Office of the
Secretary of Defense

Unmanned Aerial Vehicle Reliability Study

February 2003

Executive Summary

The combined U.S. military UAV fleet (Predators, Pioneers, and Hunters) reached the 100,000 cumulative flight hour mark in 2002. This milestone is a good point at which to assess the reliability of these UAVs. Reliability is at the core of achieving routine airspace access, reducing acquisition cost, and improving mission effectiveness for UAVs. Although it has taken the fleet 17 years to reach the 100,000 flight hour milestone (see Figure 2-2), this study is the first comprehensive effort to address formally the reliability issue for these increasingly utilized military assets. The results presented herein are based primarily on actual flight operations data and augmented by in-house reliability assessments performed by individual UAV programs and contractors.

Section 2.0 focuses on the military UAV platforms currently in service with the Air Force (Predator), Army (Hunter), and Marine Corps (Pioneer). It also presents discussions on developmental UAV systems including the Global Hawk and Shadow. This study compares not only the traditional metrics of reliability engineering (availability, mishap rate, and mean time between failure), but also presents the failure modes which have driven these metrics to their current levels. Summaries of these data are available in Table 3-1 and Table 3-2.

Section 3.0 compares U.S. UAV reliability to that of foreign UAVs and U.S. manned aircraft. Two conclusions are immediately apparent. First, U.S. and foreign (Israeli) UAVs share virtually identical percentages of failure modes (see Figure 3-7 and Figure 3-8). Second, the proportions of human error-induced mishaps are nearly reversed between UAVs and the aggregate of manned aircraft, i.e., human error is the primary cause of roughly 85% of manned mishaps, but only 17% of unmanned ones.

Effects of design, weather, and aerodynamic anomalies are also examined in Section 3.0. Interesting trends due to one such effect – low Reynolds number flight – are presented as a poorly understood contributor to the poor flying qualities, and perhaps mishaps, of some smaller UAV systems (Figure 3-11). In analogy, where the airliner sees air molecules as many ping pong balls, small UAVs see them as a few beach balls (Appendix F). Areas for research are proposed to further understand, and circumvent, these effects.

Section 4.0 of this study highlights technologies that exist in both aerospace and non-aviation related disciplines that can offer potential solutions to some of the more prevalent reliability "Achilles heels" of UAV platforms. From propulsion to human-machine interactions, new methods, procedures, hardware, and software can target current failure modes which lie at the core of the majority of UAV mishap rates, unavailability, and MTBF statistics. In some cases where cost, size, and weight are of particular sensitivity to a UAV system, there exists commercial or government-off-the-shelf technology that may be able to provide affordable, short term solutions until some of the advanced technologies are available.

Based on the reliability data and system information, this study concludes with recommendations in Section 5.0. Implicit within these recommendations is the conclusion that high reliability is not an elusive goal attainable by only the most sophisticated manned aircraft. As an example, the RQ-5/Hunter has shown that investment of resources in component quality, redundancy, and maintenance can indeed pay reliability dividends and turn a program around. The Hunter's success is underscored by the fact that it was already an in-production system which leveraged its lessons learned to transform a system from poor to respectable reliability in a relatively short period of time. This example and others prove that from designer to user, the aerospace technology and operational experience are present today to enable significant UAV reliability growth and make them highly reliable, capable, and cost-effective contributors in future military operations.

Table of Contents

Table of Figures

Table of Tables

1.0 Introduction

1.1 Purpose

The purpose of this study is to examine the reliability of current Defense Department unmanned aerial vehicles (UAVs) in order to (1) allow an assessment of the risk posed by unmanned aviation to persons and property in the development of airspace regulations and (2) identify potential means for improving their mission availability, reliability, and effectiveness.

UAV reliability is important because it underlies their *affordability* (an acquisition issue), their mission *availability* (an operations and logistics issue), and their *acceptance* into civil airspace, whether U.S., international, or foreign (a regulatory issue). Improved reliability offers potential savings by reducing maintenance man-hours per flight hour (MMH/FH) and by decreasing procurement of spares and attrition aircraft. Enhancing reliability, however, must be weighed as a trade-off between increased up-front costs for a given UAV and reduced maintenance costs over the system's lifetime.

Affordability. The reliability of the Defense Department's UAVs is closely tied to their affordability primarily because the Department has come to expect UAVs to be less expensive than their manned counterparts. This expectation is based on the UAV's generally smaller size (currently a savings of some $1,500 per pound) and the omission of those systems needed to support a pilot or aircrew, which can save 3,000 to 5,000 pounds in cockpit weight. Beyond these two measures, however, *other cost saving measures to enhance affordability tend to impact reliability*. Thus, implicit throughout this report is the idea that if a system absolutely must achieve and maintain extremely high reliability, it must be *designed and financed* appropriately.

Availability. With the removal of the pilot, the rationale for including the level of redundancy, or for using man-rated components considered crucial for his safety, can go undefended in UAV design reviews, and may be sacrificed for affordability. Less redundancy and lower quality components, while making UAVs even cheaper to produce, mean they become more prone to in-flight loss and more dependent on maintenance, impacting both their mission availability and ultimately their life cycle cost (LCC).

Acceptance. Improving reliability is key to winning the confidence of the general public, the acceptance of other aviation constituencies (airlines, general aviation, business aviation, etc.), and the willingness of the Federal Aviation Administration (FAA) to regulate UAV flight. Regulation of UAVs is important because it will provide a legal basis for them to operate freely in the National Airspace System for the first time. This, in turn, should lead to their acceptance by international and foreign civil aviation authorities. Such acceptance will greatly facilitate obtaining overflight and landing privileges when larger, high endurance UAVs deploy in support of contingencies. Regulation will also save time and resources within both the DoD and the FAA by providing one standardized, rapid process for granting flight clearances to replace today's cumbersome, lengthy (up to 60 days) authorization process. A third benefit of regulation is that it could potentially lower production costs for the military market by encouraging the use of UAVs in civil and commercial applications.

1.2 Scope

This study examines the reliability of currently fielded and emerging military UAVs. Failures are categorized within the five general areas of power/propulsion, flight control, communication, human error/ground, and miscellaneous. The analysis focused on the reliability of the UAV air vehicle (or when specified, the entire system) and does not include mission aborts due to payload-related problems unless noted. Comparisons are drawn with contemporary manned aircraft and foreign UAVs. Factors beyond component failures and operational issues affecting UAV reliability are also examined. Recommendations to improve reliability are identified (bolded and italicized) in Sections 2.0, 3.0, and 4.0 and are discussed in detail in the Section 5.0.

1.3 Definitions

Reliability is (1) the probability that an item will perform its intended function for a specified time under stated conditions, or (2) the ability of a system and its parts to perform its mission without failure, degradation, or demand on the support system. It is given as a percentage which represents the probability that a system or component will operate failure-free for a specified time, typically the mission duration. It relates closely to MTBF.

Mean Time Between Failure (MTBF) describes how long a repairable system or component will perform before failure. This is also known as Mean Time Between Critical Failure (MTBCF). For non-repairable systems or components, this value is termed Mean Time To Failure (MTTF).

Availability is a measure of how often a system or component is in the operable and committable state when the mission is called for at an unknown (random) time. It is measured in terms of the percentage of time a system can be expected to be in place and working when needed.

Maintainability is the ability of a system to be retained in or restored to a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, and doing so at prescribed levels of maintenance and repair. It is measured in terms of how long it takes to repair or service the system, or Mean Time To Repair (MTTR) in hours.

Redundancy is a technique for increasing system reliability by incorporating two or more means (not necessarily identical) for accomplishing a given system function. Conversely, having two or more of a given component does not in itself constitute redundancy. For example, loss of one of the RQ-5/Hunter's two engines does not allow the mission to continue or even return to base in all scenarios.

Survivability is the ability of a system or component to avoid or withstand a hostile environment without suffering an abortive or catastrophic impairment of its ability to accomplish its designated mission.

Vulnerability is a weakness in a system's design or performance affecting its ability to be survivable.

2.0 UAV Reliability Data

The UAVs examined in this study are built by competing manufacturers, maintained by different branches of the military, and operated in a wide variety of mission profiles. As such, the type of reliability and maintenance data that are collected, as well as the methods in which those data are tracked, are not standardized and can yield a seemingly different representation of a given vehicle's performance. The diverse terminology and equations provided to this study for reliability of UAVs are presented in Appendix A (Army), B (Navy), and C (Air Force).[1] ***Recommendation: Introduce joint standardization of reliability data tracking for operational UAV systems***

This study attempts to present the results for all systems addressed in common terms. For ease of comparison, it reduces the various raw data (Appendix E) into the following four metrics commonly used to represent aircraft reliability. Every effort has been made to reconcile varying Service and contractor methods of calculating these metrics to achieve an "apples versus apples" comparison. The method of calculating these metrics in this study is given in Appendix D.

Class A Mishap Rate (MR) is the number of accidents (significant vehicle damage or total loss) occurring per 100,000 hours of fleet flight time. As no single U.S. UAV model has accumulated this amount of flying time, each model's mishap rate represents its extrapolated losses to the 100,000 hour mark.[2] Mishap rate is expressed as mishaps per 100,000 hours.

Mean Time Between Failure (MTBF) is essentially the ratio of hours flown to the number of maintenance-related cancellations and aborts encountered. It is expressed in hours.

Availability (A) describes how a given aircraft type is able to perform its mission compared to the number of times it is tasked to do so. For this study, the ratio of hours (or sorties) flown to hours (or sorties) scheduled is used. It is expressed as a percentage.

Mission Reliability (R) is 100 minus the percentage of times a mission is canceled before take-off or aborted in-flight due to maintenance issues. It is expressed as a percentage.

Mission cancellations (mission canceled prior to takeoff) and mission aborts (mission recalled after takeoff) are attributed to one of three causes:

- Operations (decisions driven by aircrew, air traffic control, or higher headquarters)
- Weather (decisions driven by atmospheric [natural] factors)

[1] The Services have established a Memorandum of Agreement for Operational Test and Evaluation (OT&E) terminology and definitions which could serve as a guide for UAV reliability tracking. It can be viewed at http://www.cotf.navy.mil.

[2] It is important to note that this extrapolation does not reflect improvements that should result from operational learning or improvements in component technology.

- Maintenance (decisions driven by system malfunction, breakage, supply shortages, etc.)

Maintenance cancellations/aborts can be further broken down into failures of the aircraft's major subsystems, such as power plants, avionics, airframe, etc. Use of these failure modes lead to a higher fidelity representation of the vehicles' reliability. In order to make uniform comparisons between systems, the following definitions are provided and will be used to categorize areas of system failure leading to mission aborts or cancellations.

Power/Propulsion (P&P) – Encompasses the engine, fuel supply, transmission, propeller, electrical system, generators, and other related subsystems on board the aircraft

Flight Control – Includes all systems contributing to the aircraft stability and control such as avionics, air data system, servo-actuators, control surfaces/servos, on-board software, navigation, and other related subsystems. Aerodynamic factors are also included in this grouping.

Communication – The datalink between the aircraft and the ground

Human Factors/Ground Control – Accounts for all failures resulting from human error and maintenance problems with any non-vehicle hardware or software on the ground

Miscellaneous – Any mission failures not attributable to those previously noted, including airspace issues, operating problems, and other non-technical factors. Because operating environments are not uniform as a variable affecting the data, weather is excluded as a causal factor in this portion of the study.

The percentage breakout in each of these failure modes is depicted in pie charts for each type of UAV. Where data are available, two pie charts, depicting failures in early and current versions of each, are provided for comparison. The data are the average values over the applicable operating period specified in the text. In some subsequent discussions, the Power, Propulsion, and Flight Control categories may be grouped together under the heading of *Flight Critical Systems* to describe the trends associated with those systems without which the vehicle is not flight-capable.

2.1 Current Generation UAVs

The three current generation DoD UAV systems – the RQ-1 (recently re-designated MQ) Predator, the RQ-2 Pioneer, and the RQ-5 Hunter – have accumulated 100,000 flight hours during some 22,000 flights over a combined total of 36 years of operations since 1986 (see Figure 2-1 and Figure 2-2). All three systems have a common legacy; they represent Israeli UAV design practices (and reliability measures) of the 1980s.

Modifications made to these three systems since becoming operational have predominantly focused on improving their reliability. The level of UAV experience reached the 100,000-hour mark in 2002, placing the U.S. military a close second behind the Israel Defense Forces, who reached the 100,000-hour mark in 2001.

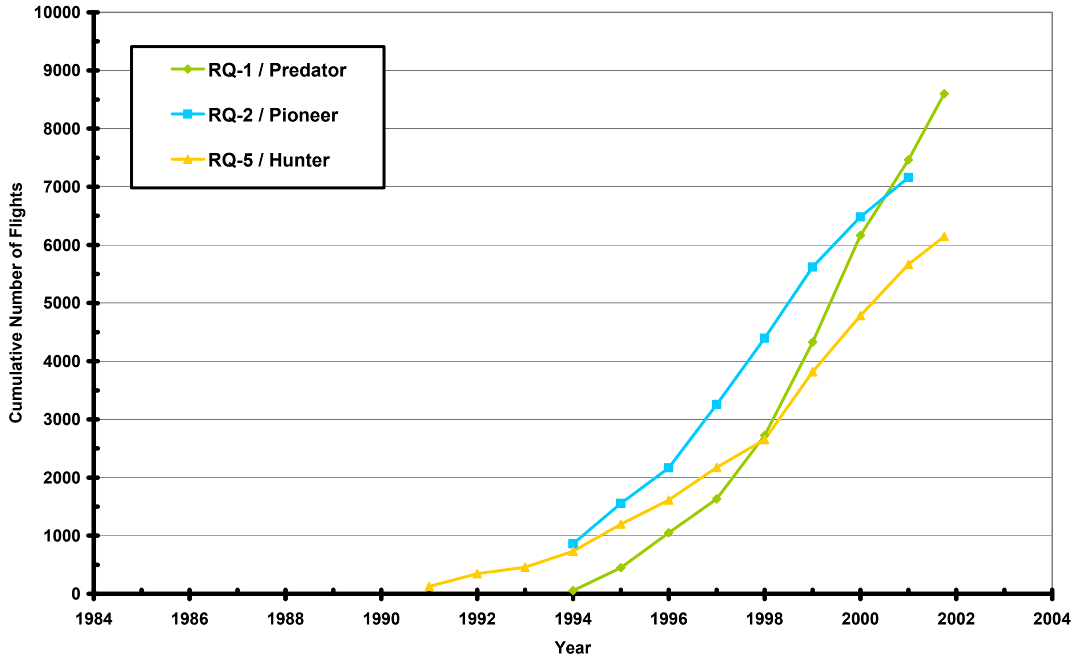


FIGURE 2-1: CUMULATIVE UAV FLIGHTS

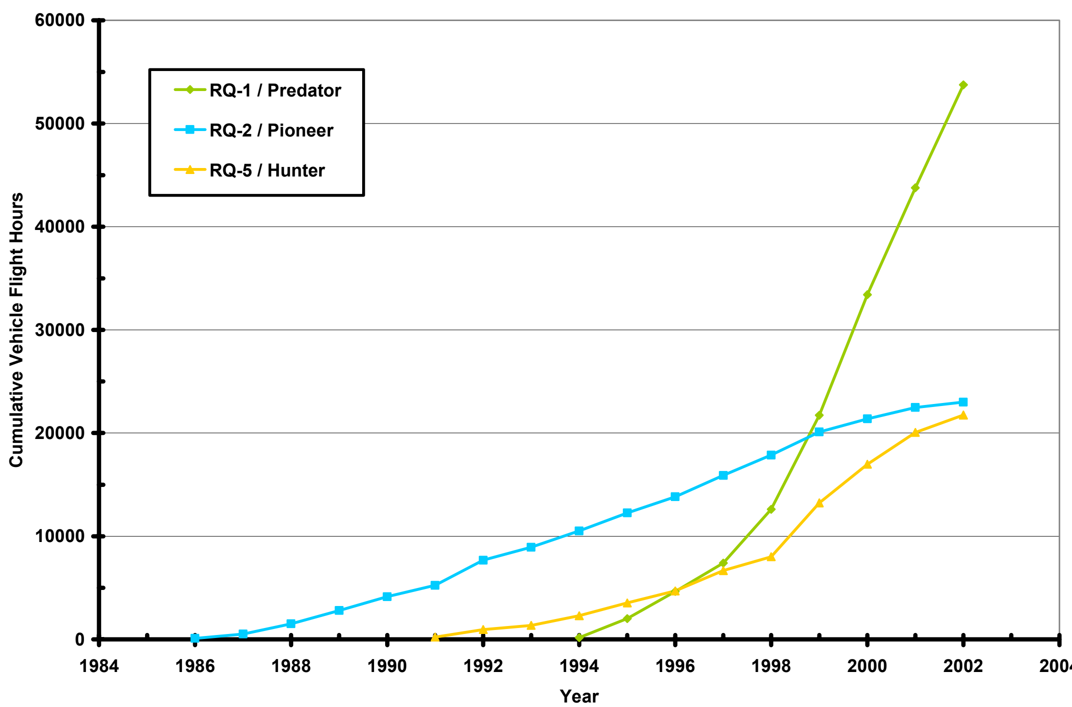


FIGURE 2-2: CUMULATIVE UAV FLIGHT HOURS

2.1.1 MQ-1 and MQ-9/Predator

The General Atomics Aeronautical Systems, Inc. MQ-1/Predator UAV, a medium altitude, long-endurance vehicle, is the largest current generation UAV in service with the U.S. military. The Predator design evolved from the DARPA/Leading Systems Amber program (1984-1990); Amber had been designed by a former IAI employee. The initial advanced concept technology demonstration (ACTD) system was denoted as the RQ-1A; the baseline production version was the RQ-1B.[3]

Predator made its first flight in June 1994, five months after going on contract. It completed its ACTD in June 1997 and was subsequently recommended for acquisition by JFCOM. Since July 1995, it has supported contingency operations in Bosnia, Kosovo, Kuwait, and Afghanistan. The Air Force operates three (eventually five) Predator squadrons with an intended total of 25 systems (four aircraft each); formal IOC is anticipated in 2003.

Predator B denotes an enlarged, turboprop-powered variant developed by the contractor to satisfy a NASA requirement for an endurance UAV for science payloads. Its first flight occurred in February 2001. In October 2001, the Office of the Secretary of Defense acquired both of the existing Predator B prototypes, which were subsequently designated as the MQ-9. Characteristics, performance, and cost of the MQ-1 and the MQ-9 are provided in Table 2-1.

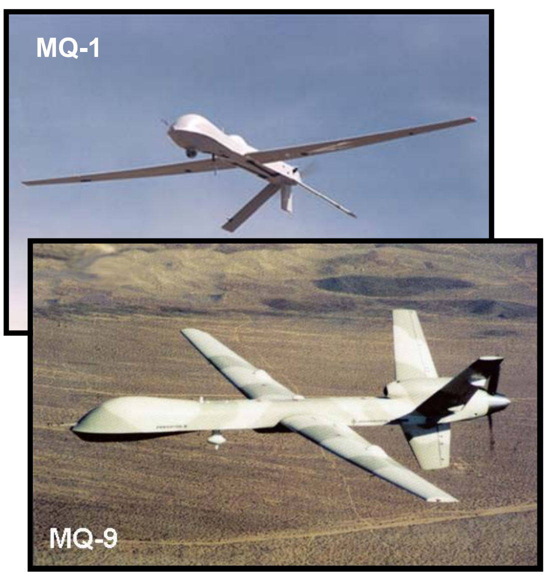


TABLE 2-1: MQ-1/MQ-9 PREDATOR DATA

	MQ-1	MQ-9
Gross Weight	2,250 lb	10,000 lb
Length	28.7 ft	36.2 ft
Wingspan	48.7 ft	64 ft
Ceiling	25,000 ft	45,000 ft
Radius	400 nm	400 nm
Endurance	24+ hrs	24+ hrs
Payload	450 lbs	750 lb (internal) 3000 lb (external)
Cruise Speed	70 kts	220 kts
Aircraft cost (w/out sensors)	$2.4 M	$6 M
System Cost (4 AVs)	$26.5 M	$47 M

Table 2-2 provides a breakout of the failure-critical components of the Predator aircraft, showing their country of manufacture and noting any known non-UAV applications. Failure-critical components are those UAV components that generally constitute a single point of failure and whose failure typically results in the loss of the aircraft, or, in the case of the sensor, a compromised mission.

[3] The RQ-1A/B designators will be used in subsequent sections to distinguish the early ACTD and production models from the current models (now referred to as the MQ-1 and MQ-9).

TABLE 2-2: MQ-1 PREDATOR KEY COMPONENTS

Component	Vendor	Model	Quantity	Country of Manufacture	Remarks
Engine(s)	Rotax	914	1	Austria	Also used on Ultralight Vehicles
Generator(s)					
Fuel Pump					
FCS Computer(s)	GA-ASI	PCM	1	USA	
FCS Software	GA-ASI		1	USA	
Actuators	MPC			USA, UK	
Air Data System					
Navigation System	Litton	LN-100G	1	USA	
LOS Data Link	L3 Comm		1	USA	
BLOS Data Link	Magnavox	UHF Satcom	1	USA	
	L3 Comm	RQ-1U	1	USA	
Sensor(s)	Wescam	14TS	1	USA	To be replaced by Raytheon MTS
	Northrop Grumman	AN/ZPQ-1	1	USA	

2.1.1.1 RQ-1A

The Predator experienced low mission completion rates during its deployments in the Balkans in 1995-1997. While the primary causal factor was weather, system failures did account for 12% of the incomplete missions. Mission-level operational data from the system deployed in Hungary were used to perform a limited assessment of system reliability based on data covering missions from March 1996 through April 1997.

Out of the 315 Predator missions tasked during that timeframe, weather and system cancellations kept nearly two-thirds on the ground (60%). Of the remaining missions that were launched, slightly under one half were subsequently aborted. These aborts were due to system (29%), weather (65%), and operational issues (6%) that included airspace conflicts, operator errors, and crew duty limitations.

Table 2-3 provides reliability metrics for the RQ-1A. Figure 2-3 indicates the failure modes which contributed to these reliability values.

TABLE 2-3: RQ-1A/PREDATOR SYSTEM RELIABILITY METRICS

	MTBF (hrs)	Availability	Reliability	Mishap Rate per 100,000 hrs
Requirement	n/a	n/a	n/a	n/a
Actual	32	40%	74%	43

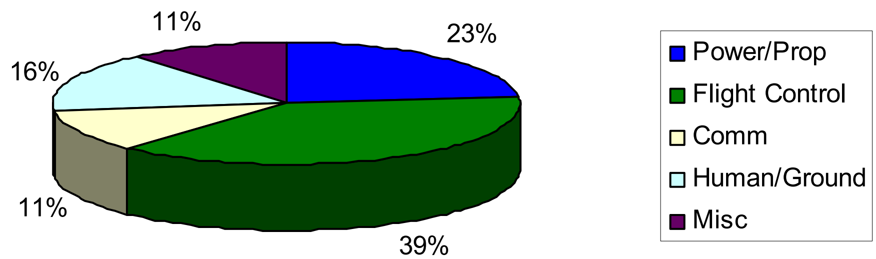


FIGURE 2-3: SOURCES OF RQ-1A/PREDATOR SYSTEM FAILURES

The failure mode breakout in Figure 2-3 comes from a total of 62 sorties that were affected by non-weather related mission aborts or cancellations. These data can be divided into three groups: 38 missions (12%) scrubbed due to system failures, an additional 18 system aborts (6%) that did not result in mission cancellation (due to launch of another vehicle or weather hold), and other issues which kept the Predator on the ground 6 times (2%).

2.1.1.2 RQ-1B

The Predator transition into production led to some problems which affected vehicle reliability. As the first ACTD program to transition to production, the Predator established the precedent, as well as the lessons learned, for the transition process. First, nearly continuous deployment commitments since March 1996 delayed operational testing for three years. Second, development of the Operational Requirements Document (ORD), usually produced early in a program to guide system design, did not begin until after the ACTD ended (as indicated by the n/a in Table 2-3). Third, additional challenges to system reliability were introduced, such as the addition of a wing deicing system (glycol-weeping wings) as well as a redesigned ground control station for greater portability.

Since this rocky start, the Predator fleet has logged over 50,000 hours and has "come of age" during Operation Enduring Freedom. As a result of its unorthodox transition process, however, Predator reliability issues were discovered during operations around the world. Although the system still experiences reliability issues and vehicle losses, its performance during these operations has been remarkably good when compared to those outlined in the ORD. These values are provided in Table 2-4.

TABLE 2-4: RQ-1B/PREDATOR SYSTEM RELIABILITY METRICS

	MTBF (hrs)	Availability	Reliability	Mishap Rate per 100,000 hrs
Requirement	40	80%	70%	n/a (50)[4]
Actual	55.1	93%	89%	31

[4] A goal of 50 mishaps per 100,000 hours was established after the ORD was written. This figure is tantamount to the expectation that every Predator has an operational life of 2,000 hours.

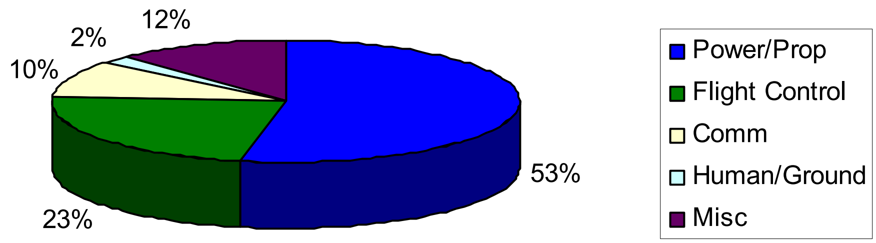


FIGURE 2-4: SOURCES OF RQ-1B/PREDATOR SYSTEM FAILURES

Figure 2-4 shows the sources of system failure for the RQ-1B Predator. The data represent all mission aborts (on the ground and in-flight) for all RQ-1B systems between January 1997 and June 2002. The share of power/propulsion failure modes has doubled in the RQ-1B compared to the RQ-1A (see Figure 2-3). The Predator program office acknowledges that the engine is the primary reliability issue. As a result, a change to the Block 30 MQ-1 to incorporate a fuel injected engine with dual alternators is intended to increase the engine's reliability and performance.

The primary distinguisher between the RQ-1A and RQ-1B models is the Rotax 914 turbocharged engine, which replaced the smaller Rotax 912 model and was implemented primarily to increase the Predator's speed. With the new engine, a variable pitch propeller was also added. The data over the five-year analysis timeframe indicate that the new variable pitch propeller accounted for 10 percent of all power/propulsion aborts, while the engine made up nearly 70 percent.

The increased *share* of power/propulsion failure modes does not necessarily mean that powerplant-related failures have increased in the B model, but that reliability improvements made in other areas (comms, etc.) have made a comparatively greater impact on system reliability. This is accompanied by a corresponding reduction in flight control failures as well as a large decrease in the share of malfunctions attributable to human errors and operations and hardware on the ground.

The significant decline in human and ground related errors (from 16 percent to 2 percent) is likely attributed to a concerted training effort according to one Predator operator. Enhancements in situational awareness also played a role in this positive trend including efforts to improve the human-machine interface (Improved Heads-Up Display). For example, periodic automated updates of the weather are supplied to the ground control station. A VHF/UHF ARC-210 radio was also added to provide voice relay capability to the pilot, enabling direct, over the horizon communication with Air Traffic Control (ATC) authorities in the area of flight. An APX-100 Identification, Friend or Foe (IFF)/Selective Identification Feature (SIF) Mode 4 transponder was added to further facilitate coordination with AWACS flight controllers. Air Force PFPS (Portable Flight Planning Software), an offshoot of the Air Force Mission Support System (AFMSS), is another tool defined in the Block 1 upgrade in which threat and mission planning information can now be passed directly to the Predator system. Provision for an auto-landing capability is hoped to decrease the influence of human errors as well.

The percentage of communications and flight control failures remained virtually unchanged between the two models.

2.1.1.3 MQ-9

To address certain reliability issues which arose during RQ-1B operations, the Predator B system, recently denoted MQ-9, is scheduled to undergo specific modifications from its predecessors designed to enhance reliability. Specifically, the MQ-9 will have actuators with an MTBF of 2,000 hours, which is over an order of magnitude improvement over the actuator MTBF of 150 hours on the MQ-1 models. There will be a triplex (double redundant) flight control system, and the control surfaces' survivability will increase with two rudders, four ailerons, and four elevators. The overall objective failure rate for the MQ-9 is on the order of 10^{-5}, or 1 in 100,000 hours of flight, a value equal to that for a number of mature manned aircraft. For a typical 15 hour flight, this translates to an operational reliability of over 99.99 percent. ***Recommendation: Perform a cost-benefit trade study for incorporating/retrofitting some or all of the Predator B's reliability enhancements into production A models***

2.1.2 RQ-2/Pioneer

The Israeli Aircraft Industries (IAI) Pioneer was purchased by the Navy in 1985 as an airborne spotter for the 16-inch guns of its four Iowa-class battleships. After testing aboard the USS Iowa in 1986, routine deployments by Pioneers aboard these ships began in 1987 in the naval gunfire support (NGFS) role. Licensed production by AAI also began during this time. The Marines took delivery of three systems in 1987, followed by the Army accepting one system in 1990 to provide an over-the-horizon reconnaissance, surveillance, and target acquisition (RSTA) capability. Six Pioneer systems participated in Operations Desert Shield and Desert Storm in 1990-91, flying a total of 800 missions and losing 19 aircraft, including one to hostile fire.

With the deactivation of its battleships, the Navy modified six of its Austin-class amphibious ships (LPDs) between 1993 and 1997 to accommodate Pioneer operations. The Army relinquished its one system to the Navy in 1995. Five years later, the Navy suspended routine Pioneer shipboard deployments in 2000 and moved its Pioneer training detachment from Ft Huachuca, AZ, to NAS Whiting, FL. The remaining five systems then served with the Navy (two systems in contingency status and one for training) and the Marines (two squadrons with one system each). The Navy ceased Pioneer operations in September 2002, leaving the Marine Corps as the sole operator. With over 20,000 hours of flight time, Pioneer is the longest serving UAV system in the U.S. military. Its system specifications and flight-critical components are provided in Tables 2-5 and 2-6.

TABLE 2-5: RQ-2/PIONEER DATA

	RQ-2B
Weight	452 lbs
Length	14 ft
Wingspan	17 ft
Ceiling	15,000 ft
Radius	100 nm
Endurance	5 hrs
Payload	75 lbs
Cruise Speed	80 kts
Aircraft cost	$650,000
System Cost (4 AVs)	$7,000,000

Pioneer has evolved through seven variants during its two decades of service life. Every variant since the third (Option II) has included modifications to enhance its reliability. The Basic variant was that of the first three systems (15 aircraft) supplied directly from IAI in 1986. AAI began licensed production of the next two systems, known as Option I, in 1986. Option II production began in 1987 (systems 6 through 9) and incorporated an upgraded flight control processor assembly, GPS navigation, larger tail surfaces, multiple control link frequencies, and breakaway parts for net recoveries. Option II+ (v.1), introduced in 1988, modified the existing nine systems with new fuselages, wing straps for more structural integrity, redesigned engine shrouds for better cooling, and added an engine fuel trap to reduce engine cut-outs inflight.

TABLE 2-6: RQ-2B/PIONEER KEY COMPONENTS

Component	Vendor	Model	Quantity	Country of Manufacture	Remarks
Engine(s)	Mannesmann Sachs AG	SF2-350	1	Germany	Also used on (AUO) motorcycles, mopeds
Generator(s)	Motorola Automotive Electronics	RA24/35MIL4	1	USA	
Fuel Pump	Motor Service International	EIF 7.21440.13	1	Germany	AUO cars, motorcycles, boats, farm vehicles
FCS Computer(s)	BAE Aircraft Controls, Inc.	489570-03-01	1	USA	
FCS Software	IAI AAI BAE	Autopilot mission control operational flight program RTM		Israel USA USA	
Actuators	IAI Malat	TLM1320100-507	8	Israel	AUO IDF UAVs
Air Data System	BAE Aircraft Controls, Inc	MIAG	1	USA	
Navigation System	BAE Aircraft Controls, Inc	MIAG	1	USA	
LOS Data Link	Tadiran	Spectra Link	1	Israel	AUO IDF UAVs
BLOS Data Link	N/A				
Sensor(s)	IAI Taman	MOKED 200A MOKED 400C	1 or 1	Israel	AUO IDF UAVs
	Wescam	12DS	1	USA	

A second version (v.2) of Option II+, introduced in 1989, added provisions for the UAV Common Automatic Recovery System (UCARS) auto-land system then under development, moved the throttle servo from the engine, and added an attitude indicator encoder. This variant was subsequently (1997) designated RQ-2A. A third version (v.3) of Option II+ appeared in 1997 and converted its air data system from analog to digital with the Modular Integrated Avionics Group (MIAG), as well as changing the pitot assembly and removing the GPS cable assembly. This variant was subsequently (1999) designated RQ-2B. All fielded Pioneers (five systems) have been upgraded to RQ-2B status.

2.1.2.1 RQ-2A/Pioneer

The reliability analysis for early-model Pioneers is based on statistical data gathered between September 1990 and April 1991 from three Marine, two Navy, and one Army Pioneer unit (total of six systems) while deployed in the Persian Gulf theater in support of Operations Desert Shield and Desert Storm. Although known as the Option II+ version of Pioneer at that time, this model was subsequently designated as the RQ-2A. At this time, it had been in service with the Navy for four years, the Marines for three, and the Army for one. It had already incorporated a number of reliability improvements to its original, imported version.

TABLE 2-7: RQ-2A/PIONEER SYSTEM RELIABILITY METRICS

	MTBF (hrs)	Availability	Reliability	Mishap Rate per 100,000 hrs
Requirement	25	93%	84%	n/a
Actual	9.1	74%	80%	363

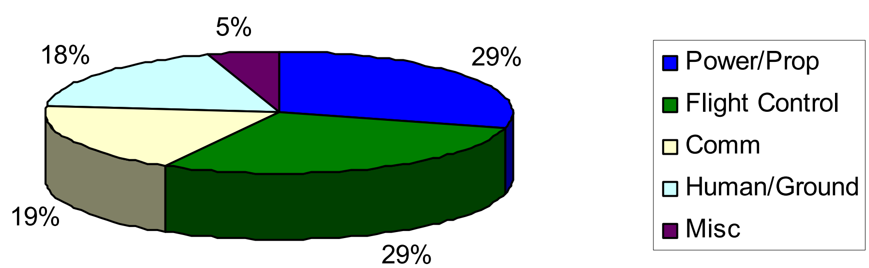


FIGURE 2-5: SOURCES OF RQ-2A/PIONEER SYSTEM FAILURES

With respect to its Operational Requirements Document, the early model Pioneer achieved less than desired reliability metrics. This was due to one of several factors. First, the Pioneer was purchased from Israel as a non-developmental system in an accelerated procurement. Once in operation, Navy and Marine users quickly identified several deficiencies that contributed to unreliability. General Charles C. Krulak, then Commandant of the U.S. Marine Corps, noted "the Pioneer does not have an automatic take-off, landing, or mission execution capability [and] that has led to a high accident rate."[5] Shipboard electromagnetic interference caused several crashes, and the engines

[5] "Riding the Dragon into the 21st Century: Innovation and UAVs in the United States Marine Corps," General Charles C. Krulak, *Unmanned Systems*, Summer 1996.

were thought to be too small and easily overstressed. In addition to the need for a more reliable engine, the Marine Corps users also felt that the system needed a smaller logistical footprint and a longer endurance. Many of these problems led to the RQ-2A failure modes of Figure 2-5.

2.1.2.2 RQ-2B/Pioneer

RQ-2Bs are modifications of the existing RQ-2A airframes, rather than new production. Twenty-five operational (out of 49 existing) RQ-2As have been converted to RQ-2Bs. There are plans to acquire spare MIAG kits through the Pioneer Improvement Program. The currently fielded version of Pioneer, the RQ-2B, is essentially a digital version of its analog predecessor, with the major distinction being the replacement of the analog air data system with the digital MIAG avionics package. MIAG incorporates the functions of many of the existing Pioneer air vehicle electronic and electro-mechanical devices. It replaces the Central Processing Assembly, airspeed transducer unit, barometric pressure unit, and the rate and vertical gyro units, components that exhibited high failure rates.

The reliability analysis for later-model Pioneers is based primarily on the Marine Pioneer squadron's VMU-1 and VMU-2 operations in the late 1990's. Some reliability terminology and maintenance explanations used by these squadrons are provided in Appendix B. The reliability data for the RQ-2B are derived from two sources: maintenance aborts and in-flight aborts. Each offers a somewhat different perspective on the reliability of the overall vehicle.

Analysis of in-flight failures during these operations led to the data presented in Table 2-8 and Figure 2-6.

TABLE 2-8: RQ-2B/PIONEER SYSTEM RELIABILITY METRICS

	MTBF (hrs)	Availability	Reliability	Mishap Rate per 100,000 hrs
Requirement	25	93%	84%	n/a
Actual	28.6	78%	91%	139

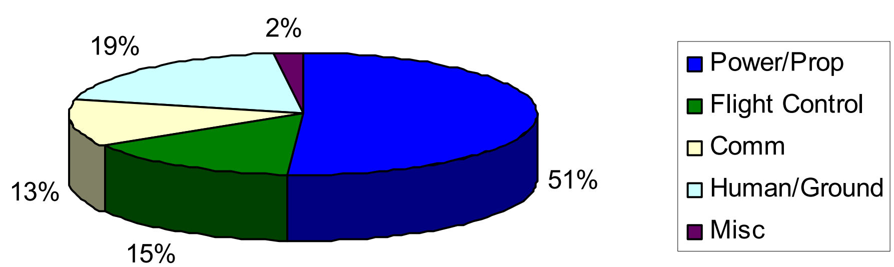


FIGURE 2-6: SOURCES OF RQ-2B/PIONEER SYSTEM FAILURES

In a distribution resembling the Predator RQ-1A data, the majority of the failures (66 percent) are attributable to the combination of malfunctions in flight control, power, and propulsion. The breakout in the flight critical systems is roughly 25 percent flight control failures and 75 percent power & propulsion failures. (Recall the corresponding RQ-2A data showed failures due to power and propulsion and flight control equally divided.)

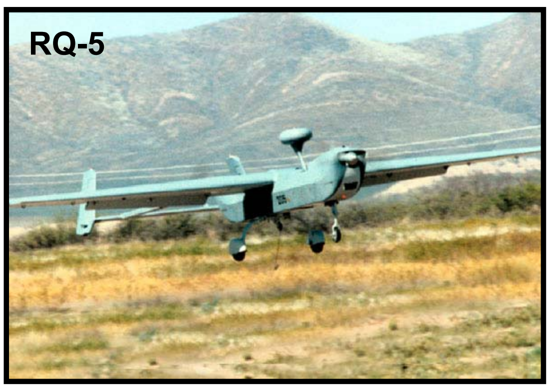
This suggests an improvement in the flight control system of the Pioneer over time, or a shift in emphasis from power and propulsion concerns. The latter explanation is supported given that the planned (1997) conversion from the Sachs to the more reliable Quattra engine was never accomplished.

2.1.3 RQ-5/Hunter

Israeli Aircraft Industries' Hunter was designed to meet the Army's 1989 Short Range UAV requirement to provide reconnaissance, surveillance, and target acquisition (RSTA) over a corps-size area of operations (108 nm/200 km deep). TRW was selected as the prime contractor for the Hunter system, which consists of eight aircraft, twelve trucks (towing two ground control stations, mission planning, launch and recovery, and maintenance stations, dish antennas, cranes, and fuel trailers), and four remote video terminals. Its characteristics are provided in Table 2-9.

First flight occurred on 30 September 1990, and initial delivery to the Army took place in December 1990. Hunter was developed as a two-aircraft-per-mission system, with one serving as the airborne relay for video from the forward collector, providing a demonstrated relay range of up to 165 nm. A Low Rate Initial Production (LRIP) contract was awarded in February 1993 for seven systems.

TABLE 2-9: RQ-5/HUNTER DATA



	RQ-5A
Weight	1,600 lbs
Length	23 ft
Wingspan	29.2 ft
Ceiling	15,000 ft
Radius	144 nm
Endurance	11.6 hrs
Payload	200 lbs
Cruise Speed	100 kts
Aircraft Cost	$1.2 M
System Cost (8 AVs)	$24 M

Seven systems of eight aircraft each were delivered between April 1995 and December 1996. A total of 62 aircraft were built by IAI/Malat and assembled by TRW. Following three crashes in close succession in August-September 1995 OSD terminated the program after LRIP completion by deciding not to award a full rate production contract. Since that redirection, however, the Hunter program has made numerous component quality related improvements and been used to demonstrate a wide variety of payloads including SIGINT, chemical agent detection, and communication relay for UAV use. It has supported National Training Center exercises and NATO operations in Kosovo, and it recently served as the surrogate TUAV for the Interim Brigade Combat Team at Ft Lewis, Washington. Table 2-10 provides a breakout of the failure-critical components for the RQ-5/Hunter.

TABLE 2-10: RQ-5/HUNTER KEY COMPONENTS

Component	Vendor	Model	Quantity	Country of Manufacture	Also Used On
Engine(s)	Motto Guzzi	V750	2	Italy	Motorcycle CA 1100
Generator(s)	Motto Guzzi	13404518-501	2	Italy	Motorcycle CA 1100
Fuel Pump	Weber Marelli	13404355	2	Italy	Motorcycle CA 1100
FCS Computer(s) Digital Central Processing Assembly (DCPA)	Elta	13406380-501	1	Israel	F-Hunter B-Hunter
FCS Software	Malat/TRW	AV-COMM-OSW 4002H436 AV-MSSN-OSW JIM152000	1	Israel/US	F-Hunter
Servo Actuators	Litton	86500000-61 TLM1320400-501	7	USA	Israeli UAVs
Air Data Module Primary/Backup	CIC	02911	2	Israel	Israeli UAVs
Navigation System	Trimble	17320-30	1	USA	Israeli UAVs
LOS Data Link	Elta	4001H350-005 4001H330-004	1 (ADT) 1 (backup ADT)	Israel	Israeli UAVs
BLOS Data Link	N/A				
Sensor(s) Multi-mission Optronic Stabilized Payload (MOSP)	IAI Tamam	1181.0001.00.19	1	Israel	Israeli UAVs

The acquisition of the Hunter system by the Army presents a case study in the peril of ignoring, and the benefits of overcoming, reliability problems. During system acceptance testing in 1995, three Hunter aircraft were lost within a 3 week period, contributing to a decision to terminate full rate production. Wanting to benefit as much as possible from its substantial investment in the Hunter, its Program Management Office and the prime contractor (TRW) performed an end-to-end Failure Mode Effect and Criticality Analysis (FMECA) and a Fishbone Analysis on each of the critical subsystems. An interconnected network of failure analysis and corrective action boards was implemented with the authority to direct design changes to Hunter. Failures of its servo actuators, the leading culprit for the series of crashes, were identified, and their MTBF increased from 7,800 hours to 57,300 hours, a sevenfold improvement. Other key components received focused attention including the data link and engine. Their before-and-after MTBFs are shown in Table 2-11.

TABLE 2-11: RQ-5/HUNTER COMPONENT MTBF IMPROVEMENTS

Component	MTBF		Improvement Factor
	Before	After	
Data link (Airborne Data Terminal)	97 hours	1277 hours	13 x
Flux valve	453 hours	2177 hours	4.8 x
Throttle actuator	331 hours	786 hours	2.4 x

Hunter returned to flight status three months after its last crash. Over the next two years, the system's MTBF doubled from four to eight hours and today stands at over 11 hours. The aircraft itself achieved its required MTBF of ten hours in 1999, and today that figure stands close to 20 hours. Prior to the 1995 stand down and failure analysis, Hunters had a mishap rate of 255 per 100,000 hours; afterwards (1996-2001) that rate was 16 per 100,000 hours. Initially canceled because of its reliability problems, Hunter has become the standard to which other UAVs are compared in reliability.

The mishap rates for the RQ-5/Hunter aircraft shown in Table 2-12 are based on the flight history of all Hunters flown by/for the U.S. Army from fiscal year 1991 through 2001. It includes test, training, and operational sorties, specifically the Technical Evaluation Test and Limited User Test sorties (1991-1995). Availability, MTBF, and reliability metrics are based on data covering all Hunters flown by/for the U.S. Army from 1996 to 2001, and therefore reflect the performance of the reliability-enhanced Hunters (LRIP Hunters) only.

TABLE 2-12: RQ-5/HUNTER SYSTEM RELIABILITY METRICS

	MTBF (hrs)	Availability	Reliability	Mishap Rate per 100,000 hrs
Requirement	10	85%	74%	n/a
Actual	11.3	98%	82%	Pre-1996: 255 Post-1996: 16

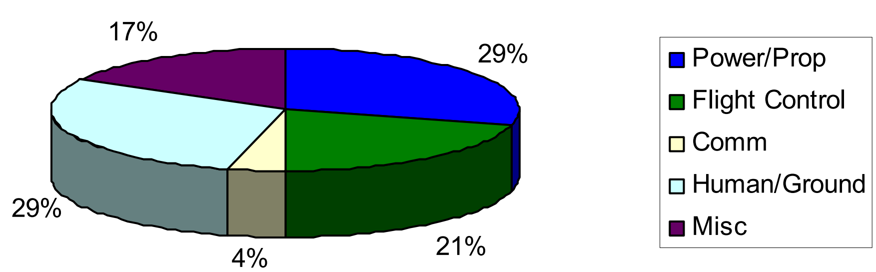


FIGURE 2-7: SOURCES OF RQ-5/HUNTER SYSTEM FAILURES

In addition to the reliability data shown in Table 2-12, an in-house reliability assessment performed by the prime contractor for the period of 20 December 1995 through 15 December 2001 found a system MTBF of 16.31 hours and an availability of 0.993. Using this MTBF value, the calculated reliability for a 2.5 hour mission is 0.86. All of these contractor-generated values are higher, yet not significantly different, than those calculated from the flight data.

The system-level pie chart (Figure 2-7) is built on data from 19 June 1994 to 16 July 2001. Excluding comm, Figure 2-7 shows that the Hunter's failures, as opposed to previous system level breakouts for Predator and Pioneer, is generally much more evenly distributed among the failure modes. This is likely due to the concerted effort of the prime contractor – after a rigorous assessment of overall system reliability – to focus improvement on those areas in which the early vehicle's reliability was lacking. The 17 percent of failures attributed to "Miscellaneous" is composed of malfunctions with the flight termination system and parachute vehicle recovery system.

To summarize, the high mishap rate of the early Hunters was comparable to that of the early Pioneers and, based on that similarity, can be largely attributed to poor Israeli design practices for their UAVs in the 1980s. The significant improvement in Hunter's mishap rate achieved since the mid-1990s is reflective of (1) joint government/contractor-focused oversight, (2) a rigorous review and analysis process being put in place, and (3) qualitative improvements in a number of failure-critical components (servo-actuators, flight control software, etc.).

2.2 Developmental UAVs

2.2.1 RQ-4/Global Hawk

Northrop Grumman's Global Hawk was developed as the conventional, non-penetrating half of the High Altitude Endurance (HAE) UAV ACTD in 1994-2000; its complement was to have been the stealthy penetrator, Lockheed Martin's RQ-3/DarkStar. First flight occurred in February 1998. Program management responsibility shifted from DARPA to the Air Force in Oct 1998, and the ACTD concluded in June 2000 with a recommendation from JFCOM to proceed to acquisition. It was approved for transition to Engineering and Manufacturing Development (EMD) and Low Rate Initial Production in February 2001.

Global Hawk completed the first trans-Pacific flight by a UAV in April 2001 during a deployment to Australia, returning to the U.S. two months later. Since November 2001, the aircraft has flown in support of counterterrorism operations in Afghanistan. Current planning calls for producing 51 aircraft and ten ground stations and to achieve initial operational capability (IOC) in 2005 at Beale AFB, CA.

TABLE 2-13: RQ-4A/GLOBAL HAWK DATA

	RQ-4A
Weight	26,750 lbs
Length	44.4 ft
Wingspan	116.2 ft
Ceiling	65,000 ft
Radius	5,400 nm
Endurance	32 hrs
Payload	1,950 lbs
Cruise Speed	345 kts
Aircraft Cost	$20 M
System Cost	$57 M

The ACTD variant is the current version of Global Hawk, the RQ-4A. The Air Force plans to enhance its capabilities and address vanishing vendor issues in a spiral development effort continuing into 2010. Reliability-related enhancements included in these spirals consist of the following.

Spiral 1 (FY01-03)

- Internal Mission Management Computer (IMMC) Improvement
- Communication (Data Link) Improvements

Spiral 2 (FY02-05)

- Engine Upgrade
- Electrical Power Upgrade

Spiral 3 (FY03-06)

- Simultaneous Imagery Recorder
- Enhanced Operational Reliability (see description below)
- Environmental Control System Enhancements
- Enhanced Fault Detection/Fault Isolation

Spiral 4 (FY04-10)

- Inflight Engine Restart Capability

The "enhanced operational reliability" effort envisioned for Spiral 3 consists of the following reliability/maintainability/supportability (RMS) and producability upgrades.

- Corrosion control
- Rain intrusion fixes
- Inertial measurement unit (IMU) integration into the flight control system
- Battery replacement
- Replacement of the radar's pump with a nitrogen bottle (improved reliability through simplification)

Taken together, these RMS upgrades are estimated to save 849 hours in assembling each Global Hawk and 2524 hours in producability tasks, savings that can be applied against the cost of making the upgrade.

Global Hawk had specified a reliability goal during its ACTD of less than one loss per 200 missions (defined as 24-hour missions, or 4800 hours). Analysis of its flight critical components predicted a reliability of one loss in 605 missions (14,520 hours). To date (February 1998 through August 2001), there have been four Global Hawk mishaps resulting in the loss of three aircraft.

The first loss (Air Vehicle 2 in March 1999) was due to an inadvertent radio transmission on the aircraft's flight termination frequency while it was airborne; this is attributed to human error. The second accident (Air Vehicle 3 in December 1999) occurred during taxi after a mission when the aircraft accelerated off the end of the taxiway, damaging its nose and sensors. This is attributed to a flight control software error. The cause of the third accident and loss (Air Vehicle 5 in December 2001) is attributed to an incorrectly installed bolt in the ruddervator that eventually failed. At the time of this second loss (December 2001), the Global Hawk fleet had accumulated nearly 1800 hours, resulting in a mishap rate of 111 losses per 100,000 hours. The fourth accident (Air Vehicle 6 in July 2002) occurred due to a single fuel nozzle in a high flow.

TABLE 2-14: RQ-4A/GLOBAL HAWK KEY COMPONENTS

Component	Vendor	Model	Quantity	Country of Manufacture	Remarks
Engine(s)	Rolls Royce	AE3007H	1	USA	Also used on Citation X, EMB 145
Generator(s)	Smiths Aerospace			USA	Starting June 2003
Fuel Pump					
FCS Computer(s)	Vista Controls		2	USA	
FCS Software					
Actuators (Spoilers)	MPC		4		
Actuators (Ruddervators)	Northrop Grumman		8	USA	
Air Data System	Rosemount	1281	2		
Navigation System	Northrop Grumman/ Litton	LN-211G	2	USA	
LOS Data Link: X (CDL), UHF	L3 Comm		1 (X band) 1 (UHF)	USA	
BLOS Data Link: Ku, UHF	L3 Comm		1 (Ku) 1 (UHF)	USA	
Sensor(s): EO/IR, SAR/ MTI	Raytheon	ERU HISAR	1 (EO/IR) 1 (SAR/MTI)	USA	

2.2.2 RQ-7/Shadow

The Army selected the RQ-7/Shadow 200 (formerly known as the TUAV) in December 1999 to meet its Brigade-level UAV requirement for support to ground maneuver commanders. Catapulted from a rail, it is recovered with the aid of arresting gear. It is capable of remaining on station for 4 hours at 50 km (27 nm) with a payload of 60 pounds. Its gimbaled EO/IR sensor relays real time video via a C-band LOS data link. Eventual Army procurement of 39 systems of four aircraft each is expected with IOC planned in 2003. The Army Acquisition Objective, with the inclusion of the Army Reserve component, is 83 systems.

TABLE 2-15: RQ-7A/SHADOW DATA

	RQ-7A
Weight	327 lbs
Length	11.2 ft
Wingspan	12.8 ft
Ceiling	15,000 ft
Radius	68 nm
Endurance	4 hrs
Payload	60 lbs
Cruise Speed	82 kts
Aircraft Cost	$325,000
System Cost (4 AVs)	$6,200,000

The RQ-7/Shadow 200 became the first UAV in recent history to meet and pass its Milestone III (full rate production) decision on 25 September 2002, having accumulated over 2,000 flight hours during 1,157 flights by 18 September 2002. While these are limited data from which to distill any measurable reliability, availability, or MTBF statistics, the failure modes for the 16 non-weather aborts logged for the Shadow between 4 January and 18 September 02 are presented below.

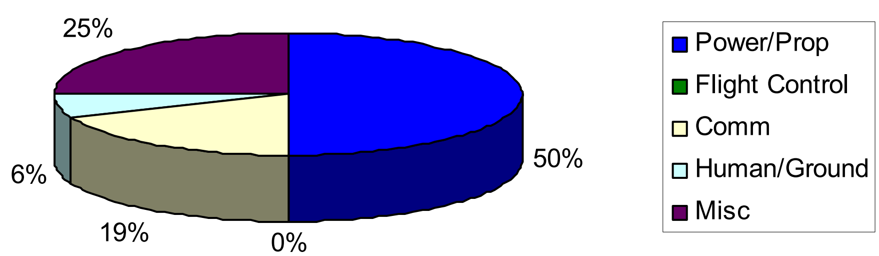


FIGURE 2-8: SOURCES OF RQ-7/SHADOW SYSTEM FAILURES

The data indicate that the Shadow's problems are dominated by power and propulsion issues. In most cases, these failures were due to fuel leaks, abnormal RPM levels, or low engine compression. Flight control issues did not contribute to any system failures for the reported time period. This appears to be due to risk avoidance rather than risk mitigation; in addition to the 16 component-related aborts, there were 12 aborts due to weather, ten of which were due to out-of-tolerance wind conditions. This may indicate a potential sensitivity of Shadow to environmental factors, a secondary failure mode of other small UAVs which is discussed in detail in Section 3.2.

The UAV systems project office at Redstone Arsenal, AL conducted a reliability, availability, and maintainability initial operational test assessment based on two weeks of flights in an operational environment. The results from this limited flight test data indicate a Mean Time Between System Abort (MTBSA) of 26.9 hours and an availability of 95.6 percent. In this case, an abort is defined as a failure which causes a delay of 10 minutes or more in providing imagery to the commander in the field. Key reliability factors identified during this test included frequently replaced propellers, bending tailhooks, and failures in the data interface box, an external box between the antenna and ground control station. Information regarding key Shadow components is unavailable because the contractor has deemed the majority of this information to be of a proprietary nature. While this policy is at times necessary to remain competitive in the UAV industry, it has also been a source of unreliability due to a lack of government insight into the parts quality of the system.

2.2.3 Dragon Eye

Dragon Eye is a small ("mini"), bungee-cord launched UAV being developed by the Marine Corps Warfighting Laboratory and the Naval Research Laboratory as an over-the-hill, reconnaissance asset for small units. Begun in February 2000, an NRL-built prototype made its first autonomous flight in March 2001. Limited rate initial production (LRIP) contracts were let to BAI and AeroVironment in July 2001 for 40 aircraft; a prime contractor for full rate production (FRP) is to be identified upon Milestone III approval in Spring 2003. Eventually, 311 systems (3 air vehicles each) are to be acquired with IOC occurring in the third quarter of FY03 and FOC in the fourth quarter of FY06.

TABLE 2-16: DRAGON EYE DATA

	Dragon Eye
Weight	4.5 lb
Length	2.4 ft
Wingspan	3.8 ft
Ceiling	1000 ft
Radius	2.5 nm
Endurance	44 min
Payload	1 lb
Cruise Speed	35 kts
Aircraft Cost	$40,000
System Cost (3 AVs)	$125,000

The required mission reliability for the Dragon Eye is .90 (threshold) and .95 (objective) based on sustained 24-hour per day/30-days continuous operation. The availability requirements are .90 (threshold) and .95 (objective). These values are based upon the available components of Block 0. Mean Time to Repair (including troubleshooting but excluding restoration time) is set at one hour (threshold) and 30 minutes (objective) at the organizational levels. At the intermediate level, MTTR levels are to be no greater than three hours (threshold) and 1.5 hours (objective). Based on these values, the required MTBF is 8 hours (threshold) and 15 hours (objective).

As in the case of the RQ-7/Shadow, a full table identifying key Dragon Eye components could not be provided due to assertions of proprietary information.

3.0 Reliability Trends and Analysis

3.1 UAV Reliability Comparisons

3.1.1 U.S. Military UAV Reliability

Figure 3-1 shows the numbers of Predators, Pioneers, and Hunters lost in Class A mishaps by year for the period 1986 through 2002. Class A mishaps are those aircraft accidents resulting in loss of the aircraft (in Naval parlance, "strike"), human life, or causing over $1,000,000 in damage. These data show a cumulative mishap rate (i.e., Class A accidents per 100,000 hours of flight) of 32 for Predator, 334 for Pioneer, and 55 for Hunter (16 since the major reliability improvements in 1996). In comparison to manned aviation mishap rates, general aviation aircraft suffer about 1 mishap per 100,000 hours, regional/commuter airliners about a tenth that rate, and larger airliners about a hundredth that rate.

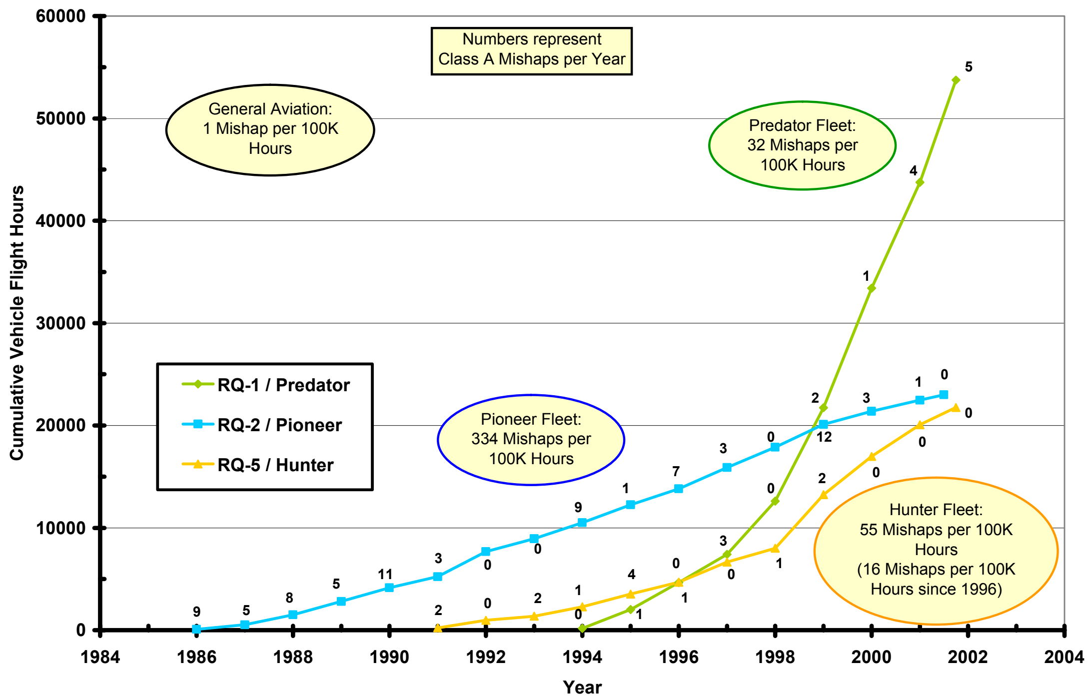


FIGURE 3-1: U.S. MILITARY UAV FLIGHT HOURS AND MISHAPS, 1986-2002

These statistics make it apparent that the reliability of UAVs needs to improve by one to two orders of magnitude to reach an equivalent level of safety with manned aircraft.

Toward this goal, the declining trend in mishap rates, as shown in Figure 3-2, is encouraging. Both Pioneer and Hunter have achieved an order of magnitude improvement: Pioneer (9.5x) in 15 years and Hunter (15x) in 11 years over their operational careers. In contrast, Predator has demonstrated an essentially constant (and low) mishap rate since its inception. This could be attributed to it having had the benefit of experience gained by its manufacturer with two immediately preceding, similar designs, Amber (1988) and Gnat 750 (1992). Given these current values and their decreasing trends, one could expect larger UAVs to reach mishap rates of 15-20 per 100,000 hours by the end of this decade.

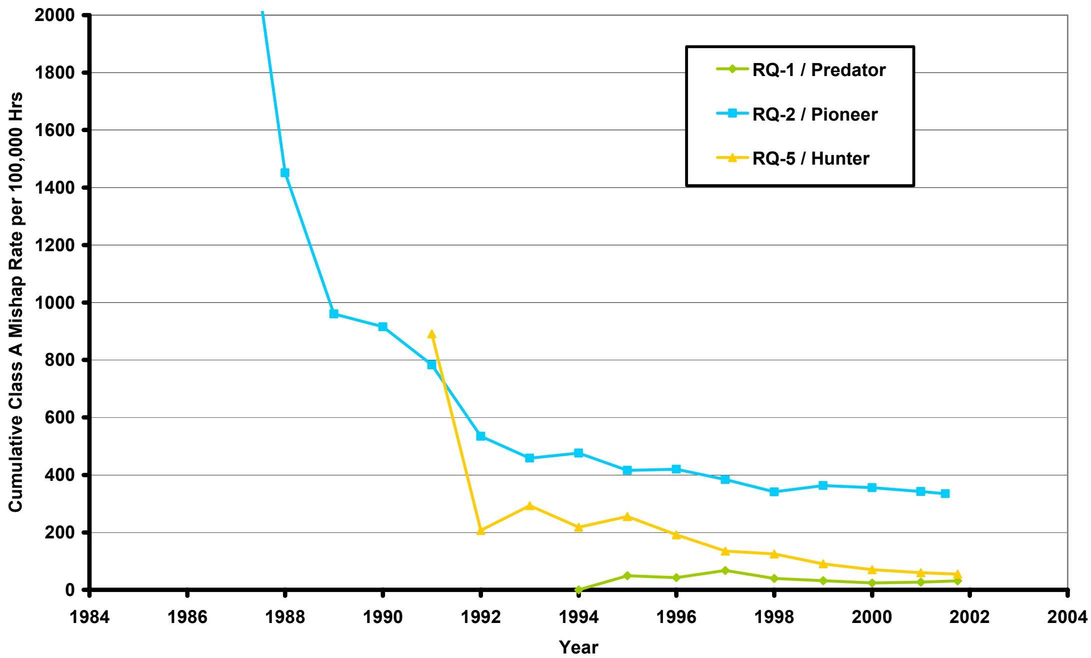


FIGURE 3-2: CUMULATIVE MISHAP RATE PER 100,000 HOURS

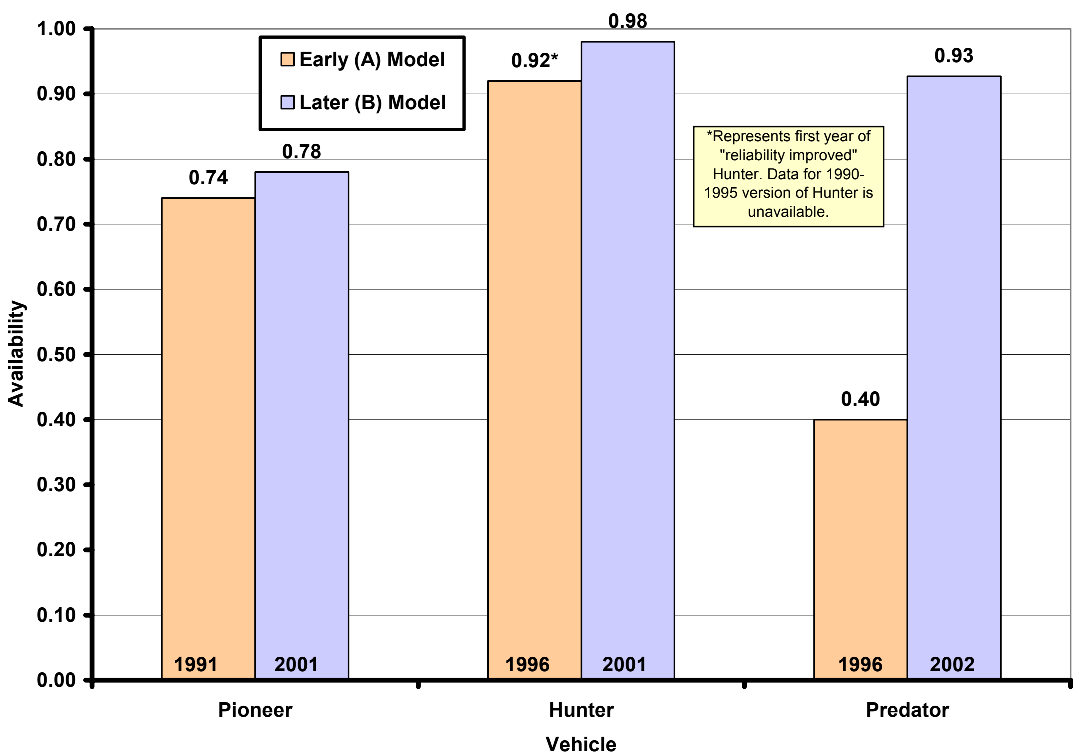


FIGURE 3-3: AVAILABILITY FOR VARIOUS UAV SERIES

Figure 3-3 presents the vehicle availability throughout the operational lifetime of the system (cumulative availability). It is based on data provided by the respective program offices, the contractors, and in some cases, the specific squadrons which operate the systems. The availability trends for the RQ-2/Pioneer and RQ-5/Hunter have remained fairly constant throughout the operational life of the air vehicle, with the values for the Hunter maintaining a particularly high value. Improved maintenance and component quality can be largely credited for this trend.

Figure 3-3 also shows that the RQ-1/Predator has enjoyed a significant increase in its availability from its early and later models. A 1997 Institute for Defense Analyses report offers a potential explanation for the poor reliability of the early model, noting that the short demonstration period was insufficient to train the military operators to maintain the system. The need for a logistics infrastructure – a major factor in availability – was identified. Early establishment of a Lead Service in order to facilitate sustainability and supportability was also noted, factors on which availability is dependent.

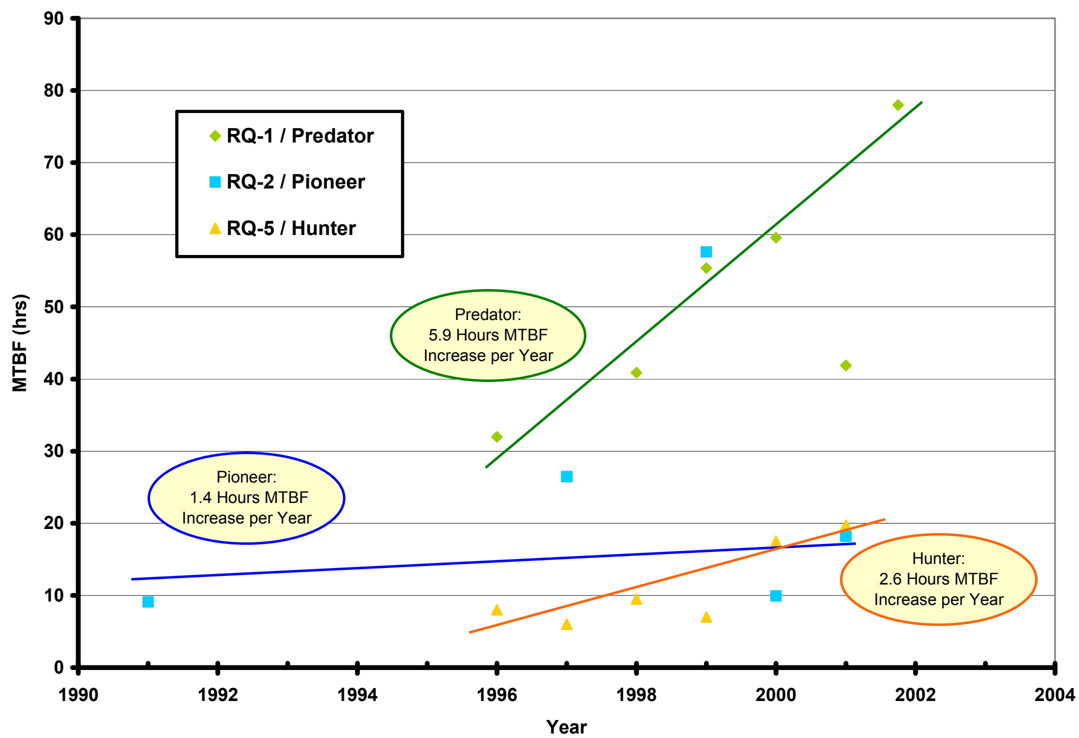


FIGURE 3-4: MEAN TIME BETWEEN FAILURE (MTBF) COMPARISON

Figure 3-4 compares the MTBF trends for the three UAVs. The RQ-1/Predator initially had a number of disconnects between the system performance and reliability expectations due to insufficient field testing and a delay in requirements baselining. This early handicap was overcome – at an average rate of 5.9 hours MTBF increase per year – through enhanced training and better maintenance practices.

Also noteworthy in Figure 3-4 is the steady MTBF increase for the RQ-5/Hunter of 2.6 hours per year. Relative to the initially poor MTBF from the early model's years, this translates to an average percentage increase of 32.5 percent per year since the reliability improvements went into effect in 1996. This improvement is a tribute to the benefit of both a thorough Failure Modes and Effects Analysis effort and sensitivity to lessons learned.

The source offering the largest operational experience is the RQ-2/Pioneer. The MTBF increase for this system has improved at a modest rate of 1.4 hours per year, a less than expected improvement over the nearly two decades in which it has provided service.

Figure 3-5 offers a similar representation of the three UAVs with respect to reliability, the probability that the system will complete its intended mission.

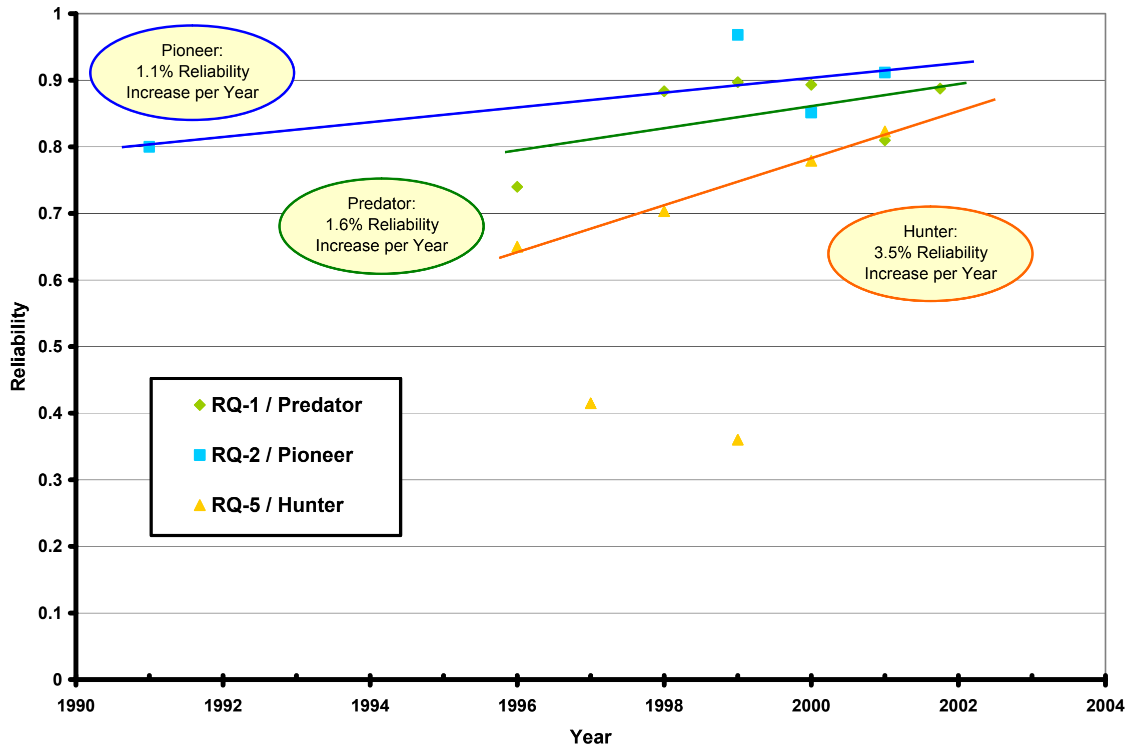


FIGURE 3-5: SYSTEM RELIABILITY COMPARISON

The RQ-5/Hunter has enjoyed the largest reliability increase (3.5 percent per year) of any of the UAVs examined. This is due to significant improvements to the critical subsystems. For example, a GAO Report[6] noted that the reliability of the engines on the early air vehicle was so low that each UAV unit equipped with two Hunter systems (16 air vehicles) was expected to replace engines at a rate of 3 to 10 per week. A second report[7] identified problems in the Hunter's flight control software and data link. Addressing these major deficiencies has yielded positive results for the Hunter program…after it had already been cancelled.

The reliability improvement from early to late models, including the over 25 percent improvement in Hunter reliability, is indicated in Figure 3-6.

---

[6] GAO NSIAD-95-52, *No More Hunter Systems Should Be Bought Until the Problems Are Fixed.*
[7] GAO NSIAD-97-138, *UAVs: DoD's Acquisition Efforts.*

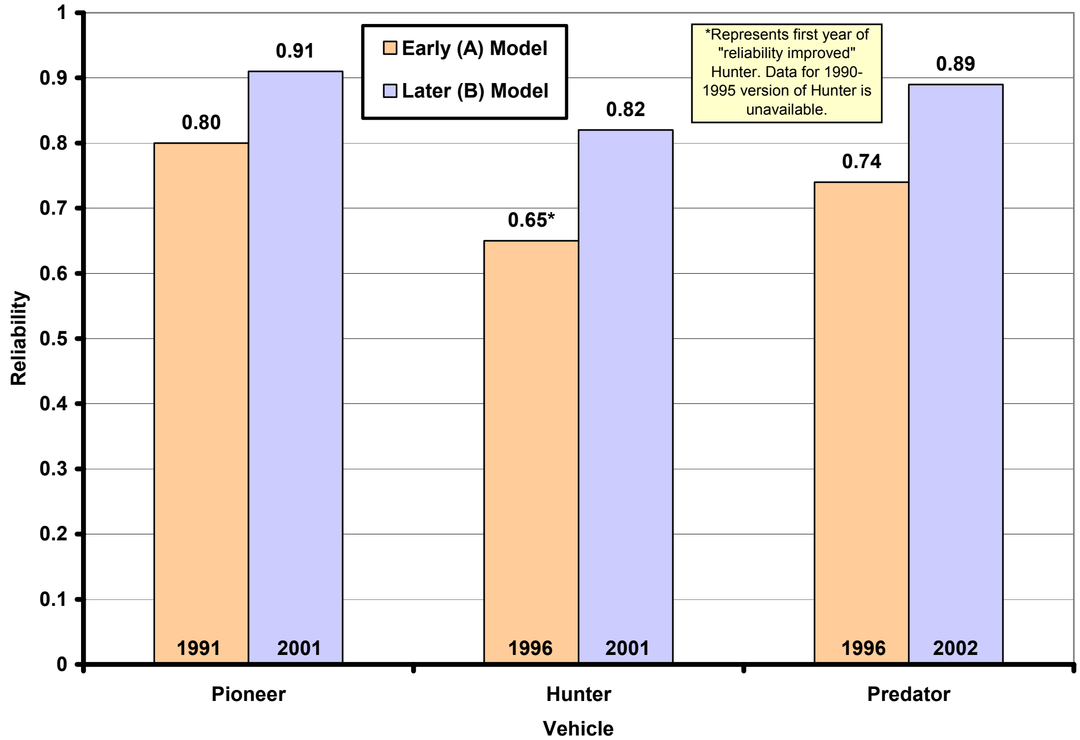


FIGURE 3-6: RELIABILITY FOR VARIOUS UAV SERIES

TABLE 3-1: SUMMARY OF UAV RELIABILITY FINDINGS

		MTBF (hrs)	Availability	Reliability	Mishap Rate per 100,000 hrs (Series)	Mishap Rate per 100,000 hrs (Model)
RQ-1A/ Predator	**Requirement**	n/a	n/a	n/a	n/a	32
	Actual	**32.0**	**40%**	**74%**	**43**	
RQ-1B/ Predator	**Requirement**	40	80%	70%	n/a	
	Actual	**55.1**	**93%**	**89%**	**31**	
RQ-2A/ Pioneer	**Requirement**	25	93%	84%	n/a	334
	Actual	**9.1**	**74%**	**80%**	**363**	
RQ-2B/ Pioneer	**Requirement**	25	93%	84%	n/a	
	Actual	**28.6**	**78%**	**91%**	**139**	
RQ-5/Hunter (pre-1996)	**Requirement**	10	85%	74%	n/a	55
	Actual	n/a	n/a	n/a	**255**	
RQ-5/Hunter (post-1996)	**Requirement**	10	85%	74%	n/a	
	Actual	**11.3**	**98%**	**82%**	**16**	

Table 3-1 summarizes the reliability metrics for all current generation military UAVs examined in this study. With respect to the required values as outlined in the operational requirements and specifications, green and red text signify instances in which the actual values meet or fall short of the requirements, respectively. In the case of the mishap rate per 100,000 hours, no requirements were identified. In addition, requirements are not available for the RQ-1A/Predator due to their development after concluding its ACTD (discussed in 2.1.1).

The mishap rate per 100,000 hours is presented in two ways. The *model/series* mishap rate illustrates "before and after" gains made in reliability and operations between subsequent versions of the same UAV model. The *model* mishap rate is a snapshot of the combined performance of all versions of each UAV. It incorporates all mishaps over that system's cumulative flight hours.

In all cases except for the RQ-2/Pioneer, the UAV systems examined in this study exceed operational requirements. The shortfalls in the RQ-2A reliability performance were amended with the next generation RQ-2B with the exception of the availability metric. The failure modes which contributed to these reliability metrics are presented in Table 3-2.

TABLE 3-2: SUMMARY OF UAV FAILURE MODE FINDINGS

	Power/ Propulsion	Flight Control	Comm	Human/ Ground	Misc
RQ-1A/ Predator	23%	39%	11%	16%	11%
RQ-1B/ Predator	53%	23%	10%	2%	12%
RQ-2A/ Pioneer	29%	29%	19%	18%	5%
RQ-2B/ Pioneer	51%	15%	13%	19%	2%
RQ-5/ Hunter	29%	21%	4%	29%	17%

There are several noteworthy trends from the summary data in Table 3-2.

- The failure due to Human/Ground related issues is significantly lower for the RQ-1B Predator. This may be largely due to the increased use of simulators for Predator training as well as enhancements made in situational awareness (discussed in Section 2.1.1.2)
- Despite some initial integration issues, a more complex solution for over-the-horizon ATC communication via the ARC-210 radio did not increase the share of mishaps due to communication hardware and software failures for the RQ-1.
- The trends in the RQ-1/Predator and RQ-2/Pioneer failures due to Power/Propulsion are very similar. The share is in the 20-30 percent range (23% and 29%, respectively) for the early, A-model systems, but doubles to the 50 percent range (53% and 51%, respectively) in the later models. As discussed, MQ-1 Block 30 upgrades are intended to address this issue for the Predator, while a planned conversion to a more reliable Pioneer engine never occurred.

- The trends in the RQ-1/Predator and RQ-2/Pioneer failures due to Flight Control issues are also very similar. From the A-model to the B-model, the share decreases by approximately one-half (39% to 23% and 29% to 15%, respectively). This may be attributed to a better understanding of the vehicle aerodynamics and flight control as well as self-imposed flight restrictions for certain operating environments.
- Despite any noticeable shifts of failure modes among the vehicles from the early to the late model, the reliability trends for the UAVs continued to be positive. This indicates an awareness of, and attention to, system deficiencies on the part of the designers and operators.

The average values for the failure modes for all five systems are presented in Figure 3-7. Three of the areas (power/propulsion, flight control, and operator training) have historically accounted for 80 percent of UAV reliability failures. The implication is that the overall mishap rate for UAVs could be significantly reduced by focusing reliability improvement efforts in these areas, which could lead to appreciable savings by having to procure fewer attrition aircraft. Further savings could result from decreased line maintenance by substituting more advanced technologies for existing ones, such as electrical systems for hydraulic ones and digital for analog sensors.

The challenge is to make tradeoffs so the recurring savings of a reliability enhancement exceed the nonrecurring investment, as well as the impact of any potential decreases in performance, incurred in making the enhancement. By focusing on making reliability improvements in propulsion, flight control systems, and operator training/interfaces, the potential savings could outweigh the cost of incorporating such reliability measures in existing and future UAV designs. This aggregate view of the Predator, Pioneer, and Hunter UAV fleet provides a good introduction into a similar perspective on foreign UAV reliability.

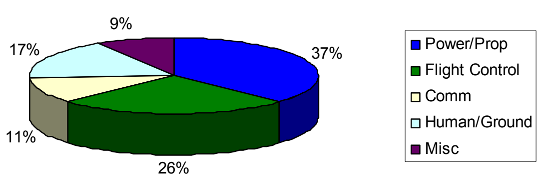


FIGURE 3-7: AVERAGE SOURCES OF SYSTEM FAILURES FOR U.S. MILITARY UAV FLEET (BASED ON 100,000 HOURS)

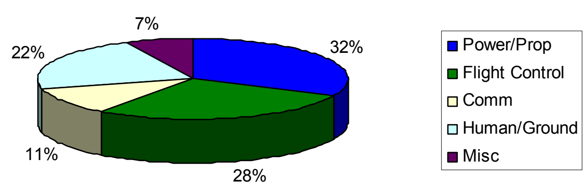


FIGURE 3-8: AVERAGE SOURCES OF SYSTEM FAILURES FOR IAI UAV FLEET (BASED ON 100,000 HOURS)

3.1.2 Foreign UAV Reliability

3.1.2.1 Israel

Israeli Defense Forces have also accumulated over 100,000 hours of operational flight experience with their UAVs. The failure modes for this period are shown in Figure 3-8. The manufacturer of most of these UAVs, Israeli Aircraft Industries (IAI), has documented the causes of failures across the past 25 years of this experience and made recommendations for improving reliability based on this analysis. Of current U.S. UAV systems, both the Pioneer and the Hunter originated as IAI designs, and the Shadow evolved from the Pioneer's design. For these three reasons, any examination of U.S. UAV reliability would be incomplete without examining the reliability of their Israeli counterparts and predecessors.

The data trends derived from the U.S. UAV operations presented in Section 2.1 and summarized in Figure 3-7 are remarkably similar (within 5%) to that shown in Figure 3-8 for the IAI UAV fleet for all failure modes. Given that the IAI data are also based on a substantial number of flight hours, one can argue that the U.S. is facing the same technical and operational problems of other operators. Furthermore, because manufacturing techniques and supply quality differ from one country to the next, it is interesting to ask the question "Why are the failures modes still similar?" One answer points to external factors and the operating environment itself, including weather and the low Reynolds number flight regime. Some insight into this idea will be presented in Section 3.2, Environmental and External Factors.

3.1.2.2 Australia

Data for the Australian Aerosonde, which has subsequently been purchased by Saab of Sweden, provide another perspective from which U.S. military UAV reliability can be gauged. From 1995 to 1998, prototype vehicles operated globally building over 700 flight hours of experience. Since this 1995 model was designed, Aerosonde has become a more robust vehicle in order to improve its operating range and enhance its reliability. The Mark 1 vehicle entered operation in 1999, and the latest version is the Mark 3.

An assessment was performed based on 1,105 flight hours between January 1999 and June 2001. It includes flights of the Mark 1, 2, and 3 air vehicles in a variety of weather conditions. The assessment calculated a mishap rate of 543 mishaps per 100,000 hours. This is based on 6 non-weather related "catastrophic" failures: power and propulsion (2), flight control (3), and airframe failure (1). If the Aerosonde follows the example of U.S. UAVs, the mishap rate will drop considerably as more flight hours are put on the system.

3.1.3 Manned Aircraft Reliability

It is also helpful to view UAV reliability from the perspective of their manned aircraft counterparts. Perhaps most striking is a 2002 Congressional Research Service report that cites 70 percent of all Class A mishaps in manned aircraft of the U.S. military are due to human error. Broadening the scope to all manned aircraft, that figure rises to a generally accepted value of 85 percent according to the independent, non-profit Flight Safety Foundation. Furthermore, these reliability figures appear to be independent of whether the aircraft is fixed or rotary wing – or even more surprising – combat or non-combat.

Figure 3-9 shows the 55-year history of U.S. Air Force mishap rates since 1947 declining rapidly from 44 to 6 Class A's per 100,000 hours during the first 15 years. Over the next 40 years, it gradually decreases to just over 1 mishap per 100,000 hours. This decline, while largely due to turbines replacing reciprocating engines, can also be attributed to improved training and operational maintenance procedures. A similar decline for unmanned aircraft can be seen in the discussion and figures of Section 3.1.

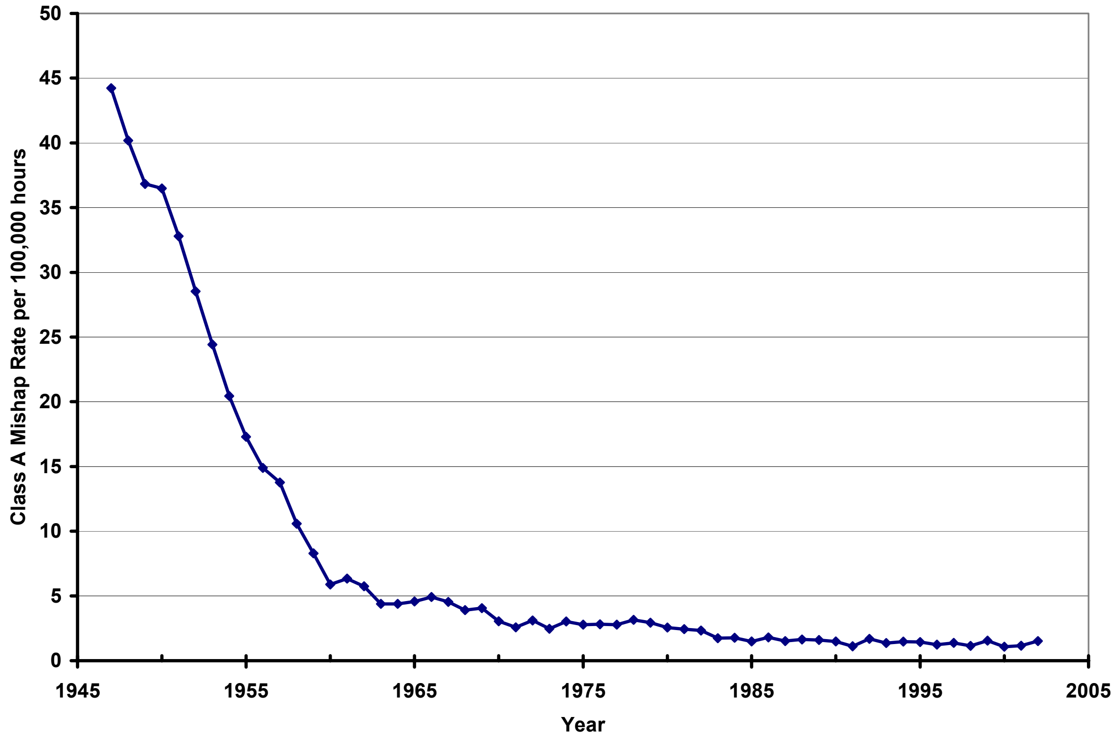


FIGURE 3-9: U.S. AIR FORCE CLASS A MISHAP RATE, 1947-2002

Table 3-3 provides available reliability metrics for various manned aircraft. Data for the RQ-1/Predator, the most reliable UAV identified in this study, are presented again for ease of comparison. To ensure consistency, the manned aircraft data were calculated using the formulas in Appendix D when appropriate operational data were available. As a result, they may differ from manufacturer's values based on other methods of calculation.

TABLE 3-3: EXAMPLES OF MANNED AIRCRAFT RELIABILITY

Aircraft	Mishap Rate (per 100,000 hrs)	MTBF (hours)	Availability	Reliability
General Aviation	1.22	*Data proprietary or otherwise unavailable*		
AV-8B	10.7		*Data unavailable*	
U-2	6.5	105.0		96.1%
F-16	3.35	51.3		96.6%
F-18	3.2			
Boeing 747	.013*	532.3	98.6%	98.7%
Boeing 777	.013*	570.2	99.1%	99.2%
Predator/RQ-1	31	55.1	93%	89%

*NTSB data for all commercial air carriers operating under 14 CFR 121.

The above table provides a cross-section of manned aircraft reliability and how it compares to the RQ-1/Predator. To examine specific mishap data for manned military aircraft, Table 3-4 presents the mishap rate for each of the four military services.

TABLE 3-4: DEPARTMENT OF DEFENSE CLASS A MISHAPS, 1980-2000

	Total # of Class A Mishaps	Mishap Rate	Fatalities	Fatalities per Mishap
Army	605	1.98	552	.91
Air Force	1,002	1.64	1,152	1.14
Marine Corps	376	4.55	494	1.31
Navy	822	2.55	665	.8
Average	701	2.68	716	1.04

If it were not that all manned aircraft exceed current UAV reliability, it would be in some respects unfair to compare aircraft with certain mission profiles to that of a UAV. For example, one would expect to see a commercial airliner with reliability much higher than a combat aircraft. When designing for reliability, however (see Section 3.3), the intended mission profile for a given aircraft does affect redundancy and component quality decisions. As a result, the remainder of this section will narrow the scope further by focusing on the reliability of a manned ISR asset that more closely resembles the intelligence gathering mission profile flown by some of today's UAVs.

U-2 Reconnaissance Aircraft

The U-2R, a manned, high-altitude ISR collection aircraft, was first flown in 1967. All U-2R models have completed engine replacement and are now designated as U-2S.

TABLE 3-5: U-2S DATA

	U-2S
Weight	40,000 lbs
Length	63 ft
Wingspan	105 ft
Ceiling	70,000+ ft
Radius	3000 nm
Endurance	14 hours
Payload	4,000 lbs
Cruise Speed	400+ kts
Aircraft cost	Classified
System Cost (4 AVs)	Classified

Because of the U-2's bicycle landing gear and high aspect ratio wing, it poses a particular challenge for pilots during take-offs and landings. Despite this, however, this aircraft is credited as having one of the highest mission completion rates in the U.S. Air Force. Figure 3-10 offers a breakout of system failure modes for the U-2S.

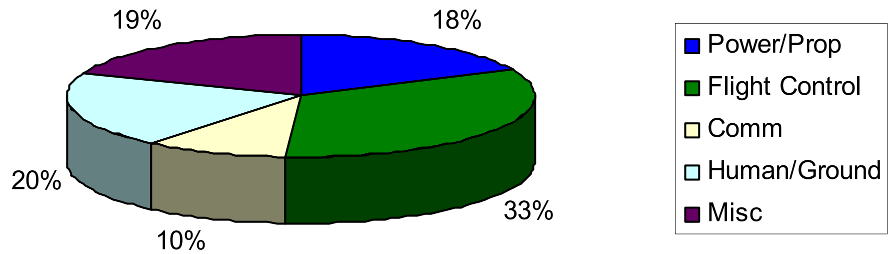


FIGURE 3-10: SOURCES OF U-2 SYSTEM FAILURES

Noteworthy is the uncharacteristically low contribution (20 percent) of human failure modes for this manned aircraft. As was discussed earlier in this section, human contributions to aircraft failures are typically much higher. One third of the failure modes for the U-2S are dominated by flight control issues. Perhaps related to this trend, it is interesting to note that relative to other manned aircraft, the U-2 operates at a lower Reynolds number. While a more detailed discussion of the low Reynolds number flight regime is provided in Section 3.2, it is sufficient at this point to draw attention to the fact that the U-2's mishap rate is four times the average for all U.S. Air Force aircraft shown in Table 3-4.

3.2 Environmental and External Factors

Although people typically associate reliability with factors internal to the system such as component reliability, there are equally influential external ones. These environmental and external influences tend to affect the entire system's reliability, vice any one component of it, and can equally affect similarly equipped systems within a fleet despite their age. The external influences that vary with location or season, such as weather-related ones, are most often mitigated with operating limitations that restrict the system's operational value. ***Recommendation: Analyze the costs and benefits of all-weather capability against mission requirements to design UAVs accordingly***

3.2.1 Precipitation

Precipitation is one environmental factor that negatively impacts more types of UAVs more so than manned aircraft. Three reasons for this are (1) the relatively smaller size of most UAVs, (2) their use of wooden propellers, and (3) less attention to watertight sealing.

By nature of their generally smaller size, UAVs are adversely impacted by a wider range of raindrop size; the light sprinkle encountered by an F-16 becomes a moderate shower to a Pioneer. Moreover, an F-16's moderate shower becomes impenetrable for the Pioneer. The only current solution to precipitation is procedural; do not take off or land in precipitation, avoid flying in it once airborne, and slow down when necessary to penetrate through it.

The smaller UAVs (Pioneer, Hunter, and below) typically use a wood, or wood with urethane, propeller as a cost and weight saving technique. Pioneers, despite having a pusher-mounted engine, consume their propellers at the rate of nearly one per flight when recovering into nets. Even when operating from runways, the lower ground clearance of

UAVs contributes to the likelihood of foreign object damage (FOD) to the propeller,[8] and a damaged propeller spinning at high RPM can render an aircraft uncontrollable quicker than human reaction can compensate. Precipitation is a special hazard to wooden propellers because the rain can quickly (in minutes) erode the leading edge of the blade, compromising the rotor aerodynamics, and eventually reducing the wood to shreds. To address this, three alternatives are (1) composite, (2) metal, or (3) wooden propellers with composite/metal leading edges.

The composite option offers a higher cost, but more durable blade and lighter weight. The metal option offers a higher cost, heavier, but more durable blade, which runs the risk of becoming bent in situations where a wooden blade is broken. A Pioneer-size wood-urethane propeller costs $275, its composite cousin is twice that at $600, and the metal version is $750, or triple that of the wood-urethane. Despite these high percentages, the absolute cost for these propellers is low, particularly considering they represent a potential single point failure of a flight critical component.

UAVs are designed solely for external maintenance in contrast to manned aircraft, which are designed for internal and limited external maintenance. Because of this, UAV fuselages are largely covered with hatches and panels to facilitate access by maintenance personnel (whose hands are one non-scaling factor). This differs from manned aircraft, where maintainers can more often climb inside the aircraft to reach malfunctioning equipment. The smaller UAVs also fly relatively slow, implying a low design emphasis on aerodynamic smoothness. These two factors in combination result in leaky UAVs due to non-sealed panel/hatch perimeters and also gaps/overhangs between access panels and the adjacent fuselage. In precipitation, water can gain access and accumulate inside the fuselage and cause a hazard to internal electronics (refer to Global Hawk's anti-rain intrusion effort in Section 2.2.1). Tighter design tolerances, coupled with sealing gaskets, could preclude this from occurring.

3.2.2 Icing

Another factor is icing, an insidious hazard to aircraft that can occur even in the absence of precipitation or visible moisture. Icing is most hazardous to flight when it accumulates on the wings, and it is the shape of these very surfaces that induces moisture to condense out of otherwise clear air and then freeze on them. Once established on wings, and perhaps later on the control surfaces, ice alters the airflow over them, adversely affecting controllability. When shed, larger accumulations of ice can pose a hazard to pusher propellers. In extreme cases, the limits of the flight control system to compensate for the icing are exceeded and/or the movement of the control surface hinges is impeded. Airfoil shape, and thus vehicle performance and controllability, can also be greatly altered. Stall speed could creep upward and pilot inputs become increasingly ineffective until the UAV stalls and crashes. Beyond the aerodynamics, even the weight of the accumulated ice can become a factor, especially on the smaller airframes of most UAVs. In terms of scale, for example, a one-tenth inch accumulation on a Pioneer's wings is equal to one inch on a Boeing 747.

---

[8] This problem is not unique to UAVs. Any aircraft with low-slung inlets can have increased FOD incident rates.

Icing has been identified as a primary or contributing cause in two Hunter mishaps and three Predator losses, accidents costing some $10 million over the past 3 years. All occurred between the months of September and April and during overseas deployments supporting contingencies, underscoring the relatively benign stateside environments used for UAV training. These incidents argue for added attention to UAV's cold weather tolerance, including test and evaluation and recurring training in cold weather operations for UAV crews.

Technical methods to mitigate this hazard are compared in Table 3-6 in terms of cost, size-weight-and-power (SWAP), and whether the method is better for preventing ice accumulation (anti-icing) or removing it once it has accumulated (deicing).

TABLE 3-6: ICING MITIGATION OPTIONS

Method	Cost	SWAP	Preventative	Removal
Ice Detection Patch	Very low	None	Yes	No
Ice Detector	Low	Low	Yes	No
Pitot Heat	Low	Low	Yes	Yes
Glycol Weeping Wing	High	Medium	Yes	No (Limited)
Deicing Boot	High	High	No	Yes
"Teflon" Surface	Medium	Low	Yes	No

3.2.3 Wind

In comparison to manned aircraft, the impact of wind also tends to pose a greater challenge to UAVs in general, and in particular to smaller members of the UAV family. This is primarily due to their design (available control surface area, actuator response frequency, vehicle speed) leading to a suboptimal response to the environment (resistance to gusts, wing loading). Some of these handicaps are inherent to the small UAV, while others are simply due to the unwillingness of the designers to commit the funding to design reliability into the system.

High wind speed plays a role not only in take-off and landing phases of operation (crosswinds), but also inflight in the form of turbulence. Just as small boats are tossed about by waves that are imperceptible aboard ocean liners, most UAVs, being smaller and slower than most manned aircraft, are more susceptible to being upset by naturally occurring eddies and air turbulence. The smaller the UAV, the more it inherently suffers from winds and turbulence. Because this effect is relative, similar minor turbulence may be imperceptible to airline passengers or at worst noticed as a bumpy ride. Tactical size UAVs, up to and including those in Predator's class, evidence this susceptibility by jumpy video (if the sensor is unstabilized), erratic flight (heard as sudden changes in propeller sound), loss of link (signal dropout), or, in the worst case, loss of control (and potential crash) when an upset exceeds the autopilot's ability to recover.

Jumpy video and erratic flight are often mitigated by designers of small UAVs by mounting imaging sensors in stabilized gimbals and replacing fixed with variable pitch propellers, respectively. Both measures increase costs and system complexity, and thereby undercut system reliability as well. Loss of link due to turbulence affecting antenna pointing accuracy can be addressed by using omnidirectional instead of directional antennas, but this incurs an operating limitation in range and can in turn lead to other communications issues. Carrying an emergency recovery parachute, which increases cost, adds complexity, and restricts operations, can mitigate mishaps due to control losses in some cases, but again can raise additional reliability concerns. As an example, Predator's rear compartment can store a tank of glycol for supplying its weeping wing system with anti-icing fluid (enhancing its ability to operate reliably in bad weather), carry an additional tank of fuel (increasing its endurance), or sacrifice both for a parachute.

3.2.4 External Factors

The smaller the UAV, the relatively larger control surfaces it needs to enhance its controllability during adverse conditions. Because control surface size and rate requirements vary with Reynolds number[9], Reynolds is another interesting external factor (in this case related to altitude) that should be examined. Reynolds number (Re), a dimensionless number, is used to describe the type of flow encountered by an object moving through a fluid. Flow is usually characterized in one of two terms, laminar or turbulent, and Reynolds number can be used to define the upper and lower boundaries of this transition region. Laminar flow, easily modeled, is rare in nature; turbulent flow, more difficult to model with computational fluid dynamics or empirical relationships, describes virtually all naturally occurring flow, specifically that of air about aircraft.

For aircraft, Reynolds number represents the ratio of the aircraft's inertia to the viscosity of the air through which it is moving. It also provides a useful scaling term used for the comparison of aircraft of various sizes, particularly small models used in wind tunnel testing. It is calculated by dividing the product of air density (ρ), aircraft speed (V), and aircraft wing chord length (x) by the viscosity of air (μ). Both air density and viscosity decrease with increasing altitude.

$$\text{Re} = \frac{\rho V x}{\mu}$$

Reynolds number is used to account for dynamic similarity among various aircraft. Some typical values for Reynolds number are presented in Table 3-7.

[9] Flight control at slow speeds (low Reynolds number) typically requires relatively larger control surfaces moving at faster rates. In a biological example, birds use their entire wing surface to create relatively fast (but minor) control inputs (in addition to using their wings for propulsion.)

TABLE 3-7: REYNOLDS NUMBER COMPARISONS

Aircraft	Cruise Speed (Mach)	Typical Altitude (ft)	Typical Reynolds Number
Boeing 777	.84	41,000	35 million
F-22/Raptor	1.5	50,000	20 million
F-16/Falcon	.85	35,000	15 million
RQ-1/Predator	.12	10,000	3 million
RQ-7/Shadow	.11	5,000	1 million
Dragon Eye	.05	1,000	0.1 million

As this study's statistics have shown, the UAVs with lower reliability are also those that are smaller, yet fly at flight profiles (altitudes and/or velocities) traditionally served by larger aircraft. While the data in this report suggest system engineering and component quality are the primary factors in unreliability, investigation of Reynolds number flight as a second order effect resulted in Figure 3-11. This figure indicates an interesting trend in mishap rate as a function of cruise Reynolds number using values typical for various manned and unmanned aircraft.

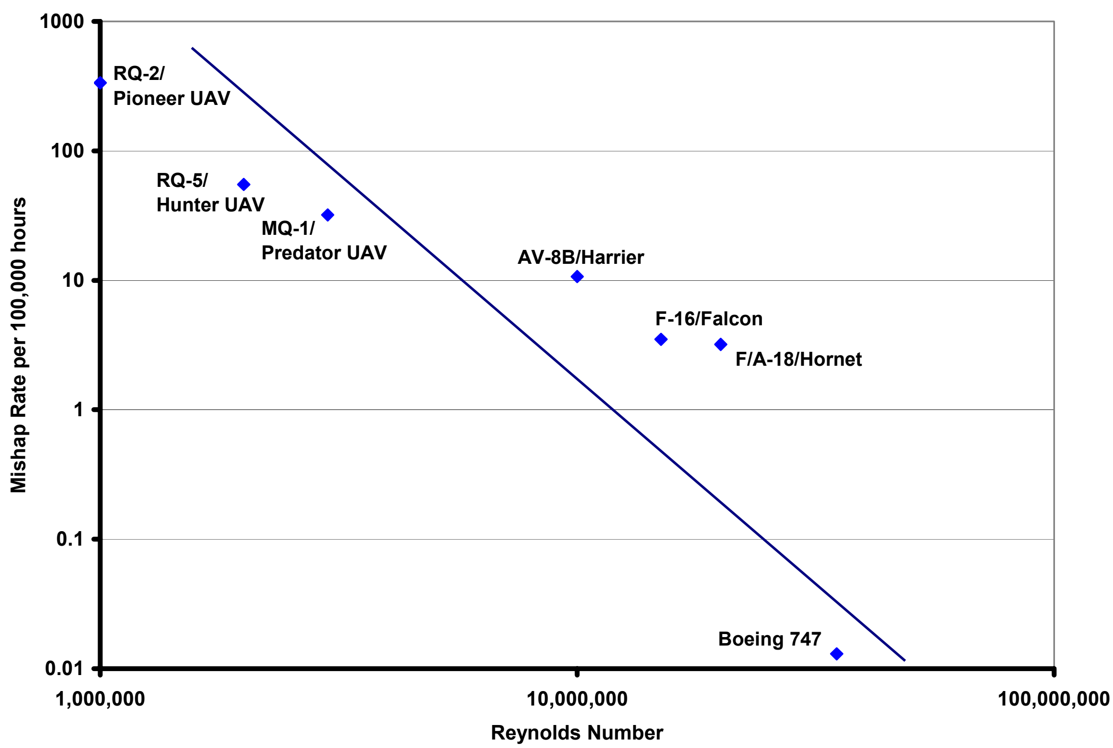


FIGURE 3-11: AIRCRAFT MISHAP RATE VERSUS REYNOLDS NUMBER

While the operational mishap rate is a function of numerous factors, many of which relate directly to vehicle cost, the trend represented in Figure 3-11 is a look at how Reynolds number can be related to the mishap rate (not component reliability) of various manned and unmanned aircraft. This information is intended to introduce the discussion of Reynolds number rather than suggest that Re is the "unifying equation" to explain all UAV unreliability. For example, fast aircraft fly at high Reynolds numbers. These same high-speed aircraft also enjoy subsystems which have required significant amounts of time and money to design (propulsion, flight control, etc.). From this one can also derive a vehicle cost to mishap relationship (see Figure 3-12) that looks similar to that in Figure 3-11.

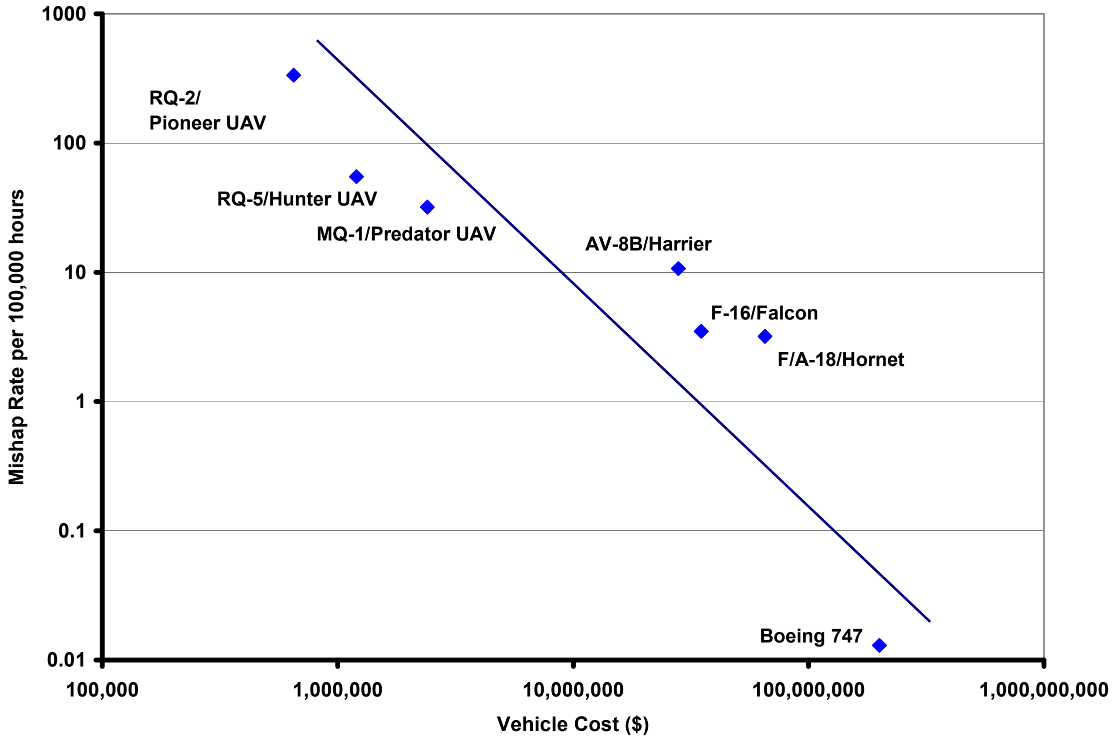


FIGURE 3-12: AIRCRAFT MISHAP RATE VERSUS COST

It should be noted, however, that similar trends can also be found when plotting mishap rate versus other variables such as gross weight or even number of passengers aboard. With this in mind, the fundamental point of this section remains the same: *low Reynolds number aerodynamics are poorly understood and further research will benefit UAV flight design.* This research could, in turn, lead to a reassessment of designing UAV subsystems for reliability which until now has been based largely on manned aircraft operations at much higher Reynolds numbers. ***Recommendation: Encourage/pursue more research into low Reynolds number flight regimes***

While the correlation in Figure 3-11 may not necessarily imply causality, there is little debate that a focus on low Reynolds flight will help enable small and micro UAVs to fly better and crash less often. Efforts in this area should be pursued in order to better understand UAV flight control in low Reynolds number regimes and how this environment may be addressed and/or exploited to enhance UAV performance.[10] As discussed in Section 3.3, however, no amount of research in this area will supplant the

[10] For a more in-depth look at how the Reynolds numbers of slow-moving/small aircraft compare to fast-moving/larger ones, a more detailed explanation is provided in Appendix F.

fact that a UAV's reliability will reflect the level of funding and effort which are devoted to its design.

3.3 Designing for Reliability

Aerospace product developers, and particularly those targeting government customers, have traditionally focused on the acquisition phase of the product's life cycle. In reality, attention to reliability must permeate all phases of the UAV life cycle. It begins with the identification of the requirement, and continues through conceptual, preliminary, and detailed design into production, operation, and retirement. Numerous lessons learned indicate that development of competitive and *thoroughly* dependable aerospace systems requires not only attention to system capability, but also sensitivity to reliability, maintainability, component quality, and performance *at the time of conceptual design*.

When the emphasis during design focuses primarily on ensuring that the product meets acquisition-centered capability requirements at the price of reliability, the result is low mission completion rates, high maintenance resource usage, and diminished capability that often times manifest themselves during operations in the field. Although useful methods (Failure Modes and Effects Analysis, Probabilistic Risk Assessment, Quality Function Deployment, etc.) exist to address many of these problems, they are most useful and cost-effective if employed early in the UAV life cycle described above. In this way, a developer transforms an idea into a system that reliably meets customer requirements from initial testing through final system attrition.

To help increase reliability while keeping costs manageable, the following principles are a few that should be considered for the design of all UAV subsystems.

- Use of standard systems engineering and layout practices
- Simplicity of design
- Testability of the design to enhance prognostic and diagnostic capabilities
- Insuring future availability of replacement materials and parts
- Sensitivity to human factors with respect to manufacturing, operation, and maintainability
- Use of redundant or fail-safe designs based on a failure modes and effects analysis
- Producability of design
- Use of preferred or proven materials and parts
- Maintaining control over material and parts quality

Recommendation: Develop and implement a Reliability Specifications Standard for UAV design

To emphasize the importance of these guidelines, the development of software – in this context, for flight control – provides an excellent illustration of the importance of designing for reliability in the initial design stages. Figure 3-13 indicates the results of a study performed by AT&T Bell Labs with respect to software development errors and associated costs. It indicates that as the development process proceeds through its necessary phases, the sources of error occur early in the cycle, while the price of fixing them begins low but increases by orders of magnitude later in the process.

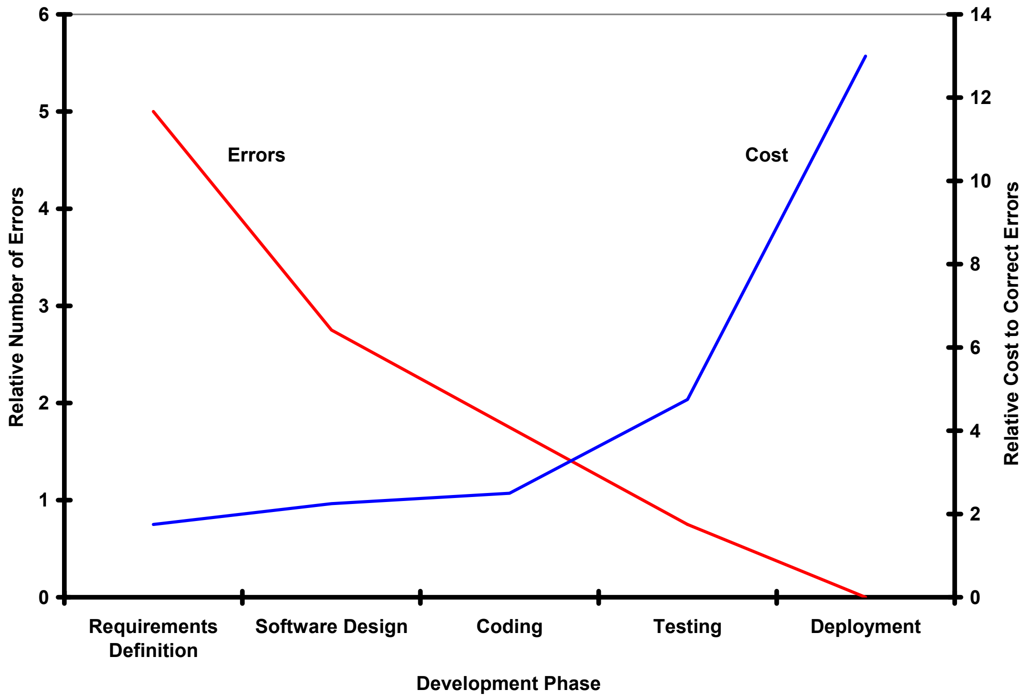


FIGURE 3-13: SOFTWARE ERROR SOURCES AND COSTS TO CORRECT

In addition to failure modes, unavailability, and mishap rates, reliability considerations must also include such issues as system interoperability, environmental (natural and man-made) survivability, and component accessibility, installability, and replaceability. For more complex components, developers must investigate even more parameters and logistical issues such as the reputation of the manufacturer as well as the components' use/performance in other applications. Any reliability issues that may have gone unadvertised given that the original component was never designed for use on an aerospace system is also a potential concern. For example, the fuel pump on the Pioneer has been used on cars, motorcycles, boats, and farm vehicles. It was never developed specifically for an aerospace application, and when contacted for further information, the company responded that it "did not even know that the pump was used on unmanned aerial vehicles."

Designing for reliability may also entail designing in subsystem or component redundancy. This is usually done for flight critical systems or when reliability analyses indicate that certain components do not achieve sufficient failure rates. This could increase product cost, but cost-benefit analyses may show that it is affordable risk mitigation. Finally, if existing, off-the-shelf technology does not prove to meet the requirements of the customer, the developer can look to new component technologies for viable solutions. To explore this topic more thoroughly, these three areas – component quality, redundancy, and component technology – are discussed in more detail to lay the foundation for the reliability-enhancing technologies presented in Section 4.0.

3.3.1 Component Quality

A system (or subsystem) is only as good as the components which comprise it, with the possibility that a "cost-effective," yet non-flight worthy part might become the failure mode for the entire system. Such design decisions for economic reasons damage not only the system hardware and the program's success, but also undermine the larger UAV community as it works to achieve routine access into civil airspace. Working against the community are the high expectations for low UAV price tags, which can be traced – directly or indirectly – to many of the failure modes outlined in Section 2.0. Simply put, reliability is inextricably tied to the level of resources spent to design, build, operate, and train appropriately.

When buying reliability, one is buying Mean Time Between Failure (MTBF). This is because the MTBF of the system, its subsystems, and the individual parts has a tremendous effect on the system reliability. This fact is underscored by the trends in Figure 3-14, which provide the reliability of a zero redundancy system for various arbitrary values of MTBF. As indicated, reliability is also a function of mission duration; the longer the mission, the less reliable a given system becomes.

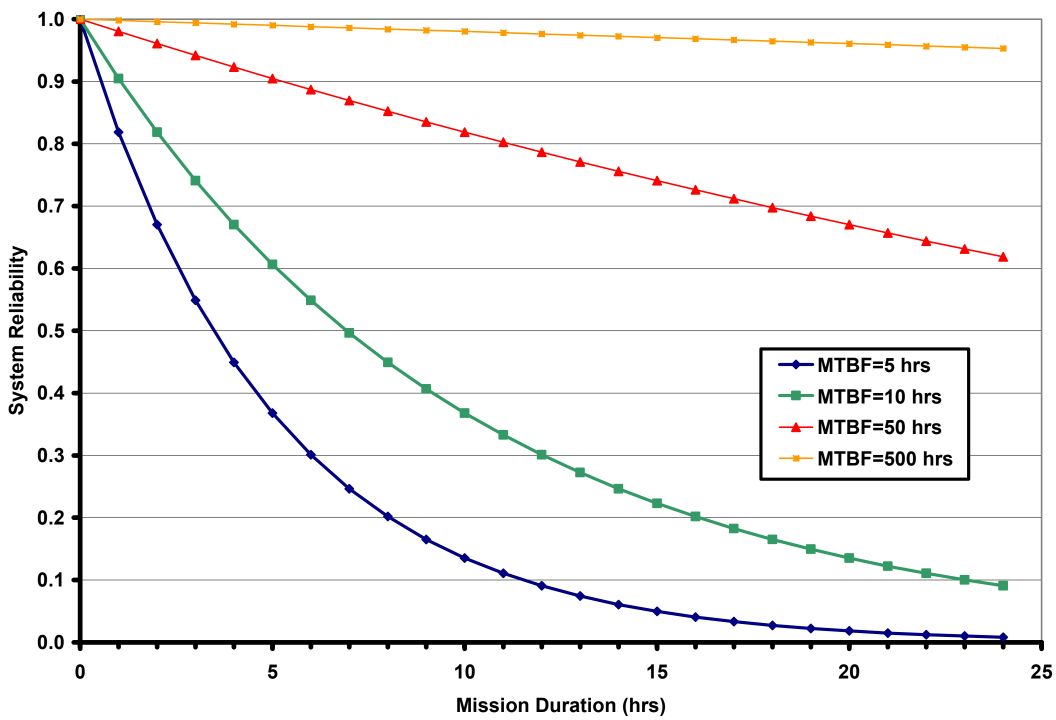


FIGURE 3-14: RELIABILITY FOR VARIOUS SYSTEM MTBF

For a given increase in MTBF, much smaller failure rates can be enjoyed. This notion is presented in Figure 3-15, which shows the probability of failure for given mission durations. Specific results for some UAVs are overlaid on Figure 3-15 based on their calculated MTBF values from Section 2.0.

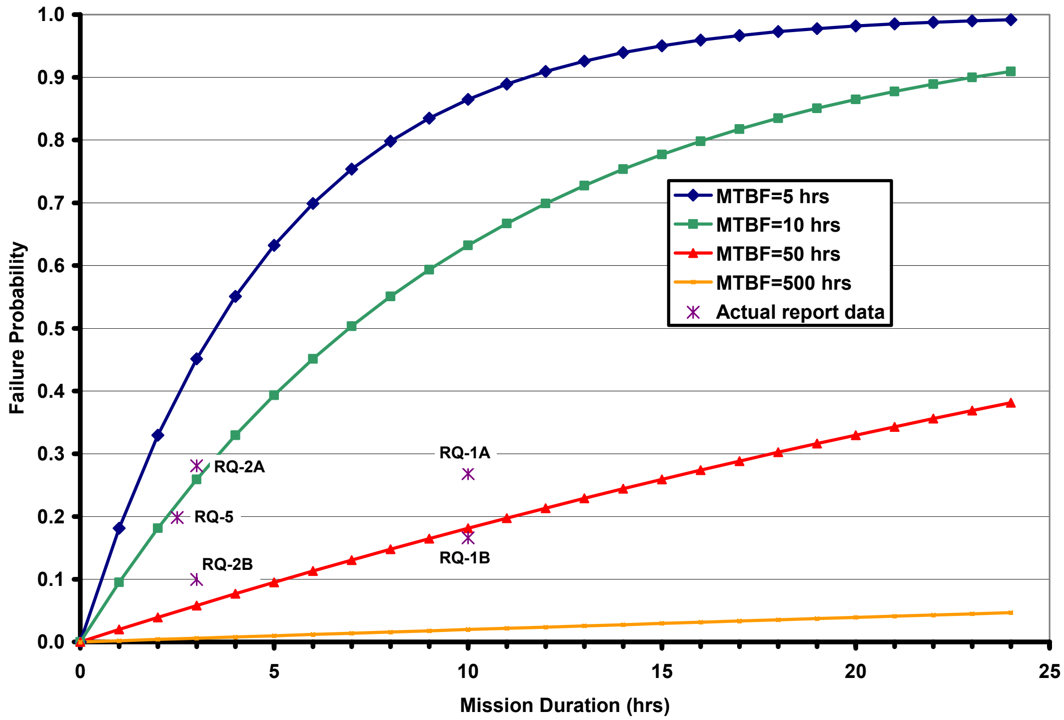


FIGURE 3-15: SYSTEM FAILURE PROBABILITY FOR VARIOUS MTBF

Within an individual subsystem, components may be aligned in a series layout such that the failure of one induces the failure of the entire series. Therefore, the individual reliability of each component in this "thread" contributes to the overall reliability of the subsystem, which affects the reliability of the UAV system. Table 3-8 provides an interesting look at how such threads can impact the system reliability. In discussing highly reliable systems, the reliability is often described by the number of "9's." For example, a system that fails 1 out of ten thousand times (R=99.99%) is said to have a reliability of four 9's.

TABLE 3-8: EFFECT OF COMPONENT QUALITY ON OVERALL SYSTEM RELIABILITY

Individual Component Quality	Number of Components per System	Overall System Reliability
Five 9's (99.999%)	10	Four 9's (0.99990000449988)
	100	Three 9's (0.99900049483834)
	1000	Two 9's (0.99004978424640)
Six 9's (99.9999%)	10	Five 9's (0.99999000004500)
	100	Four 9's (0.99990000494984)
	1000	Three 9's (0.99900049933385)
Seven 9's (99.99999%)	10	Six 9's (0.99999900000045)
	100	Five 9's (0.99999000004950)
	1000	Four 9's (0.99990000499487)

As can be seen, individual component qualities (i.e., their failure rates) can accumulate quickly so that, while one component has a reliability of 99.999 percent (one failure in 100,000), a larger system which uses 100 of them will only have a reliability of 99.9 percent (one failure in 1,000). Consequently, using sub-standard quality hardware in a single string system can lead to insufficient reliability, even if the component's advertised reliability is greater than 99 percent.

3.3.2 Redundancy

When faced with insufficient component quality, the addition of redundant threads is a common method for improving overall reliability, but at the expense of added complexity, weight, volume, power consumption, and cost. While redundancy usually improves mission reliability, it almost always has an adverse impact on logistic reliability, due to the requirement to stock more spare parts. Redundancy can be either active, in which all redundant items or systems are operated simultaneously whenever the system is active, or passive, in which the redundant items or systems are maintained in a powered down or standby mode until the primary means fails. Actively redundant systems, such as the multiple flight control computers in fly-by-wire aircraft, typically employ a voting scheme to constantly monitor each redundant thread's outputs and vote to ignore any out-of-tolerance performance. Figure 3-16 provides an example of how redundancy can lower the failure rate for a given system.

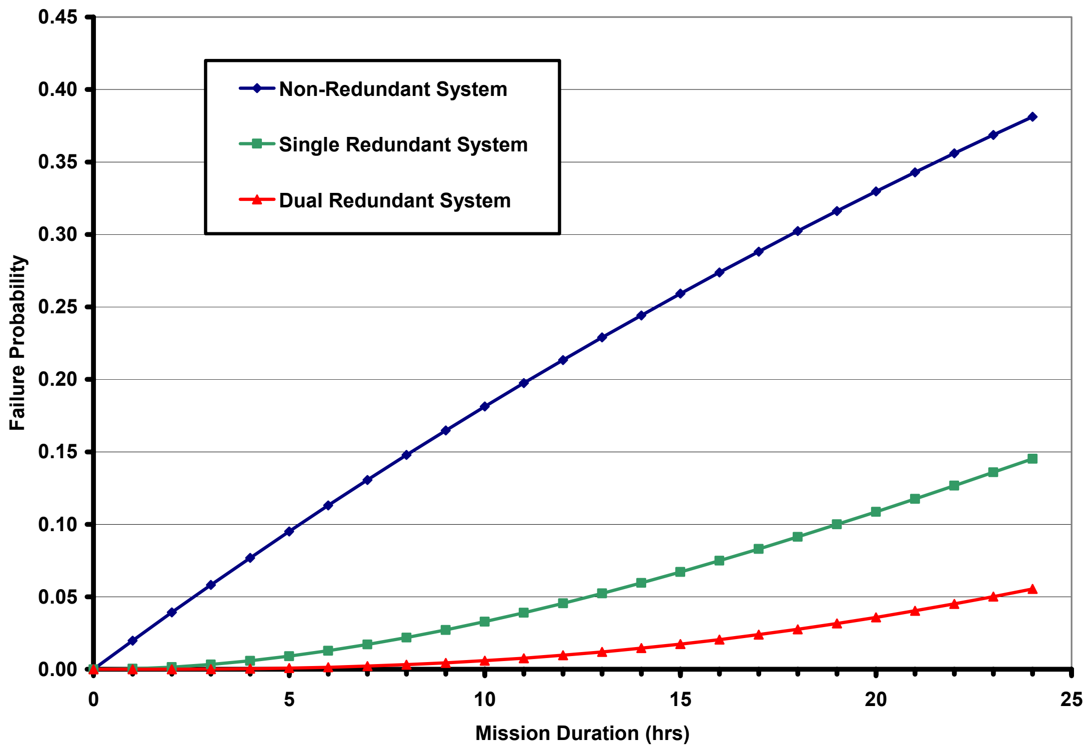


FIGURE 3-16: FAILURE PROBABILITY FOR VARIOUS SYSTEM REDUNDANCIES

The MTBF used for the calculations above was fixed at 50 hours *for each individual system*. This allowed for a variation of system redundancy to show the benefit of two or three identical, yet independent subsystems. For example, if one designs a given UAV flight control system with an MBTF equal to 50 hours, and the ORD specifies an average mission duration of 11 hours, one out of every five missions will fail. If a second flight control system is added for redundancy, that probability drops to one out of every 20 missions. Three flight control systems, such as that designed into the MQ-9, will drop the failure probability for a given mission to less than one in a hundred. (Note that the MQ-9 should have a better failure rate than this given that its flight control system MTBF will be higher than the 50 hours used in this example.)

3.3.3 New Component Technologies

When existing component quality and redundancy do not satisfy mission requirements, designers must look to emerging component technologies as a solution to reliability challenges. Table 3-9 provides various components' "weak links" and possible solutions for some major UAV subsystems.

TABLE 3-9: NEW COMPONENT TECHNOLOGIES

Area/Issue	Typical MTBO/MTBF	Primary Component Failure	Mitigation
Power/Propulsion			
Int. Combustion	250 hrs (Gas) 1000 hrs (Diesel)		
Turboprop	3500 hrs	Gearbox bearings	
Turbojet	5000 hrs		
Electric	30,000 hrs (Battery) 10,000-20,000 hrs (Fuel Cell)		Thermoelectric Generators
Communications			
Hardware	1000 hrs	1. Antenna drive 2. Power amplifier	Film Antennas ESA/μESA Environmental Control
Flight Control			
Hardware	2000 - 5000 hrs	Servos/Actuators	Self-Repairing "Smart" Flight Control System
Stability	N/A	N/A	Low Reynolds Number Research

In addition to making existing components better, research is underway which will offer more exotic solutions to existing hardware problems.

- Shape memory alloys could reduce or eliminate the need for servos and actuators.
- Biopolymers will leverage nature's design to create strong, lightweight structures resistant to fatigue.[11]

[11] For example, a spider's silk is 2-5 times stronger than steel by weight, 75% the weight of composites, and can stretch 30x its normal length.

- Autonomic (self-repairing) materials will mitigate structural issues that do arise during the mission.

Recommendation: Investigate the potential role of advanced materials and structures for enhancing UAV reliability and availability

In the following section, other advanced reliability-enhancing technologies – and more importantly, some practical solutions for use on today's UAVs – are presented that address the UAV failure modes discussed throughout this report.

4.0 Reliability Enhancing Technologies

Upcoming technologies have the promise of significantly improving the reliability of UAVs. Whether through direct subsystem improvements, weight savings which allow additional reliability enhancements to existing hardware, or cost-effective solutions which save R&D funds for more in-depth reliability analysis, UAV developers will have at their disposal numerous technical solutions, some of which are still in the 6.1 and 6.2 phases of development.

While some of these early technologies will not arrive in time to save the reliability woes of current generation UAVs, they will certainly be ready for integration into other UAVs that are well within the planning cycle of the Department of Defense. Even those technologies that are not fully mature present a unique opportunity for the UAV community; the UAV could emerge as the testbed-of-choice for advancing aerospace technologies. By supplanting manned aircraft in this role, UAV developers will be able to leverage the cutting edge technology it demonstrates rather than consistently playing "catch up" to the state-of-the-art.

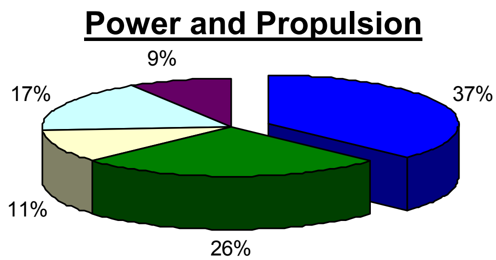
The following sections highlight a few of the promising commercial and government-off-the-shelf (COTS/GOTS) technologies/processes that could enhance UAV reliability. Summarized in Table 4-1, these current and developmental technologies are provided as examples of solutions which have the potential to address some of the major reliability shortcomings identified in this study. Technology areas for each of the major failure modes are presented at three levels of cost/complexity.

TABLE 4-1: TECHNOLOGIES TO ENHANCE UAV RELIABILITY

	Low Level COTS/GOTS	**High Level COTS/GOTS**	**Next Generation**
Power and Propulsion	Lighter Engine Blocks	Heavy Fuel Engine	Fuel Cell Technology
Flight Control	Better Component Selection Methodology	Advanced Digital Avionics Systems	Self-Repairing, "Smart" Flight Control Systems
Communications	Better Environmental Control	Electronically Steered Arrays	Film and Spray-on Antennas
Human/Ground	Enhanced Pilot Training	Auto Take-Off and Recovery	Enhanced Synthetic Vision

Recommendation: Incorporate the emerging technologies identified in Table 4-1 into the Defense Technology Objectives and the Defense Technology Area Plan

4.1 Power/Propulsion



Power and propulsion failures have been the primary cause of 37 percent of U.S. military UAV failures. Power generation onboard many UAVs parallels that on conventional aircraft in both method and specific power output, differing only by the total power output required to supply the onboard subsystems. In some designs, the power distribution is supplied by the same source as the propulsion: either a primary internal combustion engine (ICE), a secondary ICE known as an auxiliary power unit (APU), or a gas turbine engine. In other designs, the propulsion system receives, rather than generates, power from an unconventional source such as solar cells (Helios).

For most aircraft, the excess, non-propulsion power requirements to drive the hydraulic and electrical subsystems are orders of magnitude (10 to 1000 times) less than that required for propulsion. While this makes it relatively simple to calculate required subsystem power early in the design process, various problems including system inefficiencies, component reliability, and requirements creep can lead to further drains on the power available for propulsion. As a result, it is becoming more important to power/propulsion reliability that designs reduce reliance on "shared" or APU power sources, or even move away from these designs for more non-traditional power/propulsion solutions.

Payloads are also an important consideration when selecting the power subsystem of a UAV. Independent of whether the UAV has low power availability or simply high power demands, payload can present challenges to the design of this subsystem. Viewing UAVs as trucks on which various payload platforms may be carried, the required power for a payload may vary from less than 100 watts for a communications node or sensor to 10 kilowatts or more for electronic warfare or radar. Moreover, requirements and mission profiles may change from the initial design to the operational system as in the case of the Predator adding its Hellfire and laser designation capabilities.

Changing mission requirements – determining the amount of power required, the duration it must be supplied, and the peak power which must be delivered over short intervals – can also compromise performance and reliability. Even when requirements remain constant, this study indicates that in all the UAVs examined, power/propulsion issues have contributed to at least one out of four system failures. In the case of the RQ-2B/Pioneer, this contributor led to over half of the failures. To address these issues, the following section highlights some possible technologies and concepts that may alleviate the reliability deficiencies due to power and propulsion.

4.1.1 Lighter Engine Blocks

Previous experience with manned aircraft indicates exorbitant costs for new engine development; the effort to design a high-performance military aircraft engine from scratch can cost more than $1 billion. For even the most expensive of UAVs, this level of investment capital prices UAV manufacturers out of new engine development and into commercial-off-the-shelf (COTS) product lines. In some cases these COTS solutions are not an ideal fit, leading to budget-limited adaptations in which the quality control and reliability of the original product are not always maintained. In other cases, the engine selected was never intended to be placed in a flight operations environment.

New propulsion technologies must be pursued which will more appropriately fit the budgets of UAVs, and particularly those smaller vehicles that must be backpackable and offer high availability. By way of comparison, Table 4-2 shows typical costs for some highly reliable engine technologies.

TABLE 4-2: TYPICAL COSTS FOR VARIOUS PROPULSION APPLICATIONS

Propulsion Application	Typical Mission Duration	Approximate Cost Per Pound of Thrust
Cruise Missile Engine	1-6 hours	$150
Civilian Aircraft Engine	2-15 hours	$200
Military Aircraft Engine	3-10 hours	$400
Space Shuttle Main Engine	.14 hours	$500

A Boralyn molded engine block is one low-level COTS technology which can offer measurable relief from the high weights and lower wear-resistance associated with engine designs and manufacturing techniques. Boralyn is a boron carbide aluminum composite that is extremely light (6% lighter than aluminum). It boasts a specific-strength per unit mass greater than titanium, aluminum, or steel.

First designed for use on nuclear missiles, the technology has recently been declassified and made available to commercial industry. Applications in the transportation industry include engine components such as gears, drive shafts, pistons, rods, and valves. A Boralyn molded engine would also be extremely durable to regular wear. It offers at least twice the life as a cast-iron block engine. In these ways, savings and reliability may be found by reducing the number of parts and maintenance required to support engine operations and/or increase the engine lifetime. Because Boralyn molded engines may require higher initial investments for the engine design, however, trade studies would be prudent for each UAV design.

4.1.2 Heavy Fuel Engine

Currently, all non-turbine (i.e., internal combustion) UAV engines burn gasoline (Mogas or Avgas). Gasoline presents two problems in military operations. First, gasoline's higher volatility makes it a greater safety hazard than heavy fuels (diesel, JetA, JP5, etc.), especially aboard ships, due to its low flash point. Second, heavy fuels are the predominant fuels used in the field, so the need to carry gasoline in addition to diesel is a logistical burden and does not support the DoDD 4000 common fuel requirement. As a third consideration, gasoline has a lower unit energy than that of heavy fuel, meaning the specific fuel consumption (SFC) of a heavy fuel engine (HFE) can be made to exceed that of a gasoline one and thereby provide greater endurance for the same volume of fuel. The Shadow's AR 741 gasoline rotary engine has a cruise SFC of 0.52 lb/hp/hr, whereas the Deltahawk V-4 aviation diesel's is 0.39, implying this HFE could increase Shadow's endurance by one third.

Besides the safety, commonality, and fuel efficiency (SFC) aspects, HFEs offer advantages in cost, electromagnetic interference (EMI), operating simplicity, and durability.

- The RQ-7/Shadow's AR 741 engine has time-between-overhaul (TBO) of 250 hours, while that for aviation diesels is advertised at 1000 hours or more.
- CI-type diesel engines, lacking sparkplugs, naturally produce less EMI, reducing noise impacts on navigation, communication, and sensor systems.
- The lack of magnetos or electronic ignition promotes overall reliability. In addition, diesel engines, unlike gasoline ones, do not involve mixture control, so carburetors are not a factor and control inputs are simplified.
- Diesel and jet fuels, being more viscous than gasoline, naturally provide more lubricity during engine operation, which contributes to longer-lived engines.

When considering the use of HFEs for UAVs, the largest obstacle is the mass specific power. To maintain Shadow's current horsepower with a HFE, the engine weight would essentially double. To mitigate this, lightweight materials such as Boralyn (see Section 4.1.1) would be required.

4.1.3 Fuel Cell Technology

Fuel cell research and development is moving at a fast pace in numerous non-UAV related activities ranging from automobiles to the space program. Due to some requirements commonalities between these applications and various UAV mission profiles, the UAV design community should take note of the potential that fuel cell technology can offer. Early fuel cells were expensive, bulky, and heavy. In addition, because the process relies on the oxidation of hydrogen, fuel cell systems were limited by hydrogen production and storage problems.

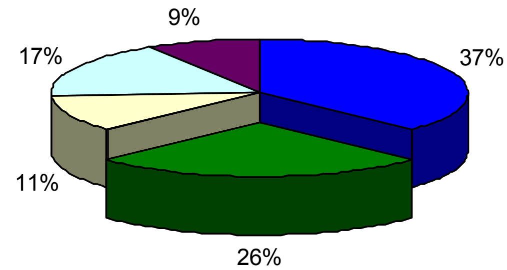
This is quickly changing, however, with fuel cell technology beginning to offer long endurance, highly efficient solutions for both power generation and storage. Additional improvements and strengths of fuel cell technology are highlighted below.

- The mass specific power (in horsepower per pound) is approaching the level of internal combustion engines.
- The sources of fuel are greatly expanded which include water (through electrolysis), hydrocarbons, and byproducts of existing petroleum processes.
- A very low noise level, which translates into higher stealth due to reduced acoustic signature.
- A very low vibration level that limits structural loading on the vehicle.

These benefits, coupled with the high reliability and reduced logistics of a system with fewer moving parts, are already attracting the attention of aerospace designers. Proof-of-concept electric aircraft in manned aviation are currently under development within DARPA and industry. Recent advances in electric motor technology, batteries, and composite structures are enabling these programs. With respect to upcoming long-duration UAV missions, fuel cells can provide power up to hundreds of kilowatts, accommodating a wide range of energy usage requirements as well as the durations over which it is to be delivered.

4.2 Flight Control

Flight control failures have accounted for 26 percent of U.S. military UAV failures. The single biggest differentiation between UAVs and manned aircraft is control. Removing the pilot from the aircraft and placing him/her on the ground, or in some cases designing for completely autonomous flight, raises numerous issues with respect to reliability. Pilots who fly can attest to the intangible, "seat-of-the-pants" feeling that assists them in controlling the aircraft from within the cockpit. In these cases, the flight control system, air data information, and other situational awareness aids are feedback for various pilot-induced control inputs.



Flight Control

Aircraft trim is an excellent example. When pilots sense that unnecessary force is required to maintain a specific aircraft attitude, they can adjust the trim to remain at that attitude or use this new sensory information to adjust to a new attitude which is more conducive to efficient flight. More importantly, the pilot can evaluate any change in flying qualities "on the scene" for other, more insidious causes. A UAV pilot does not have this ability, and as a result may inadvertently command the aircraft to fly in less than ideal conditions or miss early warning signs that might signal problems with the propulsion or flight control systems.

Operating UAVs beyond line-of-site (BLOS) can also introduce flight control issues. Communication time delays can lead to delayed control inputs that are sluggish or even detrimental to the vehicle's stability and control. As a result, UAVs rely heavily on robust flight control systems that are reliable, redundant, and intelligent enough to monitor or even anticipate problems with the air vehicle flight dynamics and controllability. The reliability of UAVs has in the past been highly dependent on flight control. Their future utility will hinge greatly on whether limitations of flight control technology can be managed by leveraging new technologies which address those limitations.

4.2.1 Better Component Selection Methodology

The small size of some UAVs moves their corresponding flight speeds and altitudes into more poorly understood low Reynolds number environments. Such flight environments challenge UAV control in part because the components were selected based more on their affordability than their quality. Such cost-based decisions can lead to inadequate performance, particularly during the more dynamic flight profiles of take-off and landing. As a result, the low-level solution to enable the goal of more reliable flight control systems is perhaps the most obvious: UAV designers must balance subsystem reliability with affordability.

For inexpensive systems, this suggests a necessary trade-off between increasing component quality and increasing system redundancy. In this subsequent choice between (1) a single-string system with high quality components and (2) a high-redundant system with mediocre components, experience from the Air Force Research Labs (AFRL) suggests that the former option usually yields the most favorable outcome. As a result, UAV systems should include the best components designed for the intended function, incorporating the operational costs for this component cost-benefit trade.

4.2.2 Advanced Digital Avionics Systems

Accurate information on the operating environment is critical to the flight control, if not the survivability, of UAVs. Without a pilot on board, for example, measuring vehicle sideslip, or the "crabbing" of the vehicle into crosswinds during flight, can be difficult to gauge. The vehicle state information provided by normal analog pitot-static probes can offer insufficient fidelity or be corrupted by contamination or freezing of the probe, providing erroneous data to the flight control system. In addition, the planned storage, unpacking, and re-storage of some UAV systems increases the likelihood that a component of an analog air data system could be damaged. This damage may or may not be detected before take-off.

Digital flight control can offer highly integrated UAV flight avionics that contain GPS, a digital central processing unit, and an inertial measurement unit which has the capability to control the air vehicle's flight and engine operations, navigation, guidance, and payload operations. Digital air data systems can incorporate readings from multiple locations on the air vehicle, offer redundancy without an increase in moving parts, and process data with algorithms tailored to various phases of flight. Systems can provide reliable information on airspeed, angle of attack, and angle of sideslip. This in turn can reduce the structural loading of the vehicle, improve overall flying qualities, and compensate for fluctuating wind conditions during the dynamic launch and recovery portions of flight.

The RQ-2B/Pioneer is an example of the reliability dividends of a digital avionics system. When the digital Modular Integrated Avionics Group (MIAG) on the RQ-2B replaced the analog version on the RQ-2A (the primary distinguisher between the two), the flight control failures were cut in half from 29 to 15 percent.

4.2.3 Self-Repairing, "Smart" Flight Control Systems

Sponsored by the U.S. Air Force, the Self-Repairing Flight Control System (SRFCS) lays promising groundwork to address the large quantity of flight control related errors noted in this report. The SRFCS is revolutionary flight control software that must be integrated into the system to augment the existing flight control capabilities. When a damaged or malfunctioning component is detected, the SRFCS adjusts the operation of the flight control system by compensating with the remaining operational flight control surfaces. This has been demonstrated on an F-15 aircraft at Dryden Flight Research Center.

The test flights demonstrated that the effect of losing individual flight control hardware, which often leads to total vehicle loss, could be mitigated through the use of an integrated control system. In addition, the UAV pilot can be notified of such in-flight failures near-real time, allowing the operator to act accordingly given the operating environment, mission requirements, and new aircraft performance capabilities. The SRFCS also has the capability to diagnose malfunctions in electrical, hydraulic, and mechanical failures.

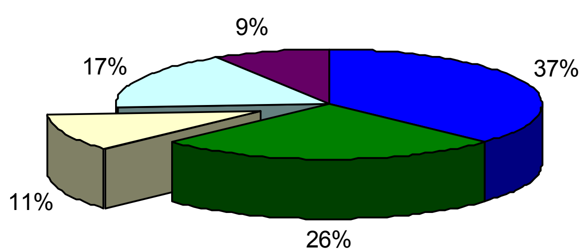
One should note that the SRFCS integration into the F-15 test aircraft was relatively inexpensive due to an existing digital control system. While integration of such a system into the control architecture of smaller UAVs may prove prohibitively expensive, an SRFCS-type system may be a highly desirable solution to the nearly 1 out of 4 failures in the Predator due to flight control.

As a component of the flight control system, actuators also contribute to the subsystem unreliability. Smart aircraft control actuators offer an advanced method to address these flight control issues. Traditional servo actuators in fly-by-wire systems do not contain control electronics. Used both in military and commercial flight systems, these servo actuators are controlled by separate flight control computers. As a result, a significant amount of dedicated wiring is required to control each aircraft actuator. This, in turn, can increases maintenance costs, lower reliability, and create vulnerability to electromagnetic interference (EMI). Given the use of UAVs in the Naval ship based environment, the latter is a particular concern.

The Smart Actuator concept is a device that contains two independent electronic channels that perform actuator control, fault monitoring, and redundancy management. Fiber optics replace the wiring as the communication medium, and in tests was found to enhance reliability and maintainability. Work begun by the U.S. Air Force and Navy on larger aircraft has shown positive results. Flight testing on an F-18 aircraft demonstrated exceptional results, and in particular, proved that "local" control of servo actuators is possible. The Smart Actuator was virtually transparent to the existing flight control system, yet provided critical aircraft state information to the aircraft's instrumentation system. Such improvements could mitigate maladies as those seen in the Hunter UAV in 1995 (Section 2.1.3).

4.3 Communications

Communication failures have been the primary cause of 11 percent of U.S. military UAV failures. The consequences resulting from a loss-of-signal with a UAV can range from mission abort and return to base to complete loss of the air vehicle. To insure against this problem, engineering efforts in data link technology have elevated the MTBF of typical data links up to 1,000 hours. Further examination of the failure modes for data links reveals that the largest contributor to communication failures is antenna drive malfunctions, followed by those of the power amplifier.



Communications

While communication technology itself is advancing rapidly, many times communication performance is only as good as its platform. Factors inherent to UAVs (e.g., sudden attitude changes, power limitations, and the need for a low observable design) can work against the communications system. This can lead to decreased signal strength, degraded signal quality, or complete loss of communication with the ground. The following sections present some reliability enhancing technology options which could reduce the share of failures due to communication problems.

4.3.1 Better Environmental Control

The power amplifier accounts for the second largest portion of communication system failures. Although the Predator, Pioneer, and Hunter use solid state amplifiers which typically have good reliability, they (and other components) are still susceptible to environmental loads. As experienced with the Predator, operating temperatures encountered by some components do not always remain between 0 and 70^{o} C. At high altitudes and in other harsh environments, a UAV's components may be operating in temperatures which vary from -55 to 85^{o} C. This presents challenges to even the most robust components.

With the move away from MIL standard parts toward COTS components, design requirements such as cost, size, and weight can begin to take precedence over robustness to make these environments even more intolerable. Environmental control of sensitive components will help to address this. Relatively inexpensive heaters and fans can be implemented to help stabilize the components' operating environment. Implementation of this hardware on those UAVs which require it may marginally increase their weight and cost; as with most reliability enhancements, trades will have to be made based on cost-benefit analysis.

4.3.2 Electronically Steered Arrays

Electronic steered arrays (ESAs) eliminate the antenna drive as a failure mode by replacing the mechanical rotation of the antenna hardware (in order to ensure maximum signal strength from the UAV). ESA "steers" the beam to allow the moving UAV to track or be tracked by the ground station without mechanical movement.

The concept of beam scanning is based on this idea. By using a phased array to shift from one array element to the next, a beam can be pointed in a direction dependent on the phase shift. Advantages which impact UAV reliability include

- Higher tracking speeds and better tracking accuracy
- Fewer mechanical parts and less parts degradation
- A redundant, independent navigation input onboard the UAV (beam scanning can be used to determine azimuth and range to the ground station, even in LOS)
- An estimated lower price (in large quantities) than mechanical systems

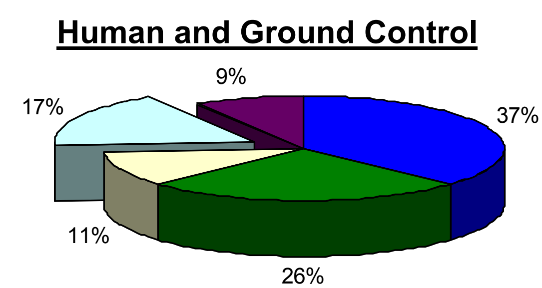
4.3.3 Film and Spray-on Antennas

Film and spray-on antennas are under development to offer a covert, lightweight, low power, broadband (2000 MHz) RF antenna. The experimental technology, one version of which would be transparent, involves a thin film of conductive substance applied to the surface of the aircraft. The paints, currently used for electromagnetic interference (EMI) shielding, will be able to transmit and receive RF signals when sprayed over a specific template and attached to an RF source.

By replacing dishes and gimbaled mountings, this advanced antenna technology will also reduce the weight of the UAV or allow for the integration of additional redundant systems. It will reduce electromagnetic interference by providing a single antenna for multiple functions (e.g., radio, data link, GPS, IFF), and eliminate blanking sectors of traditional antennas. Beyond the technical hurdles of this advanced technology, potential issues relating to degraded stealth and airframe construction must be addressed with sensitivity to the intended UAV mission profile.

4.4 Human Factors/Ground Control

The results of this study indicate that human and ground control related issues accounted for 17 percent of all system failures. This is compared to a generally accepted value of 85 percent for the aggregate of manned aircraft, as noted in Section 3.1.3. This is intuitive when one considers that by reducing the influence of human control in UAVs, the percentage of human related errors would also decrease.



Assuming that human error is consistent over similar tasks, one could even argue that human influence in unmanned vehicles is approximately 70 percent less (85%-17%) than that in piloted vehicles, even when the UAV has a remote pilot on the ground. This difference could be attributed to a different approach to the human factors issue as well as increased automation of tasks for UAVs. While this theory requires further investigation, a second, more likely explanation for the difference is that human error does remain constant between most UAVs and manned aircraft, and that in the case of UAVs, it is simply overshadowed by the high unreliability of the other subsystems.

The second theory is also supported by experience with operational and developmental UAV systems, which indicates that the human-machine synergy is much more challenging when the human is on the ground. This integration is even more difficult than anticipated because original expectations were based on the fact that a great deal of automation already exists on many manned aircraft systems. In the case of these systems, much of that automation can be overridden by a situationally-aware on-board pilot. When that decision-making capability is on the ground, however, the human-override versus complete autonomy choice raises questions as to which method is the best to implement. One example at the center of this argument arose over whether to allow a UAV to autonomously follow the resolution advisories from a Traffic Alert and Collision Avoidance System (TCAS).

Underscoring the above discussion is the simple fact that a UAV will always lack the on-board subsystem upon which most aerospace vehicles rely: the pilot. With the pilot removed from the vehicle, UAVs must depend upon (1) complete automation, (2) direct control from a human on the ground, or (3) some balance of the two in order to conduct a reliable mission with the appropriate levels of situational awareness. The following technologies and concepts illustrate various methods to increase the situational awareness as well as ensure safe operations in the air and from the ground.

4.4.1 Enhanced Pilot Training

To assess the benefit of training (e.g., classroom based, simulator based, etc.), a recent study examined aviation accidents from 1987 through 1997 involving manned aircraft. It was discovered that out of 1,400 accidents involving 13 models of commercial and general aviation aircraft, the pilots who received enhanced training were 80 percent less likely to be involved in an accident. Furthermore, the data from this 10 year period indicated that only about 20 percent of high-risk emergencies and maneuvers could be practiced in the actual flight environment. The remaining 80 percent (e.g., engine failure on take-off, inclement weather emergencies, stalls and spins, etc.) are too dangerous to train in real circumstances.

These facts present strong evidence that similar training would benefit the UAV pilot community. For example, the benefit of training is credited with the favorable reduction in the percentage of human and ground related errors between the RQ-1A and the RQ-1B (16 percent to 2 percent). Such training could also be done in a cost-effective way. Whereas in the manned aircraft world costly, high-fidelity simulators must be built to emulate the aircraft environment, most UAV systems are already suited for a realistic pilot training regimen through the existing ground station. For smaller UAVs with less complex ground terminals, enhanced training may simply involve an increased understanding of the UAV system's capabilities, its aerodynamic qualities, and the best ways in which to anticipate and mitigate devastating environmental and external factors.

4.4.2 Auto Take-Off and Recovery

Automatic launch and recovery operations provide risk reduction for the two most dynamic portions of a UAV's flight profile. By eliminating the need for an external pilot, this technology helps ensure accurate guidance and control and thus reduces the high mishap rates associated with the UAVs examined in this study.

This problem was so prevalent with the Pioneer that Marine commanders specifically noted the requirement for auto take-off and recovery in future UAV systems. On a shipboard environment, this is particularly important given the wide range of lighting, precipitation, and sea states. Auto take-off and recovery also reduces the need for pilot training and helps enhance system availability. The two most notable auto take-off and recovery systems on UAVs are the UCARS (Hunter) and TALS (Shadow).

4.4.3 Enhanced Synthetic Vision

Developments in UAV flight control continue to distance the pilot from basic aircraft control responsibility, moving them toward a systems management role. Most current, and virtually all future, UAV programs build autonomy into the air vehicles, making real time input by the UAV operator largely unnecessary. The requirement to maintain situational awareness, however, retains its historical importance with respect to safe and effective operation of the aircraft. Since the UAV pilot does not sit in the cockpit, situational awareness becomes more challenging to maintain for UAV crews.

Current UAV sensors have extremely narrow fields of view. Operating EO and SAR sensors has often been compared to looking at the world "through a soda straw." This narrow field of view makes it difficult for operators to maintain situational awareness with regard to desired collection targets, surrounding obstacles, and weather. Furthermore, appropriate control and performance information is presented to the UAV operator on a conventional computer display.

Enhanced synthetic vision (ESV) technology will help UAV operators maintain flight and sensor perspective by combining real and virtual images into one single display. By seamlessly stitching the received images from a UAV sensor onto a virtual background of the operator's choosing, the payload operator maintains sensor perspective, contributes to more efficient use of the sensor, and decreases the time required to define a target. In this way, ESV technology can be implemented in UAV GCS workstations to help increase the UAV reliability.

The ability to embed UAV sensor video into three dimensional map displays, in addition to information such as flight control, propulsion, and communications system status, can provide the UAV pilot with an expanded, up-to-date perspective to ensure safe and effective UAV flight. For example, enhanced synthetic vision would lend itself readily to Global Hawk operations if it were to be implemented into the system. The Global Hawk sensors, like most optical sensors, have a narrow field of view. Overlaying the sensor images on a synthetic environment would help improve situational assessment/awareness and the reliability for missions in progress. Specifically, it would augment the EO/IR imagery to include enroute threats, weather, sensor operations, and health monitoring of the entire air vehicle. ESV technology would also reduce potential mishaps by augmenting the pilot's duty to see and avoid other traffic.

Recommendation: Perform cost-benefit trades for low and high level COTS/GOTS approaches identified in the preceding sections to improve reliability for each fielded UAV system[12]

[12] For further and more detailed information on UAV enabling technologies such as those presented in Section 4.0, refer to *Uninhabited Air Vehicles: Enabling Science for Military Systems,* a study from the National Research Council (Publication NMAB-495).

5.0 Recommendations

Based on the preceding reliability data and trends analysis, it is possible to distill a focused set of recommendations which will have a measurable impact on UAV reliability growth. The page number on which these recommendations were introduced is provided.

R-1 Introduce joint standardization of reliability data tracking for operational UAV systems (page 3)

Data collection for this study provided insight into an inconsistent (and at times inaccurate and incomplete) reporting framework for tracking the reliability growth of various UAV fleets. This makes it particularly difficult to gauge not only the reliability of one system, but also any trends across system and Service lines. A single format, with jointly agreed definitions for data fields for key reliability metrics for UAVs, needs to be developed and implemented.

R-2 Perform a cost-benefit trade study for incorporating/retrofitting some or all of the Predator B's reliability enhancements into production Predator A models (page 10)

R-3 Perform cost-benefit trades for low and high level COTS/GOTS approaches identified in Table 4-1 to improve reliability for each fielded UAV system (page 57)

R-4 Develop and implement a Reliability Specifications Standard for UAV design (page 39)

Design changes can cost 1,000 and 10,000 times more at the LRIP and final production phases, respectively, than the same change would during product design. As a result, cost increases at the early stage for reliability downstream can in most cases be justified.

R-5 Incorporate the emerging technologies identified in Table 4-1 into the <u>Defense Technology Objectives</u> and the <u>Defense Technology Area Plan</u> (page 47)

R-6 Encourage/pursue more research into low Reynolds number flight regimes (page 38)

Just as UAVs come in many categories, so too do the flight environments in which they operate. As a result, flight in low Reynolds number regimes must be better understood to provide insight into such areas as (1) steady and unsteady flow effects, (2) three-dimensional laminar/turbulent flow transition, and (3) ideal airfoil and wing geometries at Reynolds and Mach numbers which encompass the spectrum of UAV flight profiles.

Small digital flight control systems (and compatible actuators) are under development which will enhance the controllability of small UAVs. Such systems are increasingly more lightweight and affordable and should be examined. Investments in low Reynolds number engine components are also critical. Turbomachinery for UAVs at low speeds or high-altitudes face flight *environments which are different than those to which modern propulsion has traditionally catered. Heat rejection, turbine and compressor tip losses, and low dynamic pressures are a few of the factors which can degrade the performance of a small propulsion system at these low Reynolds number conditions.*

R-7 Investigate the potential role of advanced materials and structures for enhancing UAV reliability and availability (page 45)

High temperature materials and light-weight structures can offer significant weight savings for UAV airframes. On the horizon, "smart" materials such as shape memory alloys will offer alternatives to the servos, flight control surfaces, and even de-icing systems of existing aircraft designs, which in turn will reduce components count and increase reliability.

R-8 Analyze the costs and benefits of all weather capability against mission requirements to design UAVs accordingly (page 33)

Icing has been a primary factor in two Hunter mishaps and three Predator losses. UAV cold weather tolerance, as well as operation in precipitation and suboptimal wind conditions, should be a focus for UAV designers in order to enhance their availability and reliability during real-world operations.

6.0 Conclusions

This study has addressed three fundamental questions concerning military UAVs from a common perspective for the first time:

1. How reliable are the UAVs that the DoD operates? (see Section 2.0)
2. What are the reasons for their lack of reliability, and how does it compare to that of other UAVs and manned aircraft? (see Section 3.0)
3. What can be done to improve their reliability? (see Sections 4.0 and 5.0)

The “common perspective” used in addressing question 1 comes from using the same set of reliability equations (Appendix D) across all systems' data instead of relying on the Services' differing methods of measuring UAV reliability (Appendices A, B, and C). The need to standardize on one joint format for reporting and assessing UAV reliability is one recommendation resulting from this study.

In addressing questions 2 and 3, general answers, drawn from the collective data gathered on all the UAVs examined, are provided. System-specific answers are the responsibility of each Service's program office for that system. They have the final responsibility for balancing the up-front cost of making a given reliability improvement against its projected return in value over the system's remaining lifetime. Casting Pioneers as "interim" systems and not considering Hunters to be "operational" ones throughout their service lifetimes has impacted reliability investments in them due to their “life-cycle completion” always being just around the corner.

The traditional methods of enhancing reliability – reducing complexity (i.e., component count) and/or improving quality (i.e., better component quality assurance) – produce conflicts in UAV development. The *simpler* designs (Hunter compared to Predator, Pioneer compared to Hunter) are also the smaller ones, yet they tend to exhibit *poorer* reliability. Several factors contribute to this, including environmental factors. The need to design in compensation for such factors (weather tolerance, low Reynolds number aerodynamics, etc.) forms the basis for a number of this study's recommendations.

Improving component quality to achieve overall system quality improvement, while certainly a positive factor in Hunter's rise from its unreliability in 1995, means higher priced components. This runs head-on into prevailing expectations that UAVs are (or should be) more affordable versions of manned aircraft. The cost of a reliable system – manned or unmanned – designed for a particular role is essentially the same; it is in operating and maintenance costs over the system's lifetime that a cost advantage may accrue to the unmanned aircraft.

In summary, improving UAV reliability is the single most immediate and long-reaching need to ensure their success. Their current levels of reliability impact their operational utility, their acquisition costs, and their acceptance into airspace regulations. The value of making reliability improvements must be weighed against not only acquisition cost, as is traditionally done, but also against the less quantifiable returns to be gained by a commander. As a critical resource to the commander, UAVs must be available when they are called upon and have the ability to operate freely and respond quickly in any airspace. The recommendations of this study are structured to ensure that this occurs.

Appendix A: U.S. Army UAV Reliability Definitions

MTBF = HOURS / FAILURES

Failure Rate = 1 / MTBF

1 hour divided by MTBF

SYSTEM Failure Rate $= (1/MTBF_{AV})+(1/MTBF_{GCS})+(1/MTBF_{MMP})+(1/MTBF_{LRE})+(1/MTBF_{GDT})+(1/MTBF_{MPS})$

SYSTEM MTBF = 1 / Failure Rate of System

MTBF hours divided by failure

(F) = Failure Rate

Adding all failure rate hours

SYSTEM MTBMCF =

$$1/F_{MPS}+(7/18)(F_{GCS}+F_{GDT})+(25/36)(F_{MMP}+F_{AV})+(1/9)F_{LRE}+F_{MSE}$$

$$Ao = 1- \frac{OT(MTTR+ALDT)}{TT(MTBMCF)}$$

formula

MTBMCF is what's calculated above

LEGEND:

MTBF = Mean Time Between Failures
MTBMCF = Mean Time Between Mission Critical Failures
F = Failure Rate
OT = Annual Mission Operating Hours
MTTR = Mean Time to Repair
TT = Total Hours in a Year
ALDT = Admin. & Logistics Downtime

FIGURE A-1: HUNTER SYSTEM RELIABILITY ASSESSMENT

Appendix B: U.S. Navy UAV Reliability Definitions

Equipment in service (EIS) is the number of hours that a given vehicle is in service in a month.

Non-mission capable-maintenance (NMCM) defines the percent of EIS that the vehicle is down due to maintenance.

Non-mission capable-supply (NMCS) is the percent of EIS that the vehicle is down due to supply related issues.

Mission capable (MC) conveys the percent of EIS that the vehicle is not NMCM or NMCS,

$$MC = 100 - NMCM - NMCS$$

Partial mission capable – maintenance (PMCM) is the percent of EIS that the vehicle is air worthy but not fully mission capable due to pending maintenance. Examples include a faulty catch release mechanism or a broken sensor

Partial mission capable-supply (PMCS) describes the percent of EIS that the vehicle is air worthy but not fully mission capable due to pending supplies.

Full mission capable (FMC) is the percent of EIS that the vehicle has full mission capability,

$$FMC = 100 - NMCM - NMCS - PMCM - PMCS$$

Appendix C: U.S. Air Force UAV Reliability Definitions

FORMULAS FOR LOGISTICS - QUALITY PERFORMANCE MEASURES

MC Rate

$$\frac{\text{FMC Hrs} + \text{PMCB Hrs} + \text{PMCM Hrs} + \text{PMCS Hrs}}{\text{POSSESSED Hrs}} \times 100$$

TNMCM Rt.

$$\frac{\text{NMCM Hrs} + \text{NMCB Hrs}}{\text{POSSESSED Hrs}} \times 100$$

TNMCS Rt.

$$\frac{\text{NMCS Hrs} + \text{NMCB Hrs}}{\text{POSSESSED Hrs}} \times 100$$

CANN Rt.

$$\frac{\text{\# Of Acft To Acft Canns} + \text{\# Of Engine To Acft Canns}}{\text{TOTAL SORTIES FLOWN}} \times 100$$

Code 3 Break Rt.

$$\frac{\text{\# OF SORTIES WITH CODE 3 LANDING STATUS}}{\text{TOTAL SORTIES FLOWN}} \times 100$$

4 Hr FIX Rt.

$$\frac{\text{\# OF CODE 3 BREAKS FIXED WITHIN 4 HOURS AFTER LANDING}}{\text{TOTAL CODE 3 BREAKS}} \times 100$$

8 Hr FIX Rt.

$$\frac{\text{\# OF CODE 3 BREAKS FIXED WITHIN 8 HOURS AFTER LANDING}}{\text{TOTAL CODE 3 BREAKS}} \times 100$$

12 Hr FIX Rt.

$$\frac{\text{\# OF CODE 3 BREAKS FIXED WITHIN 12 HOURS AFTER LANDING}}{\text{TOTAL CODE 3 BREAKS}} \times 100$$

Total Abort Rt. (Include Only MX, OPS & SUPPLY Aborts)

$$\frac{\text{\# AIR ABORTS} + \text{GROUND ABORTS}}{\text{TOTAL SORTIES FLOWN} + \text{GROUND ABORTS}} \times 100$$

Air Abort Rt. (Include Only MX & OPS Aborts)

$$\frac{\text{\# AIR ABORTS}}{\text{TOTAL SORTIES FLOWN}} \times 100$$

Ground Abort Rt. (Include Only MX, OPS & SUPPLY Aborts)

$$\frac{\text{\# GROUND ABORTS}}{\text{TOTAL SORTIES FLOWN} + \text{GROUND ABORTS}} \times 100$$

Avg Sortie Dur.

$$\frac{\text{HOURS FLOWN}}{\text{SORTIES FLOWN}}$$

Sortie UTE Rt.

$$\frac{\text{SORTIES FLOWN}}{\text{AUTHORIZED ACFT}}$$

Hourly UTE Rt.

$$\frac{\text{HOURS FLOWN}}{\text{AUTHORIZED ACFT}}$$

FSE Rate

$$\frac{\text{TOTAL SORTIES SCHEDULED} - \text{TOTAL DEVIATIONS}}{\text{TOTAL SORTIES SCHEDULED}} \times 100$$

Rep/Rec Rt.

$$\frac{\text{TOTAL REPEATS} + \text{TOTAL RECURS}}{\text{PILOT REPORTED DISCREPANCIES}} \times 100$$

Appendix D: Governing Equations

The following equations were compiled from various reliability documents used by the military, industry, and academia. They define the "common measure" by which the various raw data were reduced to yield the reliability data in this report.

Mishap Rate (MR)

$$MR = \frac{\#\,Class\ A}{\#\,Flt\ Hrs}\,x\,100{,}000\,hrs$$

Availability (A)

$$A = \frac{\#\,Flt\ Hrs\ Flown}{\#\,Flt\ Hrs\ Sched}$$

Mean Time Between Failure (MTBF)

$$MTBF = \frac{\#\,Flt\ Hrs\ Flown}{\#\,Mx\ Aborts\ and\ Cx}$$

$$MTBF = \frac{1}{Failure\ Rate}$$

Mission Reliability (R)

$$R = 1 - \frac{\#\,Mx\ Aborts}{\#\,Sorties\ Launched}$$

$$R(t) = e^{-(\lambda t)}$$

where λ *= Failure Rate*
t = Period of Interest (mission duration)

Mean Time to Repair (MTTR)

$$MTTR = \frac{Sum\ of\ repair\ time}{\#\,repair\ activities}$$

Appendix E: U.S. Military UAV Raw Data

MISSION DATA

Vehicle	Year	Flights	Cum Flights	Flight Hours	Cum Flight Hours	Class A Mishaps	Cum Class A Mishaps	Hours Sched	Cum Hours Sched	Mx Aborts and Cnx	Cost w/out sensors ($M)
RQ-1 / Predator	1991	0	0								2.4
	1992	0	0								
	1993	0	0								
	1994	54	54	168	168	0	0				
	1995	395	449	1859	2027	1	1				
	1996	601	1050	2627	4654	1	2			0	
	1997	583	1633	2752	7406	3	5			0	
	1998	1091	2724	5194	12600	0	5			127	
	1999	1603	4327	9138	21738	2	7			165	
	2000	1836	6163	11678	33416	1	8			196	
	2001	1299	7462	10348	43764	4	12	5169.4	5169.4	247	
	2001.75	1137	8599	9981.4	53745.4	5	17	4135.8	9305.2	128	
RQ-2 / Pioneer	1986			96	96	9	9				0.65
	1987			431	527	5	14				
	1988			989	1516	8	22				
	1989			1295	2811	5	27				
	1990			1339	4150	11	38				
	1991			1084	5234	3	41				
	1992			1132	7672	0	41				
	1993			1268	8940	0	41				
	1994	862	862	1568	10508	9	50				
	1995	692	1554	1752	12260	1	51				
	1996	614	2168	1557	13817	7	58				
	1997	1089	3257	2077	15894	3	61				
	1998	1138	4395	1973	17867	0	61			153	
	1999	1225	5620	2247	20114	12	73	2000	2000	39	
	2000	861	6481	1269	21383	3	76	1500	3500	128	
	2001	679	7160	1091	22474	1	77	1400	4900	60	
	2001.5			520	22994	0	77	1200	6100		
RQ-5 / Hunter	1991	126	126	224.8	224.5	2	2				1.2
	1992	221	347	741.2	965.7	0	2				
	1993	110	457	399.6	1365.3	2	4				
	1994	275	732	925.9	2291.2	1	5				
	1995	465	1197	1234.9	3526.1	4	9				
	1996	417	1614	1171	4697.1	0	9	1266	1266	146	
	1997	559	2173	1964.4	6661.5	0	9	2193	3459	327	
	1998	479	2652	1349.2	8010.7	1	10	1443	4902	142	
	1999	1166	3818	5224.4	13235.1	2	12	5414	10316	746	
	2000	968	4786	3749.5	16984.6	0	12	4543	14859	214	
	2001	881	5667	3078.2	20062.8	0	12	3132	17991	156	
	2001.75		6146		21754	0	12			0	

Appendix F: Flight Environment Comparison

Reynolds number helps to describe the flight environment of a given aircraft, or how the control surfaces "see" the aerodynamic flow about the aircraft. The following exercise illustrates the vast difference in the flight environments of two typical aircraft, one manned and one unmanned. By doing so, it underscores the need to better understand low Reynolds number flight regimes.

To illustrate how disparate the flight environments can be between a high cost, high reliability aircraft (in this example, a Boeing 777) and a low-cost, lower reliability UAV (a RQ-2/Pioneer), one need only ask "How must the flight profile of either aircraft change in order to match the Reynolds number of the other?" In the case of the Pioneer, it must fly at Mach 2.9 in order to reach the cruise Reynolds number (and better understood flight environment) of the Boeing 777 (B777). Figure F-1, a plot of Reynolds number as a function of altitude and speed, depicts graphically the insurmountable "hill" that the Pioneer would have to climb to reach the Boeing 777 Reynolds number value.

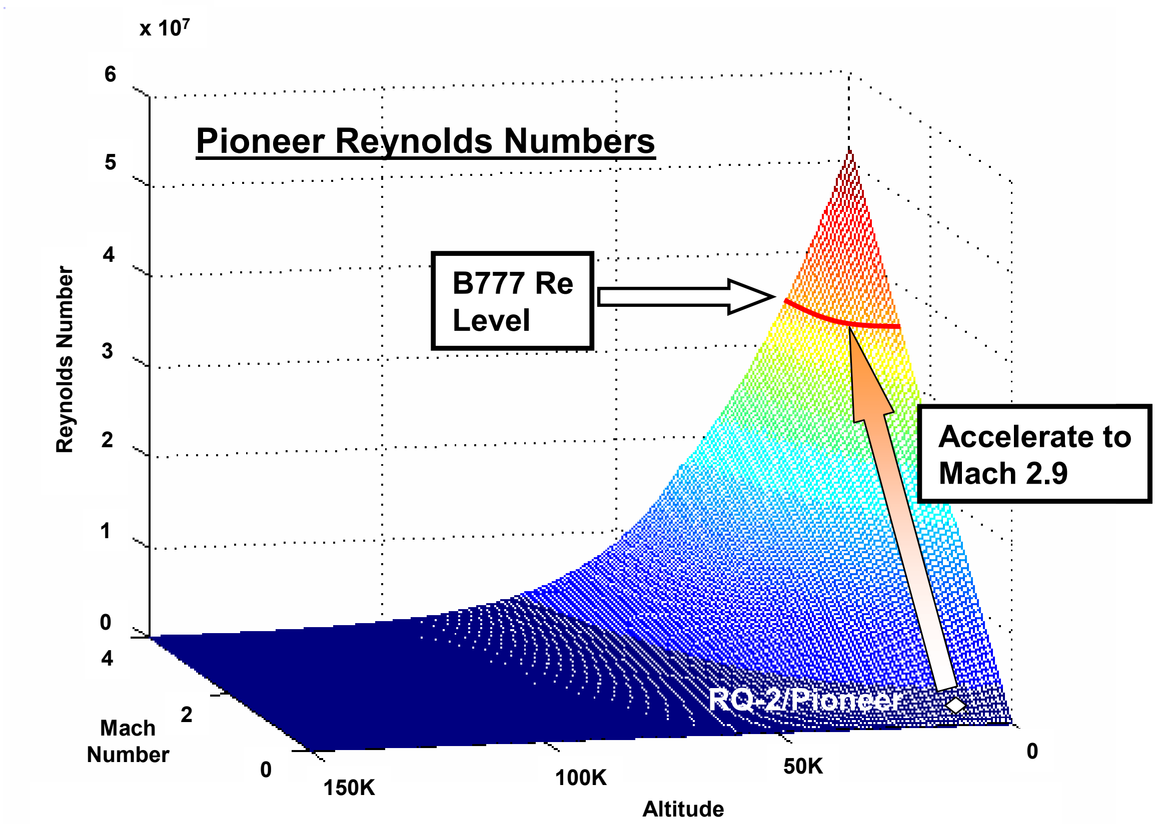


FIGURE F-1: REQUIRED PIONEER VELOCITY CHANGE TO REACH BOEING 777 REYNOLDS NUMBER LEVELS

Even if one *does* enhance the propulsion and structural integrity of a Pioneer-sized aircraft to fly at Mach 2.9, the related high-speed aerodynamics essentially moves the UAV from one extreme of the controllability spectrum to another. Simply put, there is no way to fly the smaller Pioneer at the much better understood Reynolds number of the faster, more expensive, and more reliable aircraft. Additionally, this point is also illustrated in the counter example with the Boeing 777. Figure F-2 presents the required changes in the Boeing 777 flight profile in order for its aerodynamic surfaces to "see" the atmosphere from the more challenging perspective of the Pioneer.

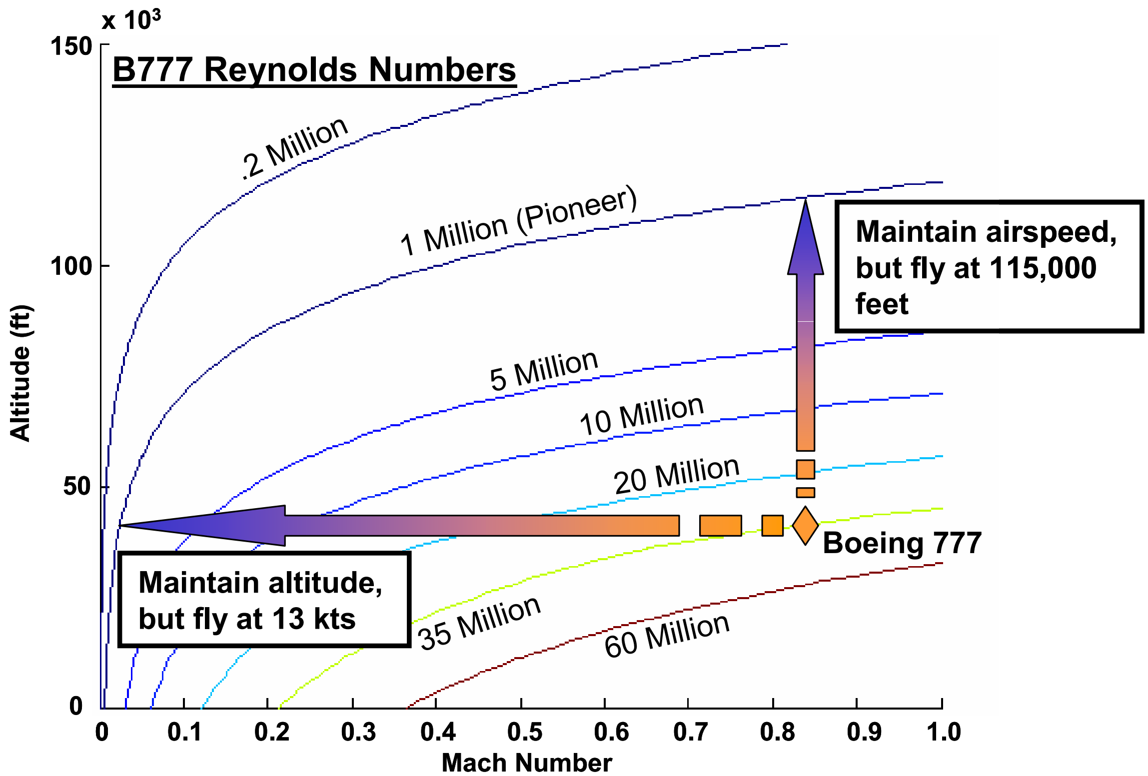


FIGURE F-2: REQUIRED BOEING 777 VELOCITY/ALTITUDE CHANGES TO REACH PIONEER REYNOLDS NUMBER

The preceding example illustrates that expecting a high Reynolds number aircraft to fly in a low Reynolds number flight regime is akin to expecting a commercial airliner to fly comfortably at 13 knots (if at its customary altitude) or 115,000 feet (if at its normal cruise speed). Relying on the traditional high Reynolds number aerodynamics that govern the stability, control, and propulsion aspects of these larger, faster aircraft is not the optimum implementation on a UAV. Consequently, low Reynolds number flight conditions must be better understood so that any necessary concessions can be made to it.