of the Pioneer system by the Navy and Marine Corps in 1986. In general, the annual flight hours flown is increasing and the mishap rate is decreasing. During Operation *Desert Shield* and *Desert Storm*, six UAV units flew just under 1000 flight hours. These units deployed with thirty air vehicles. At current mishap rates and during a deployment of equal duration, approximately one third of the air vehicles would be destroyed or damaged by flight mishaps. This prediction demonstrates unacceptable mission readiness and strains maintenance and repair capabilities.

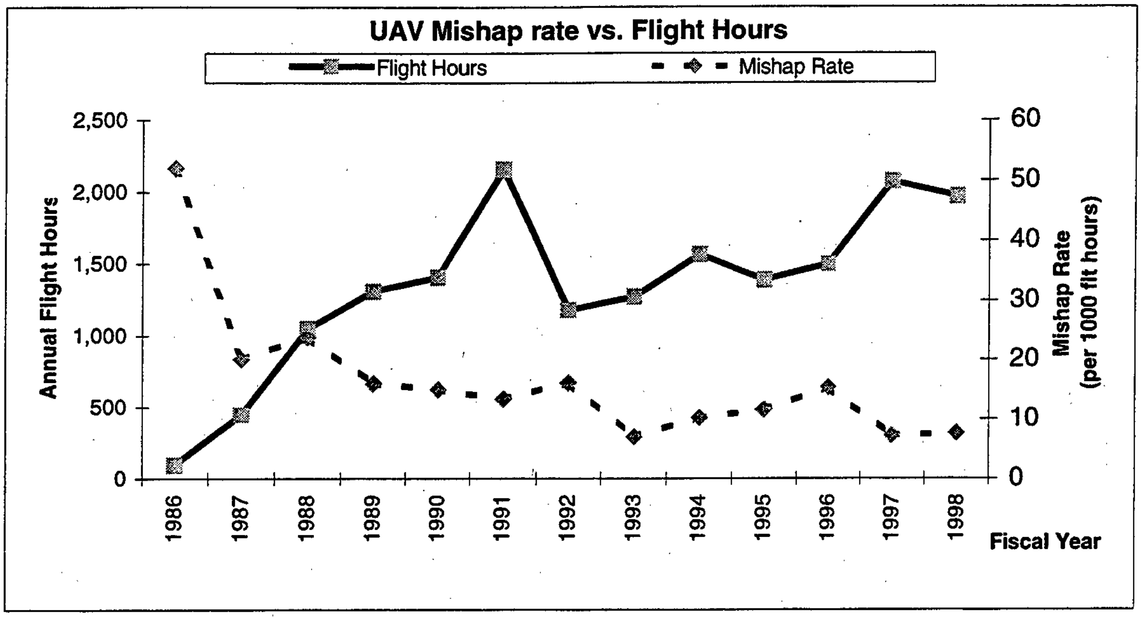

FIGURE 7: GRAPH OF MISHAP RATE AND ANNUAL FLIGHT HOURS

Year	Flight Hours	Class A	Class B	Class C	Total	Mishap Rate (per 1000 hours)
1986	96.3	2	0	3	5	51.92
1987	447.1	7	0	2	9	20.13
1988	1,050.9	5	0	20	25	23.79
1989	1,310.5	9	0	12	21	16.02
1990	1,407.9	5	1	15	21	14.92
1991	2,156.6	12	7	10	29	13.45
1992	1,179.3	3	9	7	19	16.11
1993	1,275.6	1	5	3	9	7.06
1994	1,568.0	5	5	6	16	10.20
1995	1,391.3	1	4	11	16	11.50
1996	1,500.5	9	9	5	23	15.33
1997	2,077.0	3	2	10	15	7.22
1998	1,972.3	5	6	4	15	7.61
Total	17,433.3	67	48	108	223	12.79
Class Rate		3.84	2.75	6.20	12.79	

TABLE 3: UAV MISHAPS BY YEAR AND CLASSIFICATION

C. MISHAP CODING

The frequency of mishap cause occurrences is identified in Table 4. This data is consistent with the previous studies of Schmidt & Parker (1995) and Seagle (1997). Appendix C contains the complete mishap-coding database. Of note, the frequency of human factors related mishaps is not increasing. Rather, the reporting of human factors related mishaps is increasing in detail. The Mishap Investigative Reports (MIRs) submitted since FY 93 have increased the information available upon which to assign causal factors. Table 5 is a summary of each category of mishap causation. The simulation model evaluates seven mishap intervention strategies. Each intervention strategy and its associated mishap classification category are identified in Table 6.

Mishaps	Class A	Class B	Class C	Total	Percentage
FY 86-98					
Overall	67	48	108	223	100%
Human Factors	15	24	48	87	39%
Electro-Mechanical	55	30	65	150	67%
FY 93-98					
Overall	24	31	38	93	100%
Human Factors	11	20	24	55	59%
Electro-Mechanical	17	18	21	56	60%

TABLE 4: MISHAP CAUSATION FREQUENCY

			FY 86-98		FY 93-98	
CAUSAL FACTOR		**CODE**	**#**	**FREQ**	**#**	**FREQ**
Human Factors		HF	87	39.0%	55	59.1%
Unsafe Act		UA	35	15.7%	35	37.6%
	Intended	UAI	16	7.2%	16	17.2%
	Mistake	UAIM	11	4.9%	11	11.8%
	Violation	UAIV	6	2.7%	6	6.5%
	Unintended	UAU	19	8.5%	19	20.4%
	Slip	UAUS	13	5.8%	13	14.0%
	Lapse	UAUL	3	1.3%	3	3.2%
Unsafe Condition		UC	37	16.6%	37	39.8%
	Aeromedical	UCA	9	4.0%	9	9.7%
	CRM	UCC	26	11.7%	26	28.0%
	Readiness Violation	UCV	9	4.0%	9	9.7%
Unsafe Supervision		US	40	17.9%	40	43.0%
	Unforeseen	USU	14	6.3%	14	15.1%
	Foreseen	USF	11	4.9%	11	11.8%
Electro - Mechanical		EM	158	70.9%	64	68.8%
	Engine	ENG	52	23.3%	23	24.7%
	Electrical	ELEC	59	26.5%	20	21.5%
	Launcher failure	LNCHR	8	3.6%	2	2.2%
	Net recovery failure	NET	16	7.2%	7	7.5%
	Software	SOFT	7	3.1%	5	5.4%
	Other	OTHER	20	9.0%	8	8.6%
Unknown/ unspecified		UNK	8	3.6%	7	7.5%

TABLE 5: MISHAP FREQUENCY BY CAUSATION CODE

Mishap Intervention Strategy	Mishap Category
Aeromedical Screening and Education	Unsafe Conditions (UC)
Aircrew Coordination Training / Crew Resource Management	Unsafe Acts, Unsafe Conditions (UA/UC)
Flight Simulator / TCS	Unsafe Acts (UA)
Automatic Takeoff and Landing System	Unsafe Acts (UA)
Personnel Stabilization	Unsafe Acts, Unsafe Supervision (UA/US)
Engine Upgrade	Engine (ENG)
Weatherizing the Air vehicle	Electronic (ELEC)

TABLE 6: MISHAP INTERVENTION STRATEGY AND ASSOCIATED CAUSAL CATEGORY

D. STOCHASTIC MISHAP MODEL ESTIMATES

1. Inter-event Times

Figures 8 through 13 are histogram plots of the inter-arrival times for each partition of mishap causal factors. Overlaid on the chart is a rescaled probability density function (pdf) of the hypothesized exponential distribution. Table 7 summarizes the mean, standard deviation and rate parameters for the mishap category parameter estimates. Additionally, 95%, two-sided confidence intervals are presented for each rate parameter estimate. Note that the two confidence limits are not equidistant from the point estimate. This is due to the lack of symmetry in the exponential distribution. The Kolomogorov-Smirnov goodness of fit (KS g.o.f.) test for the exponential distribution is based on the estimated rate parameter. With a significance level (α) set at 0.05, the KS g.o.f. test fails to reject that any of the distributions are exponential.

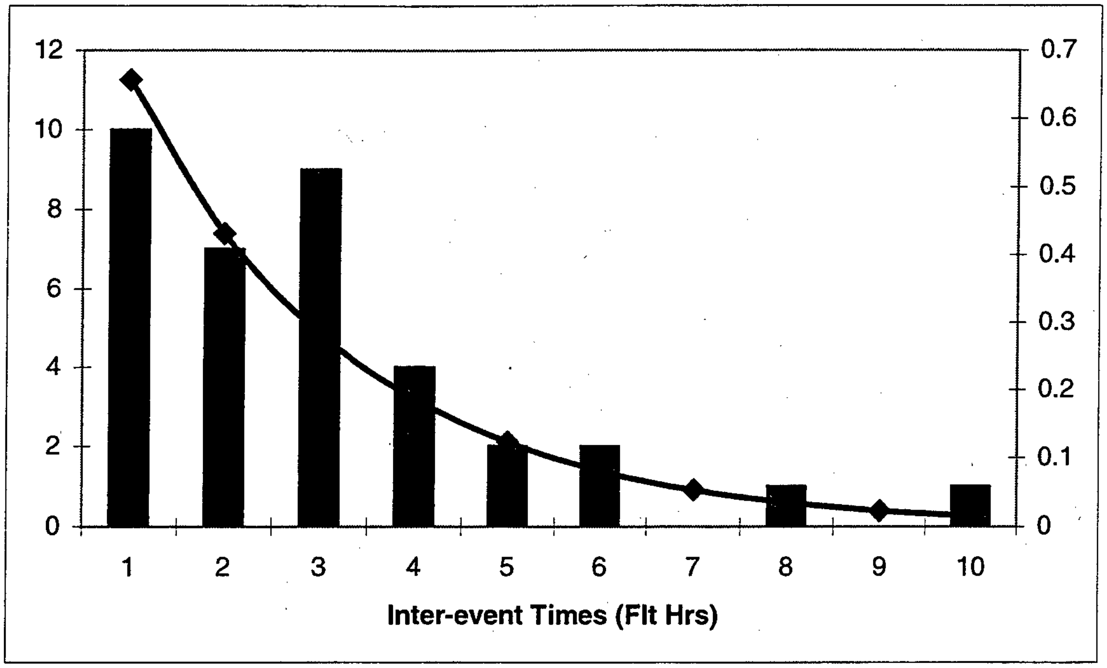

FIGURE 8: HISTOGRAM PLOT OF UC DATA

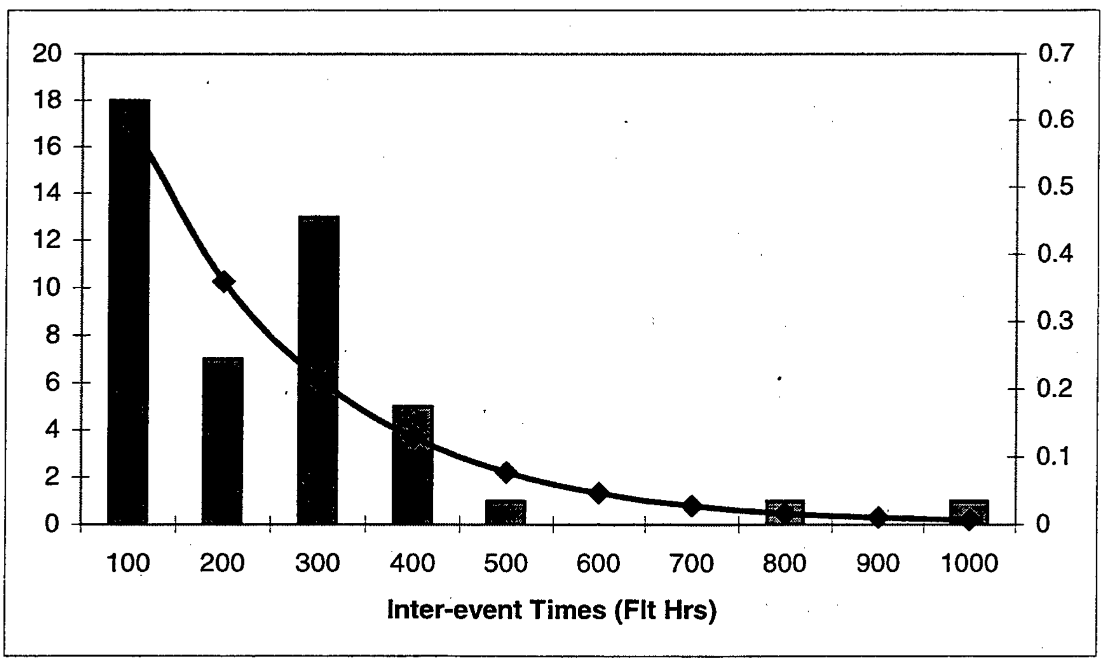

FIGURE 9: HISTOGRAM PLOT OF UA/UC DATA

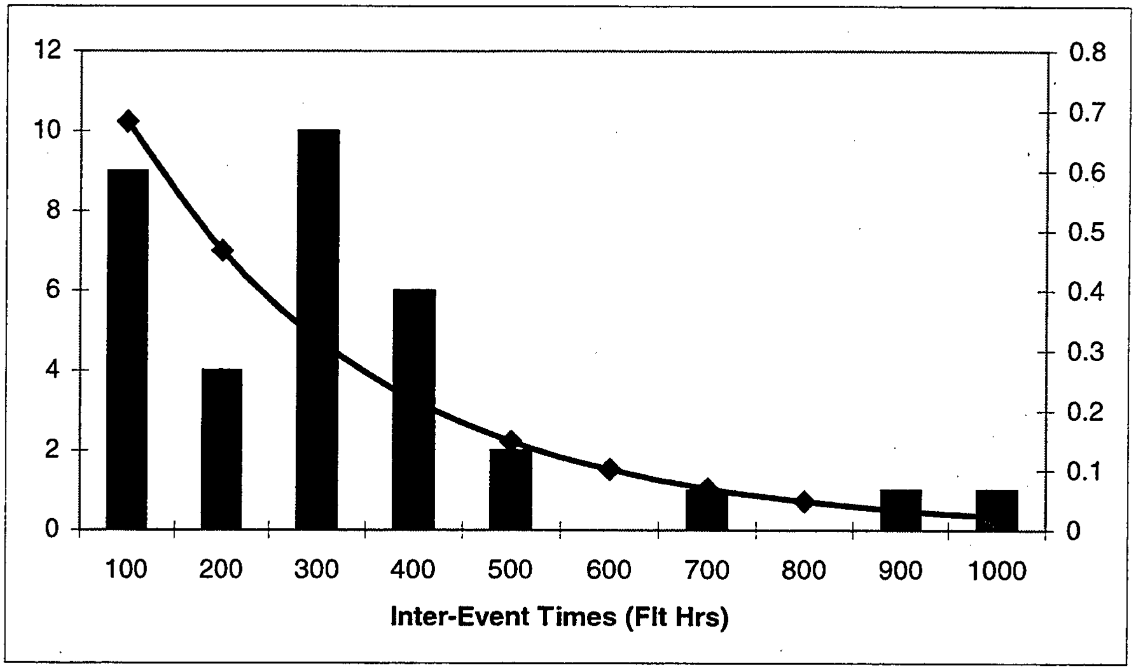

FIGURE 10: HISTOGRAM PLOT OF UA DATA

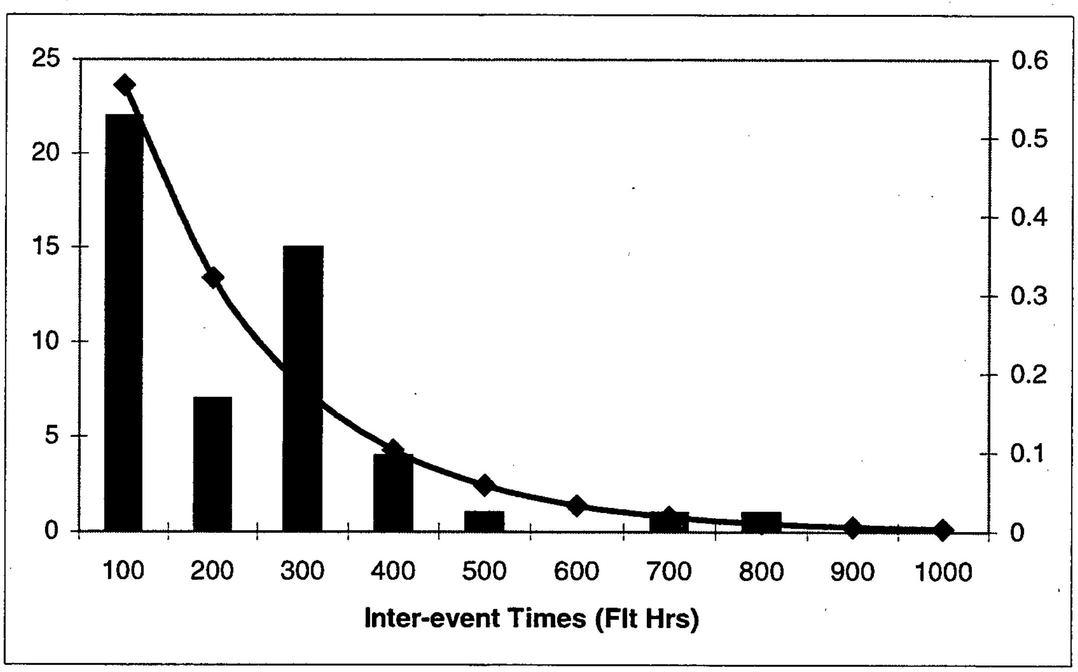

FIGURE 11: HISTOGRAM PLOT OF UA/US DATA

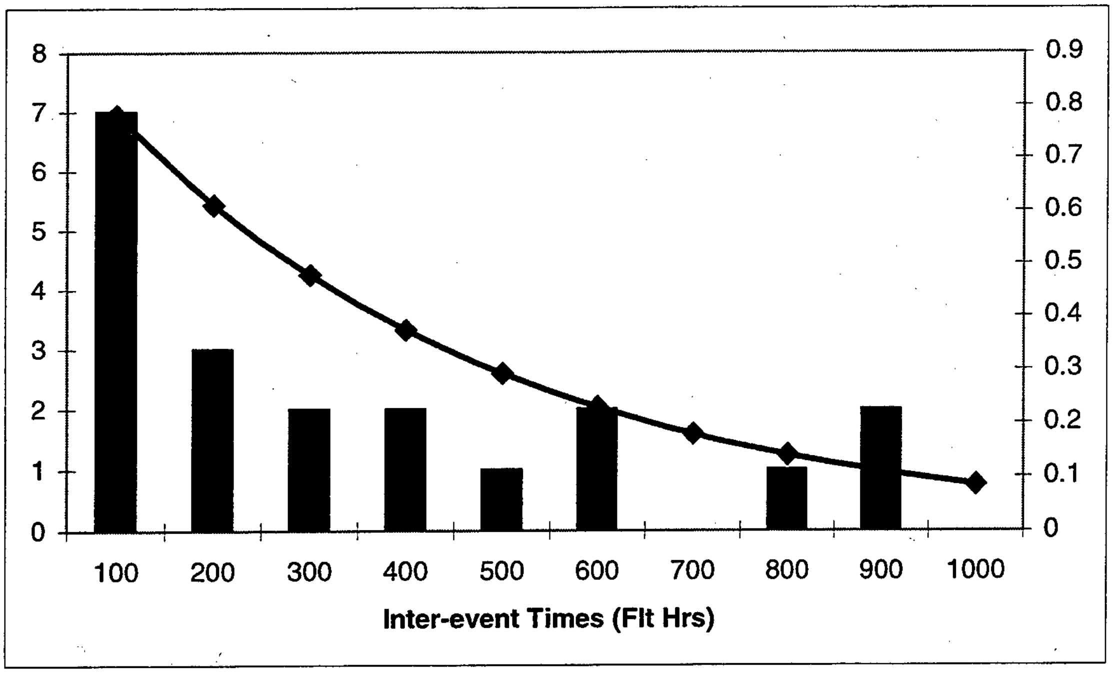

FIGURE 12: HISTOGRAM PLOT OF ENG DATA

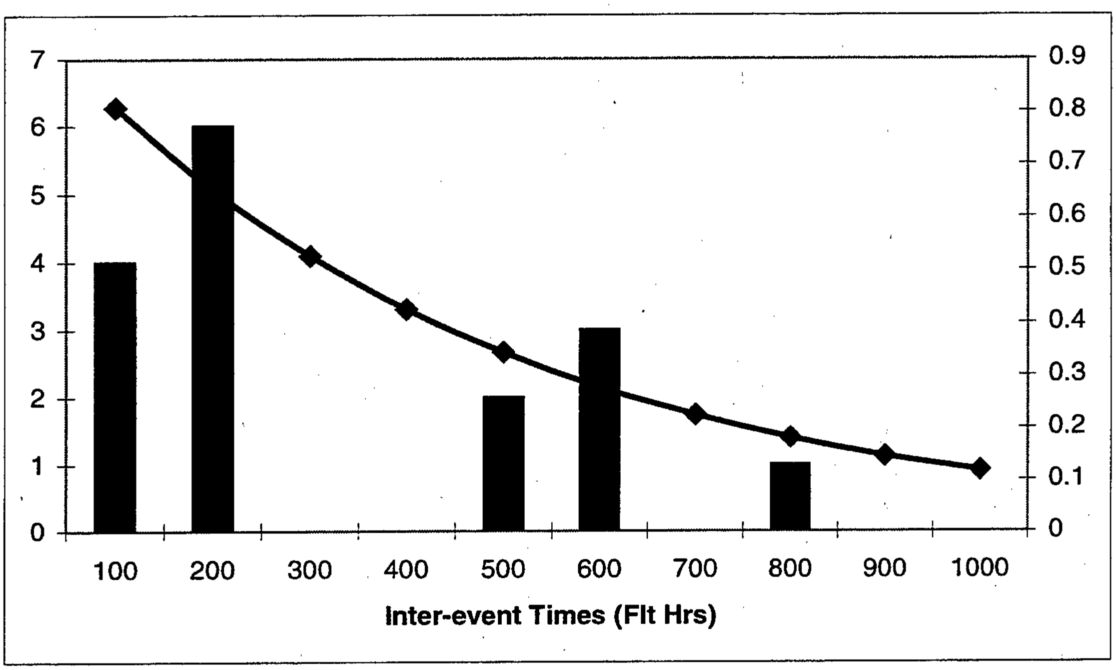

FIGURE 13: HISTOGRAM PLOT OF ELEC DATA

		Estimated Mean	Estimated Std Dev	Estimated Rate	Lower CI	Upper CI	KS g.o.f test
Category	**n**	*flight hours*	*flight hours*	*Mishaps / 1000 flt hrs*	*mishaps / 1000 flt hrs*	*mishaps / 1000 flt hrs*	*p-value*
UC	37	238.6	216.2	4.19	2.95	5.65	0.665
UA/UC	47	195.3	189.8	5.12	3.76	6.68	0.406
UA	35	262.3	212.7	3.81	2.66	5.18	0.160
UA/US	52	176.5	156.9	5.67	4.23	7.31	0.484
ENG	23	406.9	479.5	2.46	1.56	3.56	0.478
ELEC	20	467.6	453.8	2.14	1.31	3.17	0.409

TABLE 7: PARAMETER ESTIMATES FOR MEAN, STANDARD DEVIATION AND RATE

2. *Mishap Class Probability Parameters*

Table 8 is a summary of the calculations used to estimate the probability of each type of mishap (p_A, p_B, p_C). Of note, the estimated probability of each class of mishap ($p_{A\text{-Hat}}$, $p_{B\text{-Hat}}$, $p_{C\text{-Hat}}$) varies with the mishap category. For example, an engine failure is most likely to cause a catastrophic class A mishap, while the results of an unsafe act can be mitigated by other actions of the crew.

		Class A		Class B		Class C	
Code	**n**	**# mishaps**	$p_{A\text{-Hat}}$	**# mishaps**	$p_{B\text{-Hat}}$	**# mishaps**	$p_{C\text{-Hat}}$
UC	37	6	0.162	16	0.432	15	0.405
UA/UC	47	8	0.170	19	0.404	20	0.426
UA	35	5	0.143	15	0.429	15	0.429
UA/US	52	10	0.192	20	0.385	22	0.423
ENG	23	9	0.391	4	0.174	10	0.435
ELEC	20	4	0.200	10	0.500	6	0.300

TABLE 8: MISHAP CLASS PROBABILITIES

3. *Cost Parameters*

Table 9 summarizes the parametric estimates for the mishap cost distributions. Each is hypothesized to be normally distributed. All cost figures are calculated as FY98 dollars. Figures 14 through 16 are normal probability plots of the actual data versus the hypothesized distributions. Graphically, there are some discrepancies between the sample data and the hypothesized distribution. However, the KS g.o.f. tests the hypothesized distribution using the parameter estimates listed in Table 9. With a significance level (α) set at 0.05, the KS g.o.f. test fails to reject the normality of any of the cost distributions.

	Estimates		**Distribution**	**KS g.o.f.**
	Mean	**Std Dev**	**$ FY98**	**p-value**
Class A	$811,504	$189,306	N(812K, 187K)	0.4802
Class B	$479,933	$214,503	N(480K, 214K)	0.6073
Class C	$87,649	$64,065	N(88K, 64K)	0.1928

TABLE 9: FY86-FY98 MISHAP CLASS COST DISTRIBUTION

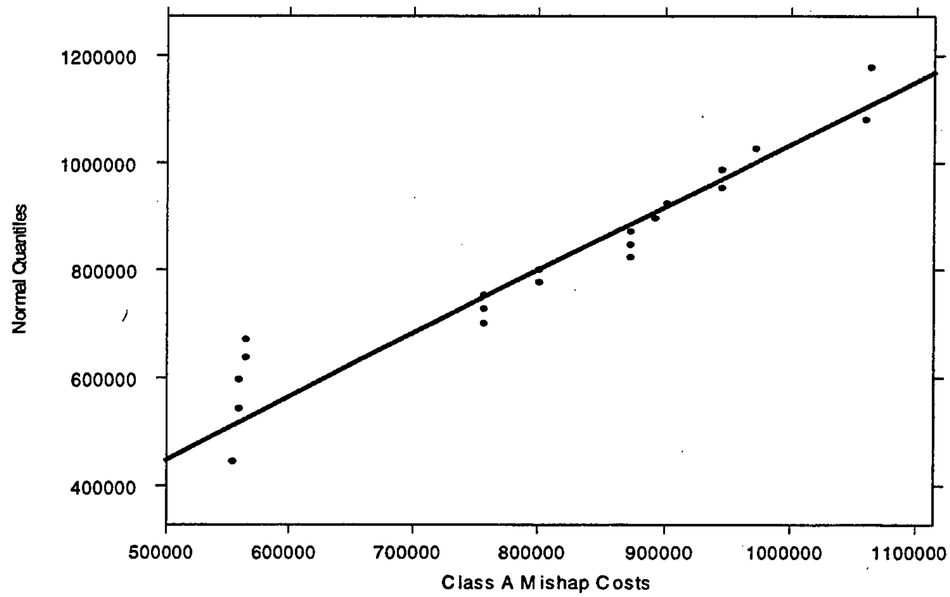

FIGURE 14: NORMAL PROBABILITY PLOT OF CLASS A MISHAP COSTS

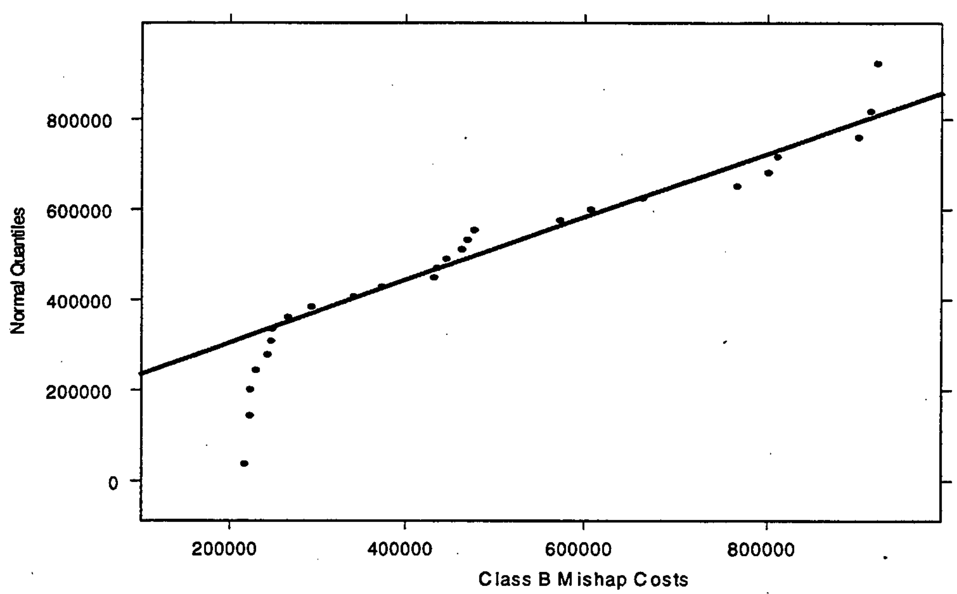

FIGURE 15: NORMAL PROBABILITY PLOT OF CLASS B MISHAP COSTS

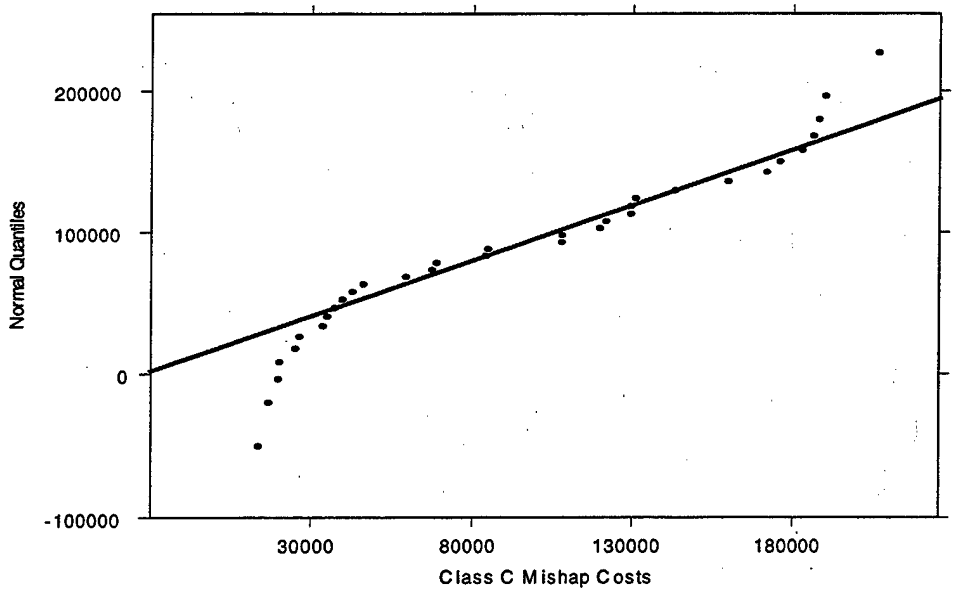

FIGURE 16: NORMAL PROBABILITY PLOT OF CLASS C MISHAP COSTS

4. Annual Flight Hours

A linear regression of annual flight hours versus the natural log of fiscal year is performed on historic flight hours flown. The equation-projected estimate of flight hours for the next fiscal year (FY99) is 1,930 flight hours. This will be used as the number of annual flight hours in the simulation. Figure 17 contains a graph of the historic flight hours and the fitted equation, adjusted to time on a linear scale.

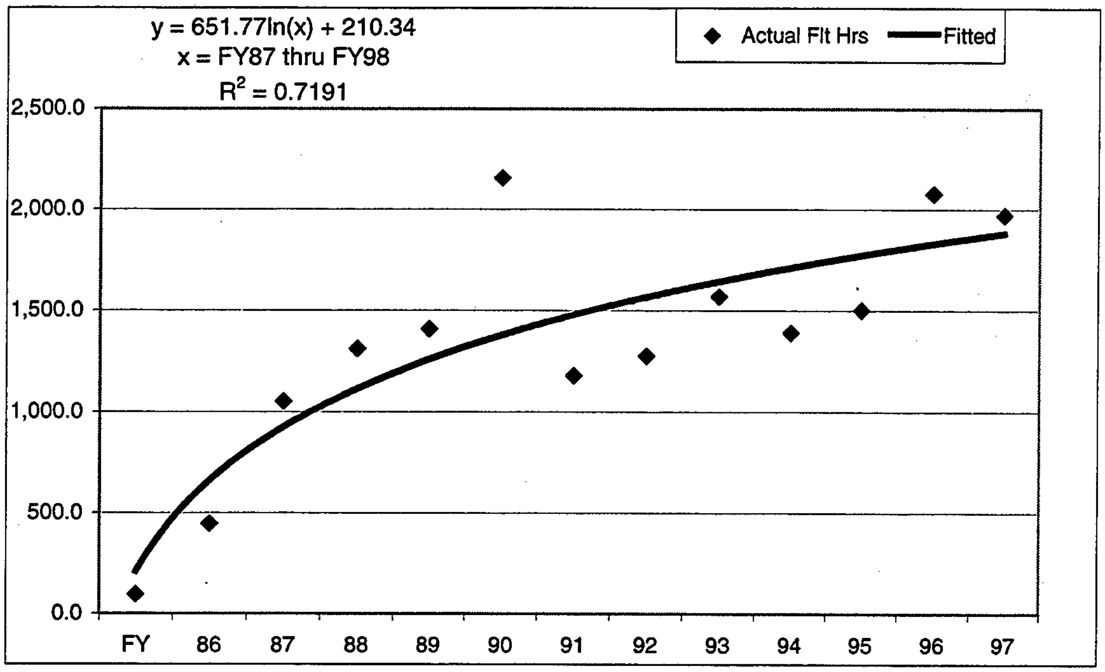

FIGURE 17: RESULTS OF ANNUAL FLIGHT HOUR REGRESSION

E. STOCHASTIC MODEL SIMULATION

1. Model: Baseline of total mishaps

The aggregate mishap model is presented in Table 10. It is used as a baseline for comparison of the remaining models. Calculating the defined readiness factor, this model indicates that UAVs never achieve a mission ready condition. Also, UAV mishap costs typically exceed $10 million. The following model simulations are used to gain insight into the cost and mission readiness improvements over current baseline conditions made by targeting mishap causes with the specified strategies.

Category: TOTAL	Baseline	λ - 10%	λ - 30%	λ - 50%
Mishap Rate / 1000 flight hours	12.79	11.51	8.95	6.4
Mean Cost (CY98 $M)	$10.91	$9.70	$7.54	$5.63
SD Cost (CY98 $M)	$2.83	$2.62	$2.30	$1.92
% change in Cost		-11.2%	-30.9%	-48.4%
Readiness Index	0.0000	0.0020	0.0640	0.3000
% change in Readiness		N/A	N/A	N/A

TABLE 10: AGGREGATE MISHAP MODEL

2. *Model: Increased Aeromedical Screening and Education*

Table 11 summarizes the unsafe conditions mishap intervention model. Even at current levels, the readiness indicator for unsafe conditions does not go below 80%. This is most likely the result of the relative probability of a class A mishaps being low compared to the aggregate model. As a result, costs are also kept low, accounting for approximately 1/3 of the aggregate mishap costs.

Category: UC	Baseline	λ - 10%	λ - 30%	λ - 50%
Mishap Rate / 1000 flight hours	4.20	3.78	2.95	2.10
Mean Cost (CY98 $M)	$3.51	$3.09	$2.60	$1.94
SD Cost (CY98 $M)	$1.44	$1.36	$1.21	$1.03
% change in Cost		-12.1%	-26.1%	-44.8%
Readiness Index	0.8400	0.9170	0.9710	0.9970
% change in Readiness		9.2%	15.6%	18.7%

TABLE 11: UNSAFE CONDITIONS MODEL

3. *Model: Aircrew Coordination Training / Crew Resource Management*

Table 12 summarizes the mishap intervention model for the aggregate of unsafe acts and unsafe conditions. ACT / CRM will have to reduce the mishap rate by over 10% in order to get readiness above the 80% level. Additionally, at $4 million per year in mishap cost contributions, unsafe acts and unsafe conditions combined contribute to approximately one-third of mishap costs.

Category: UA/UC	Baseline	λ - 10%	λ - 30%	λ - 50%
Mishap Rate / 1000 flight hours	5.11	4.60	3.58	2.56
Mean Cost (CY98 $M)	$4.01	$3.63	$2.93	$2.16
SD Cost (CY98 $M)	$1.56	$1.40	$1.29	$1.10
% change in Cost		-9.5%	-26.8%	-46.0%
Readiness Index	0.7040	0.8010	0.9350	0.9910
% change in Readiness		13.8%	32.8%	40.8%

TABLE 12: AGGREGATE UNSAFE ACTS / UNSAFE CONDITIONS MODEL

4. *Model: UAV Flight Simulator / Automated Take off and Landing System*

Table 13 summarizes the mishap intervention model for unsafe acts. This model is used to evaluate the potential results of both the flight simulator and of the take off and landing aids. While the category of unsafe acts contributes to 37% percent of mishaps, their effect on readiness is not as profound. Even in the baseline case, unsafe acts have a ready index of nearly 90 percent. Because of their nature, unsafe acts will contribute to mishap occurrences, but their individual effects do not have as great an impact on overall changes in readiness and costs.

Category: UA	Baseline	λ - 10%	λ - 30%	λ - 50%
Mishap Rate / 1000 flight hours	3.82	3.44	2.67	1.91
Mean Cost (CY98 $M)	$3.16	$2.94	$2.29	$1.74
SD Cost (CY98 $M)	$1.40	$1.29	$1.11	$0.95
% change in Cost		-6.9%	-27.6%	-44.8%
Readiness Index	0.8970	0.9430	0.9860	1.0000
% change in Readiness		5.1%	9.9%	11.5%

TABLE 13: UNSAFE ACTS MODEL

5. Model: Personnel Stabilization

Table 14 summarizes the mishap intervention model for the aggregate of unsafe acts and unsafe supervision. This is the only model that incorporates the effects of unsafe supervision. Although difficult to isolate, unsafe supervision when coupled with unsafe acts does have a profound effect on both cost and readiness. The model bears out that personnel stability has the potential to significantly improved readiness and reduced cost.

Category: UA/US	Baseline	λ - 10%	λ - 30%	λ - 50%
Mishap Rate / 1000 flight hours	5.66	5.09	3.96	2.83
Mean Cost (CY98 $M)	$4.52	$4.20	$3.39	$2.52
SD Cost (CY98 $M)	$1.76	$1.60	$1.44	$1.21
% change in Cost		-7.2%	-25.2%	-44.4%
Readiness Index	0.5570	0.6760	0.8710	0.9750
% change in Readiness		21.4%	56.4%	75.0%

TABLE 14: AGGREGATE ACT/UNSAFE SUPERVISION MODEL

6. Model: Engine Replacement

Table 15 summarizes the mishap intervention model for engine failure related events. Engine failure accounts for nearly 25 percent of mishaps. Intuitively, modifications to the engine should cause a significant cost reduction and readiness improvement. However, the model results indicate that the effect on mission readiness is negligible since the baseline readiness factor already exceeds 95 percent. Additionally, the budgetary cost of these mishaps is less than or equal to other mishap categories.

Category: ENG	Baseline	λ - 10%	λ - 30%	λ - 50%
Mishap Rate / 1000 flight hours	2.46	2.21	1.72	1.23
Mean Cost (CY98 $M)	$2.64	$2.44	$1.90	$1.49
SD Cost (CY98 $M)	$1.29	$1.28	$1.15	$0.92
% change in Cost		-7.6%	-28.0%	-43.6%
Readiness Index	0.9750	0.9780	0.9990	1.0000
% change in Readiness		0.3%	2.5%	2.6%

TABLE 15: ENGINE MODEL

7. Model: Electronic Waterproofing

Table 16 summarizes the mishap intervention model for the improvements to electronic component reliability. Electronic component failure is cited in over 20% of UAV mishaps, but similar to engine failure, its impact on readiness and annual costs is overshadowed by the other causal categories. The model indicates that the effect of electrical failures upon mission readiness is minimal.

Category: ELEC	Baseline	λ - 10%	λ - 30%	λ - 50%
Mishap Rate / 1000 flight hours	2.14	1.93	1.50	1.07
Mean Cost (CY98 $M)	$2.20	$2.06	$1.70	$1.34
SD Cost (CY98 $M)	$1.07	$1.01	$0.91	$0.83
% change in Cost		-6.6%	-23.0%	-39.2%
Readiness Index	0.9980	0.9980	1.0000	1.0000
% change in Readiness		0.0%	0.2%	0.2%

TABLE 16: ELECTRONIC MODEL

F. MODEL COMPARISON

Figures 18 and 19 are a comparison between the results of the mishap intervention simulations. Figure 18 compares the cost reduction in each category for the four runs of the model. Clearly, there is improvement across all strategies, but improvements in UA/UC and UA/US appear to cause more significant cost savings. Figure 19 illustrates the mission readiness index improvement. Inspection of the graph reveals that addressing the UC, UA/UC and UA/US categories will have the greatest impact on mission readiness. According to the simulation, none of other causal factors reduces the readiness factor below 80 percent.

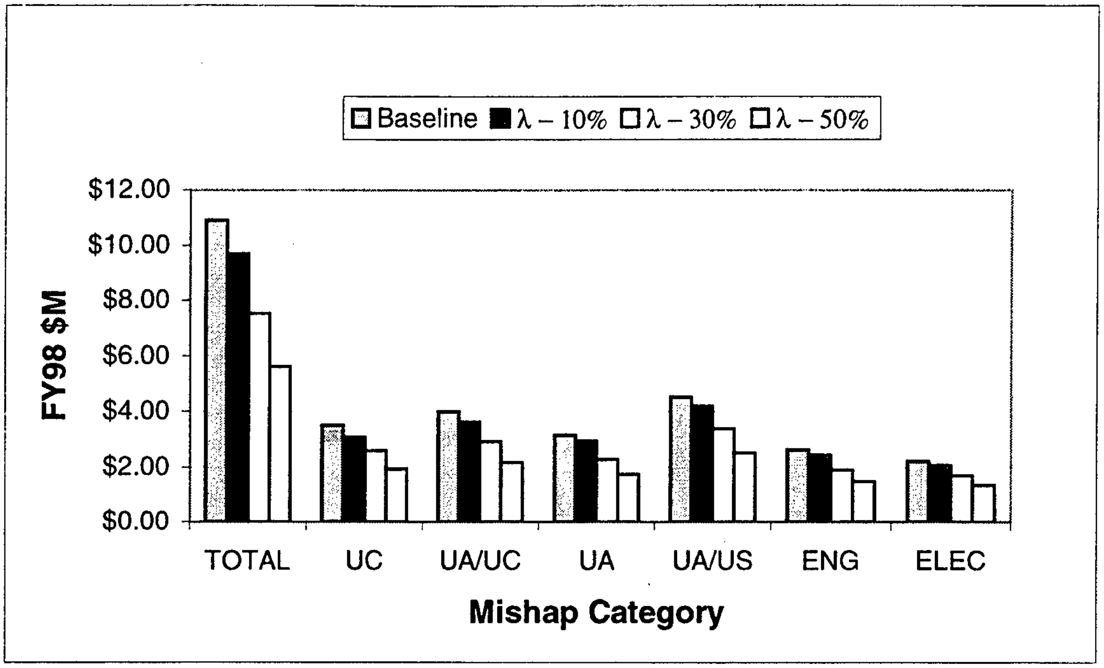

FIGURE 18: MISHAP COST REDUCTION

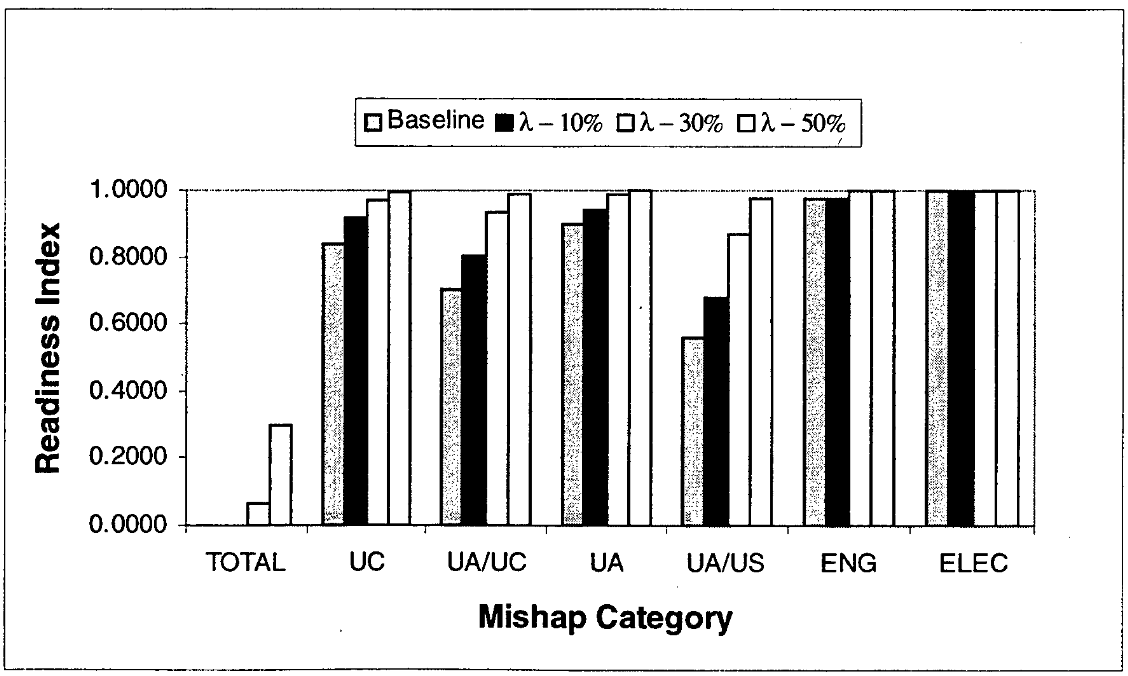

FIGURE 19: MISHAP READINESS INDEX IMPROVEMENT

V. CONCLUSIONS AND RECOMMENDATIONS

A. MISHAP CLASSIFICATION

Unmanned Aerial Vehicle (UAV) mishaps are successfully categorized by the Human Factors Accident and Classification System (HFACS) using the Naval Aviation Safety Program (OPNAVINST 3750.6Q) mishap report procedures. However, granularity at the lowest tiers of the HFACS model can be difficult to ascertain. The information available for analysis appears to vary with the writer of the report. If that individual is aware and comfortable with HFACS, the report tends to address all of the details required for future analysis. Otherwise, reports contain generalities and lack the specific details necessary to conduct an in depth analysis of the data. The planned incorporation of the HFACS taxonomy into the next revision of OPNAVINST 3750.6R, should standardize reporting procedures, and educate those preparing mishap reports on the scope that human factors can have on flight operations.

This analysis of mishap classification is conducted independently of the data partition of Schmidt & Parker (1995) and Seagle (1997). The three separate mishap categorizations are similar in terms of the relative frequency and causes of mishaps. Individual judgments were required by those conducting the study in order to place a particular mishap into a causation category. While not always agreeing in the exact classification, the three studies do conclude that human error is at least partially attributable for approximately one half of UAV mishaps. Engine and electronic failure each account for 20 to 25 percent of mishaps. Finally, although the mishap rate is decreasing, current mishap damage and losses will continue to have a profound affect on mission readiness.

B. MISHAP MODELING

The mishap occurrence distribution is modeled effectively as a Poisson process. Cost data and mishap class data distributions can also be modeled by specific distributions. These distributional quantities are effectively input into the stochastic model, allowing the analyst to simulate annual UAV flight operations accurately.

C. MODEL RESULTS

The aggregate UAV mishap rate must be reduced by one half in order to achieve a significant change in total mishap occurrences. This mishap reduction still only raises the readiness index to 0.300. (See Figure 19.) In order to focus the mishap intervention strategies, they must be analyzed in isolation. Under the current baseline rates two mishap categories, Unsafe Acts and Unsafe Conditions (UA/UC), and Unsafe Acts and Unsafe Supervision (UA/US), cause the readiness index to fall below 0.800. The simulations demonstrate that improvements up to 40.8 percent and 75.0 percent, respectively, can be achieved in these categories. This indicates that they should be considered primary targets for intervention strategies.

The other impact of the simulated UAV mishaps is cost. Again, the UA/UC and UA/US categories are the two most costly mishap causal factors. Each contributes greater than \$4 million (FY98\$) to annual mishap costs in the model. Intervention in these categories can reduce costs by 44.4 percent and 40.8 percent, respectively.

Although not considered in this model, intervention strategies should be compared to find the best value for the money invested.

Contrary to expectations, incorporating engineering modifications, (engine improvement/replacement, and electronic waterproofing) will have marginal effects on readiness and cost. At current mishap rates, the engine and electronic configuration do not degrade mission readiness below 95 percent. Additionally, their mishap costs are approximately the same as the other mishap categories. The cost involved in research, development and procurement will most likely exceed current mishap cost predictions and can be better spent improving other aspects of the Pioneer system.

D. RECOMMENDATIONS

The evaluation of the stochastic model results points to mishap intervention measures for the UA/UC and UA/US categories. This research proposes improvements to aircrew coordination training and crew resource management in order to alleviate the effects of the UA/UC category. Initiatives in this area will not only improve Pioneer UAV operations, but will have a listing impact on the UAV community, regardless of the system employed. When the Pioneer is eventually replaced, only minor modifications should be necessary to adjust to the idiosyncrasies of the new systems. The second area of intervention recommended is UAV personnel stabilization. The UAV community is still relatively new to Naval Aviation operations. As such, the community needs to mature. Unit leaders, both officer and enlisted, should have experience and knowledge of the system in order to effectively manage unit operations and individual crewmembers. A UAV career path should be created to track these individuals and assign them appropriately throughout their careers so that the UAV community can benefit from the stability and "corporate knowledge" enjoyed by other Naval flight communities.

APPENDIX A: PIONEER UAV SYSTEM DESCRIPTION

A. SYSTEM COMPONENTS

A Pioneer UAV system consists of five Pioneer air vehicles, a ground control station (GCS), a portable control station (PCS), a tracking communications unit (TCU), a data link, two remote receiver stations (RRS) and a reconnaissance payload. The system can be operated aboard specially configured USS Austin Class Landing Platform Dock (LPD-4) ships or from prepared airstrips ashore.

1. The Air Vehicle

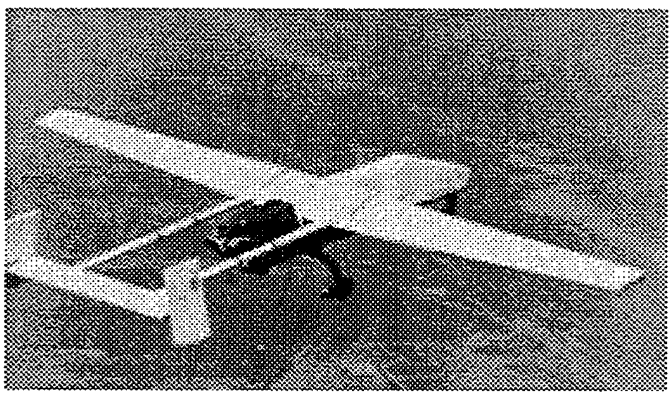

FIGURE 20: PIONEER AIR VEHICLE

The Pioneer vehicle air is 14 feet long and is pusher-propeller driven, powered by a 26 hp, two stroke, twin cylinder, rear mounted engine, similar to a snowmobile engine. The air vehicle is made of fiberglass, Kevlar and other low cost composite materials, and weighs 463 lbs. The air vehicle can operate up to an altitude of 15,000 feet, but normally flies between 3000 and 5000 feet in order to optimize payload performance. Because the air vehicle uses a laminated wood propeller, and the electronic components are not weatherized, the UAV cannot fly through visible moisture (fog, clouds, rain, etc.) or icing conditions. The air vehicle has up to four-hour time of flight at a cruise speed of 65 knots, which normally translates into 2-2.5 hours in an objective area depending on the proximity of the airstrip to the objective.

The air vehicle is launched using one of three methods. The rocket-assisted take off (RATO) is the only method available for shipboard operations. A rocket is placed under the vehicle to propel it into the air. Having reached sufficient altitude and airspeed, the rocket motor shuts down and is jettisoned from the UAV. Land-based units can also conduct RATO launch. Additionally on land, the UAV can use a standard rolling take of from a 1500-foot runway. Because of restrictive crosswind parameters, or air density constraints, a rolling takeoff may not be possible. For these instances, a pneumatic launcher mounted on a 5-ton truck can propel the vehicle to the minimum altitude and airspeed to transition to vehicle-powered flight.

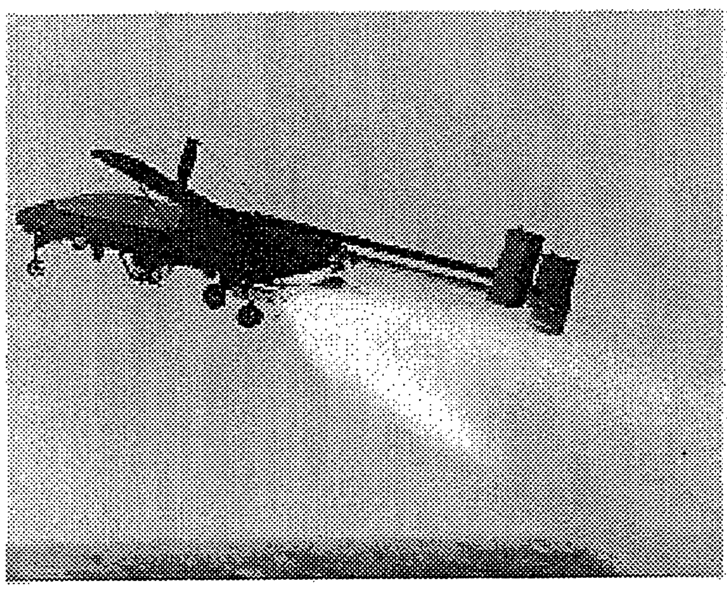

FIGURE 21: RATO TAKEOFF

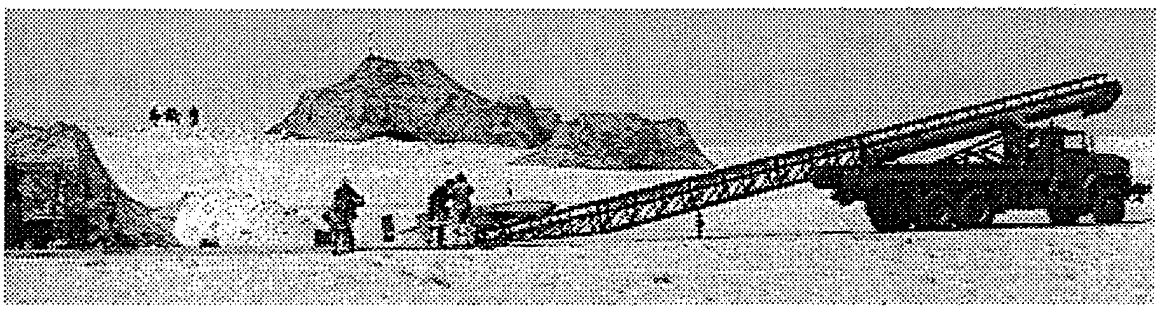

FIGURE 22: PNEUMATIC LAUNCHER TAKEOFF

There are two ways to safely recover the air vehicle. Operations at sea require the UAV to be flown into a large net suspended across the aft part of a ship's helicopter flight deck. Once, in the net, the recovery system collapses around the UAV allowing it to be lifted out. Because this recovery method is tantamount to a controlled crash, there is frequent damage to the UAV. The second recovery method, used ashore, is an arrested recovery by a miniature tailhook on an airstrip. While much more suitable for a crash free recovery, cross wind limitation must be monitored in order to assure a successful recovery (MAWTS-1, 1997).

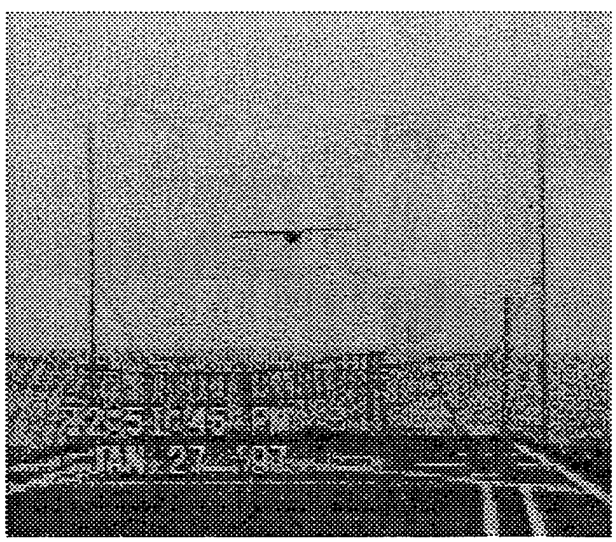

FIGURE 23: UAV SHIPBOARD LANDING

2. *The Ground Control Station (GCS)*

The GCS is the focus of activity for UAV missions. The system can either be land based or installed aboard ship. The GCS consists of three electronics bays manned by two operators. The pilot bay includes all controls, instruments and displays required to safely "fly" the vehicle. The observer bay provides control and display of the imaging payloads carried by the UAV. The tracking bay displays the UAV position based on data from the TCU and global positioning satellites (GPS) (Pioneer UAV, INC., 1999).

FIGURE 24: INSIDE THE GCS

3. *The Portable Control Station (PCS)*

The PCS provides the capability to control the UAV during pre-flight, launch and recovery operations, allowing the GCS to locate where it can most effectively conduct the mission. Because the air vehicle relies on line of site communications between the control station and the air vehicle, split sight operations are common in rugged, compartmented terrain. The PCS provides the ability to control the launch sequence from a local airstrip, and then steer the air vehicle to a predetermined handover point. There, the GCS, operating from a more advantageous location, can take control of the UAV and conduct the mission further down range (MAWTS-1, 1997).

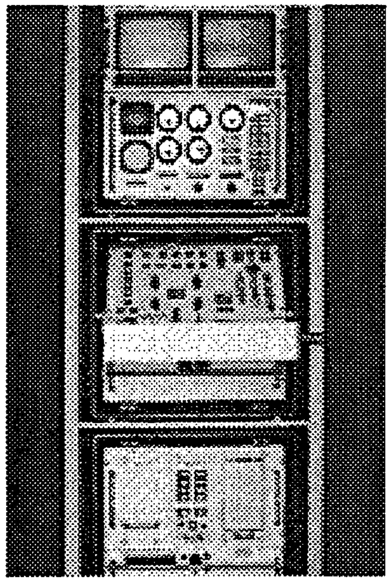

FIGURE 25: INSIDE THE PCS CONTROL BAY

4. *The Tracking Control Unit (TCU)*

The TCU shelter contains the UAV communication equipment and antennas. The TCU contains a sophisticated, jam resistant, C-band, 100 nmi. range data link. Both the video and telemetry link use directional antennas between the air vehicle and the TCU in order to ensure video quality and minimize the probability of data link intercept by the enemy. The system also has an omni-directional, UHF backup link for redundancy. The TCU can be remoted 1000 meters from the GCS by fiber-optic cable, enhancing the system's and personnel battlefield survivability (Pioneer UAV, INC., 1999).

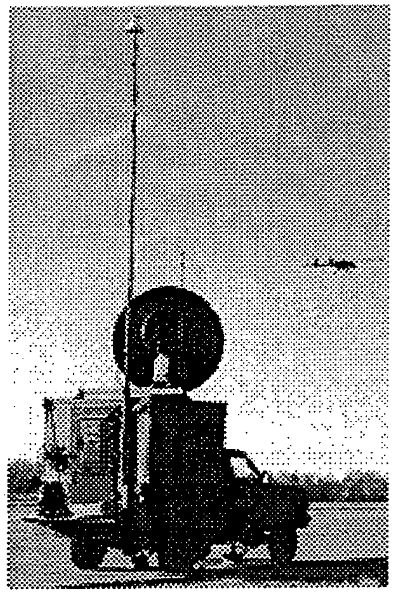

FIGURE 26: THE TCU

5. *Remote Receiving Station (RRS)*

The ruggedized RRS provides real-time reception of the UAV video picture at remote locations. The Marine Corps has mounted the RRS on a high mobility multi-wheeled vehicle (HMMWV), a light armored vehicle (LAV) and aboard a UH-1N Huey helicopter, allowing the tactical commander to have real-time imagery regardless of where the command post is locating (MAWTS-1, 1997).

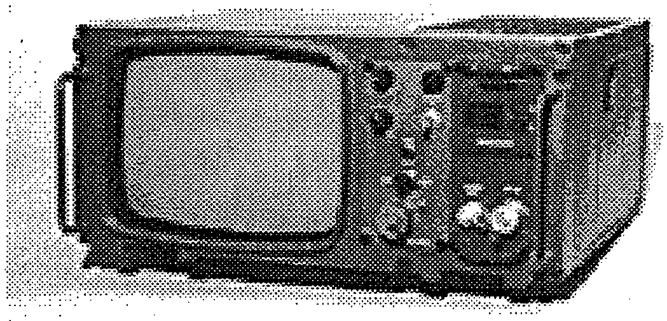

FIGURE 27: THE RRS

6. *Reconnaissance Payloads*

The air vehicle can carry one of two separate, gyrostabilized payloads: the MKD-200 electro-optical day camera, and the MKD-400(C) forward-looking infrared (FLIR) night camera. The MKD-200 E-O camera can detect targets up to 18 km range, and recognizes targets at 3 km range. The MKD-400(C) FLIR camera can detect a target at 8 km range, and recognizes a target at up to 4 km. Camera performance is enhanced by increased thermal differential between the target and the surrounding background (MAWTS-1, 1997).

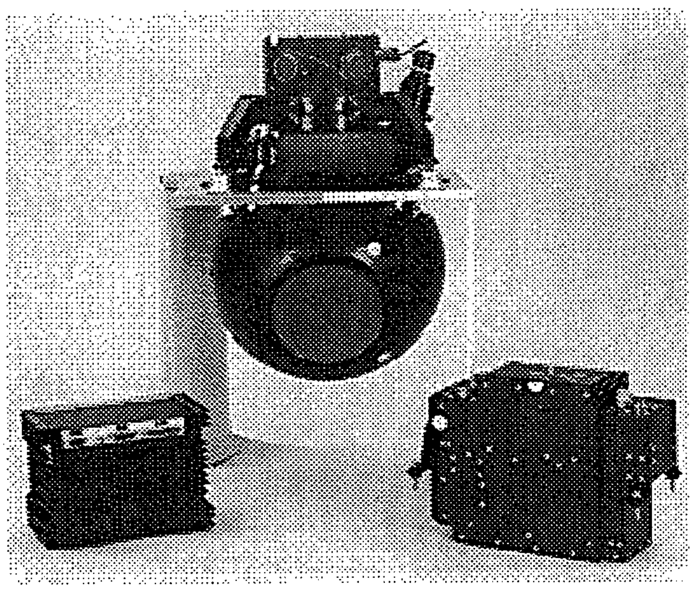

FIGURE 28: UAV PAYLOADS

B. CREW COMPOSITION

The term "unmanned" is actually a misnomer when applied to the Unmanned Aerial Vehicle system because UAV operations involve many participants. The essential members of a UAV crew include a Mission Commander, an Internal Pilot, a Payload Operator and an External Pilot. Additionally launch and recovery teams and maintenance personnel will be involved in flight operations. The responsibilities of each crewmember are summarized below (JUAVTOPS, 1997):

1. Mission Commander (MC)

The MC is typically a rated Naval Aviator or Naval Flight Officer, who has the supervisory responsibility for the UAV mission. This includes organizing the entire flight crew, coordination with external agencies and supported units during pre-mission planning, execution, and post mission debriefing.

2. Internal Pilot (IP)

Typically a senior enlisted aviation rating, who flies the UAV down range, monitors instruments to ensure proper operation, and assists the payload operator (PO) to get optimal camera position. The IP is also responsible for in-flight emergencies.

3. Payload Operator (PO)

The PO is an enlisted operator who controls the UAV camera and monitors the tracker bay to insure proper orientation. The PO assists the IP through visual navigation and during in-flight emergencies.

4. External Pilot (EP)

The EP, typically an enlisted operator, flies the UAV during launch and recovery operations. He coordinates the UAV handoff to the IP, and handles all launch and recovery emergencies.

5. Other Crewmembers

Depending on the complexity of the mission, and the experience of the crew, additional personnel may be required to augment the basic crew. Intelligence personnel may be involved to exploit the video imagery and pass that information on to the appropriate supported units. If the mission calls for fire support adjustment, an artillery or naval gunfire forward observer will be added to the crew. The crew is then rounded out with UAV maintenance and communications personnel.

APPENDIX B: MISHAP SIMULATION CODE

MishapSim( )

```
function(runs, lamda, PHat, fltHours)
{
#####
# Input:
# runs is the number of repetitions for the simulation
# lamda is the inter-arrival mishap rate for an exponential
# distribution.
# PHat is a vector of probabilities for a class A, B or C
# mishap as calculated by the ClassSim( ) function.
# fltHours is the length of the flight period to be
# simulated.
#
# Function:
# This simulation is based on an annual flight hour period.
# A random exponential variable with the inputted rate
# parameter is used to simulate the occurrence of a mishap.
# This is used to increment the time.
#
# Once a mishap is generated, a second random sample is
# drawn to determine the type of mishap (class A, B or C).
# The damage cost is also determined by the cost
# distribution data that is hardwired into the program.
#
# A cost vector and readiness index vector are built as
# each annual flight period is completed.  The weighted
# readiness index weighs a class A = 3, class B = 2, class
# C =1.  The maximum index in order to be "MISSION READY"
# is 21.  A readiness index greater than 21 indicates "NOT
# MISSION READY".
#
```

```
# Returns:
# The Function returns a vector of simulated annual costs,
# the mean and standard deviation of the  mishap cost and
# the average readiness index for the year.
#####
     readiness <- vector("integer", runs)
     totalCost <- vector("double", runs)
     for(i in 1:runs) {
          time <- 0
          mishapClass <- c("A", "B", "C")
          cost <- 0
          numA <- 0
          numB <- 0
          numC <- 0
          while(time < fltHours) {
               time <- time + rexp(1, lamda/1000)
               mishapType <- sample(mishapClass, 1, replace
                     = T, PHat)
               if(mishapType == "A") {
                    damage <- rnorm(1, 812000, 187000)
                    numA <- numA + 1
               }
               if(mishapType == "B") {
                    damage <- max(200000, rnorm(1, 480000,
                      214000))
                    numB <- numB + 1
               }
               if(mishapType == "C") {
                    damage <- max(10000, rnorm(1, 88000,
                      64000))
                    numC <- numC + 1
               }
               cost <- cost + damage
          }
          totalCost[i] <- cost
```

```
            readiness[i] <- 1
            readyFactor <- 3 * numA + 2 * numB + numC
            if(readyFactor > 21) {
                readiness[i] <- 0
            }
        }
        mishapCost <- mean(totalCost)
        SDCost <- sqrt(var(totalCost))
        readyIndex <- mean(readiness)
        return(totalCost, mishapCost, SDCost, readyIndex)
}
```

APPENDIX C: MISHAP CODING DATABASE

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
FY 86																															
86-1	1-Jun	243	64	64		C			X																						
86-2	10-Jul	282	74	74		C																		X				X			
86-3	1-Aug	304	80	80		C																		X		X					
86-4	11-Sep	345	91	91		A																		X	X						
86-5	17-Sep	351	93	93		A																		X		X					
FY 87																															
87-1	3-Jan	94	115	211		A	$421,000	$573,023																X	X						
87-2	10-Jan	101	124	220		A																		X		X					
87-3	16-Jan	107	131	227		A																		X					X		
87-4	2-Feb	124	152	248		A																		X	X						
87-5	7-Feb	129	158	254		A																		X		X					
87-6	27-Jun	269	330	426		C																		X			X				
87-7	30-Jun	272	333	429		A																		X	X						
87-8	19-Jul	291	356	429		C	$125,000	$170,137																X	X						
87-9	4-Aug	307	376	472		A																		X	X						
FY 88																															
88-1	5-Oct	5	14	558		C			X																						
88-2	16-Oct	16	46	589		C																		X	X						
88-3	22-Oct	22	63	607		A																		X						X	
88-4	30-Oct	30	86	630		C																		X						X	
88-5	6-Nov	37	106	650		A																		X		X					
88-6	22-Jan	113	324	868		C																		X		X					
88-7	5-Feb	126	362	905		C			X																						

Basic Data									Human Factors																Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
88-8	12-Feb	134	385	928		C																		X						X	
88-9	14-Feb	136	390	934		C			X																						
88-10	27-Feb	149	428	971		C			X																						
88-11	17-Apr	168	482	1,026		C	$11,182	$14,775	X																						
88-12	28-Apr	210	603	1,146		C	$26,709	$35,292	X																						
88-13	3-May	215	617	1,161		C			X																						
88-14	4-May	216	620	1,164		C			X																						
88-15	16-May	228	655	1,198		C	$37,509	$49,563	X																						
88-16	24-May	236	678	1,221		A																		X		X					
88-17	1-Jul	274	787	1,330		C	$11,182	$14,775	X																						
88-18	6-Jul	279	801	1,344		C	$173,109	$228,738																X	X						
88-19	21-Jul	294	844	1,388		A																		X		X					
88-20	9-Aug	313	899	1,442		C	$37,728	$49,853	X																						
88-21	19-Aug	323	927	1,471		C																		X		X					
88-22	26-Aug	330	948	1,491		C																		X		X					
88-23	9-Sep	344	988	1,531		A																		X		X					
88-24	13-Sep	348	999	1,543		C	$7,479	$9,882																X						X	
88-25	24-Sep	359	1,031	1,574		C																		X	X						
FY 89																															
89-1	12-Oct	12	43	1,637		A																		X		X					
89-2	15-Oct	15	54	1,648		C			X																						
89-3	25-Oct	25	90	1,684		C																		X	X						
89-4	11-Dec	72	259	1,853		A																		X	X						
89-5	30-Jan	121	434	2,029		A																		X		X					
89-6	5-Feb	127	456	2,050		C			X																						
89-7	6-Feb	128	460	2,054		C			X																						
89-8	7-Mar	157	564	2,158		C																		X						X	
89-9	21-Mar	179	643	2,237		C																		X	X						

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
89-10	12-Apr	193	693	2,287		C			X																						
89-11	28-Apr	209	750	2,345		C																		X		X					
89-12	1-May	212	761	2,355		A																		X		X					
89-13	9-May	220	790	2,384		C	$70,000	$88,765																X		X					
89-14	22-May	233	837	2,431		A																		X		X					
89-15	7-Jun	249	894	2,488		A			X																						
89-16	10-Jul	282	1,012	2,607		C																		X		X					
89-17	13-Jul	285	1,023	2,618		A																		X		X					
89-18	10-Aug	313	1,124	2,718		A																		X		X					
89-19	13-Sep	347	1,246	2,840		A																		X	X						
89-20	14-Sep	348	1,249	2,844		C																		X		X					
89-21	25-Sep	359	1,289	2,883		C																		X				X			
FY 90																															
90-1	25-Oct	25	96	3,001		C			X																						
90-2	30-Oct	30	116	3,021		C			X																						
90-3	2-Nov	33	127	3,032		C																		X				X			
90-4	3-Nov	34	131	3,036		C																		X				X			
90-5	27-Nov	57	220	3,125		C																		X				X			
90-6	29-Nov	59	228	3,132		C																		X				X			
90-7	14-Dec	74	285	3,190		A																		X		X					
90-8	4-Jan	95	366	3,271		C																		X		X					
90-9	11-Jan	102	393	3,298		C																		X	X						
90-10	9-Feb	131	505	3,410		C																		X	X						
90-11	13-Feb	135	521	3,426		C																		X			X				
90-12	27-Feb	149	575	3,480		A			X																						
90-13	15-Apr	196	756	3,661		C																								X	
90-14	16-Apr	197	760	3,665		C			X																						
90-15	17-Apr	198	764	3,669		C	$90,500	$110,352																							X

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
90-16	18-Apr	199	768	3,672		C																		X	X						
90-17	5-May	216	833	3,738		A																		X	X						
90-18	6-Jun	248	957	3,861		A																		X	X						
90-19	12-Jun	254	980	3,885		C																		X						X	
90-20	17-Jul	289	1,115	4,020		B																		X			X				
90-21	25-Aug	328	1,265	4,170		A			X																						
FY 91																															
91-1	22-Oct	22	130	4,443		B																		X	X						
91-2	19-Nov	49	290	4,602		C																		X				X			
91-3	22-Nov	52	307	4,620		C																		X				X			
91-4	30-Nov	61	360	4,673		A																		X		X					
91-5	3-Jan	94	555	4,868		C			X																						
91-6	22-Jan	113	668	4,980		B																		X	X						
91-7	24-Jan	115	679	4,992		C																		X		X					
91-8	25-Jan	116	685	4,998		C			X																						
91-9	30-Jan	121	715	5,028		A																		X		X					
91-10	31-Jan	122	721	5,034		B																		X		X					
91-11	2-Feb	124	733	5,045		A																		X						X	
91-12	4-Feb	126	744	5,057		A																		X		X					
91-13	5-Feb	127	750	5,063		A																		X	X						
91-14	6-Feb	128	756	5,069		A																		X		X					
91-15	10-Feb	132	780	5,093		C																		X		X					
91-16	19-Feb	141	833	5,146		A																		X		X					
91-17	23-Feb	145	857	5,169		C																		X	X						
91-18	24-Feb	146	863	5,175		B																		X		X					
91-19	25-Feb	147	869	5,181		C																		X		X					
91-20	25-Feb	147	870	5,183		A			X																						
91-21	25-Feb	148	872	5,184		A																								X	

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
91-22	25-Feb	148	873	5,186		C			X																						
91-23	26-Feb	148	874	5,187		A																		X		X					
91-24	26-Feb	149	877	5,190		A																		X				X			
91-25	27-Feb	149	880	5,193		A																		X		X					
91-26	28-Feb	150	886	5,199		B																								X	
91-27	8-Mar	158	934	5,246		B																		X		X					
91-28	23-Jun	265	1,566	5,878		B																		X	X						
91-29	22-Sep	356	2,103	6,416		C																		X			X				
FY 92																															
92-1	18-Oct	18	58	6,527		C	$13,500	$15,353	X																						
92-2	19-Oct	19	61	6,531		B			X																						
92-3	15-Nov	45	145	6,614		B	$1.065M	$1,211,191	X																						
92-4	19-Nov	49	158	6,627		C																		X					X		
92-5	12-Dec	72	232	6,701		B	$400,000	$454,907																X						X	
92-6	13-Dec	73	235	6,705		A	$1.065M	$1,211,191																X		X					
92-7	28-Feb	150	483	6,953		A																		X		X					
92-8	24-Mar	175	564	7,033		C	$50,250	$57,148																X						X	
92-9	25-Mar	176	567	7,036		B	$400,050	$454,964																X	X						
92-10	7-Apr	189	609	7,078		A																		X		X					
92-11	6-May	218	702	7,172		C	$111,000	$126,237																X	X						
92-12	15-May	226	728	7,198		B	$456,750	$519,447																X			X				
92-13	4-Jun	246	793	7,262		C	$7,000	$7,961																X	X						
92-14	16-Jun	258	831	7,301		C	$508,595	$578,409																X	X						
92-15	19-Jun	262	844	7,313		C																		X	X						
92-16	7-Jul	280	902	7,371		B	$322,500	$366,769																X	X						
92-17	12-Aug	316	1,018	7,487		B	$450,000	$511,771																X			X				
92-18	1-Sep	336	1,083	7,552		C	$47,250	$53,736	X																						
92-19	12-Sep	347	1,118	7,587		B	$278,300	$316,502	X																						

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUE	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
92-20	27-Sep	362	1,166	7,636		B	$459,950	$523,087	X																						
FY 93																															
93-1	14-Oct	14	49	7,698		B	$223,550	$247,536	X	X	X	X					X		X	X	X	X									
93-2	20-Oct	20	70	7,718		A			X								X		X	X	X	X		X	X						
93-3	26-Apr	207	723	8,372		C	$53,500	$59,240																X				X			
93-4	6-Jun	248	867	8,515		B	$402,500	$445,687	X	X	X	X				X	X	X	X	X	X	X	X								
93-5	20-Aug	323	1,129	8,777		C	$129,500	$143,395	X	X								X		X				X				X			
93-6	3-Sep	337	1,178	8,826		B	$517,500	$573,026																X	X						
93-7	14-Sep	348	1,216	8,865		B																		X	X						
93-8	20-Sep	354	1,237	8,886		B	$430,000	$476,138																X		X					
FY 94																															
94-1	2-Oct	2	9	8,933		B	$431,500	$468,462																X	X						
94-2	4-Oct	4	17	8,941		A	$515,000	$559,114	X	X														X				X			
94-3	25-Oct	25	107	9,032		C			X	X																					
94-4	28-Oct	28	120	9,044		A	$515,000	$559,114	X	X	X						X		X												
94-5	4-Nov	35	150	9,075		C			X	X	X			X			X	X			X		X	X				X			
94-6	4-Jan	95	408	9,332		C	$110,500	$119,965	X	X	X	X		X			X	X	X	X	X		X	X				X			
94-7	17-Jan	108	464	9,388		A	$520,000	$564,542	X								X				X	X		X					X		
94-8	1-Feb	123	528	9,453		A	$510,627	$554,367																X					X		
94-9	17-Mar	167	717	9,642		C	$63,330	$68,755	X	X	X	X					X	X													
94-10	18-Mar	168	722	9,646		A	$520,000	$564,542																X			X				
94-11	24-Mar	174	747	9,672		C	$158,236	$171,790	X								X				X			X	X						
94-12	29-Apr	210	902	9,826		C																		X				X			
94-13	25-May	236	1,014	9,938		B	$397,922	$432,007	X	X				X	X		X		X		X		X	X		X					
94-14	24-Jun	266	1,143	10,067		B	$343,573	$373,003																X	X						
94-15	4-Jul	276	1,186	10,110		B	$200,000	$217,132	X	X							X		X	X	X	X		X		X					
94-16	31-Aug	334	1,435	10,359		B	$224,388	$243,609	X	X	X	X					X		X		X										
FY 95																															

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
95-1	26-Oct	26	99	10,591		C	$101,500	$108,140																X		X					
95-2	27-Oct	27	103	10,595		C	$79,600	$84,807	X								X				X	X									
95-3	9-Nov	40	152	10,645		C	$31,584	$33,650	X	X	X	X		X	X		X	X	X		X	X		X						X	
95-4	25-Jan	116	442	10,934		C	$123,000	$131,046	X												X			X				X			
95-5	27-Jan	118	450	10,942		C	$40,000	$42,617	X												X			X	X						
95-6	17-Feb	139	530	11,022		B	$233,500	$248,775	X	X	X	X												X			X				
95-7	10-Mar	160	610	11,102		B	$274,739	$292,711	X	X				X			X		X		X			X		X					
95-8	24-Mar	174	663	11,155		C	$79,000	$84,168	X								X				X	X		X	X						
95-9	26-Apr	207	789	11,281		C	$35,000	$37,290	X	X				X	X		X		X		X			X	X						
95-10	18-May	229	873	11,365		C	$150,000	$159,812	X	X				X		X					X		X	X	X						
95-11	18-Jul	290	1,105	11,598		C	$175,000	$186,448	X												X			X	X						
95-12	26-Jul	298	1,136	11,628		B	$434,000	$462,391	X								X		X		X			X		X					
95-13	16-Aug	319	1,216	11,708		A			X	X	X	X		X	X									X	X						
95-14	17-Aug	320	1,220	11,712		C	$13,000	$13,850																							X
95-15	22-Aug	325	1,239	11,731		C	$194,120	$206,819	X	X	X	X		X	X		X		X		X										
95-16	23-Aug	326	1,243	11,735		B	$320,000	$340,933																							X
FY 96																															
96-1	13-Oct	13	53	11,937		B	$877,000	$916,023	X								X	X	X		X										
96-2	14-Oct	14	57	11,941		B	$776,800	$811,364	X	X				X	X		X	X	X		X	X									
96-3	6-Dec	66	271	12,154		B	$767,000	$801,128																X		X					
96-4	7-Dec	67	275	12,158		B	$864,000	$902,444	X												X			X		X					
96-5	7-Jan	98	402	12,285		C	$175,000	$182,787	X								X		X					X	X						
96-6	10-Jan	101	414	12,298		A	$1.014M	$1,059,118	X	X	X		X				X		X		X	X	X	X		X					
96-7	31-Jan	122	500	12,384		A	$854,000	$891,999																X	X						
96-8	14-Feb	136	558	12,441		B	$255,000	$266,346	X												X	X	X	X					X		
96-9	17-Feb	139	570	12,453		A	$1.018M	$1,063,296																X		X					
96-10	23-Feb	145	594	12,478		C	$64,500	$67,370																X	X						
96-11	3-May	215	881	12,765		B	$581,000	$606,852	X	X	X	X		X			X	X	X	X											

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
96-12	12-May	224	918	12,802		A	$863,000	$901,400																X	X						
96-13	11-Jun	254	1,041	12,925		A	$930,000	$971,381	X								X		X		X			X		X					
96-14	25-Jun	268	1,099	12,982		A	$904,000	$944,224																X	X						
96-15	26-Jun	269	1,103	12,986		C	$33,400	$34,886	X												X			X		X					
96-16	1-Jul	274	1,123	13,007		B																		X						X	
96-17	11-Jul	284	1,164	13,048		A	$767,000	$801,128																X	X						
96-18	13-Jul	286	1,173	13,056		C	$116,700	$121,893	X	X				X			X							X		X					
96-19	17-Jul	290	1,189	13,072		A	$904,000	$944,224	X	X							X		X		X										
96-20	23-Jul	296	1,214	13,097		A	$767,000	$801,128																X	X						
96-21	30-Jul	303	1,242	13,126		B	$214,000	$223,522	X	X				X																	
96-22	21-Aug	325	1,332	13,216		C	$16,300	$17,025																						X	
96-23	11-Sep	346	1,419	13,302		B	$884,000	$923,334																X					X		
FY 97																															
97-1	9-Oct	9	51	13,435		C	$26,000	$26,571																X					X		
97-2	15-Oct	15	85	13,469		C	$105,700	$108,022	X	X				X	X		X				X	X									
97-3	27-Oct	27	154	13,538		A	$854,000	$872,764	X												X			X						X	
97-4	11-Dec	72	410	13,794		A	$854,000	$872,764	X												X			X		X					
97-5	10-Jan	101	575	13,959		C	$186,000	$190,087																X	X						
97-6	11-Feb	133	757	14,141		C	$45,000	$45,989																							X
97-7	25-Mar	175	996	14,380		A	$854,000	$872,764																X	X						
97-8	28-Mar	178	1,013	14,397		C	$20,000	$20,439	X	X				X	X		X		X		X		X								
97-9	14-May	225	1,280	14,664		C			X	X				X	X		X			X	X	X									
97-10	6-Jun	248	1,411	14,795		C	$38,700	$39,550	X								X														
97-11	30-Jun	272	1,548	14,932		C	$19,600	$20,031																X	X						
97-12	25-Jul	297	1,690	15,074		C	$184,000	$188,043	X	X	X		X	X		X															
97-13	8-Sep	342	1,946	15,330		B	$650,000	$664,282	X	X				X	X		X		X		X			X		X					
97-14	9-Sep	343	1,952	15,336		B	$218,250	$223,045	X	X	X		X				X		X					X						X	
97-15	22-Sep	356	2,026	15,410		C																									X

Basic Data									Human Factors															Electro-Mech							
Mishap Num	Date	FY Day	FY Flight Hours	Cum Flt Hours	Inter-event Time	CLASS	Cost	FY98 Adjusted Cost	HF	UA	UAI	UAIM	UAIV	UAU	UAUS	UAUL	UC	UCA	UCC	UCV	US	USU	USF	EM	ENG	ELEC	LNCHR	NET	SOFT	OTH	UNK
FY 98																															
98-1	15-Nov	45	243	15,704		B	$229,800	$229,800	X								X		X		X		X								
98-2	1-Dec	61	330	15,791		B																									X
98-3	8-Jan	99	535	15,996		B	$435,300	$435,300	X	X	X	X					X				X										
98-4	12-Feb	134	724	16,185		B			X	X			X		X		X		X	X	X		X								
98-5	7-Apr	188	1,016	16,477		B	$767,000	$767,000	X	X			X		X		X		X		X		X	X		X					
98-6	28-Apr	209	1,129	16,590		C	$25,300	$25,300																							X
98-7	3-May	214	1,156	16,617		C	$175,800	$175,800																X		X					
98-8	2-Jun	244	1,318	16,779		B																		X		X					
98-9	10-Jun	252	1,362	16,823		A																		X						X	
98-10	11-Jun	253	1,367	16,828		C	$129,500	$129,500	X	X			X	X	X									X		X					
98-11	13-Jul	285	1,540	17,001		C	$129,500	$129,500																X		X					
98-12	14-Jul	286	1,545	17,006		A	$757,000	$757,000																X	X						
98-13	22-Jul	294	1,589	17,050		A																									X
98-14	26-Aug	329	1,778	17,239		A	$757,000	$757,000	X												X	X		X						X	
98-15	25-Sep	359	1,940	17,401		A	$757,000	$757,000																X						X	

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6. Commander John Schmidt, USN.. 1
   School of Aviation Safety (Code 10/Sj)
   Naval Postgraduate School
   1588 Cunningham Road
   Monterey, California 93943-5202

7. Professor Lyn Whitaker 1
   Operations Research Department
   Naval Postgraduate School
   1411 Cunningham Road
   Monterey, California 93943-5202

8. Professor Robert Reed 1
Operations Research Department
Naval Postgraduate School
1411 Cunningham Road
Monterey, California 93943-5202

9. Director, Aviation Safety 2
U.S. Naval Safety Center
375 A Street
Norfolk, Virginia 23511-4399

10. Commanding Officer 2
Marine Aviation Weapons and Tactics Squadron 1
ATTN: UAV Division and ADT&E
Box 99200
Yuma, Arizona 85369-9200

11. Major Michael G. Ferguson, USMC 2
525 Windward Drive
Chesapeake, Virginia 23320