HBEDS

Helicopter Blade Emergency Detachment System

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Project Sponsor: General Dynamics Armament and Technical Products, Burlington, VT

EXECUTIVE SUMMARY

Despite development efforts conducted by foreign and domestic research agencies, emergency egress systems have not been widely implemented in military helicopters. Proposed egress systems for the UH-1 Huey, AH-1 Super Cobra, and CH-46 Chinook were scrapped in favor of designing more crashworthy fuselages and cockpits that protected occupants upon impact. While the political and economic consequences of military casualties remain, helicopter and aerospace explosives technology have changed considerably since these studies were performed. In consideration of this, the project team has performed a feasibility study and designed a proof of principle prototype for a Helicopter Blade Emergency Detachment System (HBEDS) for military helicopters. The blade detachment system is intended to afford helicopter pilots the ability to quickly remove the main rotor blades in a life-threatening emergency. In-flight activation of the system would provide clearance for pilot ejection or the release of a ballistic helicopter parachute. Alternatively, the system could also increase crew survivability as a standalone feature during hard landing and ditching into water. The team has carried out the project under the guidance and support from the Thayer School of Engineering and General Dynamics Armament and Technical Products, the project sponsor.

Risk assessment and project specifications served as the foundation of the feasibility study and subsequent development of the prototype. To begin, numerous risks associated with implementation of the proposed system were identified and organized according to relative significance. Project specifications drawing from these risks were then defined to guide the design and development of the prototype system. A validation test for each specification was also identified to evaluate performance and feasibility. Though the majority of the specifications were evaluated through testing and analysis, the HBEDS team cited military standards as validation tests for explosive stability and durability. Although testing could not be performed by the team, these specifications could be provided to suppliers of aerospace-grade explosives in future development of the system.

The HBEDS team identified a representative helicopter platform on which to develop the prototype system. The Eurocopter EC-135 is a helicopter that exhibits modern technology with potential applications in future generations of military helicopters. Its four-blade bearingless rotor system also distinguishes it from aircraft platforms used in previous blade detachment studies, providing unique opportunities for explosive packaging and system integration. Further,

access to an EC-135 was conveniently provided by the Dartmouth Hitchcock Advanced Response Team, an emergency service team well versed in the operation and maintenance of the aircraft.

The design process involved a series of trade studies regarding the concept, layout, and integration of the system. Decision matrices were used to determine the method and location of blade detachment, the classification of explosive to be used for severance, the signal method and design of the ignition train, and the location of a signal transfer system to link the fuselage to the rotor system. The project specifications provided a framework for assessing the potential for each alternative within the context of the project objectives. On the whole, decisions were largely influenced by the stability of each alternative and its effect on the system's resistance to inadvertent activation.

Specification testing and analysis demonstrated potential for the system to meet the project objectives. Though the prototype failed to meet the cost and weight specification, the system met the requirements imposed by more critical specifications such as stability, clearance time, reliability, and safety. The HBEDS team believes each specification could be met through continued development and refinement of the proposed concept.

In conclusion, the team identified a number of recommendations for future HBEDS development. Regarding development of the system itself, the team suggests that full scale tests be conducted to observe the blade exit path and evaluate the reliability and predictability of the explosive severance system. Explosive stability must also be verified by subjecting the system to electrostatic discharge, fire, heat, ballistic shock, and other stresses according to military standards referenced within the project specifications. Finally, risks assessment and dynamics analyses highlighted the need for parallel systems to ensure safe, predictable operation of the system. In addition to an ejection or ballistic parachute system, the team recommends that post-detachment blade containment and tail rotor thrust termination systems be developed to minimize danger to occupants and bystanders following activation.

The team would like to thank Jerry Brown, Jon Piazza, Jean Davis, Dean Peterson, and General Dyanamics for their guidance throughout the project. Thanks also go to Dartmouth-Hitchcock Advanced Response Team (DHART) for allowing access to their EC-135 and providing valuable insight concerning its design and operation. We greatly appreciated the assistance from Ensign-Bickford Aerospace and Defense Company and McCormick Selph, Inc.

as we conducted controlled explosives research and from American Eurocopter Corp. as we investigated the specific layout of a helicopter engine transmission. Kevin Baron, Mike Ibey, Leonard Parker, and Pete Fontaine deserve thanks for their excellent support in the Machine Shop. Finally, the project would not have been possible with the support and assistance of the Thayer School Faculty, especially John Collier, Francis Kennedy, and Laura Ray.

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1.0 Introduction

The helicopter has unique maneuvering capabilities that set it apart from any other type of aircraft. Whereas fixed wing aircraft depend on a high forward velocity for flight, helicopters are capable of a full range of motion including forward, backward, left, right, upward, and downward movements. Though lighter-than-air craft such as zeppelins and balloons may also exhibit this capability, the helicopter is more responsive and can move with far greater speed and precision in a wider range of conditions.

The unique capabilities of helicopters have made them suitable for numerous applications. The three primary applications for helicopters are general aviation, emergency services, and the armed forces. Despite their popularity, the inherent complexity in design and operation of helicopters has contributed to a high accident rate. According to the National Transportation Safety Board (NTSB), there were 2211 general aviation and air carrier helicopter accidents from 1990-2000, of which 324 involved fatalities.[1] Within the general aviation segment, the accident rate of helicopters, expressed as the number of accidents per 100,000 flight hours, exceeds the accident rate for piston engine, turboprop, and turbojet airplanes. Despite operating at lower altitudes than these fixed wing aircraft, helicopter accidents are no less fatal than airplane accidents. The fatal accident rate for helicopters exceeds that of airplanes and is second only to gliders as the most dangerous type of aircraft.[2]

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[1] *Helicopter Accident Study*, 2002, National Transportation Safety Board, 11 Oct. 2003, <https://nasdac.faa.gov/aviation_studies/ntsb_helicopter_accident_study/helicopter_accident_study.html>.
[2] *Annual Review of Aircraft Accident Data*, 2000, National Transportation Safety Board, 11 Oct. 2003, <http://www.ntsb.gov/publictn/2003/ARG0302.pdf>.

Unlike helicopters designated for civilian use, military helicopters are deployed on intelligence, reconnaissance, transport, and combat missions. Despite extensive pilot training, the dangerous nature of many of their missions leads to a high accident rate. Over the past twenty years, the Air Force has averaged a Class A[3] accident rate of 3.11 helicopter accidents per 100,000 flight hours, nearly double the rate for fixed wing aircraft[4] (Figure 1). The Army's AH-64 Apache has been involved in 18 Class A accidents and 7 fatal accidents in the last 2 years alone.[5]

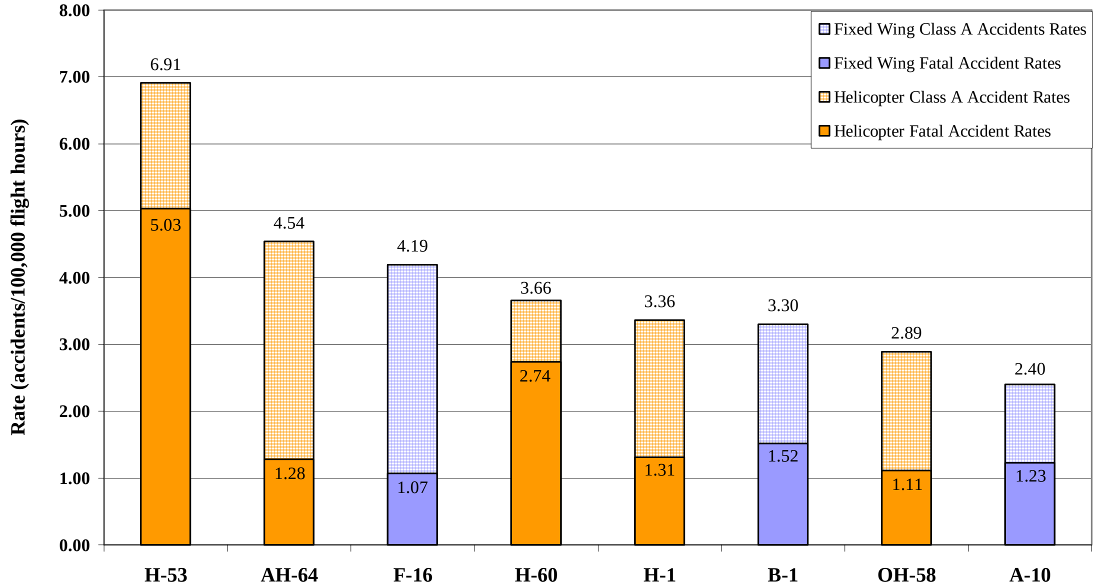

Figure 1: Class A and Fatal Accident Rates by Military Aircraft[6]

The Class A accident rate for many helicopters exceeds the accident rate for some of the military's most venerable fighter and attack fixed wing aircraft (Figure 1). While none of the helicopters in the United States military have pilot ejection systems, the F-16, B-1, and A-10

[3] Class A accidents are accidents which involve a fatality or permanent total disability, destruction of the aircraft, or total mishap cost of $1,000,000 or more.
[4] *Aircraft Statistics*, United States Air Force Safety Center, 9 Oct. 2003, <http://afsafety.af.mil/AFSC/RDBMS/Flight/stats/aircraft_stats.html>.
[5] *United States Army Safety Program Database*. Unites States Army, 12 Oct. 2003, <http://safety.army.mil/home.html>.
[6] Accident rates are calculated for the life of each aircraft through September 2003. Accident rates for H-1, H-53, H-60, A-10, B-1, and F-16 were provided by *Aircraft Statistics*, United States Air Force Safety Center. Accident rates for AH-64 and OH-58 are calculated using accidents reported in the *United States Army Safety Program Database*, United States Army. AH-64 and OH-58 flight hour data provided by Clarence E. Rash, *Accident Rates in Glass Cockpit Model U.S. Army Rotary-Wing Aircraft*, 2001, United States Army Aeromedical Research Laboartory (USAARL), 15 Oct. 2003, <http://www.usaarl.army.mil/TechReports/2001-12.PDF>. 2001-2003 flight hour estimates for AH-64 and OH-58 were calculated using 1998-2000 flight hour data.

aircraft each incorporate systems that provide an 80 to 95% ejection survival rate in the event of an impending accident.[7]

Despite these comparable accident rates, there is no widely adopted method of escape for helicopter occupants given a mid-flight emergency or a hard landing. Helicopter pilots instead depend on autorotation, an emergency landing technique equivalent to power-off gliding in an airplane. However, there are numerous situations where autorotation is not possible. During these emergencies, the spinning blades may prohibit in-flight egress or delay escape upon landing. Therefore, the project team proposes a Helicopter Blade Emergency Detachment System (HBEDS) based on the following statement of need:

> *In the event that a damaged or otherwise endangered helicopter cannot safely land through controlled autorotation, the occupants may suffer fatal injuries during the course of a hard landing or crash. Under these circumstances, there exists a need for a system to detach the main rotor blades, thereby reducing the risk of a blade strike or enabling safe, immediate egress.*

This report summarizes the development of a proof of principle system intended to fulfill the need statement. The system was developed for a specific application to demonstrate the operation and integration of the device on a representative helicopter. Included within the report and accompanying appendices are background research, trade studies documenting design decisions, the details of applying the concept to a particular platform, and the results of system testing.

2.0 Activation Envelope

Accident research and a review of accident synopses highlighted a number of accident scenarios where activation of a blade detachment system could benefit helicopter pilots and crewmembers.[8] Following this research, an activation envelope was defined within a general map of accident scenarios to illustrate the circumstances under which HBEDS could improve the survivability of helicopter crashes (Figure 2). The activation envelope is *not* intended to suggest the blade detachment system should necessarily be activated in any of the included scenarios, for this decision depends upon a complex set of factors particular to the accident sequence. The envelope instead identifies a general subset of accident scenarios for which blade detachment could potentially reduce the risk of occupant injury or death.

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[7] Ejection survival rates calculated over the lifetime of the ACES II system through September 2000. See George D'Amore and Thomas D Fadell Luna, *USAF Aces II Ejection Experience Analysis*, 2000, USAF Safety Center, 17 Oct. 2003, <http://safety.kirtland.af.mil/AFSC/RDBMS/Flight/SEFL/SEFL%20Files/1>.

[8] For details of accident research and synopses see Appendix A.

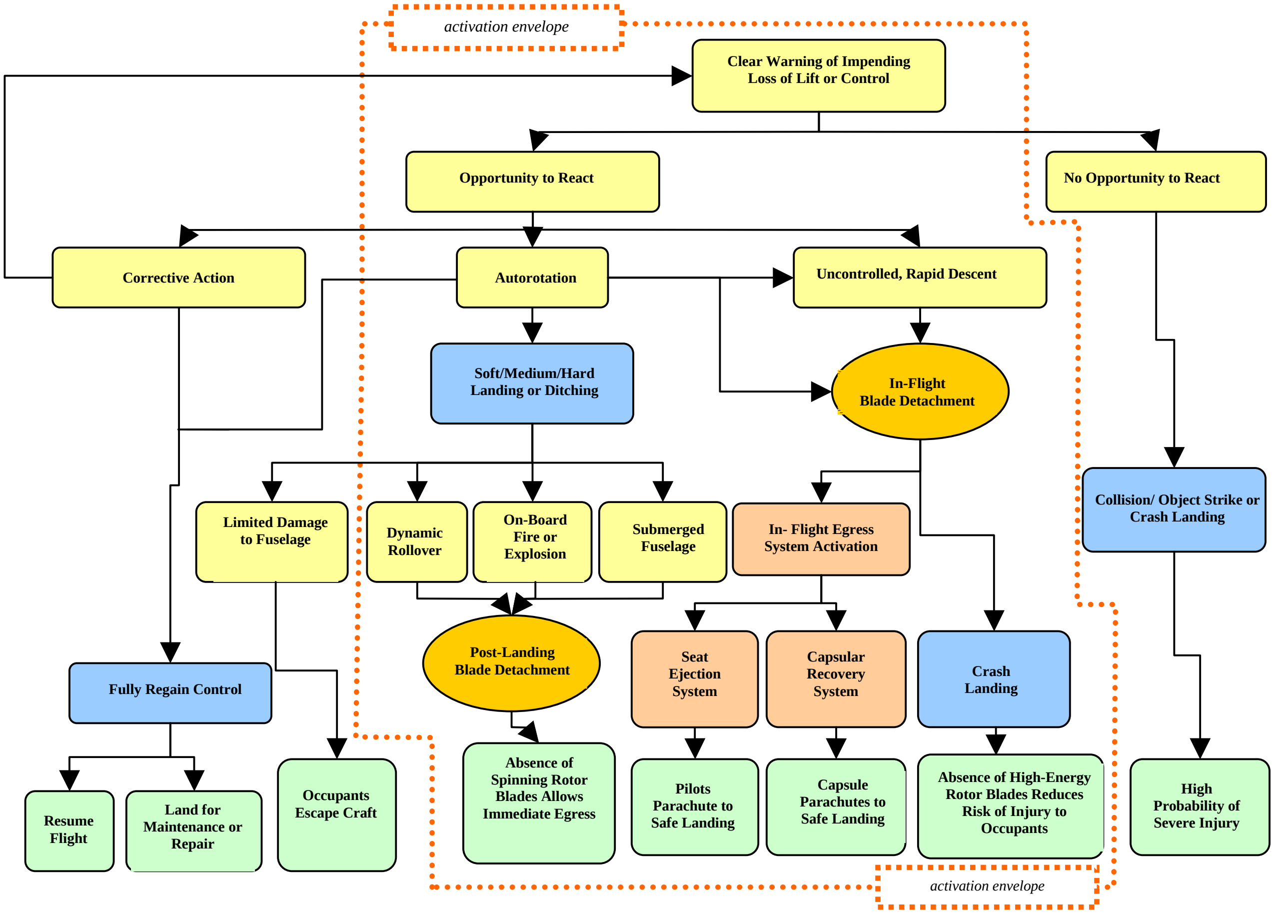

Figure 2: HBEDS Activation Envelope[9]

Post Landing Activation: Post-landing activation may increase the chances of survival if the rotating blades introduce a significant hazard following an imperfect landing. The system may be activated to prevent a dynamic rollover,[10] an event cited in 4% of non-combat Class A military helicopter accidents over the past 15 years.[11] Detaching the blades at the onset of a roll could stabilize the craft and prevent catastrophic blade strike.

The main rotor system poses other dangers in medium or hard landings, where the spinning rotor blades often prohibit immediate egress from the craft. The AH-64A Apache flight manual warns: "Danger exists that the main rotor system could collapse or separate from the aircraft after landing…a decision must be made whether occupant egress occurs before or after

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[9] Full scale diagram provided in Appendix B.

[10] Dynamic rollover - a situation that occurs when the helicopter is forced to touch down with lateral drift or body roll

[12] *Technical Manual TM 1-1520-238-10: Operators Manual for Helicopter, Attack AH-64 Apache*, 1994, United States Army, 2 Nov. 2003, <www.usarmyaviation.com/Documents/ah-64/ah64eps.doc>.

the rotor has stopped."[12] If the craft has rolled or become inverted after a hard landing, occupants may be forced to wait for the main rotor to stop rotating before exiting. If a fire, explosion, or other life-threatening situation develops, detachment of the main rotor blades will eliminate the chance of a blade strike and allow the crew to exit immediately. Hard landing, ditching, and post-landing fires and explosions were cited in 15% of Class A military helicopter accidents.[13]

In-Flight Activation: The pilot may activate the HBEDS during flight under the following scenarios: if there is no suitable area to land during autorotation; if the aircraft loses maneuvering capabilities; or if the aircraft experiences engine or transmission failure within 'Deadman's Curve'. Because kinetic and potential energy are needed to drive the main rotor during autorotation, there is a wide range of height-velocity combinations where a helicopter cannot safely land without engine power. Height-velocity diagrams (Figure 3) illustrate the regions of height above the ground and speed bounded by 'Deadman's Curve.'

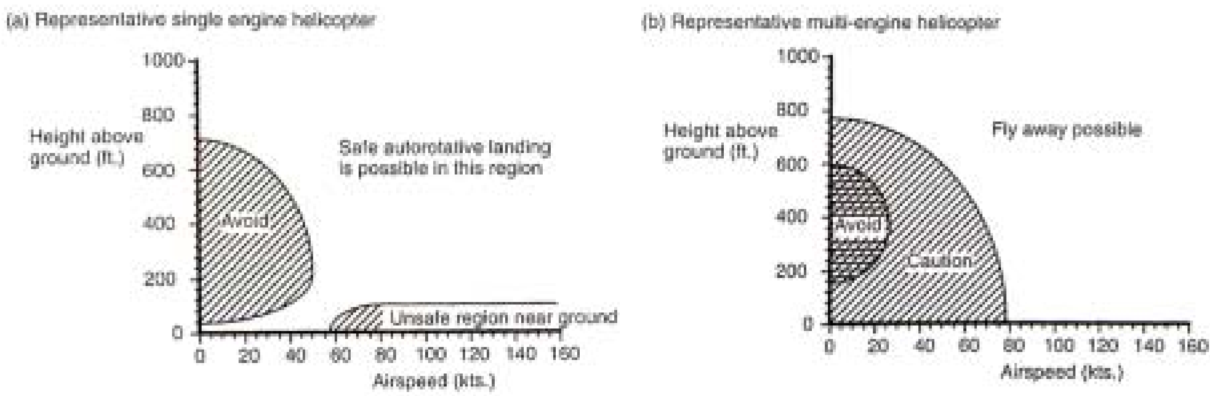

Figure 3: Height Velocity Diagrams[14]

In circumstances where a crash landing is inevitable, the blade detachment system could enable the activation of a separate emergency safety device: a ballistic parachute or an in-flight egress system. Though design of such systems is beyond the scope of this project, three existing systems demonstrate that a recoverable capsule or an ejection seat can readily be integrated into a military helicopter.[15] An in-flight egress system would complement crashworthiness design features common to many modern military aircraft. Most military helicopters currently incorporate collapsible landing gear and energy-absorbing seats to protect the pilot from impact

[13] *United States Army Safety Program Database*. Unites States Army, 30 Oct. 2003, <http://safety.army.mil/home.html>.
[14] J. Gordon Leishman, Principles of Helicopter Aerodynamics (New York: Cambridge, 2000) 183.
[15] A discussion of these egress systems in included in the State of the Art section in Appendix C.

forces during a crash landing. The AH-64, for example, is designed to absorb ground impacts of 42 feet per second with 95% pilot survivability.[16]

2.1 Envelope Event Analysis

The envelope is headed by two accident scenario requirements: a warning of a loss of control and an opportunity to react. The pilot will be unable to activate the system if either of these does not occur at the onset of the accident sequence. Though mechanical failure, pilot error, damage from enemy fire, and many other accident events would likely satisfy both criteria, a number of accident scenarios involve severe, catastrophic events that cannot be anticipated by the pilot. Because they occur either without warning or an opportunity to react, the blade detachment system is unlikely to be useful in these types of accidents. Accident scenarios can therefore be distinguished by envelope events and non-envelope events depending on whether or not they satisfy these criteria. Table 1 provides a listing of event frequencies for non-combat Class A military helicopter accidents during the period 1987-2003. Many commonly cited events fall within the activation envelope, indicating that a blade detachment device could be used in a significant portion of serious accidents.

Inside Envelope	
Class A Accident Event	%
Damage from Enemy Fire	*n/a*
*Hard Landing or Ditching**	*14*
Excessive Yaw or Spin	*11*
Engine Failure	*9*
Engine Overloading	*5*
*Dynamic Rollover**	*4*
Fuel Starvation or Exhaustion	*4*
Powertrain/Drivetrain	*2*
*Post-Landing Fire or Explosion**	*1*
Flight Control	*1*
Hydraulic System	*1*
Single Engine Landing	*1*
Uncommand Control/Input	*1*
Net Event Frequency[19]	**54**

Outside Envelope	
Class A Accident Event	%
Missile Hit	*n/a*
Controlled Flight Into Terrain	*22[17]*
Tree Strike	*12*
Wire Strike	*8*
Other Collision	*6*
Multiple Aircraft Event	*4*
Mid-Air Collision	*3*
In-Flight Fire or Explosion	*3*
In-Flight Breakup	*3*
Net Event Frequency[18]	**61**

* = post-landing activation

[16] *Boeing AH-64 Apache*, 2003, Jane's Information Group, 18 Nov. 2003, <http://www.janes.com/defence/air_forces/news/jawa/jawa001013_1_n.shtml>.
[17] Air Force data was used because the Army does not cite Controlled Flight Into Terrain (CFIT) in accident overview database. See *Aircraft Statistics*, United States Air Force Safety Center, 9 Oct. 2003, <http://afsafety.af.mil/AFSC/RDBMS/Flight/stats/aircraft_stats.html>.
[18] Figures may not add to 100% because up to three events may be cited in each accident.

Table 1: Class A Military Helicopter Accident Event Frequencies[20]

A blade detachment device could increase the survivability of a helicopter in a wide variety of accident scenarios. Incidents likely to satisfy envelope criteria are cited in 54% of Class A helicopter accidents, suggesting the blade detachment device could potentially be used in about half of all serious military accidents. This echoes earlier studies conducted by the United States Army and Navy, where it was determined that over 40% of helicopter accident fatalities could be prevented using blade detachment and in-flight egress systems.[21] Considering the life-saving potential of the system, a blade detachment device would be a notable advancement in helicopter safety.

3.0 State of the Art

Three systems have been developed for helicopters that detach the main rotor blades in the event of an emergency. The only helicopter with such a system in use today is the Kamov Ka-50/Ka-52, which is currently in production in Russia. Additionally, experimental in-flight egress systems have been developed by the U.S. Military and NASA, although neither system entered into production. Though these systems provide a means for in-flight egress, none address hard landing situations.[22]

The Ka-50 is distinguished from other helicopters not only by its blade detachment and ejection system, but also by its counter-rotating coaxial main rotors, doing away with the need for a tail rotor and allowing for a more compact airframe construction.[23] Its blade detachment system severs each blade at the root, but the team was unable to obtain information on precisely how the system transfers its activation signal to the explosives.

In 1973, at the request of the General Accounting Office, the Department of Defense (DoD) submitted a report to Congress entitled *In-Flight Escape Systems For Helicopters Should Be Developed To Prevent Fatalities.*[24] Details concerning the precise manner of blade detachment in Navy experiments are not included in the DoD report, but it is clear that the

[19] Figures may not add to 100% because up to three events may be cited in each accident.
[20] *United States Army Safety Program Database*. Unites States Army, 30 Oct. 2003, <http://safety.army.mil/home.html>.
[21] See *In-Flight Escape Systems For Helicopters Should Be Developed To Prevent Fatalities*, 1973, United States General Accounting Office, 10 Nov. 2003, <http://archive.gao.gov/f0202/094114.pdf>.
[22] For a full description of the State of the Art helicopter blade detachment systems, see Appendix C.
[24] See *In-Flight Escape Systems For Helicopters Should Be Developed To Prevent Fatalities*, Department of Defense, by the Comptroller General of the United States: June 12, 1973.

devices were implemented on two-bladed attack helicopters and the blades were detached individually with explosives.[25]

In addition to these experiments performed by the U.S. Military, NASA designed and built an experimental rotorcraft with a fully certified in-flight egress system. The Rotor Systems Research Aircraft (RSRA) had both a five-bladed main rotor system and fixed wings, allowing it to operate as either a helicopter or airplane. While there is not much information concerning the detachment methods on the Kamov or the Navy helicopters, the team was able to obtain more detailed information on the RSRA's detachment system.

The RSRA's root-mounted explosive charges severed blades at 11°, 155°, 227°[26], with the remaining two blades separated after one-fifth of a rotation. Detachment of the blades was staggered because NASA found that simultaneous detachment of the rotor blades would almost certainly result in striking the tail of the aircraft. The inherent instability caused by the rotation of the two asymmetrically aligned blades caused a 10 degree per second change in pitch and 40 degree per second change in roll of the aircraft, based on rigid body analyses,[27] although imbalance would only exist for less than a tenth of a second. In full system testing on the ground, severed blades traveled between 100 and 1000 feet when detached from a point 13 feet from the ground.[28]

A rotary transfer unit was used to relay the signal for blade detachment from the stationary portion of the aircraft to the rotating main rotor system. This device consists of an inner rotating ring of five firing pin assemblies and an outer non-rotating ring of three cam thrusters. When the pilot pulls the eject lever, the three cam thrusters extend and contact the firing pin, detaching three blades at the desired orientation relative to 0 degree aft, and then two of those three cams contact the remaining two firing pins after an additional one-fifth rotation.[29] The blades are completely free of the aircraft within 0.15 seconds of pilot initiation. The connections between all components of this emergency egress system, of which the transfer device is a centerpiece, are made using detonation transfer lines.[30] They were selected for use

[25] *In Flight Escape Systems*, 15-17.
[26] 0° is centerline aft of aircraft.
[27] Lawrence J. Bement, Rotor Systems Research Aircraft Emergency Escape System, 1978, *Proceedings from the 34th Annual National Forum of the American Helicopter Society, Washington DC, May 1978.* American Helicopter Society, 1978, p. 4.
[28] Bement,Ibid 7.
[29] Bement, 5-6.
[30] Detonation transfer line is comprised of small amounts of primary explosive within protective tubing. Bement, 2.

because they cannot be inadvertently triggered by lightning, electromagnetic induced radiation, or mechanical inputs.[31]

[31] Bement, 3-4.

3.1 Application Selection

It was hoped that the application selection decision could be made based on accident data. However, in comparing the frequency of accident events, the data failed to identify a helicopter that would benefit the most from HBEDS.[32] Therefore, selection was based on research of state of the art helicopter blade detachment systems, their applications, and what resources were available to the team in the Upper Valley.

One variable surrounding the team's helicopter application decision was the main rotor system. Main rotors are distinguished by how the blades are attached to the main drive shaft: rigid hub, articulated hub, teetering hub, and bearingless hub designs (Figure 4).

A. Articulated Hub *B. Teetering Hub* *C. Bearingless Hub*

Figure 4: Main Rotor Hub Designs[33]

A rigid hub design has several variations, but essentially it does not allow the blades to flap,[34] and may or may not allow for pitch change of the blades. Whereas the rigid hub design is not widely used, an articulated hub design is currently the most common. In this implementation, there are bearings that allow for pitch change and hinges that allow the blades to flap. Alternatively, the teetering hub design is older and now rarely used, but consists of bearings to allow for blade pitch change. The two main rotor blades are rigidly connected so that flapping can only occur in a see-saw motion: if one blade flaps up, the other must flap down. Finally, a bearingless hub design has been made possible with the development of strong and flexible composite materials that allow for both pitch change and flapping, but without hinges or bearings[35] (Figure 5).

[32] For a full account of accident data see appendix A.
[33] Photos courtesy Burkhard Domke, 2003, <http://www.b-domke.de/AviationImages/Rotorhead.html>.
[34] Flap is a term which describes helicopter blade flexing upwards or downwards about the root attachment point.
[35] Leishman, 130.

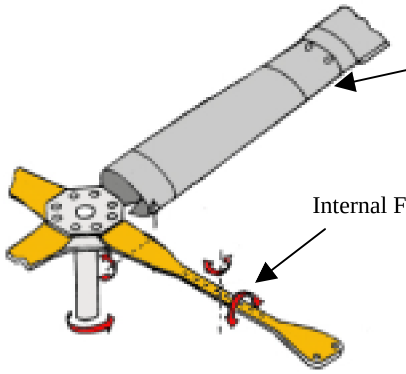

Figure 5: Bearingless Rotor Construction[36]

The project team chose to pursue an application with a bearingless rotor hub because blade detachment systems have been designed for a rigid hub (NASA's RSRA project), an articulated hub (the Ka-50 Hokum), and a teetering hub (the AH-1 Cobra), but such a device has not yet been developed for a bearingless hub. Furthermore, bearingless rotor hubs show potential to become the standard main rotor system in helicopter design. They are more responsive, take advantage of new-age composite materials, and have significantly fewer moving parts than previous hub designs, which translates into fewer parts that can fail and less necessary maintenance time on the aircraft. The UH-1Y Iroquois and the AH-1Z Super Cobra helicopters used by the US Marine Corps have recently been refurbished and now include a new four-bladed bearingless main rotor system.

While searching for a helicopter located in the Hanover area to use as a model application for the system, the team discovered that the Dartmouth Hitchcock Advanced Response Team (DHART) owns and maintains a Eurocopter EC-135 as part of its emergency rescue fleet. The EC-135, shown in Figure 6, is a twin-engine helicopter with a four-bladed bearingless rotor that is widely used in passenger transport, emergency rescue and police operations. It also has a military derivative, the EC-635, which serves as a light-utility helicopter for armed forces worldwide[37] (Figure 7). After contacting DHART, the project team was granted full access to their EC-135, as well as flight and maintenance documents. A description of the thought process behind choosing the EC-135 can be found in Appendix D.

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[36] United Technologies Corporation, "Flexbeam for A Helicopter Bearingless Main Rotor Assembly," *United States Patent 5372479*, Washington, 1994, p. 1.
[37] *EC 135 P2/T2*, Eurocopter Group, 29 Nov. 2003, <http://www.eurocopter.com/site/FO/scripts/siteFO_contenu.php?lang=EN&noeu_id=37>.

Figure 6: EC-135[38]

Figure 7: EC-635[39]

4.0 Risk Mitigation

The integration of a blade detachment system will introduce certain risks to the occupants and the aircraft. Failure of the detachment device and its associated components could easily imperil the aircraft and risk the lives of those on board. In order to manage these risks, the project group has organized a collection of hazards associated with installation of HBEDS. These include both operational risks and malfunction risks. Operational risks cover hazards such as the potential for a blade strike following detachment, accidental system activation, and improper use. Malfunction risks pertain to potential failure modes of the detachment system itself, including inadvertent system activation and faulty blade detachment. Drawing from these general headings, the group identified a number of specific risks that must be managed to ensure a safe and viable design (Table 2).

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[38] *Photo Gallery*, Eurocopter Group, 4 March 2004, <http://www.eurocopter.com/site/FO/scripts/siteFO_phototheque.php?arbo=1&noeu_id=54&lang=EN&id_rubrique=&affiche=1>.

[39] *Eurocopter EC635 H242*, Airliners.net, 4 March 2004, <http://www.airliners.net/open.file/379670/M/>.

Category		Risks Introduced	Descriptions
Operational Risks	**Danger to Others**	*Blade Strike*	*Main rotor blades strike other aircraft or personnel following detachment*
	Accidental Activation	*Accidental Activation*	*System accidentally activated by pilot or crew member during flight*
		Activation During Maintenance	*System accidentally activated by maintenance technician during service*
	Improper Use	*Unwarranted Activation*	*Pilot activates system in a non-critical situation*
		Delayed Activation	*Pilot activates system after the most severe events of the accident sequence*
Malfunction Risks	**Inadvertent Activation**	*Electrostatic Discharge*	*Inadvertent activation caused by accumulation of electrostatic charge*
		Lightning Strike	*Inadvertent activation caused by lightning strike*
		Fire or Heat	*Inadvertent activation caused by engine heat, fire, or explosion on-board*
		Ballistic Shock	*Inadvertent activation caused by foreign object impact or enemy fire*
	Faulty Detachment	*Partial Severance*	*Partial severance of blade due to damaged or defective explosive charge*
		Incomplete Detachment	*Failure to detach all main rotor blades*
		Poorly Sequenced Detachment	*Failure to detach blades in a coordinated sequence*
		No Detachment	*No blades detached following activation of the system*

Table 2: Risks Associated with HBEDS

The significance of each of these risks was determined by their consequences and probability of occurrence. A matrix relating risk consequences and probabilities gave rise to three principal classifications: major, moderate, and minor risks. The relationship between these categories is illustrated in the Figure 8.

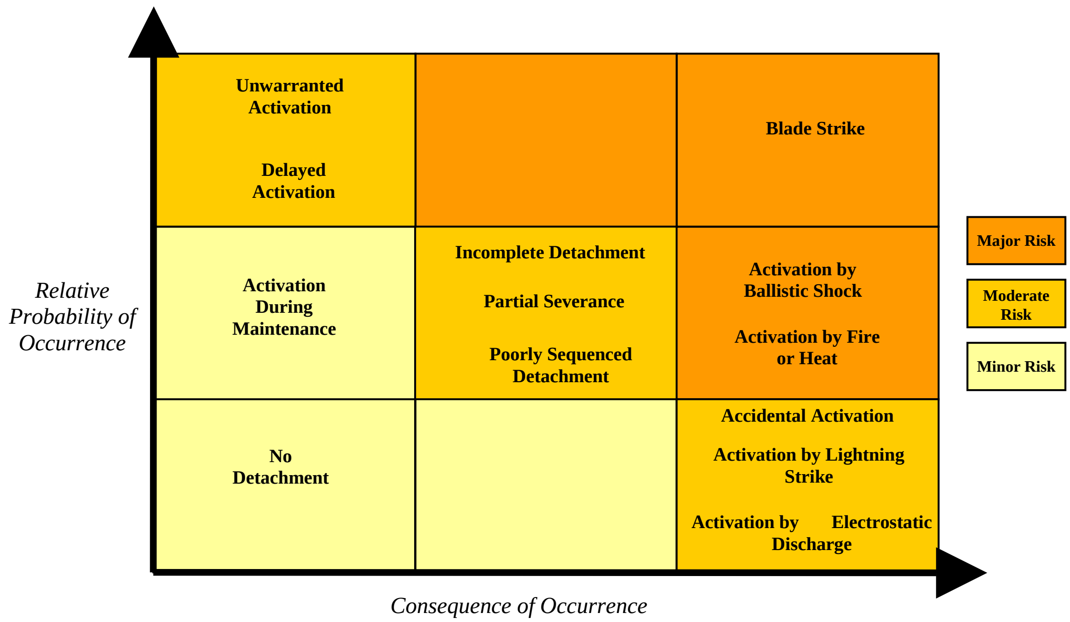


Figure 8: Risk Matrix

The rightmost column of the matrix contains major and moderate risks that introduce significant hazards to a stable, non-emergency situation. The system must be designed to minimize the likelihood of blade strikes or inadvertent activation because helicopters without detachment systems are not subject to these risks. The risk of inadvertent activation may be reduced through identification of all possible failure modes and careful design of the system. Blade strike, another major risk, is a particularly important concern because military helicopters often fly in formation and takeoff and land on populated military bases. NASA's RSRA testing demonstrated that released blades could be a serious hazard to anyone in the vicinity of the aircraft.[40]

The left and middle columns of the matrix contain moderate and minor risks with relatively small consequences. Accidental activation during maintenance, though introducing hazards to an otherwise stable situation, is unlikely to result in hazards on par with in-flight system failures. The other faulty detachment risks in these columns are incurred when the helicopter is already involved in a critical emergency situation. These involve less significant consequences because failure of the detachment system would only result in a marginal increase in accident severity.

The risk matrix identified the most critical concerns for the design and integration of HBEDS. Though each of the risks included in the diagram is significant, the project group decided that risk mitigation efforts should be focused principally on malfunction risks. Whereas operational risks may be minimized with pilot and technician training, management of malfunction risks depends solely upon careful design of the system. The group therefore aimed to minimize the risk of inadvertent activation by ballistic shock, heat, fire, lightning, and electrostatic discharge, as well as faulty detachment risks including partial severance, incomplete detachment, and poorly sequenced detachment.

Blade strike, although identified as the most significant of all risks, was not directly addressed during the design of the HBEDS because it is beyond the primary scope of the blade detachment system. However the project group does recognize this risk and recommends future development of a method or system to restrain the rotor blades following detachment.

[40] Bement 7.

5.0 Specifications

Following the risk assessment, the HBEDS team identified twelve specifications to guide development of the design. Table 3 describes these specifications, their implication to the design and decision making process, and accompanying tests that validate each.

Specification	REQ #	Par.	Description	Validation
HBEDS Definition	**REQ-1**	**1.1**	The Helicopter Blade Explosive Detachment System (HBEDS) shall be a system that allows a helicopter's main rotor blades to be detached if the craft is involved in a critical emergency situation. Such situations may include uncontrolled descent, hard landings, ditching into water, on-board fires, or explosions.	Proof of Principle Prototype
Stability	**REQ-2**	**2.1**	Ballistic shock resistance: 40-ft drop test	Explosives certified under MIL-STD-810, Meth. 522
	REQ-3	**2.2**	Electrostatic discharge resistance: 25,000V via 500pf capacitor	Explosives certified under MIL-STD-1512, Meth. 205
	REQ-4	**2.3**	Lightning strike resistance: +/-18,000V simulated strike	Explosives certified under MIL-STD-1512, Meth. 302
	REQ-5	**2.4**	Heat resistance: autoignition temperature to exceed 600˚F	Explosives certified under MIL-STD-650, Meth. 506
Strength	**REQ-6**	**3.1**	System shall be resistant to static and fatigue failure	FEA with Pro Mechanica; Instron tensile test
Efficiency	**REQ-7**	**4.1**	Mass of system to be less than 10kg	Mass measurement
	REQ-8	**4.2**	Parasitic drag on rotor to increase by no more than 5%	Estimate and compare equivalent flat plate area
Power	**REQ-9**	**5.1**	System capable of operating on 22.5V, 1.8Ah standby battery	Explosive detonation energy specification
Reliability	**REQ-10**	**6.1**	Complete blade severance with at least 95% reliability	Explosive reliability data; prototype test simulation
Clearance Time	**REQ-11**	**7.1**	Blade detachment to occur in less than 500 miliseconds	Prototype test with high speed video recording
Cost	**REQ-12**	**8.1**	Unit production cost under $20,000	Technical cost estimation
Serviceability	**REQ-13**	**9.1**	System inspection and replacement possible in under 2.5 hr.	Timed system replacement on prototype
Durability	**REQ-14**	**10.1**	Temperature shock: 1hr exposure to -65˚F and +200˚F	Explosives tested under MIL-STD-810, Meth. 503
	REQ-15	**10.2**	Vibration: 2hr exposure to random vibration at 10-2000Hz	Explosives tested under MIL-STD-1512, Meth. 113
	REQ-16	**10.2**	Materiel degradation: service life shall exceed 10 years installed	Explosive service life per MIL-STD-1512, Meth. 118
Adaptability	**REQ-17**	**11.1**	Design shall be adaptable to other aircraft	Demonstrate potential for other applications
Safety	**REQ-18**	**12.1**	Blade detachment at 5˚ and 185˚ relative to fuselage (+/- 5˚)	Prototype test with high speed video recording
	REQ-19	**12.2**	Explosive charge shall not damage fuselage	Theoretical pyrotechnics analysis

Table 3: Specifications and Tests

Stability: The explosive stability specification requires that the system be resistant to inadvertent activation by ballistic shock, electrostatic discharge, lightning strike, and elevated temperature. The four stability requirements will be tested according to the methods included in Table 3. Referenced military standards are provided in Appendix E. Recognizing the safety concerns of explosives testing at Thayer School, the stability requirements will be evaluated by reviewing published test reports for all detonators, detonating cord, pressure cartridges, and shaped charges used in the system.

Strength: The components of the proposed design must not experience stress failure during its suggested usage. The possibility of stress failure during activation will be evaluated analytically using static and dynamic calculations.

Efficiency: The efficiency specification includes two primary requirements. First, in the consideration of the effect of weight on helicopter performance, the mass of the system shall be less than 10 kilograms (kg) when measured on a calibrated scale. Second, the system shall not increase parasitic drag by more than 5 percent (%). The theoretical drag increase will be calculated by estimating the equivalent flat plate area of HBEDS components and comparing it to other drag-inducing components on the main rotor system. Though it was initially considered, there is no rotational inertia requirement to the efficiency specification because rotor revolutions per minute (RPM) is established before take-off and is seldom adjusted during flight.

Power: Because the system must be operable under adverse emergency conditions, it will be designed to operate on a backup power source such as a 22.5 volt, 1.8 ampere/hour standby battery. The detonation energy required by the explosives must be low enough to allow for activation either by this power source or a manually actuated percussion primer.

Reliability: The system will be designed to provide complete blade detachment with at least 95% reliability at 95% confidence. Published explosive failure rate data will be used in conjunction with testing of a prototype transfer system to estimate reliability. This level was established from the precedent set by the F-16's ACESII ejection system, an ejection seat with a 93.2% pilot survival rate.[41]

Clearance Time: Delays in blade detachment will reduce the chances of pilot survival in the event of an impending crash. Therefore, the system shall be capable of detaching the blades in under 500 milliseconds for all rotor speeds above 100 RPM. Clearance time will be estimated by calculations using the burn rate of the detonating cord, rotor RPM, and blade dynamics post detachment.

Cost: For the concept to be marketable, the design and production costs of HBEDS shall be less than $20,000 per unit for a 1,000-unit production run. Estimation for costs will be made with the assistance of the sponsor and experts in similar industries.

Serviceability: To minimize operating costs, system inspection and replacement shall be possible in less than 2.5 hours. Serviceability will be evaluated by timed prototype installation and removal on a rotor system mockup.

Durability: The durability specification requires that the system be resistant to temperature shock, vibration, and materiel degradation. Strong resistance to these environmental

[41] George D'Amore and Thomas D Fadell Luna, *USAF Aces II Ejection Experience Analysis*, 2000, USAF Safety Center, 17 Oct. 2003, <http://safety.kirtland.af.mil/AFSC/RDBMS/Flight/SEFL/SEFL%20Files/1>.

stresses will provide longer inspection and replacement cycles, allowing for convenient service scheduling within the existing main rotor blade maintenance interval.[42] The three primary durability requirements are defined in Table 3.

Adaptability: Because the system is being developed for an unspecified future military helicopter, the design must demonstrate potential for adaptation to a wide variety of platforms.

Safety: The safety specification is intended to ensure safe, consistent, and predictable operation of the system. HBEDS will therefore be required to release blades in a coordinated manner in order to prevent tail strikes, avoid releasing blades into the flight path, and maintain mass balance during detachment. The four-bladed main rotor on the EC-135 allows for a simple, two-stage detachment sequence whereby blades are detached in pairs at 5˚ and 185˚ (+/- 5˚) relative to the fuselage. This sequence will release the blades to either side of the helicopter, minimizing the risk of the blades striking the craft after detachment, as shown in Figure 9.

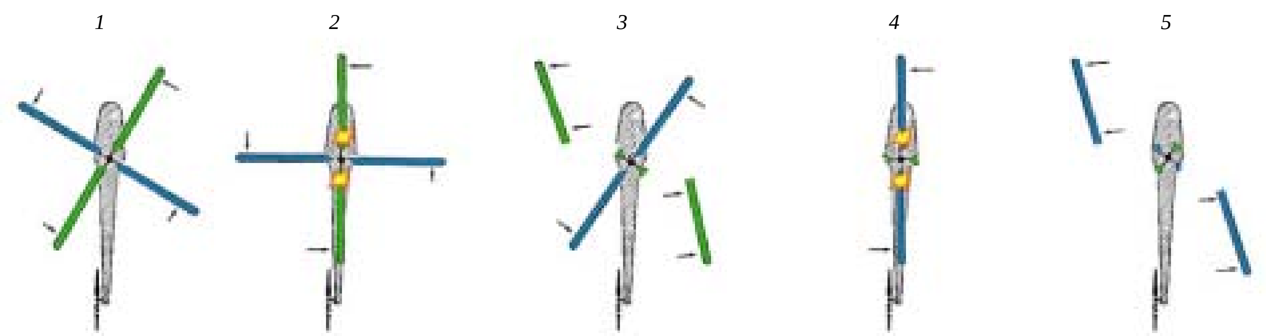


Figure 9: Blade Detachment Sequencing[43]

In addition to a coordinated detachment sequence, the safety specification requires the main explosive to inflict no damage on the fuselage and cockpit upon detonation. Because unnecessarily powerful explosives may increase the risk of injury to the crew and occupants, the explosive charges will be designed to sever unloaded blade roots with a factor of safety of 1.15. A similar factor was employed in testing of the RSRA blade detachment system. The explosive need not be designed to a higher safety factor because blade loading and centrifugal forces will greatly assist in blade severance once fracture is initiated.[44]

[42] Eurocopter's bearingless rotor blades have a service life in the neighborhood of 12,000 operating hours. See *Airworthiness Directive Schedule: SA365N Helicopter Series,* 2000, Civil Aviation Authority of New Zealand, 24 Nov. 2003, <http://www.caa.govt.nz/fulltext/nzcars/vol_2/Section_A/A2_Helicopters/sa365.PDF>.
[43] Base drawing excerpted from John Fay, The Helicopter. (North Pomfret, VT: David & Charles, 1976) p. 48.
[44] Bement, 6.

6.0 Trade Studies

Drawing from the specifications presented above, six trade studies were performed to outline the design process. They include investigating different blade detachment methods, blade detachment locations, ignition train and explosive components, transfer system locations, and transfer system methods. Summaries of all the trade studies are presented here and in Figure 10. More detailed information is provided in the Appendices F to L.

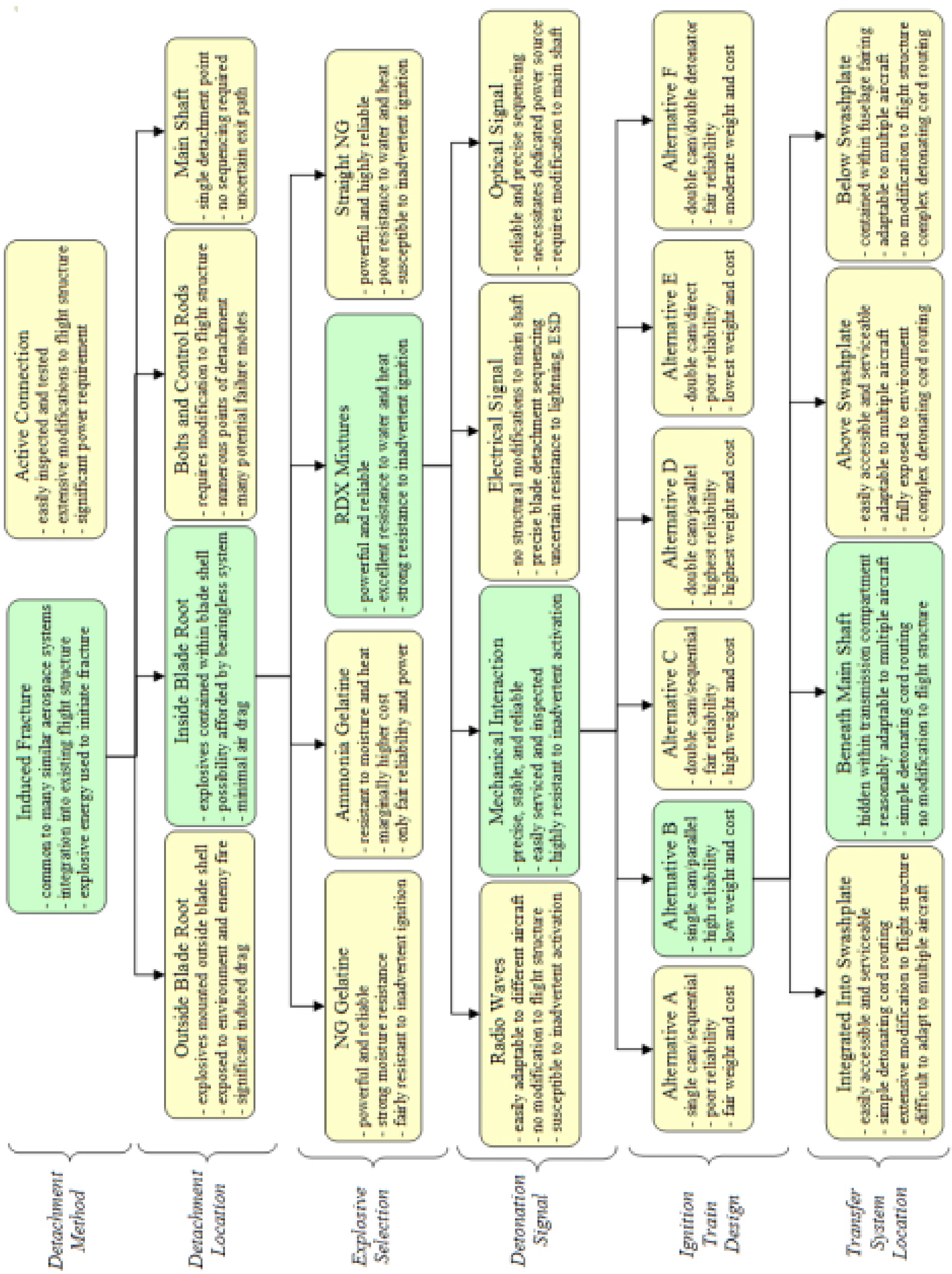


Figure 10: Trade Study Outline

6.1 Blade Detachment Method

Since General Dynamics had suggested the use of explosives to detach the blades in their initial project description, the first trade study that was performed was to confirm this was an appropriate method of blade detachment. Two separate detachment concepts were explored: Induced Fracture and Active Connection. Induced Fracture was conceived as a destructive system that would initiate structural failure by explosives, hydraulics, or ballistics. An Active Connection system was envisioned as a joint controlled by hydraulic or other mechanical means. This joint would completely release the blades or rotor assembly and could be inspected and tested in a non-destructive manner.

To determine which of these solutions has the most potential to solve the problem, a matrix (Table 4) was used to compare the methods versus a list of design criteria. Being an early conceptual exercise, the criteria were qualitative measures that the team discussed using rational thought and intuition. Extending from the project specifications, the criteria included stability, strength, efficiency, power, reliability, clearance time, cost, serviceability, durability, and adaptability. The design criteria were weighted on a scale from one to five, low to high importance. The most important criteria were stability and reliability because if the system failed to meet either of these specifications, it was unlikely HBEDS would be implemented. Each solution was rated on a scale of one (least potential) to five (highest potential) rationale outlined in Appendix F.

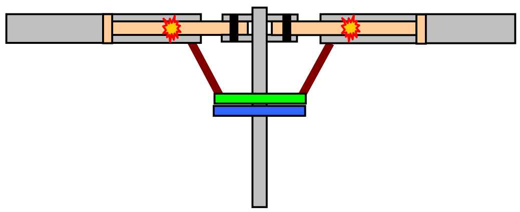
	Stability	Strength	Efficiency	Power	Reliability	Clearance Time	Cost	Serviceability	Durability	Adaptability	
Weighting Factor (1-5)	5	4	3	3	5	3	1	2	2	1	TOTAL
Induced Fracture	3	4	3	4	2	4	2	2	4	4	92
Active Control	2	2	3	1	2	4	1	4	3	2	69

Table 4: Blade Detachment Method Matrix

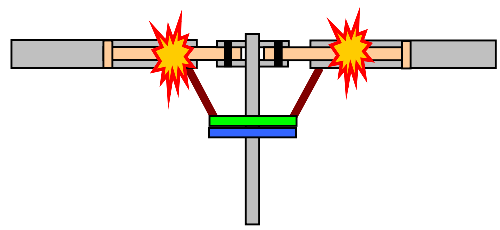
This analysis confirms that induced fracture is the best detachment method. Recognizing their long history of use in fighter jets, missiles, and spacecraft, the team identified explosives as the optimal means to fracture the main rotor blades.

6.2 Detachment Location

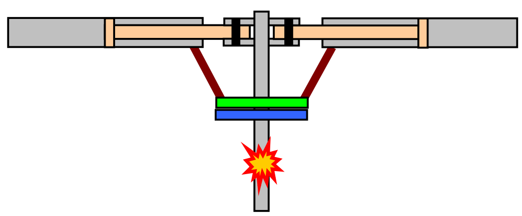
Extending from the detachment method trade study, the HBEDS team set out to determine an appropriate detachment location. Five different options were considered: inside the root of the blade; outside the root of the blade; on the main shaft below the swashplate; on the main shaft above the swashplate along with the control rods; and the bolts holding the blades to the rotor and the blades to the control rods (Figure 11).



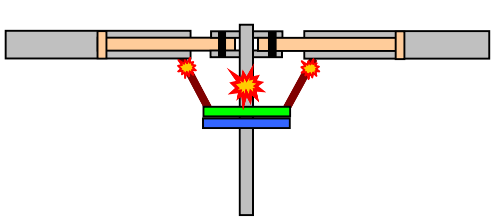
A. Inside Root



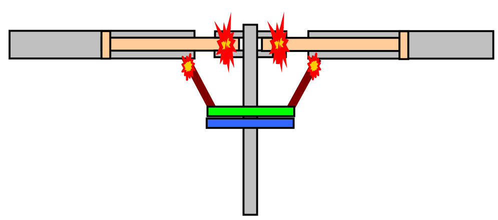
B. Outside Root



C. Main Shaft



D. Main Shaft and Control Rods



E. Bolts and Control Rods

Figure 11: Blade Detachment Location Alternatives

These locations were then analyzed based on a set of design criteria. These included stability with respect to inadvertent ignition, blade clearance time to make a safe exit, the number of detachment points, ease of blade removal, ease of installation and replacement of the system, ease of integration within the existing structure, complexity of design, and difficulty of manufacturing the system. Each location was ranked from one to five (five being the best) depending on how well it satisfied the design criteria. However, two criteria, stability and clearance time, were given a weighting of ten because they were much more vital to the success of the project. Ratings for each location are provided in Table 5 and discussed in Appendix G.

	Stability	Clearance Time	Number of Detach Points	Easy Removal of Blades	Ease of Integration	Installation/ Removal of System	Ease of Design	Ease of Manufacturing	
Weighting	10	10	4	3	3	2	2	1	**TOTAL**
Inside Root	4	5	3	4	3	3	3	2	**137**
Outside Root	3	5	3	4	4	4	4	4	**136**
Main Shaft	4	1	5	5	5	3	5	3	**119**
MS & Rods	4	1	3	4	3	3	2	3	**96**
Bolts & Rods	4	4	2	3	2	3	2	3	**116**

Table 5: Location Decision Matrix

The unfavorable clearance time ratings for the designs that detach the rotor system at the main shaft are a result of a dynamics analysis concerning the blade exit path. The analysis demonstrated that detachment at the main shaft does not necessarily provide adequate clearance for in-flight activation.[45] While inside and outside root are very similar in point totals, the HBEDS team chose to locate the system at the inside root because it takes full advantage of the open area between the flexbeam and composite sleeve on the EC-135. Additionally, the inside root scored higher than any of the other locations with respect to the two most important categories.

6.3 Explosives Trade Study

Through research of explosives, the team identified several types and classifications of compounds. The two main types are low explosives and high explosives. Low explosives, like gun powder, quickly burn from the outer surface inward; whereas, high explosives, like dynamite, detonate almost instantaneously. Within the high explosives class, there are primary explosives, used in detonators, and secondary explosives, which are initiated by primary explosives. Primary explosives are very sensitive to outside shocks while secondary explosives are more stable.

The trade study focuses on secondary high explosives because the other explosives lack the energy to weight ratio required by HBEDS. Additionally, there are five main classes of secondary high explosives: straight nitroglycerine (NG) dynamites, ammonia dynamites, straight NG gelatine dynamites, ammonia gelatine dynamites, and cyclo-trimethylene-trinitramine

[45] See Appendix H for details of blade detachment dynamics analysis.

(RDX) mixtures.[46] The primary differences between the classes are the explosive base and its state. The advantages and disadvantages for each class in terms of HBEDS are discussed in the explosive trade study.[47] Results of the analysis of each class are presented in Table 6.

	Reliability	Accidental Detonation	Intentional Initiation	Water Resistance	Heat Resistance	Temperature of Climate	Strength	Brisance	Cost	
Weighting Factor (1-5)	4	5	4	3	2	3	3	3	1	TOTAL
Straight NG	5	2	5	2	2	2	5	5	1	97
Ammonia	3	3	3	3	3	4	4	4	3	93
NG Gelatine	4	3	4	5	3	3	4	4	2	103
Ammonia Gelatine	3	4	2	5	4	4	3	3	5	98
RDX Mixtures	4	4	3	5	5	4	4	3	3	109

Table 6: Explosives Decision Matrix

The table states that a secondary high explosive from the RDX family should be used as the main charge due to its power, stability, and resistance to environmental stresses. Another consideration is that the charges will most likely be purchased from a controlled explosives company, such as McCormick-Selph, Inc. or Ensign-Bickford Aerospace and Defense Company. This supplier would design a linear shaped charge and choose the exact explosive compound that would be used in the application. Linear shaped charges are reliable, efficient severance devices that are commonly used to cut metallic and non-metallic structures along complex airframe surfaces.[48] The trade study therefore recommends RDX as a compound that could be used in linear shaped charges. A detailed description of why that class of explosive is appropriate is included in the full Explosives Trade Study, provided in Appendix I.

6.4 Signal Transfer Method

The HBEDS team considered various methods of transferring the detonation signal from the stationary fuselage to the explosives rotating with the blades. Six different signal transfer methods were analyzed against a set of design criteria. These methods include using radio waves, Hall Effect sensors, a mechanical system, an optical signal, or an electrical signal to initiate the explosives. The criteria used for this decision derive from the project specifications: stability, efficiency, power, reliability, clearance time, cost, serviceability, durability, and adaptability. These criteria were weighted from one to ten and the different methods were rated

[46] C.E Gregory, *Explosives for North American Engineers* (Germany: Trans Tech Publications, 1973) 44.
[47] See Appendix I for complete details on the Explosives Trade Study.
[48] Linear Shaped Charge Assemblies, *Aerospace and Defense Product Catalogue*, Ensign-Bickford Aerospace and Defense Company, 2003.

against them. The results of this process are shown in Table 7. A more detailed description of the reasoning behind the numbers can be found in Appendix J.

	Stability	Efficiency	Power	Reliability	Clearance Time	Cost	Serviceability	Durability	Adaptability	
Weighting Factor (1-10)	10	3	3	5	3	1	2	2	1	TOTAL
Radio Waves	2	4	2	2	2	2	2	1	5	67
Hall Effect Sensors	2	4	2	2	4	2	2	2	3	73
Mechanical Interaction	4	3	4	5	3	4	4	4	3	118
Optical Signal	2	4	2	3	4	2	2	1	4	77
Electrical Signal	2	5	3	4	5	3	4	3	3	99

Table 7: Signal Transfer Method Decision Matrix

Table 7 illustrates why a mechanical signal transfer is the best solution for HBEDS. Most of the reasoning stems from a mechanical system's stability and reliability. Therefore, as the HBEDS team designs the transfer system, a mechanical interaction will be used to transfer the activation signal from the non-rotating helicopter to the rotating explosives in the blades.

6.5 Ignition Train Trade Study

Selection of mechanical signal transfer prompted the team to investigate controlled explosive ignition trains. Such systems were employed on the NASA RSRA aircraft because they require no maintenance and, more importantly, are insensitive to lighnting, radio frequency, electrostatic discharge, mechanical inputs, heat, and fire.[49] Having identified stability as one of the key specifications for the project, the group decided to investigate different controlled explosive ignition train systems.

HBEDS requires an ignition train that transmits the explosive detonation signal from a cockpit-located initiator to the four blade-mounted linear shaped charges. In consideration of the project specifications, the HBEDS team compared multiple ignition train alternatives to assess tradeoffs in reliability, weight, and cost. Six ignition train alternatives were proposed, each exhibiting different arrangements of detonating cord, manifolds, and piston actuators.[50] Data provided by explosives manufacturers was then used to estimate the expected reliability, weight, and cost of each alternative, allowing for a quantitative comparison of the designs. The

[49] Bement, 4.
[50] Descriptions of these components and the proposed alternatives are provided in Appendix K.

characteristics of the six alternatives and corresponding reliability, weight, and cost scores are given in Table 8.

Components	Alternative A	Alternative B	Alternative C	Alternative D	Alternative E	Alternative F
Detonating Cord	23ft / 16 sections	29ft / 14 sections	25ft / 18 sections	31ft / 16 sections	31ft / 12 sections	23ft / 14 sections
Piston Actuators	1	1	2	2	2	2
Manifolds (2-1) or (2-2)	4	2	5	3	1	3
Initiators	1	1	1	1	1	1
Disarm/Interlocks	5	5	5	5	5	5
Linear Shaped Charges	4	4	4	4	4	4
Transfer Systems	1	1	1	1	1	1
Calculated Reliability	$0.9813R_{transfer}$	$0.9834R_{transfer}$	$0.9821R_{transfer}$	$0.9843R_{transfer}$	$0.9805R_{transfer}$	$0.9823R_{transfer}$
Calculated Weight	18.0lb + $W_{transfer}$	17.1lb + $W_{transfer}$	19.7lb + $W_{transfer}$	18.8lb + $W_{transfer}$	16.6lb + $W_{transfer}$	17.9lb + $W_{transfer}$
Calculated Cost	\$26,800 + $C_{transfer}$	\$24,700 + $C_{transfer}$	\$29,600 + $C_{transfer}$	\$27,500 + $C_{transfer}$	\$23,900 + $C_{transfer}$	\$26,000 + $C_{transfer}$
Reliability Score (x2)	2.1	7.6	4.2	10.0	0.0	4.7
Weight Score	5.3	8.3	0.0	2.7	10.0	5.7
Cost Score	4.9	8.6	0.0	3.7	10.0	6.3
Weighted Average Score:	3.6	8.0	2.1	6.6	5.0	5.4

Table 8: Characteristics of Proposed Alternatives

The weighted average score indicates that Alternative B is the preferred design platform for the signal transfer network. Although slightly less reliable than Alternative D, this design offers a balance of reliability, weight, and cost that make it well suited for the HBEDS application. However, though Alternative B is preferred over other alternatives, each design exhibited significant shortcomings in reliability. None of the alternatives exceeded 98.5% reliability at 95% confidence, significantly limiting the reliability potential of the entire system. A modification to the Alternative B design was therefore proposed to investigate the reliability increases that could be achieved with fully redundant transfer lines. A schematic of this ignition train design is provided in Figure 12.

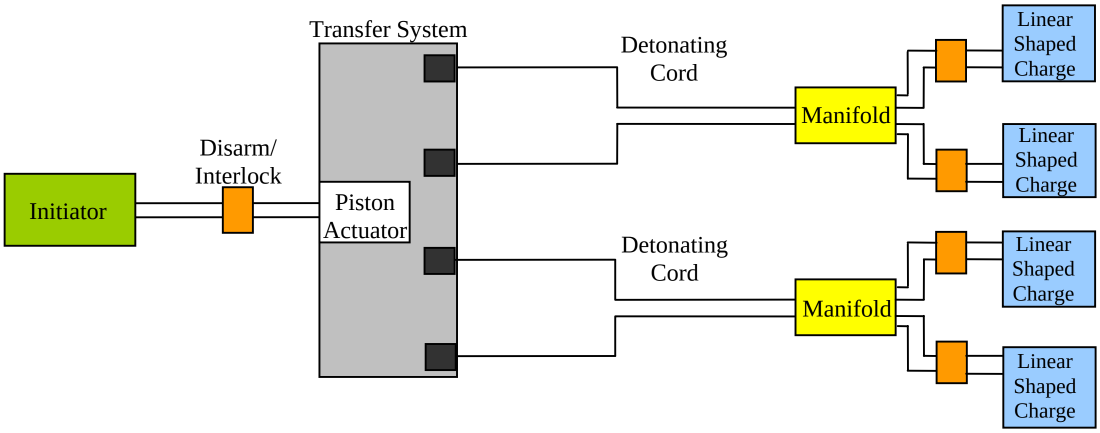


Figure 12: Proposed Modification to Alternative B

Compared to the original design, modified Alternative B had much greater reliability and only moderately increased weight and cost. Adding redundant transfer lines to the system increased the predicted reliability to 99.5% while incurring weight and cost penalties of approximately 2.7lb and \$3900. The project team believes increased reliability would make the

HBEDS concept far more acceptable to pilots, and that the additional weight and cost could be absorbed into the relatively large gross weight and high operating expenses of military helicopters. The modified version of Alternative B will therefore be analyzed throughout specification testing and later recommended for development of HBEDS beyond the proof of principle stage.

6.6 Transfer System Location

The team looked at four different possible mounting locations for the mechanical signal transfer system. These locations are above the swashplate, integrated into the swashplate, below the swashplate, and below the main shaft. The team then considered eight design criteria to evaluate the locations. It should be noted that integration was added to the list of normal criteria because how the transfer system interfaces with the existing flight structure is vital to the success of the HBEDS project. The criteria were weighted on a scale of one to five and then the locations were graded on a scale of one to five for each criterion. The results of this process are presented in Table 8 and more detailed information on the decision can be found in Appendix L.

	Stability	Efficiency	Reliability	Clearance Time	Cost	Serviceability	Integration	Adaptability	
Weighting Factor (1-5)	5	3	5	3	1	2	5	1	TOTAL
Above Swashplate	1	3	2	3	3	4	1	4	53
Integrated into Swashplate	3	4	4	3	1	1	2	1	70
Below Swashplate	3	3	3	3	3	3	1	4	66
Below Main Shaft	4	3	4	3	2	2	4	3	87

Table 8: Transfer System Location Decision Matrix

As shown in the table above, mounting the transfer system below the main shaft is the best location for HBEDS. This location scored the highest in the three most important criteria of stability, reliability, and integration.

7.0 Design and Development Overview

In light of the decisions made in the preceding trade studies, this section will expand on those decisions and describe the concept for the Helicopter Blade Emergency Detachment System. As shown in Figure 13, HBEDS gives the pilot the capability to detach the main rotor blades. This is accomplished with a lever in the cockpit to initiate the system, explosive charges located at the root of each main rotor blade, and an ignition train to provide the detonation signal.

Many of the ignition train components included in the design are provided by subcontractors; those not covered in this section are addressed in Appendix K. The majority of this section will be used to describe design work on the transfer system, which provides a mechanical transfer of the signal for detonation from the stationary engine transmission to the rotating main rotor system. Also, while the objective of this report is to provide a proof of principle of the HBEDS concept, many detailed design questions will be considered in the following pages to serve as a guide for the engineering challenges posed by such a system.

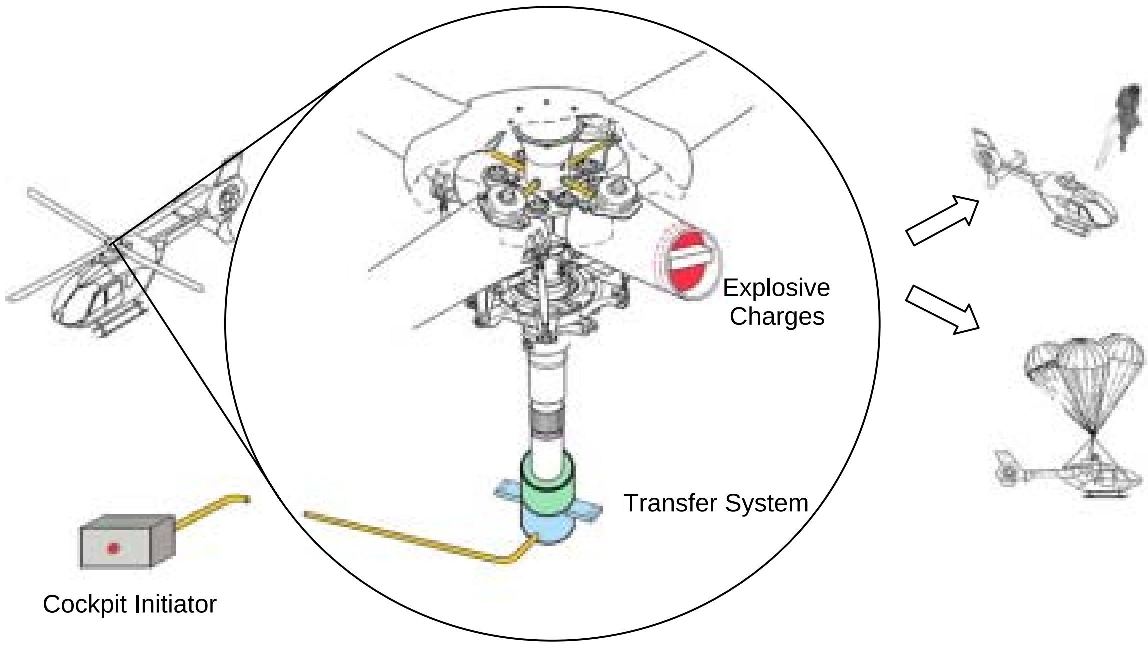


Figure 13: HBEDS Concept Diagram[51]

The specifics of the cockpit initiator will not be discussed here, as any design will have to take into account the specific cockpit layout. However, aerospace standards for such emergency systems generally dictate the use of a lever, rather than a button, to decrease the possibility of accidental activation.[52] From the cockpit, detonating cord would be routed beneath the passenger cabin along with the main bundle of wires on the EC-135, connecting the controls in the front of the aircraft with components in the rear. The detonating cord would be attached to the base of the transfer system, providing an input, and to the top of the transfer system, receiving an output. As shown in Figure 14, the detonating cord exiting the transfer system will run up the center of the hollow shaft, also known as the main mast. There is precedent for this, as a sensor currently uses this space in similar fashion. For such a design, the detonating cord

[51] Original line drawing provided by Eurocopter. See *Aircraft Maintenance Manual EC-135*, Eurocopter Group, Part 1, (1997), p. 3.
[52] The NASA RSRA aircraft used a lever to activate their blade detachment and ejection sequence.

would be bonded to the inside of the shaft in the factory rather than in the field, just as is the sensor wiring. The cords would exit the top of the shaft through a non-structural covering and out to the explosive charges on each of the four main rotor blades.

The detonating cord is not subject to space constraints, so long as the length of cord within the main mast does not interfere with the current sensor wiring. However the transfer system is a larger component that may encounter space constraints, with an approximate outside diameter and height of four inches. Given the decision made in the transfer system location trade study to place the transfer system at the base of the engine transmission case, the team needed to examine the space constraints and environment at the base of the transmission case.

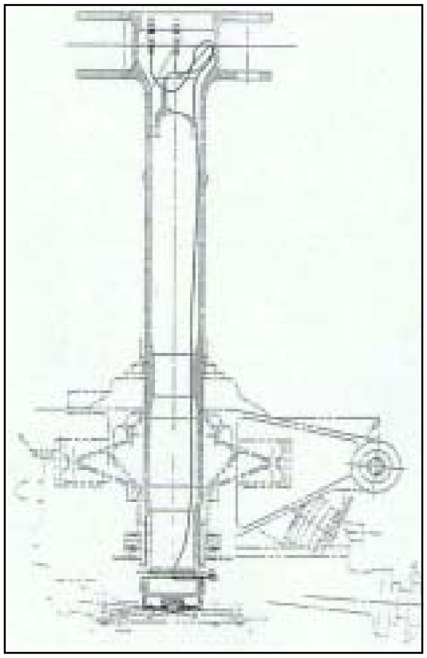


Figure 14: Internal View, Main Mast[53]

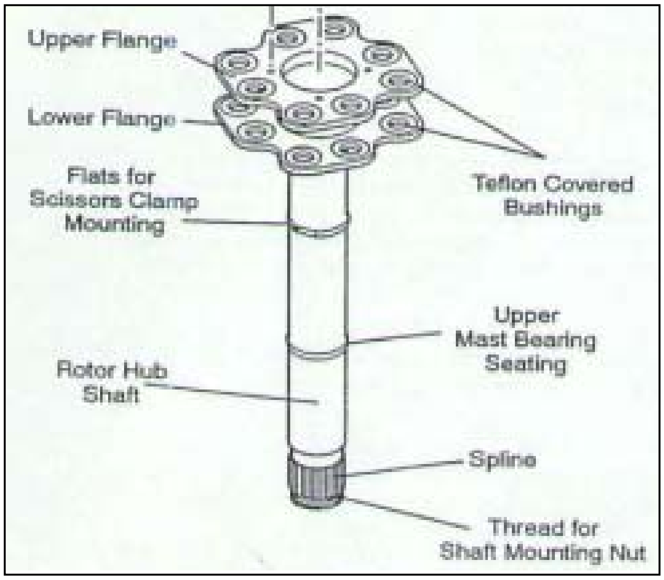


Figure 15: External View, Main Mast[54]

The transmission itself serves to integrate output from the two engines and gear it down. This power is used to drive the main mast, pictured in the center of Figure 14. The main mast, onto which the main rotor blades are attached, is supported by two large bearings, one at the top of the transmission case and another at the base of the shaft. The gap from the base of the main mast and thrust nut to an access panel is approximately three inches. Figure 15 shows a large spline at the bottom of the main mast used to transmit drive power to the mast, along with a threading arrangement for the shaft mounting nut, also called the thrust nut. The thrust nut is tightened onto the mast with 800 Newton-meters (Nm) of torque and serves to restrict the axial

[53] Eurocopter, *Aircraft Maintenance Manual EC-135.*
[54] Eurocopter, *Aircraft Maintenance Manual EC-135.*

motion of the mast. The transmission also operates with an open oil sump, meaning that the gap shown in Figure 16 below the main mast is normally filled with oil, and when the engines start that oil is partially drained and pumped to the necessary components in the transmission.[55]

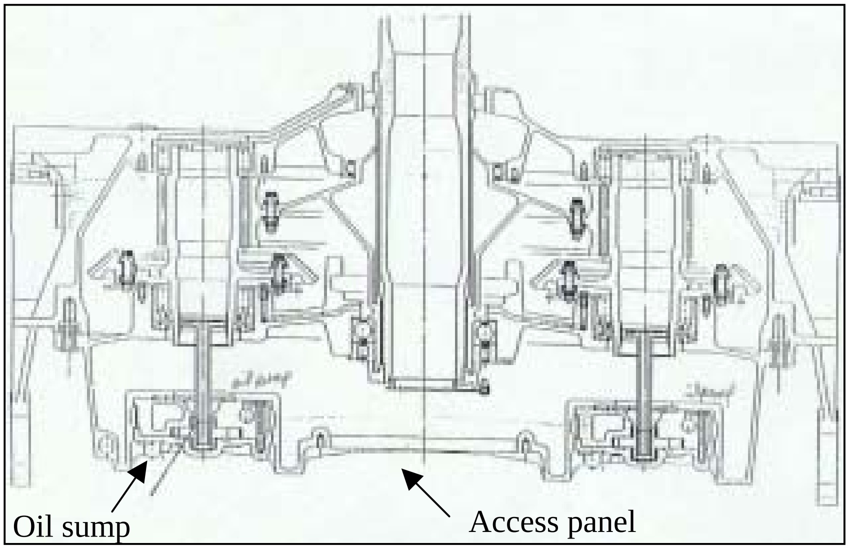


Figure 16: EC-135 Transmission Case Cross Section[56]

7.1 Internal Transfer System Design

Given this environment and space constraints, the HBEDS team sought to design the mechanical signal transfer system, provisions for attaching the rotational component to the main mast and stationary component to the transmission case, and arrangements for joining the rotary and stationary components. The transfer system design must necessarily incorporate or replace the components currently below and attached to the main mast: the thrust nut and mast moment sensor. Likewise, all design decisions were intended to minimize the likelihood of inadvertent activation of the system

Early designs focused on using an actuating cam to strike a rotating firing pin, with various orientations and housing arrangements. In the final prototype, a stacked orientation was chosen based on size constraints. A mockup was constructed to illustrate this design, shown in Figure 17. It consists of four rotating cartridges and one stationary piston actuator that bridges the gap between the two and strikes the cartridge, transferring the signal for detonation.

[55] Specific information about the engine transmission was garnered through interviews with the helicopter mechanic for the Dartmouth-Hitchcock Medical Hospital's Advanced Response Team and Eurocopter of America employees. Rod Fryman, Dartmouth-Hitchcock Advanced Response Team Mechanic, Personal communication, 8 Feb. 2004. Eric Herps, Eurocopter Technical Support Representative, Personal communication, 14 Feb. 2004. Darren Allen, Eurocopter Transmission Overhaul Manager, Personal communication, 17 Feb. 2004.

[56] Eurocopter. *Aircraft Maintenance Manual EC-135*.

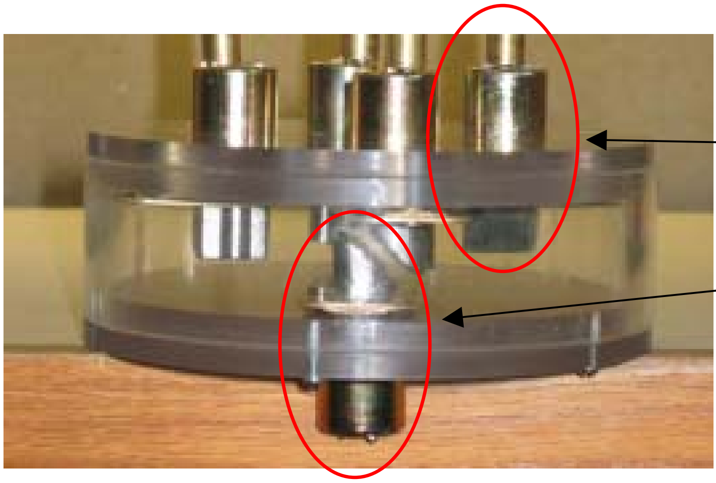


Figure 17: Transfer System Mockup

The method of striking rotating components with a relatively fixed object to transfer a signal is related to designs found in the barrel of a revolver or the mechanical firing of a gatling gun. The piston actuator is placed at the end of a length of detonating cord, and upon detonation it fires a piston with up to 1200 pounds of force,[57] which remains fixed in extension. The options for fittings at the beginning of a length of cord vary, but include those which receive electrical inputs or mechanical inputs. The latter was chosen in line with the decision in the detonation signal transfer study. The manufacturer designs mechanically activated end tips to ignite when they receive an energy input of 52 inch-ounces.[58] The team recreated the specification test provided by Ensign-Bickford Aerospace and Defense Company, and these calculations are shown in Appendix M. Pictures of these components are provided in Appendix K. At this point in the design many new terms come into use, Appendix N lists and defines these terms.

In order to integrate these sub-contractor provided parts into the transfer system, a housing was designed for the piston actuator within the stator (the stationary section of the transfer system), as well as a four cartridges on the rotor (the rotating section of the transfer system). The cartridge houses components that provide the required input to the detonating cord fitting (end tip). Four cartridges were required to provide proper sequencing and integrate with the ignition train design. Next, the design team needed to find a way, through the use of a piston capable of a force output, to provide an energy input to the detonating cord end tip. The solution

[57] *Piston Actuators,* Ensign Bickford Aerospace and Defense Product Catalogue. 2003. Ensign-Bickford Aerospace and Defense Company.
[58] Dave Stilwell, Ensign Bickford Aerospace and Defense Company, "re: quick question- detonating cord," email to the author, 3 Feb 2004.

is shown in Figure 18. All the components are cylindrical, but they are shown in cross section for clarity.

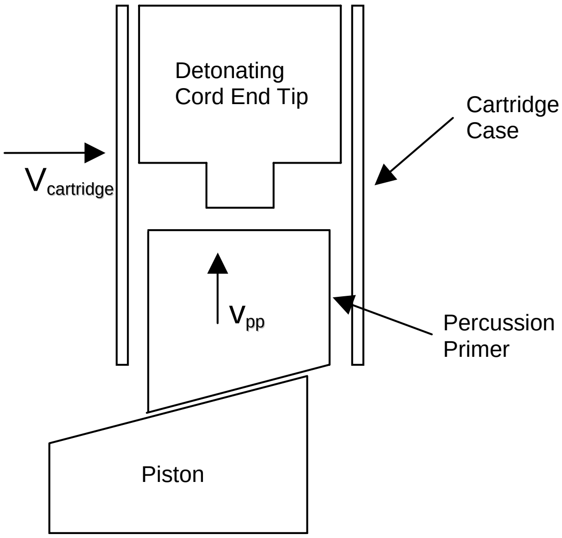


Figure 18: Cartridge and Piston

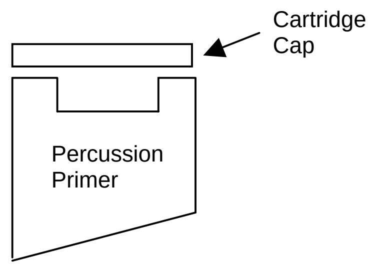


Figure 19: Percussion Primer and Cartridge Cap

Given this design, further understanding of the dynamics of the system was necessary. Under normal operating conditions, the main mast rotates at approximately 400 RPM, so the horizontal translational velocity of the cartridge is 2.3 feet per second (ft/s).[59] This relates to the vertical velocity of the percussion primer with a simple relationship involving the angle of incidence of the percussion primer. With an angle of 15 degrees,[60] the vertical velocity of the percussion primer is 0.61 ft/s.[61] It was thought at first that the kinetic energy of the percussion primer could alone provide the input necessary to the detonating cord end tip. However, this was disproved by analysis, as the energy provided was less than one percent of the requirement.[62] Consequently, a second alternative was devised, one which allowed the piston to press the percussion primer into the end tip with a sufficient force to provide the necessary input energy for detonation. This alternative would require controlled deformation of the percussion primer to avoid failure of the piston. As shown in Figure 19, a metal cap was placed on top of the percussion primer which would be designed to fail once it had provided the necessary input energy to the end tip.

Since the manufacturer specified the necessary input as an energy unit, the team next sought to relate that to the force required to cause the cartridge cap to fail. This could not be determined analytically, because the duration of impact was unknown. Several tests were

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59 Calculations shown in Appendix O.
60 Reasoning for this angle choice is explained later in text.
61 Calculations shown in Appendix P.
62 Calculations shown in Appendix Q.

conducted to come to a reasonable value for the input, and from these tests it was concluded that a 675 pound (lb) impact force was necessary to detonate the end tip.[63] A more precise value could be more accurately determined through further testing, calculations, and consultation with other companies that use detonating end tips. To account for the uncertainty in this experiment, a factor of safety of 1.5 was employed, raising the necessary applied force to approximately 1010 lbs. Given this design requirement, an appropriate thickness for the cartridge cap is 0.68 inches.[64]

In order to design the cartridge and piston components, an analysis of the forces involved to deliver that 1010 lb force must be made. This will allow the design team to choose the geometry of the percussion primer and piston and the type of bushings to be used, which comprise the cartridge walls. A free body analysis revealed seven relevant forces acting on the percussion primer, which could be altered by changing five different parameters: length, width, angle of incidence, the coefficient of friction between the percussion primer and piston, and the coefficient of friction between the percussion primer and the cartridge walls. After determining the variables in this analysis and using Newton's Second Law, the parameters were varied using Excel in order to minimize the normal forces on the cartridge wall, under certain constraints. For the details of this analysis, please refer to Figure 20, Table 10, and Appendix T.

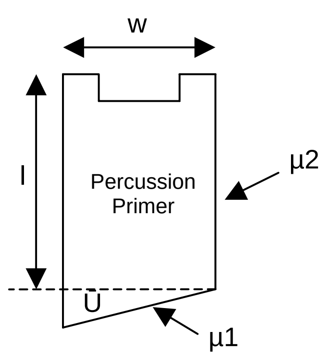


Figure 20: Cartridge Forces

Parameter	Value	Effect of increase in value
l	0.7"	little or no effect
w	0.375"	little or no effect
Ū	15º	large increase in normal forces
μ1	0.16	small increase in normal forces
μ2	0.16	large increase in normal forces

Table 10: Effect of Parameter Changes on Cartridge Forces

This analysis provided enough information to move forward with the design of the internal components. The objective was to use the piston actuator to fire a piston into the gap between the rotor and the stator, striking each percussion primer and transferring the signal for detonation. For a detailed layout of the piston and cartridge assemblies, see Appendix U. Both the piston and the percussion primer should be made of hardened steel, although due to its larger size, the piston may have a hollow interior. The angle of incidence was designed to be low

[63] Testing summarized in Appendix R

[64] Calculation based on Aluminum 6061-T6. See Appendix S for calculations.

enough to minimize normal forces on the cartridge walls, while large enough to provide sufficient vertical travel during contact. An angle of 15 degrees suited these requirements, providing the percussion primer with a 0.2 inch travel. The impact forces were best distributed across the face of the percussion primer and piston by designing their angles of incidence to be equal.

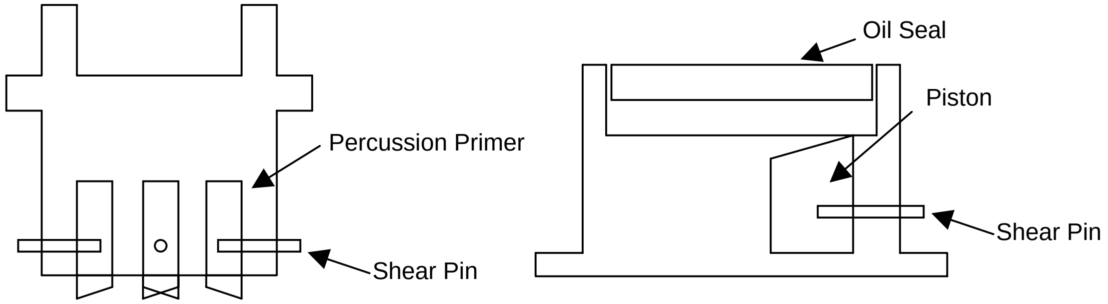
As Figure 20 shows, the friction between the steel piston and percussion primer has a small effect on the normal forces in the cartridge walls, but by greasing the contact surfaces, an acceptably low coefficient of friction can be obtained.[65] If a lower value is desired, certain alternate surfaces like zinc or magnesium can decrease this value to as low as 0.05, but the reduction in the normal forces would only be approximately 5%.[66] An appropriate grease for the steel, zinc, or magnesium surfaces would be a petroleum oil grease because its temperature range encompasses the normal operating temperature of the oil in the transmission.[67] A more robust alternative would be perfluorinated oil grease, appropriate up to temperatures of 280ºC, and is widely used in the aerospace industry.[68]

However, our analysis discovered that the friction force between the percussion primer and the cartridge wall proved to be much more important. By choosing a Teflon bearing rather than a porous metal bronze bearing, the friction coefficient ($\mu 2$) would drop from 0.16 to 0.05, yielding a 25% drop in normal forces during impact from 500 pounds to 375 pounds.[69] Bronze and Teflon bearings have static pressure limits of 8555 pounds per square inch (psi) and 2465 psi respectively,[70] so the bronze bearing was chosen because its expected load to pressure limit ratio was lower. A bronze bearing was used to support the piston within the stator as well.

The most important consideration during the design process was to ensure that the potential for inadvertent activation of the system was minimized. Keeping this in mind, a means to lock the percussion primers and piston in place during normal operation of the helicopter was devised. By cutting holes in the sides of the rotor, as shown in Figure 21, shear pins or screws

[65] Coefficient of friction values were obtained from Robert E. Green, *Machinery's Handbook, 25th Edition*. (New York: Industrial Press, 1996) 191-92.
[66] See Appendix T.
[67] Petroleum oil grease temperature range is -34 to 149ºC, while the normal operating temperature of oil in engine transmission is 50ºC. See Myer Kutz, "Lubrication of Machine Elements." *Mechanical Engineers Handbook, 2nd Edition*. (New York: John Wiley and Sons, 1998) 518. Temperature transmission provided by Rod Fryman, personal communication, 10 Feb 2004.
[68] Kutz, 518.
[69] See Appendix T.
[70] F.E. Kennedy, et. Al, "Tribology, Lubrication, and Bearing Design." *CRC Handbook of Mechanical Engineering* (1998) 156-57.

can be inserted into the percussion primer to fix it in place, and for the percussion primer to strike the detonating cord end tip, the pin must first fail. The shear pins add a degree of stability to the transfer system not evident in State of the Art research. A representative calculation is shown in Appendix V for the appropriate diameter of an aluminum shear pin: 0.063 inches for failure at 100 pounds or 0.10 inches for failure at 250 pounds. A similar arrangement was applied to the piston assembly as well. A valuable future test would be to subject the transfer system to forces experienced during operation to determine the appropriate impact force that the shear pin should protect against.



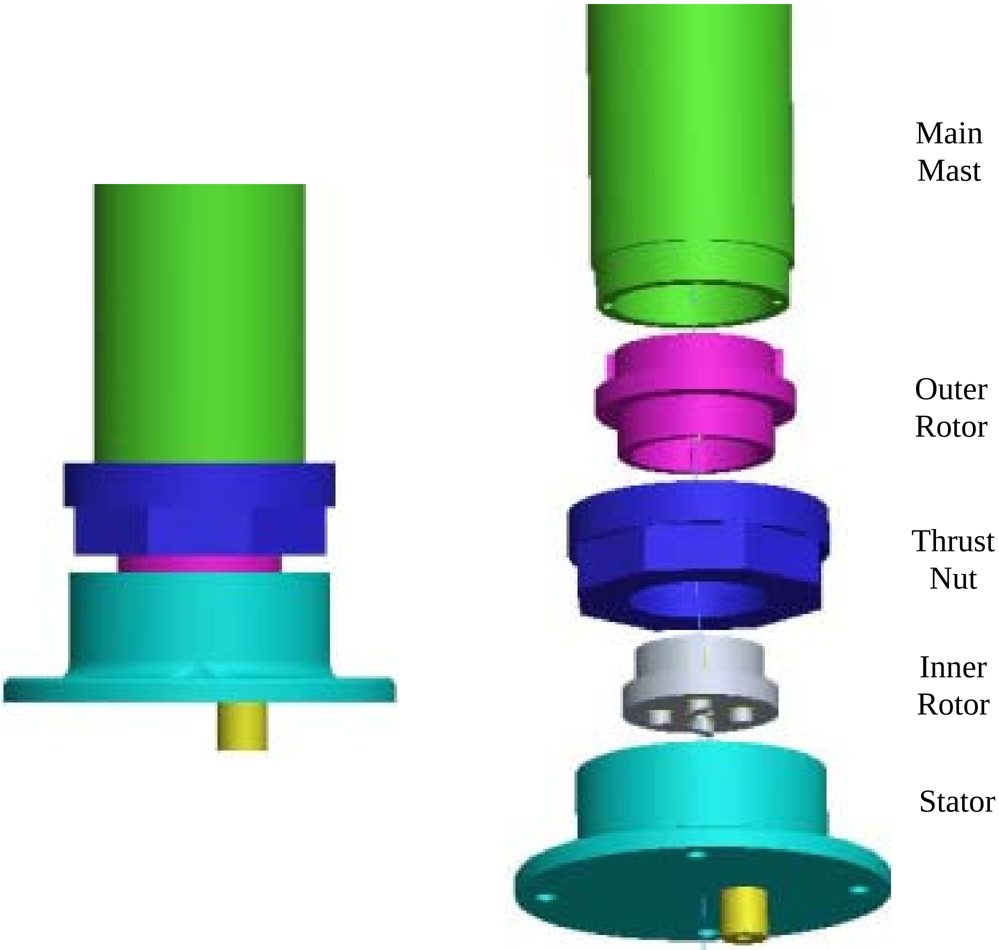
a) Rotor Assembly *b) Stator Assembly*

Figure 21: Rotor in Cross Section Illustrating Shear Pin.

7.2 Transfer System Housing Design

The next step in the design was to build the housing for these components.[71] There are several main design requirements and they are outlined below. The first main problem was addressing how the rotor should attach to the main mast. Early designs, shown in Appendix X, focused around clamping onto the main mast in much the same fashion as the swashplate is attached. However, once the exact geometry of the main mast was determined (Figure 14 and 15), a revised design was necessary for attaching the rotor to the main mast (Figure 22). This revised design also took into account the presence of the thrust nut and incorporated it in the transfer system design. In fact, slight modifications to the thrust nut allowed it to attach the rotor to the main mast as well. Alignment tabs restricted rotational motion of the rotor and ensured proper orientation of the blades at detachment,[72] while the vertical motion of the rotor was restricted by the thrust nut. By placing a rubber gasket between the lip on the thrust nut that grabs the rotor and the rotor itself, the crucial torque requirement of 800 Nm between the thrust nut and main mast can be maintained.

[71] For ProEngineer pictures of these housing components, please see Appendix W.
[72] See Appendix Y for calculations regarding all keying arrangements.



(side view) *(exploded view, parts shown in order of installation)*

Figure 22: Installed Transfer System

Finally, the rotor was broken into two sections, an inner and outer housing, to allow for detonating cord mounting from below. This is required because the detonating cord end tips are fixed in place, per their mounting arrangement in the main mast, and cannot be rotated. Thus, the outer rotor is slotted into the main mast, and each of the four detonating cords is tightened with lock nuts from below.[73] The inner rotor is then fixed into the outer rotor and the thrust nut is attached to the main mast, securing both in place. Regarding materials choice for the housing components, geometry dictated that the rotor be relatively small, which forced wall thickness in certain areas to be dangerously thin. Thus, a strong material like titanium should be used for the rotor housing. The stator itself has larger wall thickness due fewer size constraints, so aluminum would be a sufficient material.

[73] For pictures of end tips fixed onto outer rotor with lock nuts, see Appendix W.

Early designs for the stator focused on finding a way to make the rotor and stator interlock. However, contact between these parts was unnecessary because both would be adequately supported by the mast and transmission case. Instead, the stator houses an oil seal which maintains contact with the rotating rotor and prevents the flow of oil into the internal section of the transfer system. A conventional automobile oil seal was selected for this concept prototype, but a more robust alternative may be necessary for a final design. Consideration was given to the possibility of leaving the transfer system open to oil flow within the transmission. However, since the transfer system is located in the oil well, from which oil is drawn during operation, it was concluded that the system would be much less intrusive if it were sealed off and greased internally, rather than being open to oil flow and thus requiring a pump for proper circulation and excavation of the oil within and around the system. Other locations that need to be properly sealed include the shear pin entrance on the stator, as well as the contact between the stator and the base of the transmission case. For the latter case, a recessed o-ring between these two components addresses the concern.

Finally, the gap between the rotor and stator is very important because it determines whether the system can successfully transfer a signal for detonation.[74] If the gap is too large, a signal for detonation from the cockpit may be lost within the transfer system and never be transferred to the second set of detonating cords. This could be solved by reinforcing the access panel to which the stator is attached, lowering the tolerances on its location. In the alternate scenario where the gap between the rotor and stator is too small, a possibility given faulty installation, the signal for detonation could originate from the transfer system itself when the engines are next fired. This could be solved by adding a surface to the rotor that would contact the stator if it were improperly installed and the gap became dangerously small, in a sense making the installation fool-proof. Such a design change would further demand that the tolerances between the stator and rotor be small, because unwanted contact between the surfaces will cause wear and perhaps part failure (although not explosive detonation).

Concerning integration into the EC-135, the transfer system only requires modification to three components: two key slots must be added to the inside diameter of the main mast, the access panel will need a hole for the piston actuator to enter the transfer system with the detonating cord running from the cockpit, and the thrust nut will require modifications as discussed above. A fourth potential integration issue arises from the mast moment sensor, an

[74] See Appendix U for diagram.

optional accessory on EC-135s that the customer may select. It measures the moments experienced by the main mast and reads the output in the cockpit. It is of concern to the HBEDS team because several components hang down from the main mast where the transfer system is to be mounted. The components of interest mainly consist of a rotor and stator which transfer an electric signal.[75] Such components, if necessary, could be integrated into the transfer system, and a three quarter inch gap has been left in the center of the rotor for running necessary wiring or other components.

Several details should be considered in future design iterations. For one, analysis should be performed to determine whether the piston must be constrained from rotating within its bronze bushing following shear pin failure. Also, a satisfactory means for attaching the two rotor housing pieces, a part of the installations process, has not been devised. Finally, the surfaces where the piston actuator and detonating cord end tip attach, both sub-contractor provided parts, may need to be reinforced to better absorb the forces they will experience during signal transfer.

8.0 Concept Prototype Testing

A prototype was created to demonstrate the transfer system concept following the initial development of the HBEDS design. Although electronics were used to simulate the pyrotechnic ignition train components, the concept prototype operated on the same principles that would be employed in an actual system. The incoming signal was provided by a 24-volt DC push-type solenoid, a component that simulated the piston actuator. Rocker switches, electric wire, and LEDs modeled the cartridge, detonating cord, and explosive charges, respectively. Rotation of the disk caused the switches to be thrown, simulating contact between the piston and the percussion primer (Figures 23 and 24). When a switch was thrown, the prototype simulated detonation of two linear shaped charges by sending a signal to two LEDs mounted on opposing sides of the disk. The remaining LEDs were lit upon contact with the following switch, simulating the second stage of blade detachment.

[75] Diagram of Mast Moment Sensor components shown in Appendix Z.

Figure 23: Concept Prototype

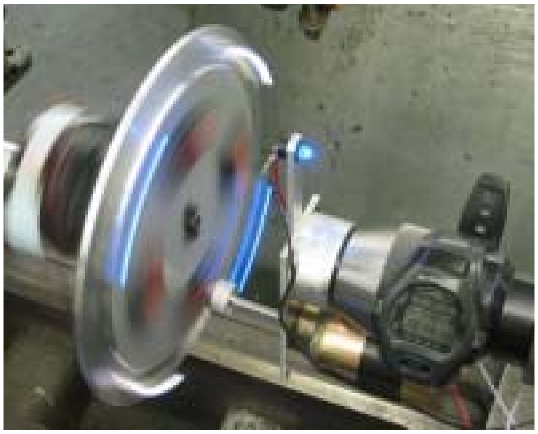


Figure 24: Concept Prototype Testing

In addition to demonstrating the transfer system design, the concept prototype was used to estimate the potential for the system to meet the reliability and safety specifications. Mounting the system to a lathe allowed the team to test and observe the system reliability over a wide range of RPM. In all, over 100 trials were performed between 40 and 600 RPM, and no failures were observed in any test. This allowed the team to conclude with 95% confidence that the reliability of the transfer system concept prototype was at least 97.25%.[76]

The safety specification was evaluated by measuring the angle at which the device simulated blade detachment. Ten trials were videotaped and the blade release angle for both stages of detachment was measured using video stills (Figures 25, 26, and 27).

Figure 25: Target Release Range

Figure 26: Stage I Detachment

Figure 27: Stage II Detachment

During testing, the concept prototype released blades between 2.5 and 7.5 degrees relative to the fuselage centerline aft, resulting in a normal distribution of measurements around 5°. As will be discussed in the safety specification validation section, it could be concluded with 99% confidence that the concept prototype released blades within the specified limits. However, despite this conclusion, the safety specification testing was limited to low RPM due to the slow (15 frames per second (fps)) frame rate on the video equipment. Tests were limited to an extremely slow rotational speed of 2.5 RPM so release angle could be measured to the nearest

[76] See Appendix AA for reliability calculations.

1 degree. Recognizing the potential for greater variability at higher rotational speeds, the team recommends that further testing beyond the proof of principle stage be conducted with a high speed camera capable of at least 3600 fps. This equipment would allow for measurements to the nearest 1 degree at rotational speeds up to 600 RPM, 50% faster than the EC-135 rotor system.

9.0 Specification Validation

The HBEDS team performed specification tests and recommended testing measure for future development. Recommendations were provided when the specifications called for explosives testing beyond capabilities of the group. Table 11 provides these recommendations and test results.

Specification	REQ #	Par.	Description	Validation
HBEDS Definition	REQ-1	1.1	The Helicopter Blade Explosive Detachment System (HBEDS) shall be a system that allows a helicopter's main rotor blades to be detached if the craft is involved in a critical emergency situation. Such situations may include uncontrolled descent, hard landings, ditching into water, on-board fires, or explosions.	Proof of Principle Prototype
Stability	REQ-2	2.1	Ballistic shock resistance: 40-ft drop test	Explosives certified under MIL-STD-810, Meth. 522
	REQ-3	2.2	Electrostatic discharge resistance: 25,000V via 500pf capacitor	Explosives certified under MIL-STD-1512, Meth. 205
	REQ-4	2.3	Lightning strike resistance: +/-18,000V simulated strike	Explosives certified under MIL-STD-1512, Meth. 302
	REQ-5	2.4	Heat resistance: autoignition temperature to exceed 600˚F	Explosives certified under MIL-STD-650, Meth. 506
Strength	REQ-6	3.1	System shall be resistant to static and fatigue failure	Alignment tabs designed for Ns = 4.0; Scott to input parameters
Efficiency	REQ-7	4.1	Mass of system to be less than 10 kg	10.7 - 11.9 kg
	REQ-8	4.2	Parasitic drag on rotor to increase by no more than 5%	Equivalent Flat Plate Area increased by less than 5%
Power	REQ-9	5.1	System capable of operating on 22.5V, 1.8Ah standby battery	Standalone system requires no power source
Reliability	REQ-10	6.1	Complete blade severance with at least 95% reliability	96.79% at 95% confidence
Clearance Time	REQ-11	7.1	Blade detachment to occur in less than 500 miliseconds	342 ms at 100 rpm for 6m clearance circle
Cost	REQ-12	8.1	Unit production cost under $20,000	$37,906
Serviceability	REQ-13	9.1	System inspection and replacement possible in under 2.5 hr.	Replacement of transfer system possible in under 2.5 hr.
Durability	REQ-14	10.1	Temperature shock: 1hr exposure to -65˚F and +200˚F	Explosives tested under MIL-STD-810, Meth. 503
	REQ-15	10.2	Vibration: 2hr exposure to random vibration at 10-2000Hz	Explosives tested under MIL-STD-1512, Meth. 113
	REQ-16	10.2	Materiel degradation: service life shall exceed 10 years installed	Explosive service life per MIL-STD-1512, Meth. 118
Adaptability	REQ-17	11.1	Design shall be adaptable to other aircraft	Design intended for use on four-bladed bearingless rotor systems with hollow main shafts
Safety	REQ-18	12.1	Blade detachment at 5˚ and 185˚ relative to fuselage (+/- 5˚)	5° and 185° +/- 5° with 99% confidence
	REQ-19	12.2	Explosive charge shall not damage fuselage	Future theoretical pyrotechnics analysis

Table 11: Specifications and Testing Results

Stability: System stability was evaluated by reviewing specifications provided by explosive manufacturers. Because the group was unable to test the explosives, qualification test data supplied by the manufacturer was used to assess system stability. A sample specification table for mild detonating cord is provided in Table 12. This component exhibits stability characteristics common to many aerospace-grade pyrotechnic devices, demonstrating resistance to the stresses highlighted in the HBEDS specifications. In recognition of the importance of stability, the group recommends that each component used in the ignition train be held to similar standards.

Ballistic Shock	6 foot drop test	fully operational
	40 foot drop test	safe to handle
Vibration	80-2000 Hz random vibration @ +/- 20g	fully operational
Acceleration	40g in any direction	fully operational
Electrostatic Discharge	25,000V from 500 pf capacitor	no fire
Heat	service temperature	-65°F to +350°F
	elevated temperature	withstand 425°F for 5 minutes

Table 12: Stability Characteristics of McCormick-Selph Shielded Mild Detonating Cord (SMDC)

Strength: The components of the transfer system were carefully selected in order to avoid the possibility of stress failure during activation. For instance, a bronze bearing rather than a Teflon bearing was chosen to house the percussion primer because its expected load to pressure limit ratio was lower.[77] Both the piston and the percussion primers are made of hardened steel, which allows them to absorb the approximately 1000 pound impact forces. Likewise, it is suggested that the rotor, and perhaps the stator as well, be made of titanium rather than aluminum to withstand the impact forces despite relatively thin wall thickness in several areas. Concern for fatigue failure rested mainly on the redesigned thrust nut, as it is the only part designed by the HBEDS team that will experience constant loading of any magnitude. To combat this fear of fatigue failure, the thrust nut was redesigned to be at least as robust as the previous version, assuming that the thrust nut designed by Eurocopter would not have experienced fatigue failure. The design team recommends further testing in future iterations of the transfer system design to confirm compliance with the strength specification.

Efficiency: The total mass of the system was calculated using mass estimates for ignition train components and densities of materials used in construction of the transfer system. Assuming the rotor and stator components will be made of titanium, the total mass of the prototype system is 11.9 kilograms, including 9.0 kilograms for the ignition train and 2.8 kilograms for the transfer system.[78] Alternatively, the transfer system would have a mass of 1.7 kilograms if it were made of aluminum,[79] resulting in a total mass of 10.7 kilograms. The

[77] See calculations in Appendix T.
[78] The calculation assumes a density of 4510 kg/m^3 for titanium. See Bernard Hamrock, Bo Jacobson, and Steven Schmid, *Fundamentals of Machine Elements* (Boston: McGraw Hill, 1999) 901.
[79] Calculation assumes a density of 2800 k/m^3 for aluminum. See Hamrock, 901.

prototype design fails to meet the 10 kilogram specification; however, the final transfer system design depends largely on material selection, and reliable mass estimates can only be made following a full strength analysis of each of the parts. The specific geometries exhibited by the prototype were somewhat influenced by the limited strength of the plastic, and the team believes that designing for titanium or aluminum construction would provide opportunities to reduce material volume.

The efficiency specification also addresses the aerodynamic drag associated with the system. Because the bulk of the system is integrated into the existing structure, installation of HBEDS is expected to cause only a very small increase in parasitic drag on the helicopter. With the explosives mounted inside the blade roots and the transfer system contained within the transmission case, the only aerodynamic drag resulting from installation will be on the ¼ inch shielded detonating cord transmitting the signal from the main shaft to each linear shaped charge. To evaluate the significance of this drag, the equivalent flat plate area of the exposed portion of the detonating cord was compared to the flexbeam to which it will be attached.[80] Equivalent flat plate area is a commonly used aerodynamic drag metric that is a factor of drag coefficient and frontal area:[81]

$$EFA_{line} = C_{D_{line}} A_{F_{line}} = (0.8)(0.0035\,ft^2) = 0.0028\,ft^2 \qquad (1)$$

$$EFA_{beam} = C_{D_{beam}} A_{F_{beam}} = (1.2)(0.0556\,ft^2) = 0.0667\,ft^2 \qquad (2)$$

$$\%_{increase} = 100\left(1 - \frac{EFA_{beam} - EFA_{line}}{EFA_{beam}}\right) = 100\left(1 - \frac{0.0667 - 0.0028}{0.0067}\right) = 4.2\% \qquad (3)$$

The equivalent flat plate area of the composite flexbeam therefore increases by only 4.2% with the addition of the detonating cord. Because the flexbeam itself represents only a small portion of the overall parasitic drag on the main rotor system[82], the total increase in parasitic drag associated with installation of the system is less than 5%.

Power: As outlined in the specifications, the system is required to operate on a backup power source such as a 22.5 volt, 1.8 ampere/hour standby battery. Selection of a percussion rather than electric initiator allows HBEDS to be a completely standalone system, avoiding the need for a power source altogether. As such, HBEDS complies with the power requirement.

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[80] Drag coefficients approximated by circular cylinder for the detonating cord and rectangular plate for the flexbeam. See *Technical Notes on Equivalent Flat Plate Area and Wind Loading,* Kathrein Scala Division, 26 Feb. 2004, <http://www.kathrein-scala.com/tech_bulletins/FlatPlate.pdf>.

[81] Leishman, 216.

[82] Leishman, 217.

Reliability: The concept prototype and ignition train trade study provided a means of approximating the reliability of the entire system. This estimate was obtained by multiplying the experimental transfer system reliability and calculated ignition train reliability:

$$R_{system} = R_{transfer} R_{ignitiontrain} = (0.9725)(0.9953) = 0.9679 \tag{4}$$

Assuming the transfer system could be made to operate as reliably as the concept prototype, the system reliability would be 0.9679 at 95% confidence. This projected reliability exceeds the success rate of the ACES II ejection seat, suggesting the reliability of the system could be deemed acceptable by military pilots.

Clearance Time: Clearance time was estimated by calculating the time for signal propagation, signal transfer, and blade exit. Signal propagation time was determined using the burn rate of the detonation cord and the approximate length of the ignition train:

$$t_{sp} = \frac{l_{train}}{rate} = \frac{(3.6m)}{(6000m/\sec)} = 6\times10^{-4}\sec \tag{5}$$

Signal transfer time depends on both the angular velocity of the main rotor system and the orientation of the percussion primers when the signal arrives at the transfer system. To account for a worst case scenario, the analysis assumes a main rotor speed of 100 RPM and required rotation of 180 degrees.

$$t_{st} = \frac{\chi_{required}}{w_{rotor}} = \frac{180\deg}{\left(\frac{100\,rev}{1\min}\right)\left(\frac{360\deg}{1\,rev}\right)\left(\frac{1\min}{60\sec}\right)} = 3.0\times10^{-1}\sec \tag{6}$$

Blade exit time also depends largely on the angular velocity of the main rotor system. Exit time may be approximated using conservation of momentum while neglecting air resistance. Assuming the clearance circle is 6 meters, the rotational speed is 100 RPM, and blade length is 5 meters with the center of mass is 3 meters from the main shaft:

$$t_{be} = \frac{r_{clearance} - r_{cm}}{v_{blades}} = \frac{(6m)-(3m)}{(2m)\left(\left(\frac{100\,rev}{1\min}\right)\left(\frac{2\pi}{1\,rev}\right)\left(\frac{1\min}{60\sec}\right)\right)^2} = 4.1\times10^{-2}\sec \tag{7}$$

Total clearance time for the worst case scenario is therefore about 342 milliseconds, well under the 500 millisecond specification.

Cost: Since HBEDS is not a final, production ready design, it is difficult to give an accurate final cost of the system when many particulars of the design have yet to be determined. However, HBEDS costs can be divided into the appropriate categories and be given values of the proper order of magnitude. Therefore, the team followed a standard cost accounting method of breaking the cost into fixed costs that can be distributed across all the systems made and variable costs that apply to each unit produced. (Table 13)

FIXED COSTS	**QUANTITY**	**PRICE / UNIT**	**TOTAL COST**	**COST / UNIT (1000)**
Engineering Design	7	$30,000	$210,000	$210
Part Testing	7	$20,000	$140,000	$140
Prototype Testing	5	$61,200	$4,306,000	$4,306
Flight Certifications	2	$75,000	$150,000	$150
		FIXED COSTS:	**$4,806,000**	**$4,806**

VARIABLE COSTS	**QUANTITY**	**PRICE / UNIT**	**TOTAL COST**
Linear Shaped Charges	4	$2,500	$10,000
Detonation Cord Sections	24	$550	$13,200
Piston Actuator	1	$1,100	$1,100
Manifolds	2	$350	$700
Disarm/ Interlocks	5	$600	$3,000
Initiator	1	$600	$600
Transfer System	1	$2,000	$2,000
Assembly Costs	1	$2,500	$2,500
		TOTAL VARIABLE COSTS:	**$33,100**

TOTAL COST (Variable and Fixed / Unit):	**$37,906**

Table 13: HBEDS Cost Analysis

The fixed costs included future engineering design work, part testing, full prototype testing, and flight certification costs. Aside from the values of each fixed cost, three significant assumptions have been made. The first is that the existing design and manufacturing facilities could accommodate the development and production of HBEDS. The second is that for each new HBEDS application, there will be some engineering design and testing that must be done above what the HBEDS team has accomplished. The third assumption is that HBEDS will be applied to a minimum of 1000 helicopters per production run.

The team figures that all seven HBEDS' components will need some amount of engineering design work above what has been accomplished this far; therefore, $30,000 is viewed as an average cost to make design changes to HBEDS so that it will fit the final application. Following that same logic is the parts testing and the prototype testing costs. All seven parts will need to be tested, so $20,000 was used per part, which includes the cost of the components and the staff required to run the tests. In addition to five full scale test systems, a complete helicopter will be required for one full flight test. Therefore, an additional $4 million is included to cover the cost of that aircraft. The final fixed cost is the flight certifications required to demonstrate airworthiness of the system. Qualification testing of the transfer system and the explosive charges is forecasted to cost approximately $75,000 per component.[83]

The variable costs are also broken into two groups. First are the seven HBEDS components at the prices assumed in the Ignition Train Trade Study.[84] The second is the additional assembly cost of HBEDS components. While installation of the system is fairly simple, a qualified technician will be required to certify the system as being flight-worthy.

These two cost categories, fixed and variable, result in a cost of around $37,900 for the entire system. This number is almost twice the cost specification; however, since all of the ignition train component costs supplied by subcontractors, the final cost is not seen as inappropriate or unjustified.[85]

Serviceability: During development of the design the team learned that beyond visual inspections, little can be done to service and maintain explosive assemblies. Instead, controlled explosives manufacturers rely on extensive qualification tests to certify that the explosive will operate as intended throughout its service life.[86] The team therefore assumed little or no maintenance of the explosive charges would be necessary, and the linear shaped charges would be permanently mounted inside the blade roots. In the case of the Eurocopter, the permanent linear shaped charges would be replaced with the blades about every 12,000 flight hours.[87]

The prototype transfer system is accessed through a large panel located at the base of the transmission casing. The removable panel provides mechanics ample access to the main shaft thrust nut and the mast moment sensor. Although the transmission is overhauled at 5000 flight-hour intervals,[88] mechanics regularly require access to this area during oil changes, and could provide fairly regular visual inspections of the transfer system. Replacement of the transfer system itself would require opening the access panel, disconnecting the stator, and removing the main thrust nut. Reassembly of the system is greatly simplified by alignment tabs provided on

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[83] Information provided by David Stillwell, Ensign Bickford Aerospace and Defense Company, “Re: quick question-detonating cord,” email to author, 21 Jan 2004.
[84] See the Ignition Train Trade Study in Appendix K.
[85] The value initially selected for the cost specification neglected to account for the high cost of aerospace grade explosive components. It is believed that the estimated cost of $40,000 is acceptable given the total cost of military helicopters.
[86] David Stillwell, personal communication, 13 Jan. 2004.
[87] Eurocopter’s bearingless rotor blades have a service life in the neighborhood of 12,000 operating hours. See *Airworthiness Directive Schedule: SA365N Helicopter Series,* 2000, Civil Aviation Authority of New Zealand, 24 Nov. 2003, <http://www.caa.govt.nz/fulltext/nzcars/vol_2/Section_A/A2_Helicopters/sa365.PDF>.
[88] Rod Fryman, personal communication, 10 Feb 2004.

the rotor components. Although formal tests of the entire system replacement time could not be tested, the team expects the transfer system could be replaced in under 2.5 hours.

Durability: Similar to the stability specification, the durability of the explosives will be validated using test data provided by controlled explosives manufacturers. Qualification tests must be performed to demonstrate resistance to temperature shock, vibration, and materiel degradation under the expected operating conditions. As described in the Specifications section, the team recommends that military standards be used as a reference for evaluating durability of explosive components in future development of the system.

Adaptability: Although the Eurocopter EC-135 was used as a model application for the development of HBEDS, the concepts employed could be applied to any helicopter with a four-bladed bearingless rotor system and a hollow main shaft extending through the transmission. As discussed in the State of the Art section, bearingless rotor technology is the future of helicopter design. Such technology was incorporated into the recent RAH-66 Comanche project and is currently being used on the AH-1Z Super Cobra (Figure 28). Also, like the EC-135, many helicopters exhibit a hollow main shaft that is easily accessible from the base of the transmission. Transmissions generally support and power the mast with multiple bearings and a spline drive, with axial loads carried by a thrust nut mounted near the base (Figure 29). Of the transmission designs reviewed during the team's research, none exhibited significant deviations from the EC-135 design. Considering the potential for bearingless rotor systems to become the industry standard, and the general commonality of helicopter transmission design, the team concludes that the concept will be reasonably adaptable to many different helicopter platforms in the future.

Figure 28: Bell AH-1Z SuperCobra[89]

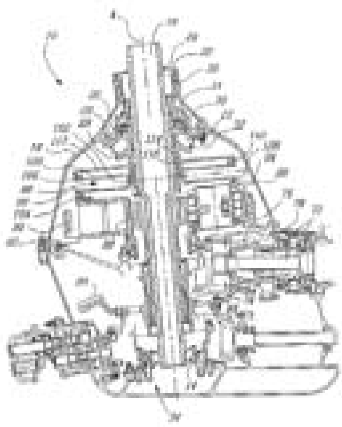

Figure 29: Typical Helicopter Transmission[90]

[89] *AH-1Z,* 2003, Bell Helicopter Texitron, 4 Mar. 2004, <http://www.bellhelicopter.textron.com/aircraft/military/bell_ah-1z.html>.

Safety: Testing of the concept prototype allowed for evaluation of the safety specification. The data for the measured blade release angle followed an approximately normal distribution centered around 5 degrees and 185 degrees relative to the fuselage (Figure 30).

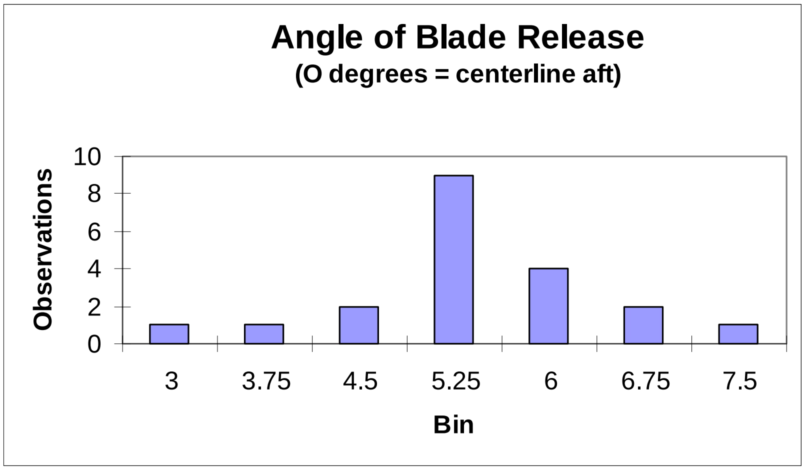

Figure 30: Blade Release Angle Histogram

To release blades within a 5 degree margin of error with 99% confidence, the blades must be theoretically be released with a standard deviation (ů) below 1.67 degrees. Using data from the twenty trials, the chi-square distribution allowed for an estimate of the upper bound of ů:

$$\omega \, \Omega \sqrt{\frac{(n\ 4\ 1)s^2}{\theta^2_{14\zeta,n41}}} \mid \sqrt{\frac{(19)(1.02)^2}{7.63}} \mid 1.61\forall\Omega 1.67\forall \qquad (8)$$

The theoretical upper bound of sigma was therefore 1.61 degrees, below the critical level of 1.67 degrees. It could then be concluded with 99% confidence that the concept prototype released blades within the specified limits, meeting the safety specification.

10.0 Post-Detachment Analysis

A helicopter flies by maintaining a delicate balance of opposing lift and drag forces. Designed to be used in life-threatening emergencies, HBEDS abandons this balancing effort by detaching the main rotor blades. Although the system calls for subsequent crew ejection or ballistic parachute deployment systems, the dynamic response of the helicopter must not subject the crew to critical accelerations (i.e. ‘g-forces’) immediately following activation. Additionally, activation of HBEDS must not destabilize the aircraft to such an extent that the risk of rollovers is increased during hard landings. Drawing from these concerns, an analysis was performed to determine whether gravitational forces and tail rotor thrust would result in undue fuselage

[90] Lazar Mitrovic, *Rotor Shaft Support and Drive Arrangement*, 2002, United States Patent and Trade Office, 4 Mar. 2004, < http://www.delphion.com/cgi-bin/viewpat.cmd/US06394387__?MODE=fstv&OUT_FORMAT=pdf>.

accelerations following blade detachment. The analysis specifically examines accelerations experienced by the pilots one second after blade detachment during a stationary hover.[91]

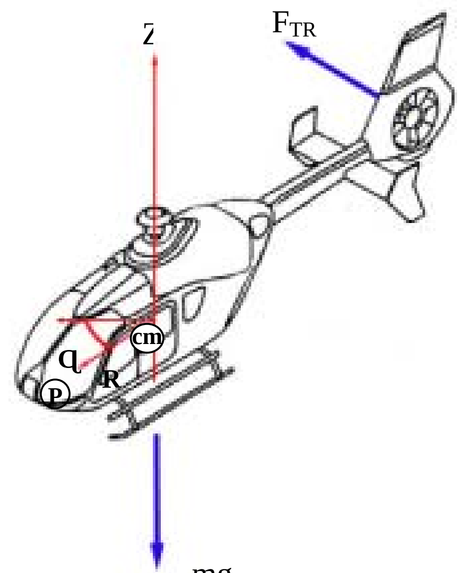

Figure 31: Free Body Diagram for Post-Detachment Analysis[92]

Following blade detachment, the aircraft will immediately begin to spin and translate due to tail rotor thrust and gravitational force (Figure 31). The resulting acceleration experienced by the pilot ($\underline{a}_p$) may be expressed as the sum of the acceleration of the center of mass ($\underline{a}_{cm}$) and the acceleration of the pilot relative to the center of mass($\underline{a}_{p/cm}$):

$$\underline{a}_p = \underline{a}_{cm} + \underline{a}_{p/cm} \qquad (9)$$

The acceleration of the pilot relative to the center of mass ($\underline{a}_{p/cm}$) is caused by yaw of the helicopter following blade detachment. Yawing and corresponding angular acceleration $\ddot{\psi}$ is governed by the reaction moment Q_r of the main rotor system, the moment of inertia I_{zz} about the center of mass, the thrust of the tail rotor $T_{TR,}$ and the length of the tail boom l_{TR}[93]:

$$Q_r + I_{zz}\ddot{\psi} = T_{TR} l_{TR} \qquad (10)$$

Following detachment of the main rotor blades, the reaction moment Q_r immediately drops out of the equation. If air resistance is neglected, the aircraft will yaw counterclockwise at the following angular acceleration if tail rotor thrust is maintained:

$$\ddot{\psi} = \frac{T_{TR} l_{TR}}{I_{zz}} \qquad (11)$$

[91] The NASA RSRA helicopter pilot ejection system is capable of ejecting occupants within 0.4 seconds of blade detachment. The analysis described herein assumes a 1 second delay to assess a worst case scenario. See Bement, 3.
[92] Helicopter line drawing provided by Eurocopter. See *Aircraft Service Maintenance Manua EC-135.*
[93] Leishman, 224.

The moment generated by the tail rotor ($T_{TR}l_{TR}$) will be assumed to be equal and opposite to the moment applied by the powertrain during a stationary hover.[94] The turbine engines of the Eurocopter EC-135 each provide about 355 shaft horsepower to the main rotor system at 395 RPM[95], generating the following moment:

$$(2 \times 355hp)\left(\frac{550\,ft \cdot lb}{1\sec}\right)\left(\frac{60\sec}{395\,rev}\right)\left(\frac{1\,rev}{2\pi}\right)\left(\frac{4.48\frac{kg \cdot m}{\sec^2}}{1\,lb}\right)\left(\frac{1m}{3.3\,ft}\right) = 12820\frac{kg \cdot m^2}{\sec^2} = T_{TR}l_{TR} \qquad (12)$$

The mass moment of inertia I_{zz} is calculated about a vertical axis through the center of mass of the helicopter. This mass moment may be estimated by approximating the aircraft as a sum of simple shapes of varying mass. The mass moment of inertia of the EC-135 was approximated as 3980 kg-m^2 (Appendix BB). The angular acceleration caused by the tail rotor is then calculated using this equation:

$$\ddot{\theta} = \frac{T_{TR}l_{TR}}{I_{zz}} = \frac{\left(12820\frac{kg \cdot m^2}{\sec^2}\right)}{\left(3980\,kg \cdot m^2\right)} = 3.22\frac{rad}{\sec^2} \qquad (13)$$

Having obtained an expression for the angular acceleration of the aircraft, acceleration of the pilots relative to the center of mass may be expressed in polar coordinates r,θ,k:

$$\underline{a}_{p/cm} = (\ddot{r} - r\dot{\theta}^2)\underline{e}_r + (r\ddot{\theta} + 2\dot{r}\dot{\theta})\underline{e}_\theta + \ddot{z}\underline{k} \qquad (14)$$

$$\underline{a}_{p/cm} = (-2m)\left(3.22\frac{rad}{\sec}\right)^2\underline{e}_r + (2m)\left(3.22\frac{rad}{\sec^2}\right)\underline{e}_\theta + \left(0\frac{m}{\sec^2}\right)\underline{k} \qquad (15)$$

$$\underline{a}_{p/cm} = \left(-20.7\frac{m}{\sec^2}\right)\underline{e}_r + \left(6.4\frac{m}{\sec^2}\right)\underline{e}_\theta + \left(0\frac{m}{\sec^2}\right)\underline{k} \qquad (16)$$

Translational acceleration of the center of mass is caused by gravitational force and the thrust of the tail rotor. Because the pilot sits ahead of the center of mass, the translational acceleration of the aircraft is opposite the pilot's acceleration in the $\underline{e}_\theta$ direction:

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94 Stationary hover normally requires only about 70% of maximum power in the Eurocopter EC-145, an aircraft similar in design to the EC-135. See R. Randall Padfield, *Flying the EC-145*, AIN Online, 19 Feb. 2004. <http://www.ainonline.com/Features/pilotreport03/AIN_pr_ec145.html>.

95 About 90% of engine power is directed to the main rotor system with the remaining 10% used to drive the tail rotor. See Leishman, 224. The maximum continuous power rating of the EC-135 is 562 shaft horsepower provided by each Pratt and Whitney 206B2 turbine engine. See *EC-135 T2/P2*, Eurocopter, 19 Feb. 2004, <http://www.eurocopter.com/site/FO/scripts/siteFO_contenu.php?lang=EN&noeu_id=37>.

$$-T_{TR} = M\bar{a}_{cm_\theta} \tag{17}$$

$$\bar{a}_{cm_\theta} = \frac{-T_{TR}}{M} = \frac{\left(-12820\frac{kg \cdot m^2}{sec^2}\right)\left(\frac{1}{6.275m}\right)}{(1585kg)} = -1.29\frac{m}{sec^2} \tag{18}$$

Neglecting air resistance, the gravitational force also causes the center of mass to accelerate at a constant rate in the –*k* direction:

$$\underline{a}_{cm_k} = g = -9.81\frac{m}{sec^2} \tag{19}$$

The acceleration of the center of mass expressed in cylindrical coordinates is therefore:

$$\underline{a}_{cm} = \left(0\frac{m}{sec^2}\right)\underline{e}_r + \left(-1.3\frac{m}{sec^2}\right)\underline{e}_\theta + \left(-9.8\frac{m}{sec^2}\right)\underline{k} \tag{20}$$

The total acceleration of the pilot is then obtained using equation (1):

$$\underline{a}_p = \underline{a}_{p/cm} + \underline{a}_{cm} = \left(-20.7\frac{m}{sec^2}\right)\underline{e}_r + \left(5.1\frac{m}{sec^2}\right)\underline{e}_\theta + \left(-9.8\frac{m}{sec^2}\right)\underline{k} \tag{21}$$

The magnitude of this acceleration indicates the total 'g-force' experienced by the pilots:

$$a_p = \sqrt{a_r^2 + a_\theta^2 + a_z^2} = \sqrt{20.7^2 + 5.1^2 + 9.8^2} = 23.5\frac{m}{sec^2} = 2.4g \tag{22}$$

If tail rotor thrust is maintained following blade detachment, the analysis implies that the total acceleration experienced by the pilots one second after blade detachment is less than 2.5g's. This acceleration is within human tolerance levels, suggesting that the fuselage response soon after the main rotor blades are released will not be violent enough to directly cause injury to the pilots.[96] A tail rotor thrust termination device would therefore not be necessary if HBEDS were used in conjunction with a pilot ejection system designed for these conditions. Considering the elevated g-forces experienced during ejection from fighter jets,[97] helicopter pilots would easily be able to endure the acceleration of the aircraft for a period of one second after blade detachment.

Though a tail rotor thrust termination device may not be necessary for in-flight egress, such a device would be needed if the pilots and crew were to remain aboard the aircraft. If a

[96] Humans can tolerate accelerations of at least 5g's for 5 seconds in the longitudinal (vertical) direction before entering the transition to blackout. Greater accelerations may be tolerated in other directions. See plot of tolerable accelerations versus elapsed time at <<http://www.hq.nasa.gov/office/pao/History/conghand/fig15d5.gif>> Accessed 2/19/04.

[97] Modern ejection seats typically subject pilots to 12-14 g's in the vertical direction. See "The Ejection Site." <<http://www.ejectionsite.com/ejectfaq.htm>> Accessed 23 Feb. 2004.

parachute recovery system is deployed, the tail rotor thrust must be eliminated in order to limit the yaw rate of the aircraft during its decent. Excessive yaw rate would subject the pilots to elevated g-forces and also make for an unstable, dangerous landing. Similarly, if HBEDS is activated during the course of a hard landing, the unbalanced tail rotor thrust is likely to destabilize the aircraft and increase the risk of a rollover.

In consideration of these risks, the HBEDS team recommends that a device or mechanism be provided to control tail rotor thrust immediately following main rotor blade detachment. Tail rotor thrust could be quickly reduced by a variety of mechanisms. For example, a device could be designed to stall or zero the angle of attack of the tail rotor blades, thereby eliminating thrust by an aerodynamic means. Alternatively, because the tail rotor carries far less angular momentum than the main rotor system, a device could simply apply a brake to the tail rotor driveshaft soon after the main rotor blades are detached. Either method would quickly reduce tail rotor thrust and thereby maintain stability during parachute touchdowns and hard landings.

11.0 Economic and Political Analysis of HBEDS

While the cost analysis presented in the specification testing and validation section outlines the cost of producing HBEDS, this section discusses the economic and political effects of helicopter accidents and how the system might lessen the consequences of both.

11.1 Economic Effects of Helicopter Accidents

To show the positive economic effects of HBEDS, the team has performed a brief and conservative economic analysis of helicopter accidents. The team performed a study of the costs associated with military fatalities, including death benefits paid to families and the cost of training pilots and soldiers to replace those lost in helicopter accidents. The average death benefits package is worth over $220,000.[98] Using this figure alone, HBEDS would need to save 172 lives to justify a 1000 unit production run. If the system is assumed to last ten years, then that is just over seventeen soldiers a year that must be saved due to HBEDS. This number uses only death benefits to justify HBEDS, which means that many other costs, like training new pilots and putting new soldiers through basic training, have been neglected. These numbers are extremely difficult to determine, but the team approximates an average value of this training to

[98] See Michael White, *Military Fatalities*, 2004, 1 March 2004, http://lunaville.org/warcasualties/Details.aspx and *Comparison of Death Benefits Payable to Military Members Who Die on Active Duty and Federal Civil Service Employees*, Department of Defense Civil Personnel Management Service, 1 Mar. 2004, <http://www.cpms.osd.mil/icuc/attacks/Death%20benefits%20Chart.htm>.

be $80,000.[99] That would lower the required number of saved servicemen to fewer than thirteen a year for ten years per helicopter application.

In the two most recent conflicts, Operation Enduring Freedom and the Iraq War, the fatalities due to helicopter crashes account for 34.5% of the fifty-five fatalities citing causes of death in Afghanistan and 18.4% of all 549 fatalities in Iraq.[100] If HBEDS were implemented on military helicopters and used in the activation envelope the team specified, approximately 40% of these fatalities could have been prevented,[101] saving nine lives in Afghanistan and forty lives in Iraq. These fifty soldiers that could have been saved in the last three years is well over the number required to justify HBEDS, especially considering that those numbers only include fatalities in combat and do not include fatalities in training missions and other locations.

11.2 Political Effects of Helicopter Accidents

Fatal military helicopter accidents have political effects not expressed in monetary terms. Military casualties can diminish public support of a war effort, create divisions amongst political leaders, and dissuade voters. The public has shown a remarkably low tolerance for military deaths in many recent conflicts. Before the United States became involved in the Kosovo conflict, 60% of Americans supported sending US troops to enforce a peace treaty. However, despite this support, 59% also said peace in Kosovo was not worth US military casualties.[102]

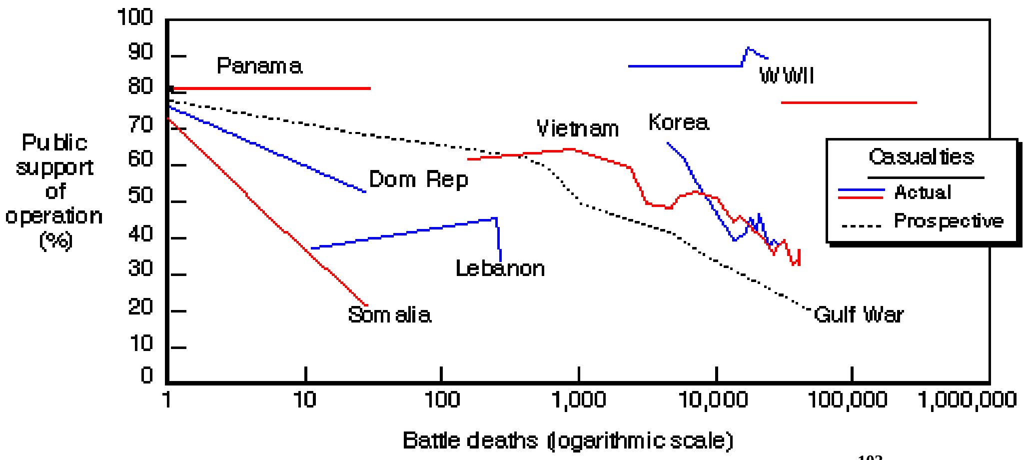

Figure 32: Public Support of War versus the Associated Deaths[103]

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[99] This number was chosen by studying many of the costs of military training as reported by Rod Hafemeister, Militaryreporter.org, 1 Mar. 2004, <http://www.militaryreporter.org>.
[100] Numbers and percentages may change after report submission. See Michael White, *Military Fatalities*, 2004, 1 March 2004, <http://lunaville.org/warcasualties/Details.aspx>.
[101] See Section 2.1: Envelope Events Analysis for discussion of envelope event frequencies.
[102] Gary Langer, *Support for Kosovo Action Up*, 1999, ABC News, 15 Oct. 2003, <http://abcnews.go.com/sections/world/DailyNews/990324kosovopoll.html>.
[103] Eric V. Larson, *Casualties and Consensus: The Historical Role of Casualties in Domestic Support for U.S. Military Operations*, 1996, RAND, 12 Oct. 2003, <http://www.rand.org/publications/RB/RB2502/RB2502.html>.

Furthermore, military casualties can severely undermine public support for military action if the public does not believe the conflict is central to national interests. Figure 32 shows that public support remained stable throughout critical operations such as World War II but quickly eroded as the death toll inched higher in other more isolated conflicts. The first military deaths in the Dominican Republic and Somalia had a particularly devastating affect on public support, resulting in 15% and 40% decreases after only 10 deaths. This effect was most recently witnessed four months into Operation Enduring Freedom when national polls reported that the majority of Americans believed the number of US casualties was "unacceptable."[104]

12.0 Recommendations and Conclusions

The team believes the HBEDS concept is practical and feasible for application on military helicopters. The proposed design satisfies many of the project specifications, and the team believes all specifications could be met through further development, with the possible exception of the cost specification. Further development of the concept should maintain a focus on stability while aiming to meet the cost, efficiency, and durability specifications. To this end, the HBEDS team presents five recommendations for continued development of the system:

Recommendation #1: Subsequent transfer system prototypes could be designed to operate with hydraulic lines, thereby allowing for repeated non-destructive testing. Such a device would serve as a simple and practical model for the actual system, enabling more realistic tests than those conducted with the electrical concept prototype. Specifically, full scale transfer system mockups would allow for strength testing of the transfer system's rotor, stator, and cartridge components, ensuring their resistance to static failure upon activation of the system.

Recommendation #2: Development of a complete system will require collaboration with controlled explosives manufacturers. Explosive severance of composite structures is a complex science that calls for extensive testing and advanced pyrotechnic analysis. If severance of the composite blade structure is deemed impractical, explosive devices could instead be installed at the steel blade grips to separate each blade from the rotor system. As discussed in the Detachment Location trade study, this arrangement would also require four additional explosive assemblies to detach the control rods to allow the blade to freely exit.

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[104] *Rising Doubts: President Facing New Challenges of Credibility and Casualties*, 2003, ABC News, 15 Oct. 2003, <http://abcnews.go.com/sections/politics/US/poll030711_bush.html>.
[106] *Helicopter Accident Study*, 2002, National Transportation Safety Board, 11 Oct. 2003, <https://nasdac.faa.gov/aviation_studies/ntsb_helicopter_accident_study/helicopter_accident_study.html>

Recommendation #3: Explosive components should be supplied by manufacturers that can ensure their compliance with the stability and durability specifications. Tests for resistance to heat, moisture, vibration, ballistic shock, electrostatic discharge, and lightning strikes should be conducted in accordance with the military standards referenced herein. Additional tests shall be performed to demonstrate resistance of the detonating cord to repeated flexure as experienced by the rotor blades' composite flexbeams.

Recommendation #4: Future development of the system should involve full scale testing of the explosives and transfer system. Though the reliability and effectiveness of the linear shaped charges may be tested using weighted blade stubs, some tests should be run with full blades to observe the blade exit path and confirm compliance with the safety specification. As discussed in the testing section, high speed video equipment is necessary to measure the angle of blade release. Testing on a full scale helicopter will expose the system to realistic service temperatures and stresses, ensuring the system will operate properly once implemented.

Recommendation #5: Accompanying systems are necessary for HBEDS to be a safe and effective system. Risk assessment exercises identified the dangers introduced by releasing the main rotor blades at high velocity. Helicopters are commonly used in populated areas and activation of HBEDS introduces risks to anyone in the vicinity of the aircraft. The team therefore recommends development of a system to mitigate the risk of blades strikes following blade detachment. Additionally, a tail rotor thrust termination system is necessary if HBEDS is activated during a hard landing or if in-flight activation is followed by ballistic parachute deployment. Although pilots and crew are subject to tolerable accelerations shortly after blade detachment, continued thrust from the tail rotor will destabilize the aircraft and thereby reduce the chances of survival for those who remain on board.

In conclusion, the HBEDS concept described in this report represents a series of design decisions intended to maximize system stability. Because the device is intended for use in adverse emergency situations, the proposed pyromechanical system is resistant to electrostatic discharge, lightning, heat, and ballistic shock, and is designed to operate independent of the aircraft power system. The proposed system also represents a departure from blade detachment devices seen on other aircraft; to the team's knowledge, no detachment system has ever been developed for a four-blade bearingless rotor system. The HBEDS concept therefore has a unique signal transfer and sequencing mechanism that sets it apart from the two-blade Army/Navy study, five-blade NASA RSRA, and coaxial-rotor Kamov aircraft. Also, none of these designs considered the explosive packaging opportunities presented by the structure of bearingless rotor blades, neglecting the improved protection and aerodynamic efficiency possible by locating explosives within the blade root.

Given the advancements outlined in the report, the team recommends further development of HBEDS to realize its life-saving potential, alone or in tandem with helicopter ejection or ballistic parachute systems.

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Appendix A: Accident Synopses and Event Analysis

Selected Accident Synopses: National Transportation Safety Board Accident Database

NTSB Identification: FTW03FA118
Aircraft: Bell 407, registration: N175PA
Injuries: 2 Fatal, 3 Serious.

On March 27, 2003, at 1636 central standard time, a Bell 407 helicopter, N175PA, registered to I Inc., of Kirkland, Washington, and operated as a Public Use aircraft under contract to the US Forest Service (USFS), was destroyed when it crashed into heavily wooded terrain near Broadus, Texas, while conducting low level flight operations in support of the Federal Emergency Management Agency's (FEMA) mission to support an inter-agency (NASA, Texas Forest Service, USFS) recovery effort of Columbia Shuttle Debris. The pilot and 1 crewmember were fatally injured and 3 other crewmembers sustained serious injuries. Visual meteorological conditions prevailed and a VFR flight following plan was filed for the Title 14 Code of Federal Regulations Part 91 Public Use flight. The flight originated at 1515 from Lufkin, Texas.

The helicopter was completing its second search mission of the day while hovering about 125 feet above the ground. During interviews with the NTSB investigator-in-charge, the surviving passengers reported that the helicopter lost power and descended rapidly into the 80-foot tall trees with no warning. The helicopter came to rest on its right side at the base of a 80-foot tree on a heading of 078 degrees magnetic. The cockpit section of the fuselage was found crushed and the main cabin was mostly intact. The engine compartment was intact, and all engine components, lines, electrical connections, and accessories appeared to be undamaged. The electronic control unit (ECU) was removed on-scene for data download. The ECU's connectors were found tight and secure with no damaged pins.

After the wreckage was recovered, the engine was removed and set up in a test cell. During the test cell run, it was discovered that the power lever angle (PLA) indicator on the Hydro Mechanical Unit (HMU) responded erratically to normal throttle inputs when the engine was operated in the electromechanical mode. The engine operated normally in the manual mode. Further testing and evaluation of the HMU revealed anomalies with the potentiometer component of the system.

NTSB Identification: LAX02FA116
Aircraft: Sikorsky S-61A, registration: N318Y
Injuries: 1 Fatal, 1 Serious.

On March 26, 2002, at 1538 pacific standard time, a Sikorsky S-61A twin engine helicopter, N318Y, was destroyed when it impacted terrain while maneuvering near Dunsmuir, California. The helicopter was registered to and operated by Croman Corporation of White City, Oregon. The commercial pilot was fatally injured and the commercial co-pilot sustained serious injuries. Visual meteorological conditions prevailed, and a flight plan was not filed for the 14 Code of Federal Regulations Part 133 external load flight. The local business flight originated from a staging area near the McCloud River's Lakehead area at 1500.

According to the operator, the helicopter had been maneuvering in the area as part of a logging operation. One witness, a ground worker, was in radio contact with the pilot. The worker stated that the pilot was supposed to drop chokers near him. (A choker is a steel cable that is fitted around a log and is standard equipment for logging operations.) The witness stated that he had radioed to the pilot and informed the pilot that he had moved 100 yards toward Mount Shasta, thus providing the pilot with a reference point to drop the chokers, and the pilot acknowledged. There were no further radio transmissions received from the pilot. The helicopter did not drop the chokers at the point the witness expected, and it over flew the intended drop zone. The witness stated that the helicopter appeared to be "gliding," and a tan smoke was coming from the engine/transmission area. He stated that "the blades were not moving as fast as they should have been," and "the blades were coning extensively." Two other witnesses reported that the main rotor blades had slowed down and that they could count each blade. Subsequently, the helicopter impacted the ground and a fire erupted.

The helicopter came to rest in a densely wooded area of the Shasta National Recreational Area. The accident location was recorded by a global positioning satellite (GPS) receiver at north 041 degrees 02.289 minutes latitude and west 122 degrees 11.404 minutes longitude, and at an elevation of 2,240 feet msl. The helicopter came to rest on sloping terrain that varied between 20 and 80 degrees, and the nose was oriented on a magnetic heading of 345 degrees. The cockpit, cabin, and transmission were consumed by fire. The five main rotor blades and five tail rotor blades were identified on-site and did not exhibit leading edge damage or trailing edge delamination.

NTSB Identification: MIA98WA259
Aircraft: Robinson R22B, registration: LQBJP
Injuries: 1 Fatal.

On September 29, 1998, about 1530 eastern daylight time, a Robinson R22B helicopter, Argentina registration LQ-BJP, operated by Policia Pcia Bs As, crashed into the ground after an in-flight separation of the tail section near Buenos Aires, Argentina. Visual meteorological conditions were reported in the area and no flight plan was filed. The commercial-rated pilot, received fatal injuries. The flight departed from Claypole, Argentina, at an unknown time.

The flight was supporting a ground mission and was at an altitude of 300 to 450 feet above the ground when the tail section of the helicopter separated in flight. The helicopter then fell to the ground and was spread over an area of about 510 feet.

The investigation is under the jurisdiction of the Government of Argentina. Any further information pertaining to this accident may be obtained from:

Junta De Investigacion De Accidentes De Av. Civil Government of Argentina Buenos Aires, Argentina Telephone: 011-541-381-6333 Facsimile: 011-541-381-6333

This report is for informational purposes only and contains only information obtained for or released by the Government of Argentina. The Government of Argentina has requested that the parts of the helicopter be examined at the NTSB's Materials Laboratory, Washington, D.C.

NTSB Identification: LAX97LA176
Aircraft: Hughes 369D, registration: N5105N
Injuries: 2 Fatal, 2 Serious.

The helicopter was cruising at low level when the engine failed. The pilot turned toward a landing area and entered an autorotation with a quartering tailwind. During the autorotation, the helicopter continued to descend, remaining in a nose low attitude, until striking the ground. Impact occurred on up sloping terrain, and the helicopter was damaged. A computation of the weight and balance revealed the helicopter's moment arm exceeded the forward CG limit by about one inch, and limited aft cyclic control. An examination of the engine revealed that a stator vane had failed due to excessive erosion and fatigue cracking. The condition had not been detected during a compressor case erosion inspection, 60 flight hours before the accident.

NTSB Identification: NYC95LA147
Aircraft: BELL 47G-3B-1, registration: N48316
Injuries: 1 Fatal.
At the end of an aerial application mission, the helicopter was refueled, and the pilot departed for home base. A few minutes after takeoff, the helicopter collided with trees. Examination of the engine and drive train revealed no preimpact failure; however, the collective pitch control yoke bearing had failed. The ball bearings and race in the yoke bearing were observed to be pitted, and the ball bearings were worn undersized. The last inspection of the yoke bearing occurred about 9 years and 839 flight hours before the accident, during the 1,200 hour inspection. The yoke bearing was not required to be inspected during the recent 600 hour inspection. The bearing was an on-condition item, and did not have a scheduled time change. The bearing could not be inspected, while installed on the helicopter.

Accident Event Frequency

While helicopters have proven to be successful in many applications, their inherent complexity in design and operation have contributed to a high accident rate. According to the National Transportation Safety Board (NTSB), there were 2211 general aviation and air carrier helicopter accidents from 1990-2000, of which 324 involved fatalities.[106] Within the general aviation segment, the accident rate of helicopters, expressed as the number of accidents per 100,000 flight hours, exceeds the accident rate for piston engine, turboprop, and turbojet airplanes. Despite operating at lower altitudes than these fixed wing aircraft, helicopter accidents are no less fatal than airplane accidents. The fatal accident rate for helicopters exceeds that of airplanes and is second only to gliders as the most dangerous type of aircraft (Figure A.1). Helicopters used in emergency service applications have exhibited similarly high accident rates; the United States Forest Service, for example, reports a helicopter accident rate of 9.72 accidents per 100,000 flight hours, more than 4 times the rate for their fixed wing aircraft.[107]

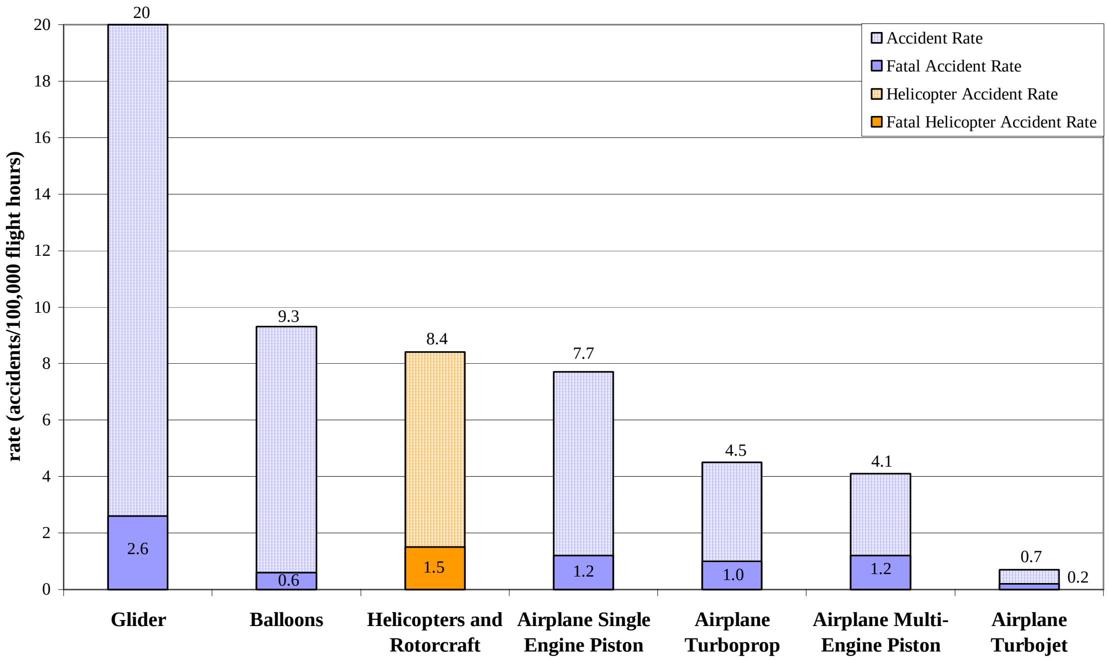


Figure A.1: General Aviation Accident and Fatal Accident Rates by Type Aircraft[108]

Unlike helicopters designated for civilian use, military helicopters are deployed on short range intelligence, reconnaissance, transport, and combat missions. Despite extensive pilot

[107] Data compiled from *Aviation Safety Summary FY 2002*, 2003, United States Department of Agriculture: Forest Service, 11 Oct. 2003, <http://www.fs.fed.us/fire/av_safety/fy_safety_reports/fy02avsumm.pdf.>.
[108] *Annual Review of Aircraft Accident Data*, 2000, National Transportation Safety Board, 11 Oct. 2003, <http://www.ntsb.gov/publictn/2003/ARG0302.pdf>.

training, the dangerous nature of many of their missions leads to a high accident rate. Over the past twenty years the Air Force has averaged a Class A[109] accident rate of 3.11 helicopter accidents per 100,000 flight hours, nearly double the rate for fixed wing aircraft.[110] (Figure A.2) The Army's AH-64 Apache has been involved in 18 Class A accidents and 7 fatal accidents in the last 2 years alone.[111]

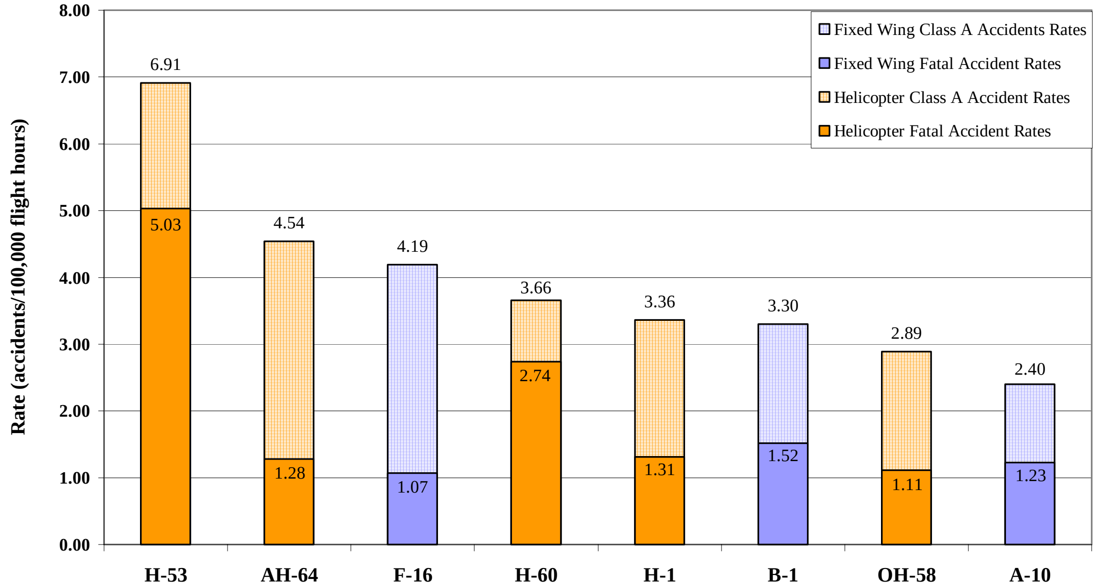


Figure A.2: Class A and Fatal Accident Rates by Military Aircraft[112]

The Class A accident rate for many helicopters exceeds the accident rate for some of the military's most venerable fighter and attack fixed wing aircraft. (Figure A.2) While none of the helicopters in the United States military have pilot ejection systems, the F-16, B-1, and A-10

[109] Class A accidents are accidents which involve a fatality or permanent total disability, destruction of the aircraft, or total mishap cost of $1,000,000 or more.

[110] *Aircraft Statistics*, United States Air Force Safety Center, 9 Oct. 2003, <http://afsafety.af.mil/AFSC/RDBMS/Flight/stats/aircraft_stats.html>.

[111] *United States Army Safety Program Database*. Unites States Army, 12 Oct. 2003, <http://safety.army.mil/home.html>.

[112] Accident rates are calculated for the life of each aircraft through September 2003. Accident rates for H-1, H-53, H-60, A-10, B-1, and F-16 were provided by *Aircraft Statistics*, United States Air Force Safety Center. Accident rates for AH-64 and OH-58 are calculated using accidents reported in the *United States Army Safety Program Database*, United States Army. AH-64 and OH-58 flight hour data provided by Clarence E. Rash, *Accident Rates in Glass Cockpit Model U.S. Army Rotary-Wing Aircraft*, 2001, United States Army Aeromedical Research Laboartory (USAARL), 15 Oct. 2003, <http://www.usaarl.army.mil/TechReports/2001-12.PDF>. 2001-2003 flight hour estimates for AH-64 and OH-58 were calculated using 1998-2000 flight hour data.

aircraft each incorporate systems that provide an 80 to 95% ejection survival rate in the event of an impending accident.[113]

As shown above, the number of fatal accidents per flight hour of the H-60 Black Hawk helicopter, for example, was shown to be 2.5 times greater than that of the F-16 fighter jet. This research highlights the need for improved helicopter safety equipment and continues to serve as the foundation for the HBEDS project and it was hoped that further research would find an appropriate application. To that end, the field of helicopters included in the research was narrowed to four modern US Army helicopters: the OH-58 Kiowa, AH-64 Apache, H-60 Black Hawk, and AH-1 Super Cobra. The Kiowa, Apache, Black Hawk, and Super Cobra have extensive accident histories, having logged 250 non-combat related Class A accidents involving 193 deaths since 1987. Although also involved in numerous accidents, it was decided that the older UH-1 Huey and H-47 Chinook helicopters would not be included in the study because they are near the end of their life cycle and are therefore less relevant platforms for future HBEDS applications. Table A.1 provides a listing of these aircraft and the total number of accidents and accident fatalities for each.

Helicopter	Class A Accidents	Accident Fatalities
OH-58	100	41
AH-64	68	20
H-60	62	123
UH-1	60	83
H-47	33	47
AH-1	20	9
H-6	16	9
H-54	1	0
Total	*360*	*332*
Yearly Average	*21.4*	*19.7*

Table A.1: US Army Class A Helicopter Accidents and Accident Fatalities, 1987-2003[114]

The United States Army Safety Center classifies helicopter accidents by a listing of 81 events encompassing pilot errors, system failures, and environmental factors.[115] Accident reports

[113] Ejection survival rates calculated over the lifetime of the ACES II system through September 2000. See George D'Amore and Thomas D Fadell Luna, *USAF Aces II Ejection Experience Analysis*, 2000, USAF Safety Center, 17 Oct. 2003, <http://safety.kirtland.af.mil/AFSC/RDBMS/Flight/SEFL/SEFL%20Files/1>.

[114] *United States Army Safety Program Database*. Unites States Army, 30 Oct. 2003, <http://safety.army.mil/home.html>.

cite up to three events for each of the 250 Kiowa, Apache, Black Hawk, and Super Cobra Class A accidents. Figure A.2 includes the ten most commonly cited events in these accident reports and the citation frequency for each. Collision with terrain is more frequently cited in accidents involving the OH-58 and H-60, suggesting uncontrolled descents and crash landings are more often experienced in these larger utility helicopters. The data also show a relatively high frequency of object strikes and excessive yaw or spin for the AH-1 and AH-64, both extremely maneuverable attack helicopters that regularly fly high-speed, 'nap-of-the-earth' flight missions.

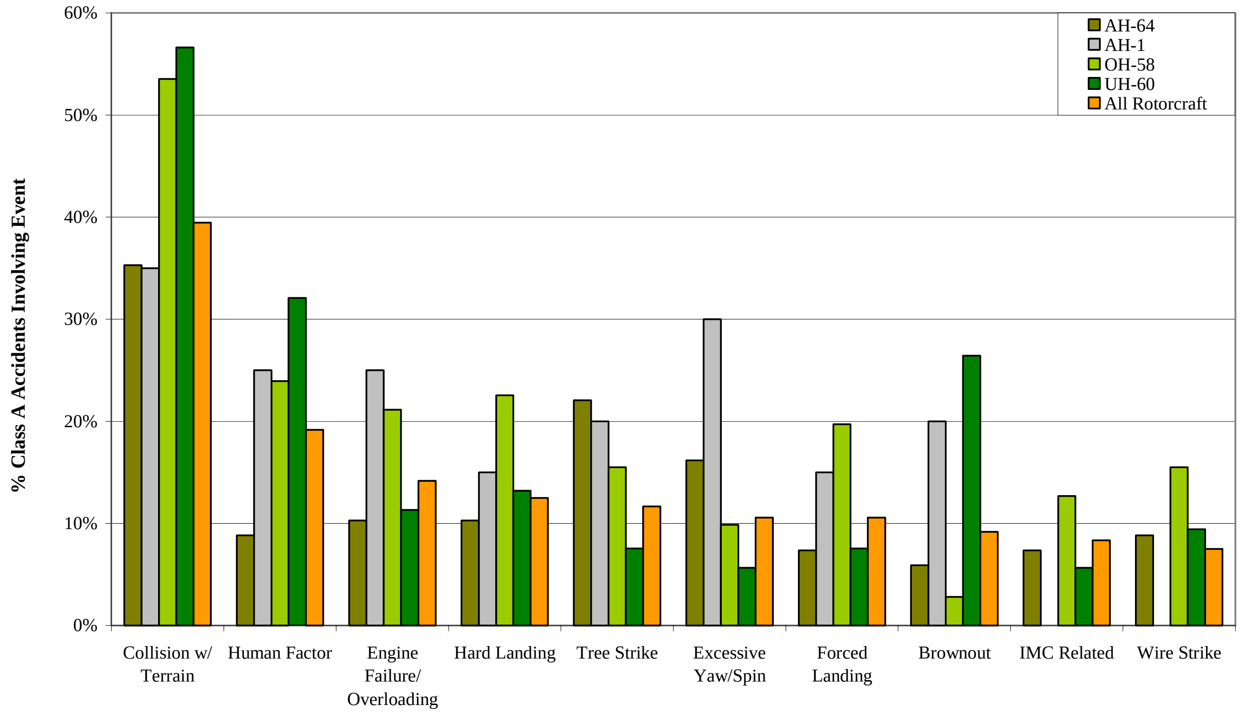
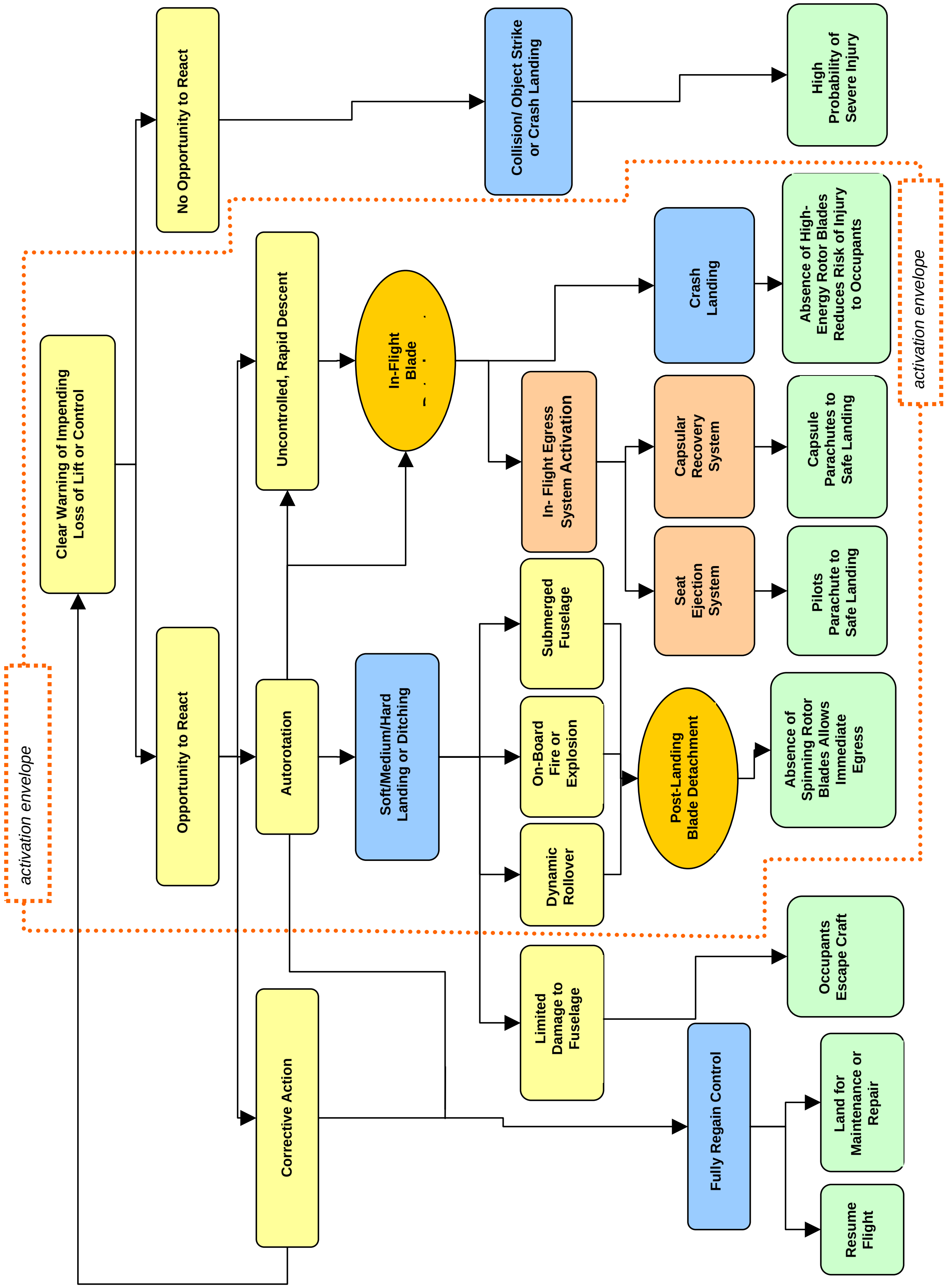


Figure A.2: Event Frequency for Class A Helicopter Accidents, 1987-2003[116]

Though the accident event frequencies vary somewhat between the four helicopters, the data fails to identify a helicopter that would benefit most from HBEDS. The small sample sizes—especially for the Super Cobra—contribute to error in the event frequency calculations and thereby diminish the significance of any apparent differences. Because the accident event frequencies do not distinguish the four helicopters, it is unclear which platform is best matched to the HBEDS activation envelope.

[115] *United States Army Safety Program Database*. Unites States Army, 30 Oct. 2003, <http://safety.army.mil/home.html>http://safety.army.mil
[116] *United States Army Safety Program Database*.

Appendix B: Activation Envelope


Clear Warning of Impending Loss of Lift or Control
No Opportunity to React
Opportunity to React
Collision/ Object Strike or Crash Landing
High Probability of Severe Injury
Uncontrolled, Rapid Descent
Autorotation
Corrective Action
In-Flight Blade
Soft/Medium/Hard Landing or Ditching
In- Flight Egress System Activation
Crash Landing
Absence of High-Energy Rotor Blades Reduces Risk of Injury to Occupants
Capsular Recovery System
Capsule Parachutes to Safe Landing
Seat Ejection System
Pilots Parachute to Safe Landing
Submerged Fuselage
On-Board Fire or Explosion
Dynamic Rollover
Limited Damage to Fuselage
Post-Landing Blade Detachment
Absence of Spinning Rotor Blades Allows Immediate Egress
Occupants Escape Craft
Fully Regain Control
Land for Maintenance or Repair
Resume Flight
activation envelope
activation envelope

Appendix C: Detailed information on the State of the Art

The Russian company Kamov manufactures the only operational helicopter in the world with a blade detachment system: the single-seat Ka-50 Black Shark (Figure C.1), and its two-seat derivative, the Ka-52 Alligator. The Ka-50, code named 'Hokum' by NATO, is the most widely used of the two. In production since 1994, it is designed for destroying armored vehicles, slow-speed air targets, and manpower on the battlefield.[117] The Ka-50 is distinguished from other helicopters not only by its blade detachment and ejection system, but also by its counter-rotating coaxial main rotors, doing away with the need for a tail rotor and allowing for a more compact airframe construction.[118]

The K-37-800 rocket-assisted ejection system allows the Ka-50's pilot to escape at all altitudes and speeds. Once the ejection sequence is initiated, explosions at the rotor blade roots cause separation of all six blades. Then, both sides of the cockpit canopies are ejected sideways while a rocket, attached by a tether to the cockpit seat, pulls the pilot's seat out of the cockpit. Eventually the rocket is released and the chute is deployed, ensuring a safe landing for the pilot. This ejection sequence can occur at any time within the performance envelope of the Ka-50, including inverted flight, and is completed in a maximum of six seconds.[119]

Figure C.1: Ka-50 Black Shark[120]

[117] Airforce Technology. *KA-50 BLACK SHARK ATTACK HELICOPTER, RUSSIA.* 2003. Net Resources International Limited. 17 Oct. 2003. < http://www.airforce-technology.com/projects/ka50/>.
[118] De Villiers, Cesare. *The Heart stopping Hokum and derivatives: a brief history.* 2003. SA Flyer Magazine. 14 Oct. 2003. <http://www.saflyermag.co.za/Military/military_july_2003.htm>.
[119] Razorworks. *Ka-52 Hokum B "Alligator".* 2003. Razorworks. 16 Oct. 2003. <http://www.razorworks.com/enemyengaged/hokum/>.
[120] Kamov Ka-50 Black Shark Army Attack Helicopter, 1992, Moscow Air Show MAKS-92, 6 Mar. 2004, <http://www.geocities.com/iek_17/gallery/ka-50.htm>.

In 1973, at the request of the General Accounting Office, the Department of Defense (DoD) submitted a report to Congress entitled *In-Flight Escape Systems For Helicopters Should Be Developed To Prevent Fatalities.*[121] Written at a time when there were over 1000 helicopter crash deaths per year in Vietnam,[122] this report investigated the viability of an in-flight egress system for both utility and transport helicopters. In-flight egress systems could prevent fatalities, improve soldier morale, and save money on new pilot training and costly death payments to families.[123] During the 1960s, multiple government agencies and government contractors demonstrated that helicopter in-flight egress was possible through several notable tests. However, a final system was never adopted because the added weight to the aircraft was deemed unacceptable and great advancements were being made in increasing the crashworthiness of helicopters.[124]

Details concerning the precise manner of blade detachment in Navy experiments during the late 60s and early 70s are not included in this report, but it is clear that the systems on attack helicopters detached the blades individually with explosives.[125] Two distinct types of experiments were made: capsule recovery and ejection/extraction. The capsule recovery system was tested on the CH-46D Sea Knight and UH-1E Huey and consisted of explosively breaking the aircraft into segments, but maintaining the integrity of the cabin surrounding the pilot and/or passengers, which could then be safely parachuted to the ground (Figure C.2). This system was tested successfully several times but added a large weight burden to the aircraft.[126] The lighter ejection/extraction system (Figure C.3) was a separate project and, although the Navy determined that the concept was technically feasible on the AH-1 Cobra, full tests were not completed by the time of this report. Such a system would detach the blades at their root and then eject the pilots individually, but each equipped seat would still add approximately 200 pounds to the aircraft.[127]

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[121] *In-Flight Escape Systems For Helicopters Should Be Developed To Prevent Fatalities*, Department of Defense, by the Comptroller General of the United States: June 12, 1973.
[122] Statistic calculated through years 1968-1970. See *In-Flight Escape Systems*, 1.
[123] *In-Flight Escape Systems,* 2.
[124] *In-Flight Escape Systems,* 25-26.
[125] *In-Flight Escape Systems,* 15-17.
[126] *In-Flight Escape Systems,* 10-12.
[127] *In-Flight Escape Systems,* 16-17.

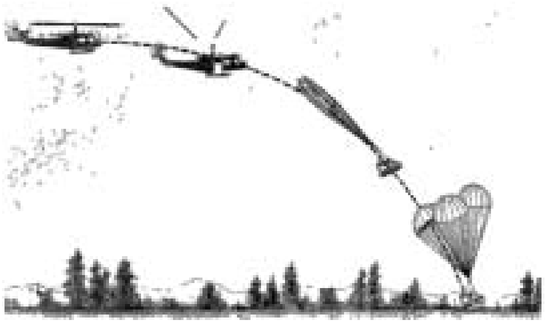

Figure C.2: UH-1E Capsule Recovery Sequence[128]

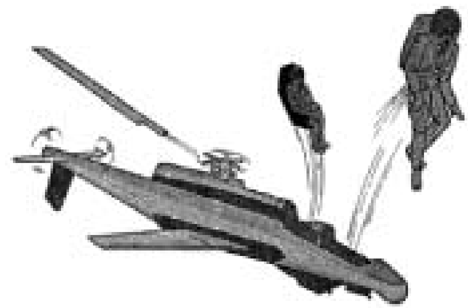

Figure C.3: Seat Ejection/Extraction System[129]

In addition to these experiments performed by the U.S. Military, NASA designed and built an experimental rotorcraft with a fully certified in-flight egress system, shown in Figure C.4 and Figure C.5. The Rotor Systems Research Aircraft (RSRA) had both five bladed main rotor system and fixed wings, allowing it to operate as either a helicopter or airplane. An ejection function was developed for the aircraft in order to ensure the safety of the crew in light of its mission, which could include flying at high altitudes as a fixed wing aircraft and testing less qualified experimental rotor systems.[130] Once the ejection sequence was initiated, two members of the crew would be free of the aircraft at 1.0 seconds, followed by the third member whose ejection was staggered to avoid collision, at 2.3 seconds[131].

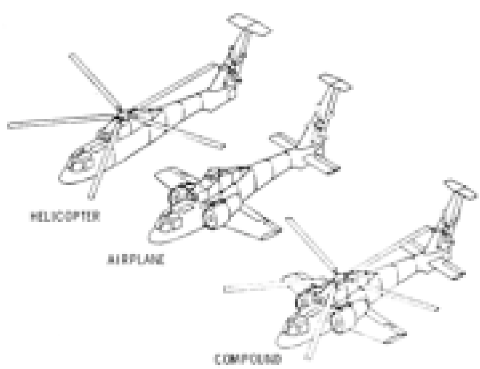

Figure C.4: RSRA Configurations[132]

Figure C.4: RSRA X-Wing Derivative[133]

Given that simultaneous detachment of the rotor blades would almost certainly result in striking the tail of the aircraft, detachment of the blades was staggered. Explosive charges at

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[128] *In-Flight Escape Systems, 11.*
[129] *In-Flight Escape Systems, 12..*
[130]Bement, 1.
[131] Bement, 2.
[132] Bement, 1.
[133] *NASA X-Wing Research Vehicle.* 1986. National Aeronautics and Space Administration. 6 March 2004. <http://www.dfrc.nasa.gov/Gallery/Photo/X-Wing/Small/EC86-33555-2.jpg>.

roots severed each blade at 11°, 155°, 227°[134], and the other two blades were severed after a one-fifth rotation. The inherent instability caused by the rotation of the two asymmetrically aligned blades caused a 10°/second change in pitch and 40°/second change in roll of the aircraft, based on rigid body analyses,[135] although this problem would only exist for less than a tenth of a second. In full system testing on the ground, severed blades traveled between 100 and 1000 feet when detached from a point 13 feet from the ground.[136]

A rotary transfer unit was used to relay the signal for blade detachment from the stationary portion of the aircraft to the rotating main rotor system. This system consists of an inner rotating ring of five firing pin assemblies and an outer non-rotating ring of three cam thrusters. When the pilot pulls the eject lever, the three cam thrusters extend and contact the firing pin, detaching three blades at the desired orientation relative to 0° aft, and then two of those three cams contact the remaining two firing pins after an additional one-fifth rotation[137]. The blades are completely free of the aircraft within 0.15 seconds of pilot initiation. Connections between all components of this emergency egress system, of which the transfer system is a centerpiece, are made using detonation transfer lines comprised of small amounts of primary explosive enclosed within protective tubing.[138] They were selected for use because they cannot be inadvertently triggered by lightning, electromagnetic induced radiation, or mechanical inputs.[139]

[134] 0° is centerline aft of aircraft.
[135] Bement, 4.
[136] Bement, 7.
[137] Bement, 5-6.
[138] Bement, 2.
[139] Bement, 3-4.

Appendix D: Description of the Application Decision

Purpose**:** In order to design an Emergency Blade Detachment Device (the system), an appropriate helicopter (the application) must be chosen, because main rotor design varies slightly from aircraft to aircraft.

Framework**:** All possible main rotor systems (the type) will be examined: rigid hub, articulated hub, teetering hub, and bearingless hub. An appropriate application of this type will be chosen according to the *purpose* and given the *factors to consider* and *assumptions*. This *thought process* will be described and a *decision* will be made.

Factors to Consider

- Whether a past system has already been developed for this type
- Whether such a system will have a large enough market, now or in the future
- Whether the project group will have access to an application of this type

Assumptions

- A system can be developed for any type mentioned above

Background

- A rigid hub design has several variations, but essentially it does not allow the blades to flap (to flex upwards or downwards about their root attachment point) and may or may not allow for pitch change of the blades.
- An articulated hub design is currently the most common. There are bearings that allow for pitch change and hinges that allow the blades to flap.
- A teetering hub design is older and now rarely used. There are bearings to allow for blade pitch change, but the two main rotor blades are rigidly connected so that flapping can only occur in a see-saw motion: if one blade flaps up, the other must flap down.
- A bearingless hub design makes use of strong and flexible composite materials to allow for both pitch change and flapping, but without hinges or bearings.

Thought Process

- A system has already been developed for the following types: Rotor Systems Research Aircraft (RSRA) S-72 for rigid hub, Ka-50 Hokum for articulated hub, and AH-1 Cobra for teetering hub. A system has not yet been developed for a bearingless hub type.
- Bearingless rotor types seem to be the wave of the future in main rotor system design. They are more responsive, take advantage of new-age composite materials, and have significantly fewer moving parts than previous types, which translates into fewer parts that can fail and less necessary maintenance time on the aircraft. The newest helicopter in the US military arsenal, the RAH-66 Comanche, has a bearingless rotor design. Helicopters used by the US Marine Corps, the UH-1Y Iroquois and the AH-1Z Super Cobra, are currently undergoing refurbishment, including the installment of a new four-bladed bearingless main rotor system. Commercially, Eurocopter has been an industry leader in bearingless rotor technology, but both Bell and Sikorsky now have prominent models that use this design.
- The project team has met with difficulty in gaining access to an Army/National Guard base in Concord, NH. Also, the only helicopter in the Hanover area is an EC-135 at the Dartmouth Hitchcock Medical Center. The project team is allowed full access to this helicopter, as well as access to flight and maintenance documents. This application is a bearingless rotor type.

Decision

Given that:

- Bearingless rotor types will at least be a prominent share of the market, if not the primary type, in the next half century,
- The project group has open access to a bearingless rotor application,
- And blade detachment design work, to the knowledge of the project group, has not yet been done on a bearingless rotor type.

The project group chooses the bearingless rotor type with the EC-135 as its application. The Helicopter Blade Emergency Detachment System protoype will be developed to function on an EC-135 with the full knowledge that such a system may not be appropriate for the commercially flown EC-135, but that such a system could be easily be applied to a more suitable military application, like the Super Cobra, Tiger, or EC-635.

Appendix E: Military Standards[140]

MIL-STD-1512 (USAF)
21 March 1972

METHOD 118

SHELF LIFE (ENVIRONMENTAL CONDITIONS)

1. Purpose. This shelf life test is conducted to determine whether or not the effects of exposure to elevated temperatures for specified time periods will degrade electrical and mechanical characteristics of electroexplosive subsystems components. In some cases, tests must be run to determine if degradation has occurred.

2. Procedure. The electroexplosive subsystem, or its components, shall be tested in accordance with MIL-STD-202, method 206. Any evidence of degradation affecting safety or reliability shall be considered a failure.

3. Summary. The following details shall be specified in the individual specification:

a. Distance from specimens where temperature measurements are to be made

b. Still air requirement (see test method)

c. Method of mounting, and distance between specimens

d. Test temperature and tolerances

e. Operating conditions

f. Test condition letter

g. Initial measurement

h. Final measurement

i. Failure criteria.

118-1 METHOD 118

[140] United States Department of Defense. *Electroexplosive Subsystems, Electrically Iniitated, Design Requirements and Tests Methods: MIL-HDBK-1512*. Washington: GPO, 1997.
United States Department of Defense. *Environmental Engineering Considerations and Laboratory Tests: MIL-STD-810F*. Washington: GPO, 1989.

METHOD 113

VIBRATION

1. Purpose. The purpose of this test is to evaluate the safety and reliability characteristics of electroexplosive subsystems and components under vibration conditions.

2. Procedure. The test shall be in accordance with MIL-STD-202, method 201. Any evidence of malfunction or degradation of performance affecting safety or reliability shall be considered a failure. Components shall be tested with cables and connectors attached.

3. Summary. The following information shall be specified in the individual specification:

a. Test curve

b. Special details for test including conditions which will impose normal loads on terminals

c. Initial and final measurements

d. Failure criteria

e. Procedure number.

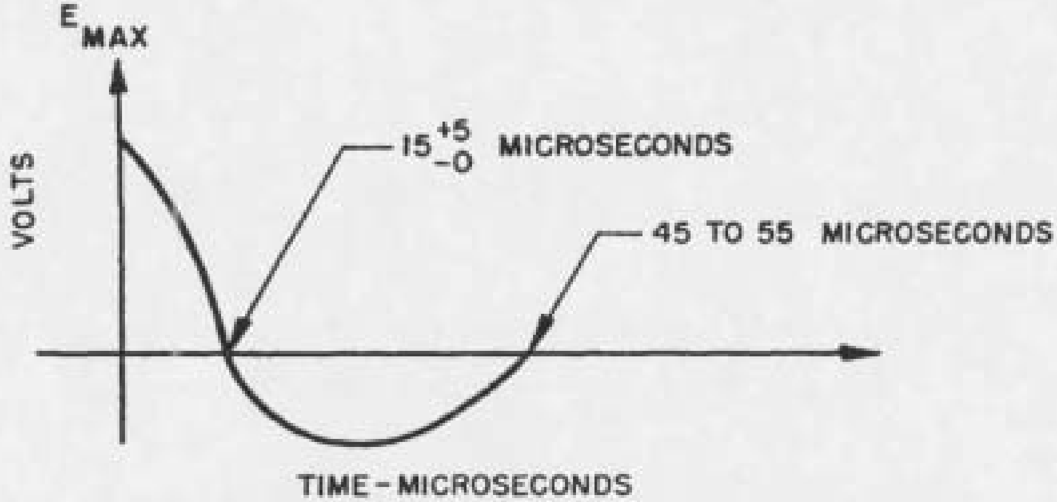
METHOD 302

LIGHTNING STRIKE INDUCED ENERGY

1. Purpose. This test is performed to demonstrate the adequacy of design protection from hazards of induced electrical energy in the grounding system from lightning strikes.

2. Procedure:

a. Electroexplosive subsystem shall be subjected to a peak simulated lightning induced transients of $\pm$1,800V, with the following wave shape:



b. The method of applying the simulated lightning transient is snown in figure 302-1, and should be applied to the complete electroexplosive subsystem.

c. All terminals of the equipment to be tested shall be wired as used in the installation. In the test setup, the size of all interconnecting wires shall be as specified for the installation. The length of these wires shall be as short as possible, but shall not exceed 60 feet. The equipment shall be energized and operated.

d. Each equipment in the subsystem shall be individually tested by lifting the equipment grounding connection from case-to-structure and applying the transient between the subsystem ground and the equipment case.

e. The values of C and R (figure 302-1) are adjusted to obtain the desired shape of the transient. The variable voltage supply is adjusted to a value such that the transient on the output terminals has the required amplitude.

f. Certain equipment may be protected by zener diodes, capacitive filters and other similar devices, which prevent the transient voltage from building up. For this reason and also to prevent the equipment from being subjected to undesirable transients, prior to applying the transient to the equipment, the transient shall be shaped on a 50-ohm noninductive resistor placed across terminals 1 and 2 of the transient source. When the desired amplitude and wave shape has been obtained, the 50-ohm resistor shall be removed and the transient source connected to the test setup as shown on figure and applied to the subsystem. Positive and negative transients are applied by interchanging the connections of terminals 1 and 2.

MIL-STD-1512 (USAF)
21 March 1972

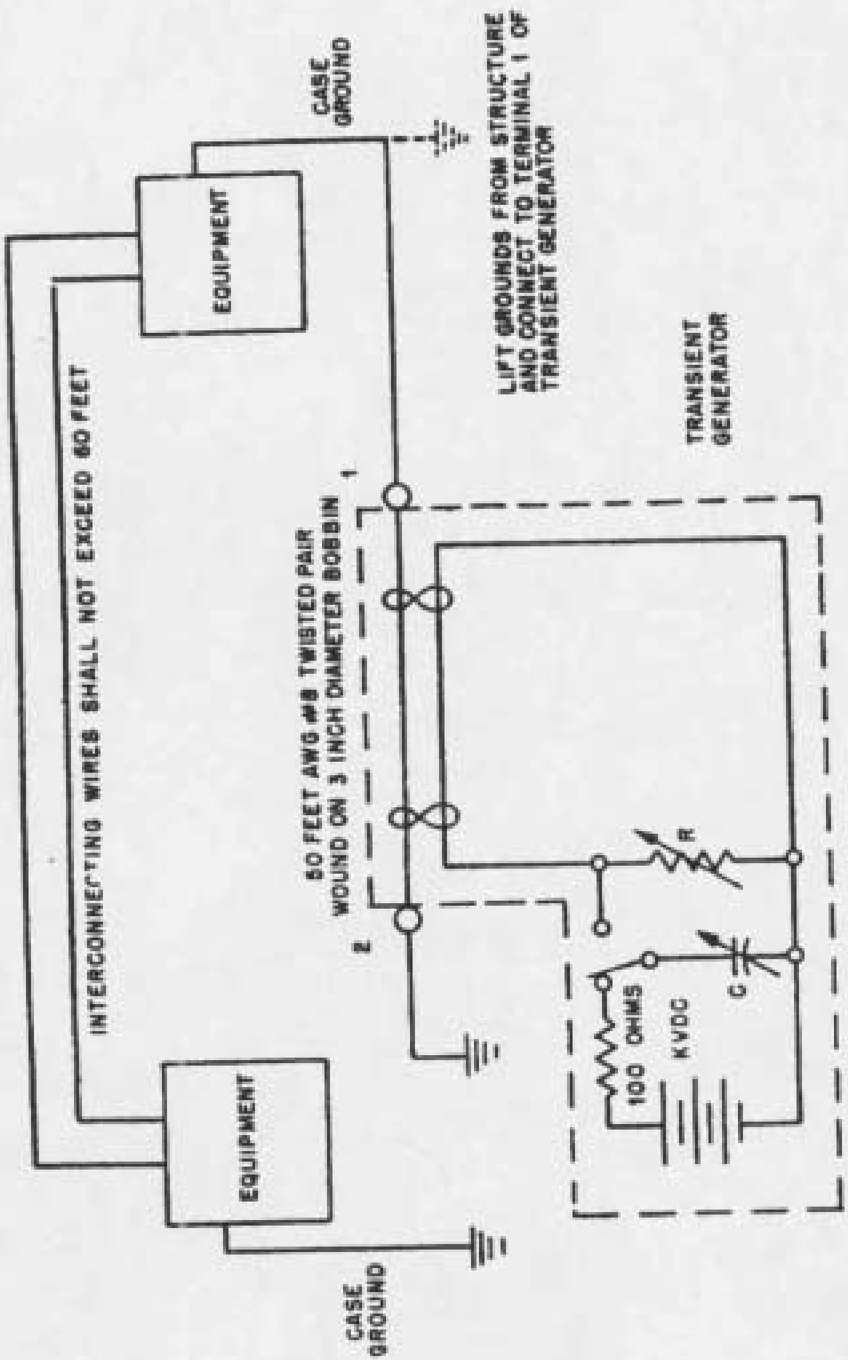


Figure 302-1. Method Of Applying Lightning Induced Transients

302-3

METHOD 302

METHOD 205

STATIC DISCHARGE SENSITIVITY

1. Purpose. The purpose of this test is to test the safety of an electro-explosive device under electrostatic discharge conditions.

2. Procedure:

   a. Thirty electroexplosive devices are required

   b. Precondition the test item by performing the necessary environmental tests

   c. Establish the environmental conditions for this test and let stabilize for the required time

   d. Discharge 25 kv from a 500-pfd capacitor applied through a 5k resistor at the test points. All possible modes, such as pin-to-case, pin-to-pin, etc, shall be tested. Figure 205-1 shows the static discharge test circuit

   e. Perform the test statistically in accordance with Handbook 106.

3. Note. Since in general, human charges rarely exceed 25,000V, any functioning at lower voltage indicates a definite personnel hazard. Some flexibility can be obtained in performing these tests if nonfires from other tests are utilized for testing to determine the most hazardous mode. Then, all 30 electroexplosive devices can be tested in that mode. If no mode shows any specific evidence of sensitivity, equal numbers of electroexplosive devices can be tested for each mode or retested in two or more modes. This flexibility should permit maximum information to be obtained with minimum expense.

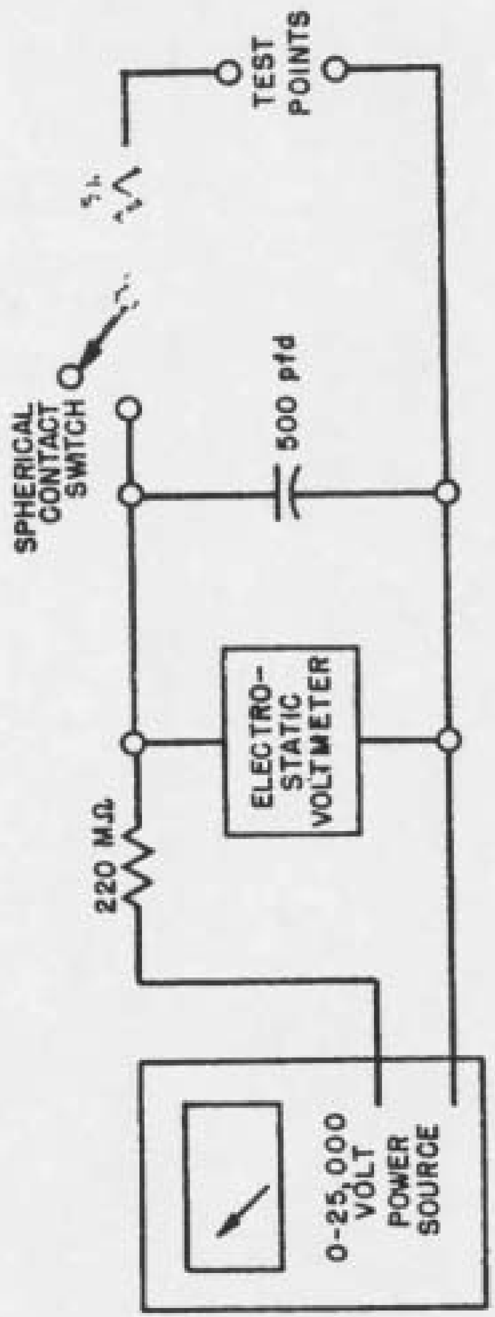


Figure 205-1. Static Discharge Test Circuit

METHOD 503.4

TEMPERATURE SHOCK

NOTE: Tailoring is essential. Select methods, procedures, and parameter levels based on the tailoring process described in Part One, paragraph 4.2.2, and Appendix C. Apply the general guidelines for laboratory test methods described in Part One, paragraph 5 of this standard.

1. SCOPE.

1.1 Purpose.

Use temperature shock tests to determine if materiel can withstand sudden changes in the temperature of the surrounding atmosphere without experiencing physical damage or deterioration in performance. For the purpose of this document, "sudden changes" is defined as, "greater than 10°C per minute."

1.2 Application.

1.2.1 Normal environment.

Use this method when the requirements documents specify the materiel is likely to be deployed where sudden significant changes of air temperature may be experienced. This method is intended to only evaluate the effects of sudden temperature changes of the outer surfaces of materiel, items mounted on the outer surfaces, or internal items situated near the external surfaces. Typically, this addresses:

a. The transfer of materiel between heated areas and low temperature environments.

b. Ascent from a high temperature ground environment to high altitude via a high performance vehicle (hot to cold only).

c. Air delivery/air drop at high altitude/low temperature from aircraft enclosures when only the external material (packaging or materiel surface) is to be tested.

1.2.2 Safety and screening.

Except as noted in paragraph 1.3, use this method to reveal safety problems and potential flaws in materiel normally exposed to less extreme rates of temperature change (as long as the test conditions do not exceed the design limitations of the materiel). Although not intended to be used for environmental stress screening (ESS), with proper engineering this method can also be used as a screening test (using more extreme temperature shocks) to reveal potential flaws in materiel exposed to less extreme temperature change conditions.

1.3 Limitations.

This method is not intended for materiel that will not experience sudden extreme temperature changes because of its packaging, installed location, etc. This method does not replace the assessment of performance characteristics after lengthy exposure to extreme temperatures, such as with methods 501.4 and 502.4. Additionally, this method does not address the temperature shock experienced by materiel transferred between air and liquid or two liquids, the thermal shock caused by rapid transient warmup by engine compressor bleed air, or aerodynamic loading. Except for ESS, this method is inappropriate if the actual transfer time in a service environment will not produce a significant thermal shock. Additionally, this method does not address materiel that has been exposed to heat from a fire and subsequently cooled with water.

SUPERSEDES PAGE 503.4-1 OF MIL-STD-810F.

2. TAILORING GUIDANCE.

2.1 Selecting this Method.

After examining requirements documents and applying the tailoring process in Part One of this standard to determine where thermal shocks are foreseen in the life cycle of the materiel, use the following to confirm the need for this method and to place it in sequence with other methods.

2.1.1 Effects of thermal shock environments.

Effects of thermal shocks are usually more severe near the outer portions of materiel. The further from the surface (depending, of course, on the properties of the material involved), the slower and less significant the thermal changes. Transit cases, packaging, etc. will lessen the effects of thermal shock on the enclosed materiel even more. Sudden temperature changes may either temporarily or permanently affect operation of materiel. The following are examples of problems that could result from thermal shock exposure that may relate to the materiel being tested. Consider the following typical problems to help determine if this method is appropriate for the materiel being tested. This list is not intended to be all-inclusive.

a. Physical.
   (1) Shattering of glass vials and optical materiel.
   (2) Binding or slackening of moving parts.
   (3) Cracking of solid pellets or grains in explosives.
   (4) Differential contraction or expansion rates or induced strain rates of dissimilar materials.
   (5) Deformation or fracture of components.
   (6) Cracking of surface coatings.
   (7) Leaking of sealed compartments.
   (8) Failure of insulation protection.

b. Chemical.
   (1) Separation of constituents.
   (2) Failure of chemical agent protection.

c. Electrical.
   (1) Changes in electrical and electronic components.
   (2) Electronic or mechanical failures due to rapid water or frost formation.
   (3) Excessive static electricity.

2.1.2 Sequence among other methods.

a. General. See Part One, paragraph 5.5.

b. Unique to this method. Use test item response characteristics and performance determination information obtained from the high and low temperature tests to better define the test conditions to be used for this procedure.

2.2 Selecting Procedures.

This method includes two test procedures, Procedure I (Steady State) and Procedure II (Cyclic). Determine the procedure(s) to be used.

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2.2.1 Procedure selection considerations.

When selecting procedures, consider:

a. The expected exposure temperatures in service.

b. The materiel's logistic or deployment configuration.

c. Environmental stress screening (ESS) requirements.

2.2.2 Difference between procedures.

While both procedures involve temperature conditioning and performance testing, they differ on the basis of temperature stabilization prior to shocks.

a. Procedure I - Steady State. Procedure I employs constant temperature at each of the extreme shock conditions because, in many instances, the thermal shock itself so outweighs the other thermal effects that the test may be performed using two constant temperatures. This is particularly the case when more severe shocks are desired, such as for evaluation of safety or initial design, and when extreme values will be used.

b. Procedure II - Cyclic. When a careful simulation of a real environment is required, use Procedure II because the upper temperature follows part of an appropriate diurnal cycle. From the requirements documents determine the function (operational requirement) to be achieved by the materiel and a definition of the circumstances responsible for the thermal shock.

2.3 Determine Test Levels and Conditions.

Having selected this method and relevant procedures (based on the test item's requirements documents and the tailoring process), complete the tailoring process by identifying appropriate parameter levels and applicable test conditions and techniques for these procedures. Base these selections on the requirements documents, the Life Cycle Environmental Profile, Operational Environment Documentation (see Part One, figure 1-1), stress screening requirements and information provided with this procedure. Consider tailoring known service extreme temperatures if the intent of the test is to reproduce induced strain rates found in service. Use values other than those suggested if realistic. Consider the following when selecting test levels. This method addresses several exposure situations: aircraft flight exposure, air delivery - desert, and ground transfer or air delivery - arctic. Based on the anticipated deployment, determine which test variation is applicable. The extreme exposure range should determine the test conditions, but extend the test levels as necessary to detect design flaws.

a. Aircraft flight exposure. This is appropriate if the materiel is to be exposed to desert or tropical ground heat and possible direct solar heating and, a few minutes later, exposed to the extreme low temperatures associated with high altitude.

b. Air delivery - desert. This is appropriate for materiel which is delivered over desert terrain from unheated, high-altitude aircraft, but use the ambient air temperature (no solar loading).

c. Ground transfer or air delivery - arctic. This is intended to test materiel for the effects of movement to and from heated storage, maintenance, or other enclosures or a heated cargo compartment in cold regions.

d. Engineering design. This is used to detect marginal design issues.

e. ESS. ESS is used for evaluating workmanship practices.

2.3.1 Climatic conditions.

Identify the appropriate climatic conditions for the geographic areas in which the materiel will be operated and stored. Actual response temperatures achieved when materiel is exposed to the climatic conditions of the various ground climatic categories could be obtained from the test results of high and low temperature exposure (methods 501.4, 502.4, and 505.4) for either the operational or storage configuration. The latter assumption must take into account the induced effects of solar radiation during storage and transit in various climates.

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2.3.2 Exposure conditions.

Select the test temperatures from field data or from the requirements documents, if available. If not available, determine the test temperatures from the anticipated deployment application or world areas in which the materiel will be deployed, or from the most extreme nonoperating temperature requirements. Except for stress screening purposes, recommend using a range of temperatures that reflects that anticipated in service rather than some arbitrary extreme range.

a. Deployment application (aircraft flight exposure). The thermal stresses and rates that materiel will experience during exposure to the air flight operational environment are dependent upon the ambient conditions, flight conditions, and performance of the onboard environmental control systems. The temperature and humidity at various altitudes can be found in MIL-HDBK-310.

b. Air delivery/air drop. The test conditions for this exposure are based upon the probable conditions in the cargo compartment of the aircraft (or other transport location) and on the ground at the point of impact. Use a lower temperature extreme that assumes an unheated, unpressurized aircraft cargo compartment with the aircraft at an altitude of 8 kilometers (26,200 ft). This is the limiting altitude for cargo aircraft because of oxygen-pressure requirements when the aircraft cargo compartment is unpressurized immediately before air drop operations. The temperature at this altitude can be found in MIL-HDBK-310. Determine the high temperature surface extremes from the appropriate tables in Method 501.4. NOTE: Materiel packaging will normally mitigate thermal shocks. The air delivery/air drop scenario may not involve significant thermal shock to the materiel itself.

c. Ground transfer/air delivery - arctic. The conditions developed for heated enclosures located in cold regions are 21°C (70°F) and 25 percent relative humidity. These conditions roughly correspond to normal heating practices in the Arctic and on aircraft. Base selection of the outside ambient conditions upon the climatic categories or areas listed in the appropriate table in Method 502.4.

d. Engineering design. Use test conditions that reflect the extreme anticipated storage conditions.

2.3.3 Test duration (number of shocks).

For materiel that is likely to be exposed only rarely to thermal shock, perform one shock for each appropriate condition. There is little available data to substantiate a specific number of shocks when more frequent exposure is expected. In lieu of better information, apply three shocks or more at each condition, the number depending primarily on the anticipated service events. The objective of this test is to determine the effect of rapid temperature changes on the materiel. Therefore, expose the test item to the temperature extremes for a duration equal to either the actual operation, or to that required to achieve temperature stabilization.

2.3.4 Extreme high temperature exposure.

Materiel is likely to experience the highest heating during storage in the sun in the Hot Dry and Basic Hot climatic regions. Therefore, conduct transitions from hot to cold with the test item stabilized at its high storage temperature. Conduct transitions from cold to hot with the high temperature facility's air temperature at the maximum storage temperature of the appropriate cycle. Immediately following the cold-to-hot transfer, cycle the high temperature facility through the appropriate diurnal cycle (Method 501.4) from the beginning of the hour at which the maximum air temperature is experienced until the test item maximum operational response temperature is reached (see Method 501.4, paragraph 2.3.3b). Other tests, such as stress screening, may require even more extreme temperatures.

2.3.5 Test item configuration.

The configuration of the test item strongly affects test results. Therefore, use the anticipated configuration of the item during storage, shipment, or use. As a minimum, consider the following configurations:

a. In a shipping/storage container or transit case, and installation of a thermally conditioned item into a container conditioned at another temperature.

b. Protected or unprotected.

c. Deployed (realistically or with restraints).

SUPERSEDES PAGE 503.4-4 OF MIL-STD-810F.

d. Modified with kits for special applications.

e. Packaged for airdrop.

2.3.6 Temperature stabilization.

Stabilize the test item temperature (prior to transfer) for as long as necessary to ensure a uniform temperature throughout at least the outer portions of the test item.

2.3.7 Relative humidity.

For most test programs, the relative humidity (RH) is not controlled. During the thermal shock test it may, however, have a significant effect on some materiel, e.g., cellulosic materials which are typically porous, into which moisture can migrate and then expand upon freezing. Do not attempt to control relative humidity unless specifically required.

2.3.8 Transfer time.

Ensure the transfer time reflects the time associated with the actual thermal shock in the life cycle profile. It should be as rapid as possible, but if the transfer takes more than one minute, justify the extra time.

2.4 Special Considerations.

The test conditions as presented in this procedure are intended to be in general agreement with other extremes described in this document. The primary purpose in establishing these levels is to provide realistic conditions for the traverse between the two temperature extremes. Therefore, before transfer, stabilize the test item at the most realistic temperature that would be encountered during the specific operation, or possibly the most extreme test item stabilization temperature, if appropriate. Consider tailoring known service extreme temperatures, if the intent of the test is to reproduce induced strain rates found in service.

3. INFORMATION REQUIRED.

3.1 Pretest.

The following information is required to conduct temperature shock tests adequately.

a. General. Information listed in Part One, paragraphs 5.7 and 5.9, and Appendix A, Task 405 of this standard.

b. Specific to this method.

(1) Test item configuration.

(2) Test temperature extremes or test item thermal rates of change.

(3) Duration of exposure at each temperature.

(4) Test item response temperature (from method 501.4).

(5) For Procedure II, the high temperature cycle, and the initial temperature for the temperature cycling.

(6) The component/assembly/structure to be used for thermal response and temperature stabilization purposes (if required). (See Part One, paragraph 5.4.)

3.2 During Test.

For test validation purposes, record deviations from planned or pre-test procedures or parameter levels, including any procedural anomalies that may occur.

3.3 Post-test.

Record the following post-test information.

a. General. Information listed in Part One, paragraph 5.13, and in Appendix A, Task 406 of this standard.

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b. Specific to this method.

(1) Previous test methods to which the specific test item has been exposed.

(2) Duration of each exposure.

(3) Status of the test item for each visual examination.

(4) Test temperatures.

(5) Results of operational checks.

(6) Transfer times (e.g., "door open" to "door closed").

4. TEST PROCESS.

4.1 Test Facility.

4.1.1 Apparatus.

The required apparatus consists of two chambers or cabinets, or a two-celled chamber in which the test conditions can be established and maintained. Unless otherwise specified, use chambers equipped so that, after transfer of the test item, the test conditions within the chamber can be stabilized within five minutes. Use materiel handling equipment, if necessary, for transfer of the test item between chambers.

4.1.2 Instrumentation.

Use chambers equipped with auxiliary instrumentation capable of monitoring (see Part One, paragraph 5.18) the test conditions throughout an envelope of air surrounding the test item(s). (See Part One, paragraph 5.3.) Quick-disconnect thermocouples may be necessary for monitoring test item conditions following changes.

4.2 Controls.

4.2.1 Temperature.

Unless otherwise specified in the test plan, if any action other than test item operation (such as opening of the chamber door, except at transfer time) results in a significant change (more than 2°C (3.6°F)) of the test item temperature or chamber air temperature, stabilize the test item at the required temperature before continuation.

4.2.2 Air velocity.

Unless justified by the materiel's platform environment, and to provide standard testing conditions, use an air velocity that does not exceed 1.7 m/s (335 ft/min) in the vicinity of the test item.

4.3 Test Interruption.

a. General. See Part One, paragraph 5.11 of this standard.

b. Specific to this method.

(1) Undertest interruption. If, before the temperature change, an unscheduled test interruption occurs that causes the test conditions to exceed allowable tolerances toward standard ambient temperatures, reinitiate the test at the point of interruption and reestablish the test item at the test condition. If the

SUPERSEDES PAGE 503.4-6 OF MIL-STD-810F.

interruption occurs during the transfer, reestablish the test item at the previous temperature and then transfer.

(2) Overtest interruption. Follow any interruption that results in more extreme exposure of the test item than required by the materiel specification by a complete physical examination and operational check of the test item (where possible) before any continuation of testing. This is eìpecially true where a safety problem could exist, such as with munitions. If a problem is discovered, the preferable course of action is to stop the test and start over with a new test item. If this is not done and test item failure occurs during the remainder of the test, the test results could be invalid due to the overtest condition. If no problem is discovered, reestablish pre-interruption conditions and continue from the point where the test tolerances were exceeded.

4.4 Test Execution.

The following steps, alone or in combination, provide the basis for collecting necessary information concerning the materiel's susceptibility to temperature shock.

4.4.1 Preparation for test.

4.4.1.1 Preliminary steps.

Before starting the test, review pretest information in the test plan to determine test details (e.g., procedures, test item configuration, temperature levels, cycles, temperature stabilization determination, durations, etc.). (See paragraph 3.1 above.)

4.4.1.2 Pretest standard ambient checkout.

All test items require a pretest standard ambient checkout to provide baseline data. Examine munitions and other appropriate materiel by nondestructive examination methods. Conduct the checkout as follows:

Step 1. Stabilize the test item at standard ambient conditions (Part One, paragraph 5.1).

Step 2. Conduct a complete visual examination of the test item (evaluate against paragraph 2.1.1) with special attention to stress areas such as corners of molded areas and interfaces between different materials (e.g., component lead/ceramic interfaces of visible electronic parts), and document the results for comparison with post test data.

Step 3. Conduct an operational checkout in accordance with the approved test plan and record the results.

Step 4. If the test item operates satisfactorily, proceed to the next Step. If not, resolve the problems and restart at Step 1, above.

Step 5. Prepare the test item in accordance with Part One, paragraph 5.8 and in the required test item configuration.

4.4.2 Procedures.

The following procedures provide the basis for collecting the necessary information concerning the materiel in a severe temperature shock environment. The procedures depicted on figures 1 and 2 arbitrarily begin with the lower temperature, but could be reversed to begin with the higher temperature if it is more realistic. Specific points on figures 1 and 2 (in parentheses) are referenced in the following text.

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4.4.2.1 Procedure I - Shock from constant extreme temperatures. (Figure 503.4-1.)

Step 1. With the test item in the chamber, adjust the chamber air temperature to the low temperature extreme specified in the test plan (a). Maintain this temperature for a period as determined in the test plan (a-b).

Step 2. Transfer the test item in no more than one minute (b-c) to an atmosphere at temperature T2 that will produce the thermal shock specified in the test plan, and maintain this temperature as specified in the test plan (c-e).

Step 3. If required in the test plan, evaluate the effects of the thermal shock on the test item to the extent practical.

Step 4. If other cycles in reversed directions are required, transfer the test item to the T1 environment in less than one minute (e-f) and stabilize as required in the test plan (f-h), evaluate the thermal shock effects (if required), and continue as in steps 2 and 3 above. If other one way shocks are required, return the test item to the T1 environment at a rate of not more than 3°C/minute and repeat Steps 1-3. If no other shocks are required, go to Step 5.

Step 5. Return the test item to standard ambient conditions.

Step 6. Examine the test item and, if appropriate, operate. Record the results for comparison with pretest data.

4.4.2.2 Procedure II - Shock to/from cyclic high temperatures. (Figure 503.4-2.)

Step 1. With the test item in the chamber, adjust the chamber air temperature to the low temperature extreme specified in the test plan (a) at a rate not to exceed 3°C/min. Maintain this temperature for a period as determined in the test plan (a-b).

Step 2. Transfer the test item to the maximum air temperature of the high temperature cycle (c) (as specified in the test plan) in no more than one minute. As soon as the chamber door is closed and the chamber recovers to the peak temperature, cycle the chamber through part of the appropriate diurnal cycle until the chamber air temperature reaches the test item response temperature (d) (obtained from Method 501.4, paragraph 2.3.3b). Maintain this temperature as specified in the test plan (d-e).

Step 3. If no other cycles are required, return the test item to standard ambient conditions and proceed to Step 7.

Step 4. Transfer the test item to the lower temperature environment (f) in no more than one minute and stabilize as required in the test plan (f-h). If other cycles are required, proceed to Step 6.

Step 5. If no other cycles are required, return the test item to standard ambient conditions, and proceed to Step 7.

NOTE: Unless the requirements documents indicate otherwise, if the test procedure is interrupted because of work schedules, etc., maintaining the test item at the test temperature for the time required will facilitate completion of the test when resumed. If the temperature is changed, before continuing the test, restabilize the test item at the temperature of the last successfully completed period before the interruption.

Step 6. Repeat steps 2, 3, and 4 as specified in the test plan.

Step 7. Examine the test item and, if appropriate, operate. Record the results for comparison with pretest data.

5. ANALYSIS OF RESULTS.

Follow the guidance provided in Part One, paragraph 5.14, to assist in the evaluation of the test results. Analyze any failure of a test item to meet the requirements of the materiel specifications.

SUPERSEDES PAGE 503.4-8 OF MIL-STD-810F.

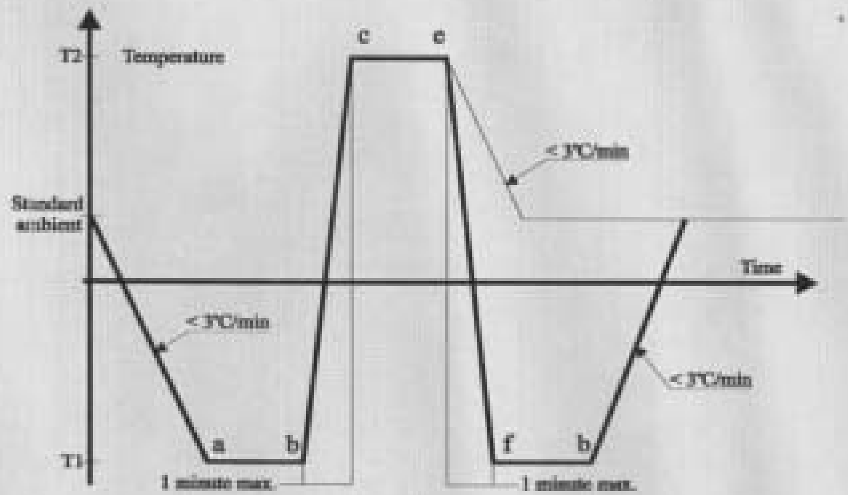

FIGURE 503.4-1. Shocks from constant extreme temperature.

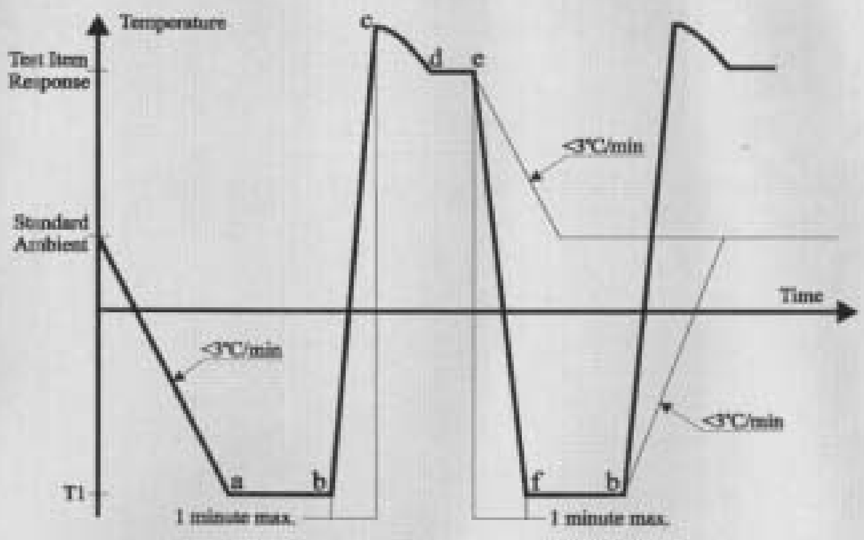

FIGURE 503.4-2. Shocks from cyclic high temperature.

METHOD 522

BALLISTIC SHOCK

NOTE: Tailoring is essential. Select methods, procedures, and parameter levels based on the tailoring process described in Part One, paragraph 4, and Appendix C. Apply the general guidelines for laboratory test methods described in Part One, paragraph 5 of this standard.

1. SCOPE.

1.1 Purpose.

This method includes a set of ballistic shock tests generally involving momentum exchange between two or more bodies or momentum exchange between a liquid or gas and a solid performed to:

a. provide a degree of confidence that materiel can structurally and functionally withstand the infrequent shock effects caused by high levels of momentum exchange on a structural configuration to which the materiel is mounted.

b. experimentally estimate the materiel's fragility level relative to ballistic shock in order that shock mitigation procedures may be employed to protect the materiel's structural and functional integrity.

1.2 Application.

1.2.1 Ballistic shock definition.

Ballistic shock is a high-level shock that generally results from the impact of projectiles or ordnance on armored combat vehicles. Armored combat vehicles must survive the shocks resulting from large caliber non-perforating projectile impacts, mine blasts, and overhead artillery attacks, while still retaining their combat mission capabilities. Reference d discusses the relationship between various shock environments (ballistic shock, transportation shock, rail impact shock, etc.) for armored combat vehicles. Actual shock levels vary with the type of vehicle, the specific munition used, the impact location or proximity, and where on the vehicle the shock is measured. There is no intent here to define the actual shock environment for specific vehicles. Furthermore, it should be noted that the ballistic shock technology is still rather limited in its ability to define and quantify the actual shock phenomenon. Even though considerable progress has been made in the development of measurement techniques, currently used instrumentation (especially the shock sensing gages) is still bulky and cumbersome to use. The development of analytical (computational) methods to determine shock levels, shock propagation, and mitigation is lagging behind the measurement technology. The analytical methods under development and in use to date have not evolved to the level where their results can be relied upon to the degree that the need for testing is eliminated. That is, the prediction of response to ballistic shock is, in general, not possible except in the simplest configurations. When an armored vehicle is subjected to a non-perforating large caliber munition impact or blast, the structure locally experiences a force loading of very high intensity and of relatively short duration. Though the force loading is localized, the entire vehicle is subjected to stress waves traveling over the surface and through the structure. In certain cases, pyrotechnic shocks have been used in ballistic shock simulations. There are several caveats in such testing. The characteristics of ballistic shock are outlined in the following paragraph.

1.2.2 Ballistic shock - momentum exchange.

Ballistic shock usually exhibits momentum exchange between two bodies or between a fluid and a solid. It commonly results in velocity change in the support materiel. Ballistic shock has a portion of its characterization below 100 Hz, and the magnitude of the ballistic shock response at a given point reasonably far from the ballistic shock source is a function of the size of the momentum exchange. Ballistic shock will contain material wave propagation characteristics (perhaps substantially nonlinear) but, in general, the material is deformed and accompanied by structural damping other than damping natural to the material. For ballistic shock, structural connections do not necessarily display great attenuation since low frequency structural response is generally easily transmitted over joints. In processing ballistic shock data, it is important to be able to detect anomalies. With regard to measurement technology, accelerometers, strain gages, and shock sensing gages may be used (see ref. a). In laboratory situations, laser velocimeters are useful. Ballistic shock resistance is not, in general, "designed" into the materiel. The occurrence of a ballistic shock and its general nature can only be determined empirically from past experience based on well-defined scenarios. Ballistic shock response of materiel in the field is, in general, very unpredictable and not repeatable among materiel.

1.2.3 Ballistic shock - physical phenomenon.

Ballistic shock is a physical phenomenon characterized by the overall material and mechanical response at a structure point from elastic or inelastic impact. Such impact may produce a very high rate of momentum exchange at a point, over a small finite area or over a large area. The high rate of momentum exchange may be caused by collision of two elastic bodies or a pressure wave applied over a surface. General characteristics of ballistic shock environments are as follows:

a. near-the-source stress waves in the structure caused by high material strain rates (nonlinear material region) that propagate into the near field and beyond;

b. combined low and high frequency (10 Hz – 1,000,000 Hz) and very broadband frequency input;

c. high acceleration (300g – 1,000,000g) with comparatively high structural velocity and displacement response;

d. short-time duration (<180 msec);

e. high residual structure displacement, velocity, and acceleration response (after the event);

f. caused by (1) an inelastic collision of two elastic bodies, or (2) an extremely high fluid pressure applied for a short period of time to an elastic body surface coupled directly into the structure, and with point source input, i.e., input is either highly localized as in the case of collision, or area source input, i.e., widely dispersed as in the case of a pressure wave;

g. comparatively high structural driving point impedance (P/v, where P is the collision force or pressure, and v the structural velocity). At the source, the impedance could be substantially less if the material particle velocity is high;

h. measurement response time histories that are very highly random in nature, i.e., little repeatability and very dependent on the configuration details;

i. shock response at points on the structure is somewhat affected by structural discontinuities;

j. structural response may be accompanied by heat generated by the inelastic impact or the fluid blast wave;

k. the nature of the structural response to ballistic shock does not suggest that the materiel or its components may be easily classified as being in the "near field" or "far field" of the ballistic shock device. In general, materiel close to the source experiences high accelerations at high frequencies, whereas materiel far from the source will, in general, experience high acceleration at low frequencies as a result of the filtering of the intervening structural configuration.

1.3 Limitations.

Because of the highly specialized nature of ballistic shock and the substantial sensitivity of ballistic shock to the configuration, apply it only after giving careful consideration to information contained in references c and d.

a. This method does not include special provisions for performing ballistic shock tests at high or low temperatures. Perform tests at room ambient temperature unless otherwise specified or if there is reason to believe either operational high temperature or low temperature may enhance the ballistic shock environment.

b. This method does not address secondary effects such as blast, EMI, and thermal.

2. TAILORING GUIDANCE

2.1 Selecting the Ballistic Shock Method.

After examining requirements documents and applying the tailoring process in Part One of this standard to determine where ballistic shock effects are foreseen in the life cycle of the materiel, use the following to confirm the need for this method and to place it in sequence with other methods.

2.1.1 Effects of ballistic shock.

In general, ballistic shock has the potential for producing adverse effects on all electronic, mechanical, and electro-mechanical materiel. In general, the level of adverse effects increases with the level and duration of the ballistic shock and decreases with the distance from the source (point or points of impact) of the ballistic shock. Durations for ballistic shock that produce material stress waves with wavelengths that correspond with the natural frequency wavelengths of micro electronic components within materiel will enhance adverse effects. Durations for ballistic shock that produce structure response movement that correspond with the low frequency resonances of mechanical and electro-mechanical materiel will enhance the adverse effects. Examples of problems associated with ballistic shock include:

a. materiel failure as a result of destruction of the structural integrity of micro electronic chips including their mounting configuration;

b. materiel failure as a result of relay chatter;

c. materiel failure as a result of circuit card malfunction, circuit card damage, and electronic connector failure. On occasion, circuit card contaminants having the potential to cause short circuits may be dislodged under ballistic shock. Circuit card mounts may be subject to damage from substantial velocity changes and large displacements.

d. materiel failure as a result of cracks and fracture in crystals, ceramics, epoxies or glass envelopes.

e. materiel failure as a result of sudden velocity change of the structural support of the materiel or the internal structural configuration of the mechanical or electro-mechanical materiel.

2.1.2 Sequence among other methods.

a. General. See Part One, paragraph 5.5.

b. Unique to this method. Unless otherwise identified in the life cycle profile and, since ballistic shock is normally experienced in combat and potentially near the end of the life cycle, normally schedule ballistic shock tests late in the test sequence. In general, the ballistic shock tests can be considered independent of the other tests because of their unique and specialized nature.

2.2 Selecting a Procedure.

This method includes five ballistic shock test procedures. See paragraph 2.3.4 for the "default" approach to ballistic shock testing when no field data are available.

a. Procedure I - Ballistic Hull and Turret (BH&T), Full Spectrum, Ballistic Shock Qualification. Replication of the shock associated with ballistic impacts on armored vehicles can be accomplished by firing projectiles at a "Ballistic Hull and Turret" (BH&T) with the materiel mounted inside. This procedure is very expensive and requires that an actual vehicle or prototype be available, as well as appropriate threat munitions. Because of these limitations, a variety of other approaches is often pursued. The variety of devices used to simulate ballistic shock is described in reference d of this method.

b. Procedure II - Large Scale Ballistic Shock Simulator (LSBSS). Ballistic shock testing of complete components over the entire spectrum (10 Hz to 100 kHz) defined in table 522-I and on figure 522-1 can be accomplished using devices such as the Large Scale Ballistic Shock Simulator (LSBSS) described in reference d. This approach is used for components weighing up to 500 Kg (1100 lbs), and is considerably less expensive than the BH&T approach of Procedure I.

c. Procedure III - Limited Spectrum, Light Weight Shock Machine (LWSM). Components weighing less than 113.6 kg (250 lbs) and shock mounted to eliminate sensitivity to frequencies above 3 kHz can be tested over the spectrum from 10 Hz to 3 kHz of table 522-I and figure 522-1 using a MIL-S-901 Light Weight Shock Machine (LWSM) adjusted for 15 mm (0.59 inch) displacement limits. Use of the LWSM is less expensive than full spectrum simulation, and may be appropriate if the specific test item does not

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respond to high frequency shock and cannot withstand the excessive low frequency response of the drop table (Procedure V).

d. Procedure IV - Limited Spectrum, Medium Weight Shock Machine (MWSM). Components weighing less than 2273 kg (5000 lbs) and not sensitive to frequencies above 1 kHz can be tested over the spectrum from 10 Hz to 1 kHz of table 522-I and figure 522-1 using a MIL-S-901 Medium Weight Shock Machine (MWSM) adjusted for 15 mm (0.59 inch) displacement limits. Use of the MWSW may be appropriate for heavy components and subsystems that are shock mounted and/or are not sensitive to high frequencies.

e. Procedure V - Drop Table. Light weight components (typically less than 18 kg (40 lbs)) which are shock mounted can often be evaluated for ballistic shock sensitivity at frequencies up to 500 Hz using a drop table. This technique often results in overtest at the low frequencies. The vast majority of components that need shock protection on an armored vehicle can be readily shock mounted. The commonly available drop test machine is the least expensive and most accessible test technique. The shock table produces a half-sine acceleration pulse that differs significantly from ballistic shock. The response of materiel on shock mounts can be enveloped quite well with a half-sine acceleration pulse if an overtest at low frequencies and an undertest at high frequencies is acceptable. Historically, these shortcomings have been acceptable for the majority of ballistic shock qualification testing.

NOTES:

Related shock tests:

1. High Impact / Shipboard Equipment. Perform shock tests for shipboard equipment in accordance with MIL-S-901. The tests of MIL-S-901 are tailorable through the design of the fixture that attaches the test item to the shock machine. Ensure the fixture is as similar to the mounting method used in the actual use environment. High impact shocks for Army armored combat vehicles should be tested using Method 522, "Ballistic Shock."
2. Fuzes and Fuze Components. Perform shock tests for safety and operation of fuzes and fuze components in accordance with MIL-STD-331.
3. Combined Temperature and Shock Tests. Perform shock tests at ambient conditions unless a high or low temperature shock test is required.)

2.2.1 Procedure selection considerations.

Based on the test data requirements, determine which test procedure is applicable. In most cases, the selection of the procedure will be dictated by the actual materiel configuration, carefully noting any gross structural discontinuities that may serve to mitigate the effects of the ballistic shock on the materiel. In some cases, the selection of the procedure will be driven by test practicality. Consider all ballistic shock environments anticipated for the materiel during its life cycle, both in its logistic and operational modes. When selecting procedures, consider:

a. The operational purpose of the materiel. From the requirements documents, determine the functions to be performed by the materiel either during or after exposure to the ballistic shock environment.

b. The natural exposure circumstances for ballistic shock. The natural exposure circumstances for ballistic shock are based on well-selected scenarios from past experience and the chances of the occurrence of such scenarios. For example, if an armored vehicle is subject to a mine blast, a number of assumptions must be made in order to select an appropriate test for the ballistic shock procedure. In particular, the size of the mine, the location of major pressure wave impact, the location of the materiel relative to the impact ‡point,‡ etc. If the armored vehicle is subject to non-penetrating projectile impact, the energy input configuration will be different from that of the mine, as will be the effects of the ballistic shock on the materiel within the armored vehicle. In any case, condition each scenario to estimate the materiel response as a function of amplitude level and frequency content. It will then be necessary to decide to which scenarios to test and which testing is most critical. Some scenario responses may "envelope" others, which may reduce the need for certain testing such as road, rail, gunfiring, etc. In test planning, do not break up any measured or predicted response to ballistic shock into separate amplitude and/or frequency ranges utilizing different tests to satisfy one procedure.

c. Required data. The test data required to determine whether the operational purpose of the materiel has been met.

d. Procedure sequence. Refer to paragraph 2.1.2.

SUPERSEDES PAGE 522-4 OF MIL-STD-810F.

TABLE 522-I. Ballistic shock characteristics.

Average Shock				Worst Case Shock		
Max. Resonant Freq. (Hz)[2]	Peak Displacement (mm)	Peak Velocity (m/s)	Peak Value of SRS[1] (g's)	Peak Displacement (mm)	Peak Velocity (m/s)	Peak Value of SRS[1] (g's)
10	15	1.0	6.0	42	2.8	17
29.5	15	3.0	52.5	42	8.5	148
100	15	3.0	178	42	8.5	502
1,000	15	3.0	1,780	42	8.5	5,020
10,000	15	3.0	17,800	42	8.5	50,200
100,000	15	3.0	178,000	42	8.5	502,000

[1] SRS (Shock Response Spectrum) is Equivalent Static Acceleration for a damping ratio equal to 5 percent of critical.
[2] Tests involving all frequencies from 10 Hz to maximum frequency indicated.

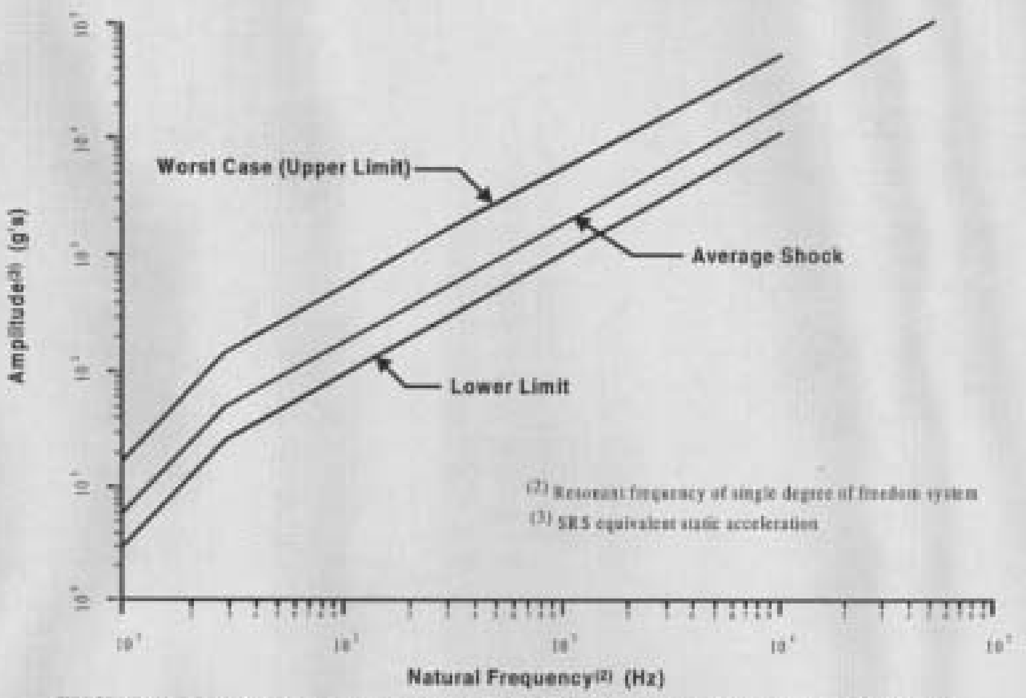


FIGURE 522-1. Shock response spectra of "default" ballistic shock limits (Tables 522-I & II).

TABLE 522-II. SRS function for shock.

Boundary	Natural Frequency	
	From 10 to 29.5 Hz	From 29.5 to 10 kHz
Upper Bound	$SRS = 0.1702\ f^2$	$SRS = 5.020\ f$
Lower Bound	$SRS = 0.03026\ f^2$	$SRS = 0.89272\ f$

Appendix F: Detachment Method Decision Support

Purpose*:* To decide the best method of detachment for HBEDS given a list of design criteria; this method is critical to the design of the final product.

Framework*:* All detachment methods will be examined to choose an appropriate point of detachment given the *purpose*, *assumptions*, and *design criteria*.

Assumptions:

- A system can be designed for each method that will completely release the blades
- There is not a need for a secondary force to move the blades away from the helicopter

Detachment Methods:

- Induced Fracture – a destructive system that would initiate structural failure by explosives, hydraulics, or ballistics
- Active Connection – a joint whose connection is controlled by hydraulics, explosives, or other mechanical system

Design Criteria:

- Stability: The blade detachment system must present an extremely low risk of inadvertent or inadvertent activation, because an unstable detachment system may have a disastrous effect on the aircraft
- Strength: The structure of the rotor blade connection system must not fail under the expected service loads.
- Efficiency: The method must not adversely affect the flight performance of the selected helicopter. Added rotor mass, drag, and rotational inertia may reduce responsiveness, lower load carrying capacity, and increase fuel consumption.
- Power: Because the method must be operable under critical circumstances when the helicopter may be damaged, the power required for activation will be minimized. The detachment method must be capable of operating on the backup power system of the selected helicopter.

- Reliability: The method must ensure synchronized and complete rotor blade detachment upon activation. The blades must detach completely and be free to simultaneously move away from the aircraft in order to avoid rotor imbalance.
- Clearance Time: The detachment method must release the blades and quickly provide clearance in order to be effective. Extended delays in activation, detachment, and clearance confirmation will reduce the chances of pilot survival in the event of an impending crash.
- Cost: The initial purchase price of the system must be commensurate with the overall cost of the selected helicopter.
- Serviceability: The system must be made accessible to minimize costs associated with inspection, servicing, and replacement.
- Durability: The system must be incorporated into the maintenance and parts replacement schedule of the selected helicopter.
- Adaptability: The detachment method will be used on a specific application, yet consideration will be given to broader helicopter applications. The method must be independent of special features that may be unique to the initial application.

Thought Process:

Weighting:

- All criteria were weighted on a scale of one to five, one being of least importance and five being most important.
- Stability and reliability are most important because if the detachment method fails either of these, then it will never be implemented. - 5
- The next most important criteria is strength because if the detachment method weakens the helicopter, it is not a viable method. - 4
- The third group is efficiency, power, and clearance time for the reason that the system must not hamper the performance of the aircraft, must be functional no matter what the condition of the helicopter, and it must ensure the blades have left the vicinity of the helicopter to provide a window of opportunity for the next system in the chain. - 3

- The last five criteria are really secondary considerations behind the first five; therefore, they were all weight either a one or two. The two's deal with having good maintenance abilities and a long service life.

Grading of Locations: (Table F.1)

- All locations were graded on a scale of one to five (low to high) on their ability to meet the characteristic. A grade of zero would result in the location being removed from consideration.
- Induced fractured scored better than active control almost across the board because induced fracture requires a lot less change to the components of the helicopter.
- Induced fracture does require the addition of components not normally found on a helicopter which is why its serviceability is lower than active control.
- The key criteria where there is a big difference in the two methods are stability, strength, and power.

	Stability	Strength	Efficiency	Power	Reliability	Clearance Time	Cost	Serviceability	Durability	Adaptability	
Weighting Factor (1-5)	5	4	3	3	5	3	1	2	2	1	TOTAL
Induced Fracture	3	4	3	4	2	4	2	2	4	4	92
Active Control	2	2	3	1	2	4	1	4	3	2	69

Table F.1: Decision matrix for device location versus design criteria

Decision:

This analysis showed that the best detachment method is induced fracture, as General Dynamics suggested. Therefore, explosives will be used to detach the blades from the helicopter in HBEDS.

Appendix G: Blade Detachment Location Decision Support

Purpose: To decide the best point of detachment for the blade detachment device given a list of design criteria; this location is critical to the design of the final product.

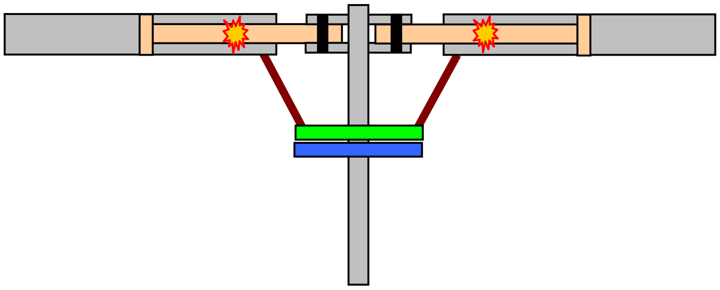
Framework: All logical detachment locations will be examined to choose an appropriate point of detachment given the *purpose*, *assumptions*, and *design criteria*.

Assumptions:

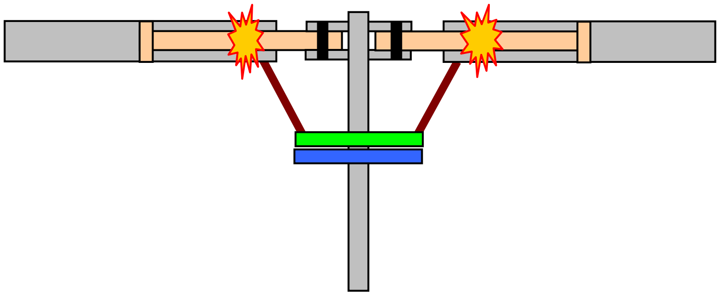
- A system can be designed for each location including a transfer system from the stationary helicopter to the spinning blades if necessary
- There is an explosive suitable to destroy any material in the rotor or blade
- Entire blade or rotor system does not need to be removed to satisfy project objectives

Locations:

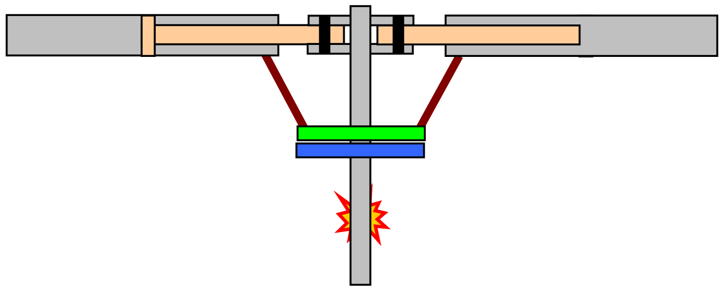
- inside the root of the blade



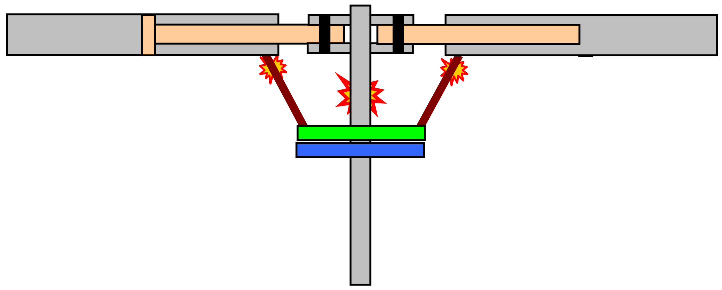
- outside the root of the blade



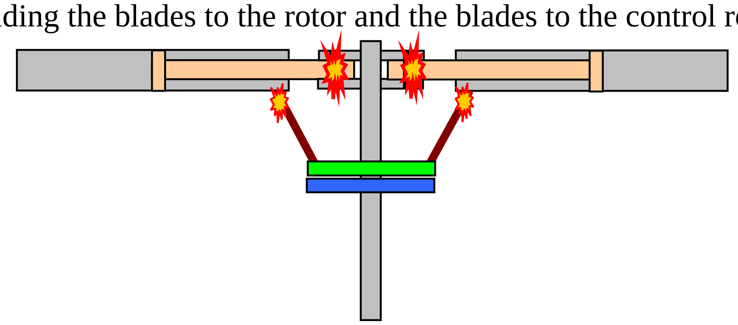
- on the main shaft below the swashplate



- on the main shaft above the swashplate along with the control rods



- the bolts holding the blades to the rotor and the blades to the control rods



Design Criteria:

- stability with respect to inadvertent ignition – evaluates the level of system protection, given its location, from enemy fire, weather, and heat
- clearance time until a safe exit of the blade - the blades safely move away from the helicopter once the device has been activated
- number of detachment points - more detachment points mean more explosives, which leads to two situations, inadvertent ignition of one explosive or failed ignition of one explosive; Additionally, it is difficult to coordinate multiple explosive charges
- how easy would it be to remove the blades - how many things must be moved or disconnected to detach the blades for service

- how easy would it be to install or remove the system - any restrictions on the area in which the system was installed and access to the system for service or inspection
- how easy would it be to integrate the system - affects as few critical components as possible
- difficulty of designing the system – how many components are changed by the device and is there a need for a transfer system from the stationary helicopter to the rotating part of the rotor or the blades
- difficultly of manufacturing the system - the number of changes that would have to be made to the current manufacturing process in order to build the detachment device

Thought Process:

Weighting:

- All criteria were weighted on a scale of one to ten, one being of least importance and ten being most important
- two most important design criteria => stability and clearance time. Therefore, these two design criteria were given weightings of ten to make them almost two thirds of the points available.
- the number of detachment points relays the complexity of the system and was weighted a four
- The final five design criteria are really secondary considerations and were weighted between a one and three.
- Since blades are often removed for service or transportation, the easy of removal of blades was given a three along with the integration of the system because the number of critical components affected directly impacts the serviceability and life of the device.
- The installation and removal of the system was weighted a two because it related to so many other design criteria like integration and easy removal of blades that there was a need to minimize double counting of design criteria.
- The ease of design, criteria determines the amount of work necessary to complete the project and understand all the components. While this is important from a time standpoint, it is not crucial and was therefore weighted a two.

- The ease of manufacturing the device was weighted a one because as long as the device can be made, this only affects its cost which is much less important than its ability to function properly.

Grading of Locations: (Table G.1)

- All locations were graded on a scale of one to five on their ability to meet the characteristic. A grade of zero would result in the location being removed from consideration.
- Stability => The outside root was given the lowest grade of a three due to its susceptibility to enemy fire and the elements, while the other locations were all given fours because of better protection from enemy fire and the elements. Main shaft seems like a candidate for a five according to the protection argument; however, its close proximity to the engines and the heat they create lowered it to a four.
- Clearance Time => Inside and outside root were given a five in this category because they detach the high-energy blades which carry themselves away from the helicopter, as proven by NASA's RSRA experiments. While the bolts with control rods are a similar situation, there is worry that the blades will not slide smoothly out of the clamp in which they are held. Finally, the two main shaft options were given a one because of the dynamic analysis presented in APPENDIX H where it was shown that the rotor system may only raise a few meters above the helicopter which means that there is a high likelihood that the rotor system and blades would continue to pose a threat to the helicopter and it's occupants. Additionally, there are concerns that the rotor system might hit the helicopter upon detachment, potentially causing damage to the helicopter.
- Number of detachment points => Ranked by the higher the number the lower the grade. Therefore, the main shaft was given a five because it had one detachment point, the inside and outside roots a three because they have four, the main shaft and control rod a three for having five points, and the bolts and rods a two for having twelve points.
- Easy removal of the blades => The main shaft was given a five because it does not affect the blades at all while the inside root, outside root, and the main shaft control rods all have four connections that need to be disassembled before the blades can be removed. Therefore, these locations were given a four. The bolts and control rods has twelve

connections that must be broken before the blades can be removed resulting in a ranking on a three.

- Integration => More critical components affected the lower the score. Mainshaft does not affect anything so it received a five. The outside root only has to run lines to the blades so it was given a four while the inside root and main shaft with control rods were given a three because the interior design of the blades is critical and the controls are critical to the helicopters ability to change blade pitch. Finally, the bolts and rods option was given a two for affecting the bolts that hold the blades to the rotor and the control rods.
- Easy installation/removal of blades=> The outside blade root has the fewest restrictions on the device so it was given a five, where as the rest are more difficult to access and were given threes.
- Ease of Design => The main shaft gets a five because there is no need for a transfer system while the other locations require one and the explosive will simply consist of a shaped charge pointed at the driveshaft. Inside root and outside root are very close but the requirement to get the explosive inside the blade on the inside root lowers it to a three while outside root gets a four. Main shaft with control rods and bolts with control rods received a two because of the changes in design to structurally loaded parts, the bolts and control rods, in addition to the transfer system requirements.
- Ease of Manufacturing => Outside root was given a five because it could be strapped to the outside of a blade with no changes in the manufacturing process besides the addition of a transfer system. The main shaft option was given a four because of the complex location of the system and large charge that would be needed to sever the drive shaft. Main shaft with rods and bolts with rods were both given fours because of the changes in manufacturing the bolts used in assembly in addition to the transfer system and explosive size reasons. Finally, the inside root was given a three because the assembly of the blade would require a whole new technique due to the explosive inside in addition to the transfer system requirement.

	Stability	Clearance Time	Number of Detach Points	Easy Removal of Blades	Ease of Integration	Installation/ Removal of System	Ease of Design	Ease of Manufacturing	
Weighting	10	10	4	3	3	2	2	1	**TOTAL**
Inside Root	4	5	3	4	3	3	3	2	**137**
Outside Root	3	5	3	4	4	4	4	4	**136**
Main Shaft	4	1	5	5	5	3	5	3	**119**
MS & Rods	4	1	3	4	3	3	2	3	**96**
Bolts & Rods	4	4	2	3	2	3	2	3	**116**

Table G.1: Decision matrix for device location versus design criteria

Additional Thoughts:

- Inside root is sleeker, more clandestine.
- Inside root is closer to the two things we need to blow up: inside composite bone, outside shell
- Inside root has no impact to airfoils, whereas an outside root design would create a bulge and disrupt airflow

Decision:

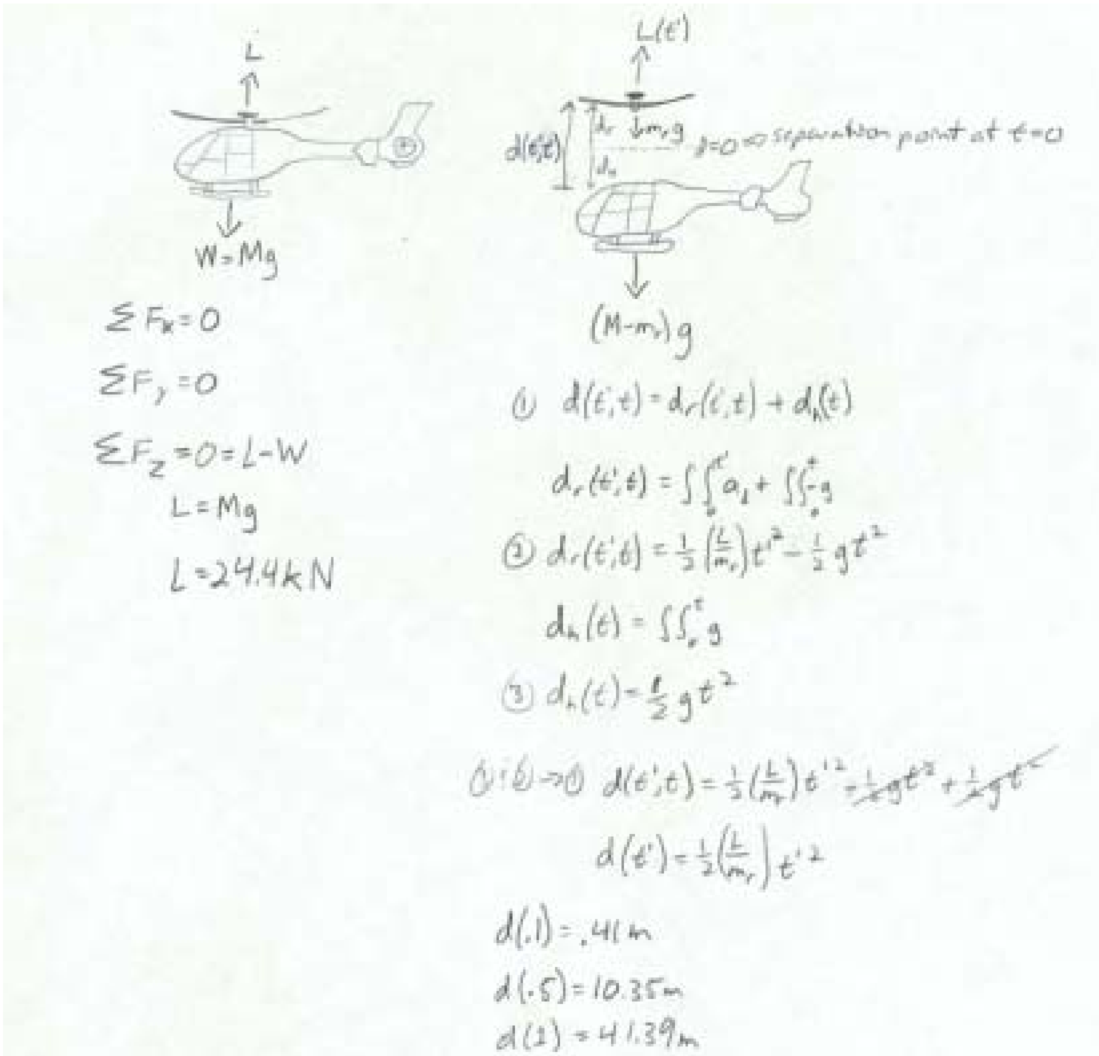
While inside and outside root are very similar in point totals, we chose to detach on the inside of the blade at the root because it takes full advantage of the composite blades used on the bearingless rotor EC135/EC635 and offers greater protection for the explosive. Additionally, the inside root scored higher in our two most important categories than any of the other locations.

Appendix H: Dynamic Analysis of Rotor System Detachment

Assumptions:

- One of the worst cases is helicopter at hover (no directional movement) => lift on blades equals the weight
- No air resistance Č no drag
- No wind
- Angle of attack of the blades will go to zero rapidly because they wish to take the path of least resistance
- Lift is a step function where the force, L, is active for a time, t', then no longer active at time t'+1. Evaluate 3 scenarios: t' = 0.1s, 0.5s, 1.0s
- Next action in the emergency sequence (parachute, ejection, or impact) will occur between t = 2.0s and 5.0s
- Weights (from Eurocopter):
  - EC135 Ą 1490kg
  - Avg. Load Ą 1000kg
    - Helicopter Total (M) Č 2490kg
  - Blades Ą 74.8 kg
  - Rotor Hub Ą 110kg
    - Rotor System Total (m_r) Č 409.2kg

Analysis:



Discussion:

Given the assumptions made for the analysis. The separation distance is not dependent on the time after activation but solely on the time which the lift force is acting on the rotor system. Given the three different times for which L is active, we cannot support the statement that the rotor system will have moved to a safe distance away from the helicopter, allowing for parachute deployment, ejection seat activation, or a hard landing.

Appendix I: Explosives Trade Study

Introduction:

The objective of this trade study is to develop an understanding of explosives and detonation techniques that will lead to a choice of a suitable class of explosive for the helicopter blade detachment device. With the design for the device finished, the criteria for the explosives can be established, which will enable this trade study to determine an appropriate explosive. Additionally, there is a discussion of the appropriate detonation technique after the conclusion of the explosive choice.

Definition:

An explosive is a substance that generates massive amounts of gas and heat due to a rapid chemical change, which occurs without an external oxygen supply, caused by an outside shock or exposure to heat.

Types of Explosives:

Explosives have many applications from blasting earth for mining to rockets to signaling flares and as a result of all those applications, there are several types and classifications of explosives. The two main types are low explosives and high explosives. Low explosives, like gun powder, quickly burn from the outer surface inward; whereas, high explosives, like dynamite, detonate, which means that they decay almost instantaneously. Within the high explosives class, there are primary explosives, used in detonators, and secondary explosives, which are initiated by primary explosives. Primary explosives are very sensitive to outside shocks while secondary explosives are more stable. This trade study will focus on high explosives because low explosives lack the energy and power required to deform or destroy the composites of a helicopter's blades. In order to save weight on the final design, secondary high explosives will be the specific focus of this trade study because they have a higher power to weight ratio than a primary high explosive.

Compositions of High Explosives:

The four most common explosive bases are nitroglycerine (NG), ammonium nitrate (AN), and cyclo-trimethylene-trinitramine (RDX). NG is a powerful explosive base; however, it is extremely unstable and has a very high freezing point of 55^{o} F. AN was initially used solely as an oxidizing element in blasting agents, but its stability has lead to its use in high explosives in place of NG and other more reactive explosives. RDX is a newer more stable compound given its strength.

Classes of Secondary High Explosives and their Characteristics:

There are five main classes of secondary high explosives based on the different bases: straight NG dynamites, ammonia dynamites, straight gelatine dynamites, ammonia gelatine dynamites, and RDX mixtures.[141] Straight NG dynamites have a high velocity of detonation (VOD), good water resistance, and good resistance to flames; however, they are very sensitive to friction and external shocks and they are expensive. Ammonia dynamites come in high and low VOD varieties, but both are weaker than straight NG dynamites. They also exhibit good water resistance but are more shock resistant than NG dynamites. Straight gelatine dynamites have a high VOD, excellent water resistance, and are more stable than their solid counterparts. Ammonia gelatine dynamites have a similar relationship to straight gelatine dynamites as straight NG dynamites have to straight ammonia dynamites. Ammonia gelatine dynamites are also the least costly of the group. (Table I.1) The final class is the RDX mixtures, which is typically a combination of the RDX base, a white crystal, and a wax which is then pressed into a charge. RDX mixtures can be manipulated to have certain desired characteristics easier than the other classes because of the possible compounds that the crystal can be mixed. Typically, RDX mixtures exhibit high VOD and great resistance to water, flames, and other shocks.

Item	Unit	Dynamites		Gelatines	
		Straight	Ammonia (High-density)*	Straight	Ammonia
COMPOSITIONS:					
Nitroglycerine (NG)	% by weight	20.2—56.8	12.0—22.5	20.2—49.6	22.9—35.3
Sodium nitrate (SN)		59.3—22.6	57.3—18.2	60.3—38.9	54.9—33.5
Ammonium nitrate (AN)		—	11.8—50.3	—	4.2—20.1
Nitrocellulose		—	—	0.4—1.2	0.3—0.7
Carbonaceous fuel		15.4—18.2	10.2—8.6	8.5—8.3	8.3—7.9
Sulphur		2.9—0	6.7—1.6	8.2—0	7.2—0
Antacid		1.3—1.2	1.2—1.1	1.5—1.1	0.7—0.8
PROPERTIES:					
Weight strength	%	20—60	20—60	20—90	30—80
Cartridge strength	%	20—60	15—52	30—80	35—72
Cartridge count	per 50 lb case	100—106	110	85—105	90—106
Specific gravity	—	1.4—1.3	1.3	1.7—1.3	1.6—1.3
Confined VOD	ft/sec	9000—19000	8000—12500	11000—23000	14000—20000
Water resistance	—	poor-good	fair	excellent	excellent
Fume class	—	3	1	3—1	1

* Low density ammonia dynamites have a weight strength of 65 %, cartridge strengths of 20—50 %, cartridge counts of 174—120, specific gravities of 0.8—1.3, and two velocity ranges 6300—8100 and 8300—11000 fps. Water resistance is poor-fair, with fume class of 1.

Table I.1: Compositions and Properties of NG and AN High Explosives[142]

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[141] Gregory, C.E. *Explosives for North American Engineers*. (Germany: Trans Tech Publications, 1973) 44.
[142] Gregory, 44.

Another important characteristic to discuss is the explosives resistance to inadvertent detonation. One such case is inadvertent ignition due to impact with a foreign object. Figure I.1 shows the relationship between the velocity and size of an object that is required to cause an unintentional detonation of a secondary explosive (TNT) and a primary explosive (PETN). As shown, secondary high explosives are more stable than primary high explosives. A second situation is where excessive heat causes an inadvertent ignition. Most high explosives have ignition temperatures above their melting points, meaning the fear is of a hot spot. Unfortunately, it is hard to handle hotspots and any explosive is susceptible to them; however, some explosives, like ammonia gelatins, do have higher ignition temperatures than others. Additionally, many RDX mixtures will actually slowly burn in high heat situations instead of explode.

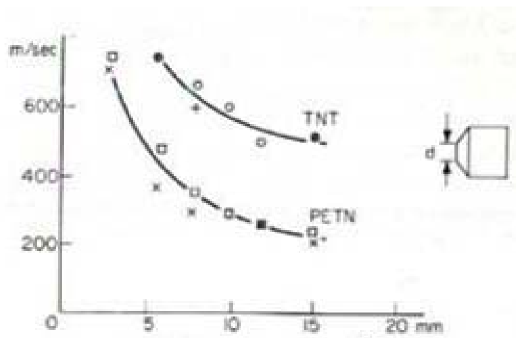

Figure I.1: Critical Velocity versus Diameter of Impact Area for Samples of PETN and TNT[143]

Specifications and Explosive Evaluation:

Table I.2 shows a list of specifications for the explosive that should be used in the blade detachment device. Specifications include reliability, stability, strength, and cost.

Specifications	Qualification or Quantification
Reliable High-Order Detonation	complete detonation more than 99% of the time
Sensitivity to Inadvertent Detonation	cannot accidentally detonate due to impact, electrical shock, or heat
Sensitivity to Intentional Initiation	must ignite upon outside initiation shock
Stability (ability to withstand conditions)	cannot deteriorate under the operational conditions of the aircraft
Water resistance	must survive water dump of 2000 gallons over 24hrs
Heat resistance	cannot ignite at 200F
Climate Temperature resistance	must be able to operate from -50F to 150F
Strength (ability to destroy)	must destroy the composite material it is acting upon
Brisance (ability to shatter)	must have a high velocity of detonation (VOD)
Cost	reasonably inexpensive

Table I.2: List of Specifications and their Qualification or Quantification

Using these specifications, an evaluation of different classifications of explosives can be performed. Many steps were required to get to the results of the evaluation that are presented in

[143] Johansson, C. H. and P. A. Persson. *Detonics of High Explosives*. (New York: Academic Press, 1970) 112.

Table I.3. The first step was to weight the specifications depending on their importance to the project. While reliability and intentional initiation would have received a weighting of five on their own, the fact that they are very similar in their specifications lead to a ranking of four for each so there was no double counting of the overlapping traits. Since inadvertent detonation is equally as important as reliability and intentional initiation because if the blades accidentally detach during a flight that could lead to the loss of aircraft and crew, inadvertent detonation was given a weighting factor of five. Climate and water resistance were given a weighting of three because they are more important than heat resistance, because a focused heat on the explosive is very unlikely to occur. Strength and brisance[144] are also very closely related because an explosives ability to destroy is often a direct result of how much it shatters. Therefore, like reliability and intentional initiation, strength and brisance were given a factor of three, which is lower than if there had only been one of the two specifications. Being a military application, cost is a minor factor in the choice of an appropriate explosive for the design.

	Reliability	Inadvertent Detonation	Intentional Initiation	Water Resistance	Heat Resistance	Temperature of Climate	Strength	Brisance	Cost	
Weighting Factor (1-5)	4	5	4	3	2	3	3	3	1	TOTAL
Straight NG	5	2	5	2	2	2	5	5	1	97
Ammonia	3	3	3	3	3	4	4	4	3	93
NG Gelatine	4	3	4	5	3	3	4	4	2	103
Ammonia Gelatine	3	4	2	5	4	4	3	3	5	98
RDX Mixtures	4	4	3	5	5	4	4	3	3	109

Table I.3: Proposed Explosives Versus Specifications

As discussed above, the straight dynamites are more explosive than the gelatines, which means they have more power per grams of explosive and they are more volatile. Additionally, the NG dynamites are more explosive than the ammonia dynamites. RDX is a very energetic explosive base and its mixtures tend to have very good power to weight ratios. This means that the straight dynamites, the NG dynamites, and the RDX mixtures are more qualified according to specifications like reliability, intentional initiation, strength, and brisance because they are likely to explode even with partial initiation and when they explode they create a large destructive force. These same traits go against these two types of dynamites in the inadvertent detonation

[144] Brisance is the shattering action of the explosive.

and heat resistance specifications because they are so volatile and easy to ignite. The RDX mixtures are actually more stable and do not suffer from the same logic in the grading due to the traits that were discussed before.

Gelatines and RDX mixtures are insensitive to water due to the wax that they are mixed with, so they were given fives in the water resistance category. Ammonia and RDX are not very sensitive to climate temperatures resulting in a ranking of four for all the ammonia dynamites and the RDX mixtures in the temperature of climate specification. Finally, NG costs more than ammonia, so the cost grades went from one for straight NG to five for the ammonia gelatine. RDX mixtures have a more widely dispersed price range, so it was given a three.

Conclusions:

As shown in Table I.3, a RDX mixture is the best class of explosive for our application given the device design. This explosive was chosen due to its resistance to outside shocks, strength, and reliability. Another consideration is that our charges will be purchased from a company like McCormick-Selph or Ensign-Bickford that specializes in the design of explosives. This company would design the shaped charge and choose the exact explosive composition that would be used in the application. Shaped charges use a copper billet surrounded by explosive to create a cutting force along a line. (Figure I.2) When the explosive ignites, the copper is liquefied and cuts through the material on which the shaped charge is placed.

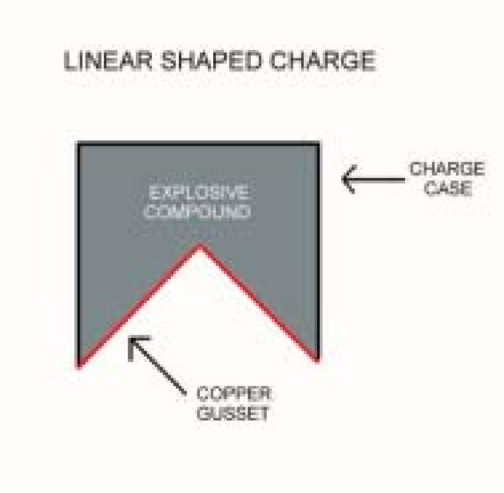

Figure I.2: Linear Shaped Charge Diagram

After a discussion of the system design with Dave Stilwell from Ensign-Bickford's aerospace division, the group believes that a linear shaped charge could be designed to fix inside the blade to cut both the center rib and the outer shell.

Additional Notes:

There are two main techniques for triggering the detonation of the explosive. The first is an electrical transfer system and the second is an explosive transfer system. Both systems ignite a priming charge made of a mix of lead azide and lead styphnate with aluminum powder. This priming charge then sets of the base charge of penta-eruthritol-tetra-nitrate (PETN), which will detonate the explosive.[145]

The electrical system would use the closing of a circuit to create an electrical impulse across a wire in a detonating cap which would generate heat and ignite the priming charge. An electric detonator would limit the ignition system's susceptibility to heat and fire.

Alternatively, an explosive system would use the pressure created by releasing a mechanical device would ignite detonation transfer lines. These lines carry heat to the explosive and that heat causes the explosive charge to detonate. Detonation transfer line explosives include substances like PETN, an unstable primary explosive; however, their quantities and mixtures in the lines make them extremely stable even to large outside shocks. This set-up would limit the systems susceptibility to an electrical shock like lightning or static charges.

Mr. Stilwell believes that using a detonation transfer line system is the safest and most reliable method of initiating the explosive. Therefore, the team will design a schematic for the lines including the necessary interrupters and manifolds that will be required to make the system safe when not in use and propagate the signal to all four blades of the helicopter.

[145] Gregory, 68.

Appendix J: Signal Transfer Method Decision Support

Purpose*:* To decide the best method of transferring a signal from the stationary helicopter to the rotating blades for HBEDS given a list of design criteria; this location is critical to the design of the final product.

Framework*:* All logical methods will be examined to choose an appropriate method given the *purpose*, *assumptions*, and *design criteria*.

Assumptions:

- A system can be designed for each method that will allow transfer of a signal from the stationary helicopter to the rotating explosives in the blades
- The ignition train components will interface with the signal transfer method and will not be affected by the method

Detachment Methods:

- Radio Waves – would be a system that sends a radio signal from the cockpit to a receiver mounted near the explosives to detonate them
- Hall Effect Sensors – would be a magnetic system that could transfer a signal through the main shaft to detonating cord mounted on the inside
- Mechanical Interaction – operates by placing an object into the path of a trigger pin when activation is required
- Optical Signal – would use a laser beam or other optical signal transfer method to send an optical signal to a receiver near the explosives
- Electrical Signal – would use and electrical rotor and stator to transfer a signal to the explosives

Design Criteria:

- Stability: The transfer system method must present an extremely low risk of inadvertent or inadvertent activation. Because an unstable or insecure method may have a disastrous effect on the aircraft.

- Efficiency: The method must not adversely affect the flight performance of the selected helicopter. Added rotor mass, drag, and rotational inertia may reduce responsiveness, lower load carrying capacity, and increase fuel consumption.
- Reliability: The method must not affect the systems ability to ensure synchronized and complete rotor blade detachment upon activation.
- Clearance Time: The transfer system method must provide a quick signal transfer which lets the explosives release the blades and ensures a safer environment. Extended delays in activation, detachment, and clearance confirmation will reduce the chances of pilot survival in the event of an impending crash.
- Cost: The method should not add an absurd cost to the HBEDS system.
- Serviceability: The method must be accessible to minimize the costs of inspection, service, and replacement of warn parts.
- Integration: It must be possible to integrate the transfer system method with the helicopters other components.
- Adaptability: The method will be for a specific application, yet consideration will be given to allow for potential application to a wide range of aircraft. The method will be independent of special features that may be unique to the specific application. This implies that the method will be adaptable to other aircraft at a similar cost.
- Power: Because the system must be operable under critical circumstances when the helicopter may be damaged, the power required for activation will be minimized. The transfer system method must be capable of operating on the backup power system of the selected helicopter.
- Durability: The method must be incorporated into the maintenance and parts replacement schedule of the selected helicopter.

Thought Process:

Weighting:

- All criteria were weighted on a scale of one to ten, one being of least importance and ten being most important.

- Stability is by far the most important criteria for selecting an appropriate method of detachment, which is why it was weighted a ten (twice the next highest weighting). The ten weighting was given to stability because the method must not have any possibility of activating until it is called upon. If it were to activate, there would be disastrous effects.
- Reliability came next with a five because once called upon, the system needs to work.
- Efficiency, power, and clearance time are all critical to the success of the project, but they can all be designed around so they were weighted as threes.
- Cost, serviceability, durability, and adaptability are secondary considerations which are not vital to the success of the project so they are weighted either a one or two depending on their importance.

Grading of Locations: (Table F.1)

- All locations were graded on a scale of one to five on their ability to meet the characteristic. A grade of zero would result in the location being removed from consideration.
- Stability => The only method that we saw as not having an easy means of inadvertent activation was the mechanical system. There are lots of radio waves in the air and shielding our system from those would be though. A helicopter is full of electrical and mechanical components that could potentially create a magnetic field and trip a hall sensor. The optical system just seems inherently unstable given sunlight, laser targeting systems, and other things. Finally, an electrical system would have to be shielded for the static electricity build-up on the blades.
- Efficiency => The most efficient system is the electrical system because it would add the lease weight to the rotor system. The electrical system is followed by optical, hall effect, and radio systems. Then the mechanical system because it would require some structurally significant pieces to take the weight applied on impact.
- Power => Mechanical was the clear winner in this category because it only requires the stored energy in the rotor system to work. Electrical was next because it only requires a small voltage and amperage to work. The other three followed because they require quite a bit of electrical energy to work.

- Reliability => Follows some of the same logic as stability; however, now those things that interfere with the method may prevent it from operating properly when activated. Mechanical is extremely reliable because when an object is placed in the controlled path of another object, they're going to hit. Electrical is also very reliable because now that static electricity may just activate the system earlier than expected, same with the optical system. The Hall Effect sensors and radio waves could potentially be blocked out by other magnetic fields or radio waves which would prevent activation of the explosive.
- Clearance Time => The grading for this category was done based on the speed of activation. Electrical was the fastest because the signal travels at close to the speed of light and therefore it received the highest grade followed by optical and Hall Effect systems (with signal travel near the speed of light). Mechanical was next because its activation speed is actually faster than the speed of sound required by radio waves, especially when the sending and receiving process is taken into account.
- Cost => Mechanical is very simple and therefore cheap. Electrical is too, however, it requires a fancy shielding system. The last three are hard to differentiate, so they were all given a two based on the fact that their components have to be more expensive than the other two.
- Serviceability => The easiest two systems to service are the mechanical system and the electrical system because the mechanical system can be inspected visually and the electrical system can be tested with test currents. The other three require at least a basic knowledge of the principles on which the work and then a fairly complex test system.
- Durability => The mechanical system is the most durable because it has no components that can really degrade over time. The electrical system is next because its components are fairly simple and stable. The Hall Effect system was graded a two because its components are more likely to fail than the electrical system, but not as likely as either the radio or optical system.
- Adaptability => The most adaptable system is the radio system because it has no reliance on any component or geometry of the helicopter. The optical system has very little reliance on the helicopter, but it does need a clear line of sight. Finally, the mechanical, electrical, and Hall Effect systems were all given threes because they rely on the internal geometry of the helicopter.

	Stability	Efficiency	Power	Reliability	Clearance Time	Cost	Serviceability	Durability	Adaptability	
Weighting Factor (1-10)	10	3	3	5	3	1	2	2	1	TOTAL
Radio Waves	2	4	2	2	2	2	2	1	5	67
Hall Effect Sensors	2	4	2	2	4	2	2	2	3	73
Mechanical Interaction	4	3	4	5	3	4	4	4	3	118
Optical Signal	2	4	2	3	4	2	2	1	4	77
Electrical Signal	2	5	3	4	5	3	4	3	3	99

Table F.1: Decision matrix for transfer system method versus design criteria

Decision:

Given this logic and the resulting matrix about the five transfer system methods, the HBEDS team believes that the mechanical system is clearly better than the others and will therefore be used in the HBEDS transfer system.

Appendix K: Ignition Train Trade Summary

Background

Controlled explosive components are commonly used for explosive signal transfer in many aerospace applications, including ejection seats and canopy fracture mechanisms for fixed wing aircraft. The mild detonating cord, manifolds, piston actuators and other components utilized in these systems are designed for extremely high reliability and resistance to stresses experienced during flight. Prior to installment, each component undergoes rigorous qualification testing to ensure the system will not be susceptible to activation by stresses such as fire, heat, vibration, ballistic shock, lightning strike, or electrostatic discharge. Owing to the proven stability, performance, and reliability of these systems, explosive signal transfer has been identified as the most promising method of controlling the detachment sequence.

The HBEDS explosive detonation signal will be transmitted from a cockpit-located initiator to four blade-mounted linear shaped charges by way of an ignition train. Within this network of detonating cord, manifolds, and interlocks, the energetic signal passes through a transfer system that links the cockpit to the rotor system and coordinates the blade detachment sequence. The complexity of this arrangement has prompted the HBEDS team to investigate various ignition train alternatives in a trade study. Drawing from the project specifications, a number of ignition train designs will be considered and compared quantitatively according to reliability, weight, and production cost.

Statement of Purpose

The ignition train trade study shall identify a reliable, lightweight, low cost method of transferring an explosive signal from the initiator to the linear shaped charges.

Decision Criteria

Reliability: The reliability of the ignition train is a critical design parameter. Expected reliability will be calculated based on manufacturer test data for each component while taking into account redundancies evident in the alternative designs. The reliability of the transfer system, herein referred to as $R_{transfer}$, describes the probability that the signal will be properly transmitted from between the stationary and rotating systems. $R_{transfer}$ will be assumed to be constant amongst the transfer line schematics, and will later be estimated through prototype testing.

Weight: The weight of the explosive signal transfer system must be kept to a minimum because excess mass has a significant effect on the flight performance of a helicopter. The overall weight of the ignition train designs will be calculated by summing the estimated weights of each included component.

Cost: Extensive qualification testing is necessary to ensure the reliability of each component used in the system. Owing to the expenses associated with these destructive tests, the ignition train is expected to make up a significant portion of the overall cost of HBEDS. The cost of the explosive components will therefore be minimized to ensure the system meets the cost specification. In preparing for this analysis, the HBEDS team has obtained cost estimates for various explosive components based on a forecasted production of 1000 systems.

Components

Each proposed ignition train alternative is a unique arrangement of seven controlled explosive components commonly used in aerospace applications:

Mild Detonating Cord (Lines): Shielded Mild Detonating Cord (SMDC) and Flexible Mild Detonating Cord (FMDC) use a secondary explosive such as HNS to transfer an energetic signal along their length.[146] Each cord section is fitted with end tips that allow the signal to be transferred to other controlled explosive components.

Manifolds: Manifolds are inert connectors that allow SMDC and FMDC to be linked in a variety of configurations. Manifolds are commonly used for splitting an energetic signal amongst multiple detonating cord sections.

Figure K.1: Flexible Mild Detonating Cord[147]

Figure K.2: Manifolds[148]

[146] Flexible Mild Detonating Cord, *Aerospace and Defense Product Catalogue*, Ensign-Bickford Aerospace and Defense Company, 2003.
[147] Flexible Mild Detonating Cord, *Aerospace and Defense Product Catalogue*, Ensign-Bickford Aerospace and Defense Company, 2003.

Piston Actuator: Activated by SMDC or FMDC, these use an explosive charge to extend a pin from the fixed body of the part, thereby providing the capacity to perform work. Piston actuators may be designed to provide up to 1200 pound of force upon activation.[149] The piston actuators used in HBEDS will be used to extend the cams mounted to the stationary ring of the transfer system.

Initiator: Provides a means for the pilot to initiate the explosive transfer signal. Most initiators detonate explosive lines by either percussion primers or the application of an electric current.

Figure K.3: Initiator[150]

Figure K.4: Piston Actuator[151]

Disarms/Interlocks: Mechanical interlocks interrupt the ignition train, allowing the pilots or maintenance technicians to disarm or disconnect the system when the aircraft is on the ground.

Linear Shaped Charge (LSC): Linear shaped charges are destructive explosive assemblies capable of severing structural members along a desired plane using a plasma cutting jet. Containing RDX, PBXN-5, or HNS explosive within an aluminum or lead sheath, they can be designed to cut through metallic and non-metallic surfaces along complex airframe shapes.[152]

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[148] Manifolds, *Aerospace and Defense Product Catalogue*, Ensign-Bickford Aerospace and Defense Company. 2003.
[149] Piston Actuators, *Aerospace and Defense Product Catalogue*, Ensign-Bickford Aerospace and Defense Company, 2003.
[150] Intelligent Initiators, *Aerospace and Defense Product Catalogue,* Ensign-Bickford Aerospace and Defense Company, 2003.
[151] Piston Actuators, *Aerospace and Defense Product Catalogue*.
[152] Linear Shaped Charge Assemblies, *Aerospace and Defense Product Catalogue*, Ensign-Bickford Aerospace and Defense Company, 2003.

Figure K.5: Interlock[153]

Figure K.6: Linear Shaped Charge[154]

Transfer System: Mechanical assembly that transmits the explosive signal between the stationary piston actuator and transfer lines rotating with the main shaft. Unlike other ignition train components discussed above, the transfer system will be a device designed by the HBEDS team.

Design Alternatives:

Six alternative designs were proposed for the signal transfer network. Each design is a unique arrangement of the aforementioned components that has a corresponding reliability, weight, and cost. Diagrams illustrating each alternative use the following component representations:

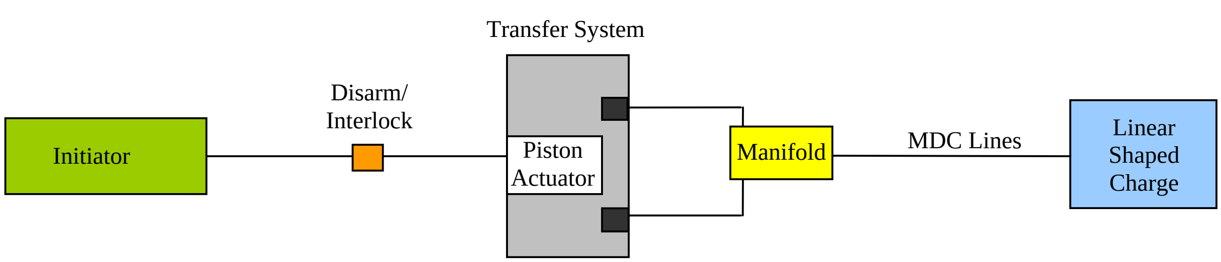

Figure K.7: Component Representations

Alternative A: Single Cam/Sequential Transfer

This design incorporates a single cam activated by a piston actuator on the stationary ring. Redundant lines on the rotating ring lead to a two-to-one manifold, from which the signal is transferred through single line towards the blades. At the top of the shaft, the two lines are split

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[153] Disconnects, *Aerospace and Defense Product Catalogue*, Ensign-Bickford Aerospace and Defense Company, 2003.

[154] Linear Shaped Charge Assemblies, *Aerospace and Defense Product Catalogue*.

to the four blades. As seen in all other alternatives, the design incorporates one interlock in the cockpit and four others at the root of each blade. This arrangement allows the pilot to easily disarm the system when seated in the cockpit and enables maintenance technicians to remove each blade without disassembly of the entire ignition train.

Alternative B: Single Cam/Parallel Transfer

Similar to Alternative A, this design utilizes a single cam on the stationary ring. However, instead of transferring the signal between four manifolds, this design transfers the signal in two lines running parallel towards the blades. Running each of the line pairs through a four-port manifold synchronizes the detonation of the linear shaped charges and provides a degree of redundancy on the rotating segment of the system.

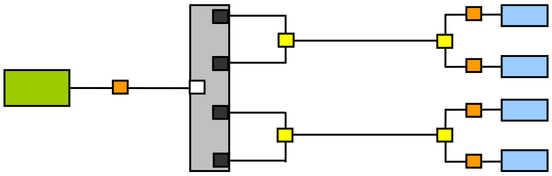


Figure K.8: Alternative A

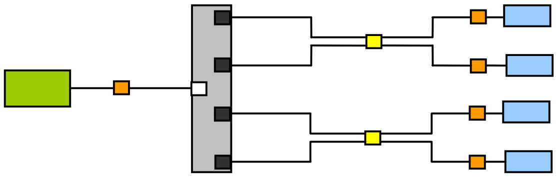


Figure K.9: Alternative B

Alternative C: Double Cam/Sequential Transfer

Unlike the previous alternatives, the double cam/sequential transfer design uses two cams oriented 180 degrees apart on the stationary ring of the transfer system. Though the redundant firing pins set this system apart from the single cam designs, the rotating component of the system resembles the sequential transfer schematic seen in Alternative A.

Alternative D: Double Cam/ Parallel Transfer

This design combines the double cam of Alternative C with the parallel transfer seen in Alternative B. Accordingly, both the stationary piston actuators and rotating transfer lines are redundant in this system.

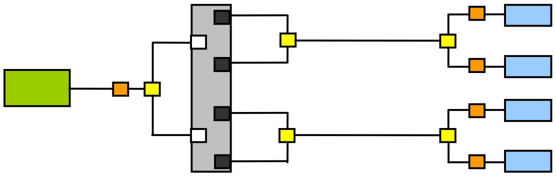


Figure K.10: Alternative C

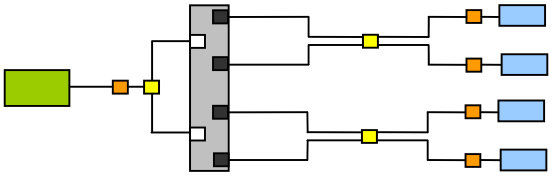


Figure K.11: Alternative D

Alternative E: Double Cam/Direct Transfer

This design transmits the signal through a double cam stationary ring and then directly to the linear shaped charges. Because both piston actuators are required to properly coordinate and synchronize the detachment sequence, no redundancy is built in to the system.

Alternative F: Double Cam/Double Detonator

This design incorporates two cams on the stationary ring oriented at 180 degrees and only two firing pins oriented at 90 degrees on the rotating ring. Assuming 270 degrees of rotation is allowable between detachment phases, the piston actuators and transfer lines on the non-rotating ring can be considered redundant. If failure occurs on one of these paths, the system will still provide coordinated detachment in the correct orientation.

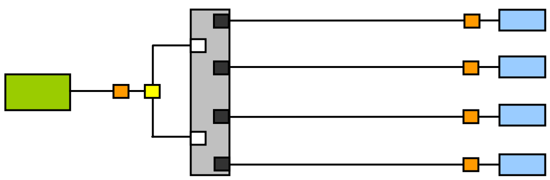


Figure K.12: Alternative E

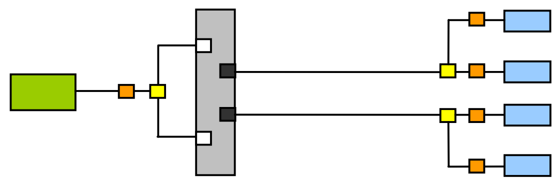


Figure K.13: Alternative F

Assumptions

- Alternatives A, B, C, D, E, and F could each be designed to fit within the spatial constraints of the helicopter.
- The reliability of each individual component is independent of location within the ignition train and position on the helicopter.
- The distance between the cockpit-located initiator and the base of the main shaft is 7 ft, the length of the main shaft is 3 ft, and the distance from the top of the main shaft to the linear shaped charges is 2 ft.
- The reliability rate of the entire system can be estimated using the following reliability rates of the individual components:[155]

R_{lines}	$R_{pinpush}$	$R_{manifold(241)}$	$R_{manifold(242)}$	$R_{initiator}$	R_{disarm}	R_{LSC}	$R_{transfer}$
0.999	0.999	0.9999	0.9999	0.999	0.9999	0.999	Constant

Table K.1: Component Reliability

- The weight of the signal transfer system may be approximated using the following component weights:[156]

[155] Reliability rates are estimated using 95% reliability data from McCormick-Selph, Inc. and Ensign-Bickford Aerospace and Defense Company. See McCormick-Selph, Inc, 15 Jan 2004, http://www.mselph.com and Ensign-Bickford Aerospace and Defense Company, *Aerospace and Defense Product Catalogue*.

W_{lines}	$W_{endfitting}$	$W_{pinpush}$	$W_{manifold(241)}$	$W_{manifold(242)}$	$W_{initiator}$	W_{disarm}	W_{LSC}	$W_{transfer}$
0.037*lb/ft*	0.02*lb*	0.75*lb*	0.75*lb*	1.00*lb*	1.00*lb*	0.75*lb*	2.00*lb*	Constant

Table K.2: Component Weights

- Assuming a production run of approximately 1000 units, the costs of the supplied explosive signal transfer components are:[157]

$C_{line\ section}$	$C_{pin\ pusher}$	$C_{manifold(2-1)}$	$C_{manifold(2-2)}$	$C_{initiator}$	C_{disarm}	C_{LSC}	$C_{transfer}$
$750	$1000	$300	$300	$600	$400	$2500	Constant

Table K.3: Component Costs

Reliability, Weight, and Cost Calculations

Calculations for reliability included the known reliability rates of each component along with the unknown reliability of the transfer system, $R_{transfer}$:

$$R_A \,|\, (R_{initiator})(R_{lines})^{12}(R_{disarm})^5(R_{piston})(R_{transfer})(2R_{lines}\ 4\ R_{lines}{}^2)^2(R_{manifold})^4(R_{LSC})^4 \,|\, 0.9813R_{transfer}$$

$$R_B \,|\, (R_{initiator})(R_{lines})^{10}(R_{disarm})^5(R_{piston})(R_{transfer})(2R_{lines}\ 4\ R_{lines}{}^2)^2(R_{manifold})^2(R_{LSC})^4 \,|\, 0.9834R_{transfer}$$

$$R_C \,|\, (R_{initiator})(R_{lines})^{12}(R_{disarm})^5(R_{manifold})^5(2R_{lines}R_{piston}\ 4\ R_{lines}{}^2R_{piston}{}^2)(R_{transfer})(2R_{lines}\ 4\ R_{lines}{}^2)^2(R_{LSC})^4 \,|\, 0.9821R_{transfer}$$

$$R_D \,|\, (R_{initiator})(R_{lines})^{10}(R_{disarm})^5(R_{manifold})^3(2R_{lines}R_{piston}\ 4\ R_{lines}{}^2R_{piston}{}^2)(R_{transfer})(2R_{lines}\ 4\ R_{lines}{}^2)^2(R_{LSC})^4 \,|\, 0.9843R_{transfer}$$

$$R_E \,|\, (R_{initiator})(R_{lines})^{12}(R_{disarm})^5(R_{manifold})(R_{piston})^2(R_{transfer})(R_{LSC})^4 \,|\, 0.9805R_{transfer}$$

$$R_F \,|\, (R_{initiator})(R_{lines})^{12}(R_{disarm})^5(R_{manifold})^3(2R_{lines}R_{piston}\ 4\ R_{lines}{}^2R_{piston}{}^2)(R_{transfer})(R_{LSC})^4 \,|\, 0.9823R_{transfer}$$

Similarly, weight and cost calculations included the estimates for each component and the unknown weight and cost of the transfer system. These parameters were calculated using the following equations:

$$W_{A,B,C,D,E,F} \,|\, (0.037\Delta Length\ 2\ 0.04\Delta Sec)\ 2\ (0.75\Delta Piston)\ 2\ (0.75\Delta Mnfld)\ 2\ (1.00\Delta Init)\ 2\ (0.75\Delta Disarm)\ 2\ (2.00\Delta LSC)\ 2\ W_{transfer}$$

$$C_{A,B,C,D,E,F} \,|\, (750\Delta Sec)\ 2\ (1000\Delta Piston)\ 2\ (300\Delta Mnfld)\ 2\ (600\Delta Init)\ 2\ (400\Delta Disarm)\ 2\ (2500\Delta LSC)\ 2\ C_{transfer}$$

Results

A comparison of the six proposed alternatives revealed numerous tradeoffs associated with the design of the ignition train. Compared with the single cam systems seen in Alternatives A, and B, the double cam designs in C and D offer a modest gain in reliability due to redundant lines and piston actuators on the stationary ring. However, the additional manifold, mild

[156] Weight of detonating cord and end tips correspond to McCormick-Selph RDC product. Other weights estimated using dimensional and material data provided by McCormick-Selph, Inc. and Ensign-Bickford Aerospace and Defense Company. See McCormick –Selph, Inc., 15 Jan. 2004, <http://www.mselph.com> and Ensign-Bickford Aerospace and Defense Company, *Aerospace and Defense Product Catalogue*.

[157] Costs estimated from personal communication with Geoff Arnold, McCormick-Selph, Inc. “Re: Helicopter Egress Systems,” 2 Dec. 2003 and David Stillwell, Ensign-Bickford Aerospace and Defense Company, personal communication, 21 Jan. 2004.

detonating cord, and piston actuator used in these double cam designs result in a 1.7 lb weight increase and $2,800 in additional unit cost. Reliability can instead be improved using the parallel transfer line design used in Alternatives B and D. Running parallel transfer lines coupled with 2-2 manifolds increases reliability and lowers both weight and cost relative to the sequential designs proposed in Alternatives A and C. Alternative B, the single cam/parallel line design, offers a particularly strong combination of all three parameters included in the study. Lastly, the proposed line routing designs for Alternatives E and F are shown to be lightweight and low cost methods of transferring the explosive signal. In particular, Alternative E is 0.5 lb lighter and $800 cheaper than any of the other designs.

Components	Alternative A	Alternative B	Alternative C	Alternative D	Alternative E	Alternative F
Detonating Cord	23ft / 16 sections	29ft / 14 sections	25ft / 18 sections	31ft / 16 sections	31ft / 12 sections	23ft / 14 sections
Piston Actuators	1	1	2	2	2	2
Manifolds (2-1) or (2-	4	2	5	3	1	3
Initiators	1	1	1	1	1	1
Disarm/Interlocks	5	5	5	5	5	5
Linear Shaped Charges	4	4	4	4	4	4
Transfer Systems	1	1	1	1	1	1
Calculated Reliability	$0.9813R_{transfer}$	$0.9834R_{transfer}$	$0.9821R_{transfer}$	$0.9843R_{transfer}$	$0.9805R_{transfer}$	$0.9823R_{transfer}$
Calculated Weight	18.0lb + $W_{transfer}$	17.1lb + $W_{transfer}$	19.7lb + $W_{transfer}$	18.8lb + $W_{transfer}$	16.6lb + $W_{transfer}$	17.9lb + $W_{transfer}$
Calculated Cost	$26,800 + $C_{transfer}$	$24,700 + $C_{transfer}$	$29,600 + $C_{transfer}$	$27,500 + $C_{transfer}$	$23,900 + $C_{transfer}$	$26,000 + $C_{transfer}$

Table K.4: Comparative Characteristics of Alternatives A, B, C, D, E, F

A decision matrix was constructed to quantitatively compare the reliability, weight, and cost data for each design alternative. Each decision criteria was normalized on a scale from 0-10 with the highest scores given to designs with maximum reliability and minimum weight and cost. Additionally, the reliability parameter was doubly weighted because this requirement is a key specification for the entire system.

Decision Parameters		**Normalized Scores (0-10)**					
Criteria	Weighting	Alternative A	Alternative B	Alternative C	Alternative D	Alternative E	Alternative F
Reliability	*2*	*2.1*	*7.6*	*4.2*	*10.0*	*0.0*	*4.7*
Weight	*1*	*5.3*	*8.3*	*0.0*	*2.7*	*10.0*	*5.7*
Cost	*1*	*4.9*	*8.6*	*0.0*	*3.7*	*10.0*	*6.3*
Weighted Average Score:		***3.6***	***8.0***	***2.1***	***6.6***	***5.0***	***5.4***

Table K.5: Signal Transfer Decision Matrix

The decision matrix demonstrates that Alternative B is the preferred design platform for the signal transfer network. This result agrees with the team's initial intuition to select Alternative B over Alternative D, justifying the small sacrifice in reliability for significantly reduced weight and cost. Alternative B is still more reliable than all other designs, and the reliability of Alternative D only exceeds it by only 0.1%. Further, at 17.1lb and $24,700, the design is lighter and cheaper than all but the minimalist Alternative E, saving 1.7 lb and $2800 relative to Alternative D.

Modification of Selected Alternative

Following the initial selection, a variation on the Alternative B design was proposed to investigate the reliability increases that could be achieve using fully redundant transfer lines. The design follows the same premise of Alternative B yet incorporates additional detonating cord lines from the cockpit to the transfer system and from the manifolds to the linear shaped charges.

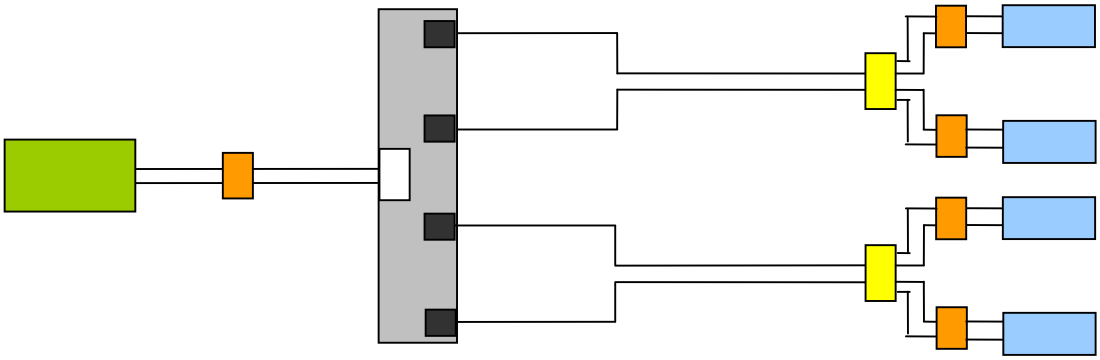


Figure K.14: Proposed Modification to Alternative B

As shown in the above diagram, the modification calls for larger, six port manifolds as well as dual port interlocks, linear shaped charges, and piston actuators. The reliability, weight, and cost for these components are approximated as the following:[158]

$R_{manifold(2\text{-}4)}$	$R_{disarm(2\ port)}$	$R_{LSC(2\ port)}$	$R_{pin\ push(2port)}$
0.999	0.9999	0.999	0.999

Table K.6: Revised Component Reliability

$W_{manifold(2\text{-}4)}$	$W_{disarm(2\ port)}$	$W_{LSC(2\ port)}$	$W_{pin\ push(2port)}$
1.25*lb*	1.00*lb*	2.00*lb*	0.75*lb*

Table K.7: Revised Component Weights

[158] Weight of detonating cord and end tips correspond to McCormick-Selph RDC product. Other weights estimated using dimensional and material data provided by McCormick-Selph, Inc. and Ensign-Bickford Aerospace and Defense Company. See McCormick –Selph, Inc., 15 Jan. 2004, <http://www.mselph.com> and Ensign-Bickford Aerospace and Defense Company, *Aerospace and Defense Product Catalogue*. Costs estimated from personal communication with Geoff Arnold, McCormick-Selph, Inc. "Re: Helicopter Egress Systems," 2 Dec. 2003 and David Stillwell, Ensign-Bickford Aerospace and Defense Company, personal communication, 21 Jan. 2004.

$C_{manifold(2-4)}$	$C_{disarm(2\ port)}$	$C_{LSC(2\ port)}$	$C_{pin\ push(2port)}$	$C_{line\ section}$
$350	$600	$2500	$1100	$550[159]

Table K.8: Revised Component Costs

The reliability, weight and cost of the modified Alternative B may then be calculated using the same methods employed in the original analysis:

$$R_B' = (R_{initiator})(2R_{lines} - R_{lines}^{2})^{12}(R_{disarm})^5(R_{piston})(R_{transfer})(R_{manifold})^2(R_{LSC})^4 = 0.9953R_{transfer}$$

$$W_B' = (0.037\times 44 + 0.04\times 24) + (0.75\times 1) + (1.25\times 2) + (1.00\times 1) + (1.00\times 5) + (2.00\times 4) = 19.8lb + W_{transfer}$$

$$C_B' = (550\times 24) + (1100\times 1) + (350\times 2) + (600\times 1) + (600\times 5) + (2500\times 4) = \$28{,}600 + C_{transfer}$$

Compared to the original design, modified Alternative B exhibits much greater reliability and moderately increased weight and cost. Adding redundant transfer lines to the system increases the predicted reliability to $0.9953R_{transfer}$, a substantial increase over all designs previously considered. Assuming a reliable transfer system could be incorporated into the ignition train, this modified signal transfer network suggests that the entire system could be made to operate at a high level of reliability. Gains in reliability achieved by redundancy are however balanced with increases in weight and cost. The proposed modifications to Alternative B result in a 2.7lb weight penalty and $3900 in additional cost, both considerable increases that partially offset the gains in reliability. However, the project team believes the increased reliability would make the concept far more acceptable to pilots, and that the additional weight and cost could be absorbed into the relatively large gross weight and high operating expenses of military helicopters. The modified version of Alternative B will therefore be analyzed throughout specification testing and later recommended for development of HBEDS beyond the proof of principle stage.

[159] Cost per unit line section is expected to be discounted for the modified Alternative B because the order quantity for the line lengths is doubled.

Appendix L: Transfer System Location Decision Support

Purpose*:* To decide the best location of the transfer system for HBEDS given a list of design criteria; this location is critical to the design of the final product.

Framework*:* All logical locations will be examined to choose an appropriate point of detachment given the *purpose*, *assumptions*, and *design criteria*.

Assumptions:

- A system can be designed for each location that will transfer a signal from the stationary helicopter to the rotating explosives in the blades
- The ignition train components will work no matter the location and will not be affected by the location

Detachment Locations:

- Above the swashplate – signal transfer would occur above and outside the swashplate
- Integrated into the swashplate – signal transfer would occur inside the swashplate
- Below the swashplate – signal transfer would occur below the swashplate and inboard of the lower control rods
- Below the main shaft – signal transfer would occur at the base of the main shaft

Design Criteria:

- Stability: The transfer system location must present an extremely low risk of inadvertent or inadvertent activation. Because an unstable location may have a disastrous effect on the aircraft.
- Efficiency: The location must not adversely affect the flight performance of the selected helicopter. Added rotor mass, drag, and rotational inertia may reduce responsiveness, lower load carrying capacity, and increase fuel consumption.
- Reliability: The location must not affect the systems ability to ensure synchronized and complete rotor blade detachment upon activation.

- Clearance Time: The transfer system location must let the explosives release the blades and quickly provide clearance in order to be effective. Extended delays in activation, detachment, and clearance confirmation will reduce the chances of pilot survival in the event of an impending crash.
- Cost: The location should not add an absurd cost to the HBEDS system.
- Serviceability: The location must be accessible to minimize costs associated with inspection, servicing, and replacement.
- Integration: It must be possible to integrate the transfer system with the helicopters other components at the given location.
- Adaptability: The location will be for a specific application, yet consideration will be given to allow for potential application to a wide range of aircraft. The location will be independent of special features that may be unique to the specific application. This implies that the location will be adaptable to other aircraft at a similar cost.

Thought Process:

Weighting:

- All criteria were weighted on a scale of one to five, one being of least importance and five being most important.
- Stability and reliability are most important because if the transfer system location weakens the systems ability to meet either of these, then it will never be implemented. – 5
- Additionally, if the transfer system cannot be integrated at the given location, then it will prevent HBEDS from ever being successfully integrated into a helicopter. – 5
- The second group is efficiency and clearance time for the reason that the location must not hamper the performance of the aircraft or the ability of the blades to leave the vicinity of the helicopter. – 3
- The last three criteria are really secondary considerations behind the first five; therefore, they were all weight either a one or two. Based on precedents from other decisions.

Grading of Locations: (Table L.1)

- All locations were graded on a scale of one to five on their ability to meet the characteristic. A grade of zero would result in the location being removed from consideration.
- Stability => Above the swashplate was given a one because the ways it could inadvertently be initiated are almost infinite. Integrated into the swashplate and below the swashplate were both given threes because they are pretty stable locations, but not as stable as below the main shaft where there is lots of protection.
- Efficiency => Above the swashplate was given a three due to the drag it would create, while below the swashplate and below the main shaft were given threes because out the added weight to the rotation shaft. Integrated into the swashplate was given a four because so little weight would have to be added to the rotating components that compared to the explosives and detonating cord it would be negligible.
- Reliability => Above the swashplate was seen as the least reliable location because it is easy for other objects or circumstances to prevent it from working properly. Then below the swashplate was given a three because is more secure and therefore reliable than above the swashplate but not a reliable as the two locations that integrated into other components.
- Clearance Time => None of these locations has an obvious advantage or disadvantage when it comes to clearance time, so they were all given threes.
- Cost => The real cost differentiation, is not in the components, but in the engineering design work that would go into each location. The worst is integrating into the swashplate because it is already such a crucial complex component of the helicopter that integrating the transfer system would just add that much more complexity. Below the main shaft is not as complex or crucial as integrating into the swashplate, but the transfer system would still have to interface with the transmission. Finally, above and below the swashplate really don't have to interact with any other system, so they were the easiest to fit and make work and therefore got threes.
- Serviceability => The serviceability rankings are based on which location is easiest to access, inspect, and then service. Above the swashplate is the most exposed and therefore easiest to service, followed by below the swashplate, below the main shaft, and finally integrated into the swashplate.

- Integration => Both above and below the swashplate are extremely difficult to integrate into the helicopter because routing the detonating cord to and from the transfer system becomes a major problem (discussed in greater depth in the design section). Integrated into the swashplate is not easy either because the transfer system cannot affect the performance of the swashplate.
- Adaptability => Both above and below the swashplate received a good grade because they do not rely on many specifics of the helicopter's design; where as, below the main shaft relies on generally true design traits, but not always true. Integrated into the swashplate gets low marks because no two swashplate systems are alike, even though their components are in general similar.

	Stability	Efficiency	Reliability	Clearance Time	Cost	Serviceability	Integration	Adaptability	
Weighting Factor (1-5)	5	3	5	3	1	2	5	1	TOTAL
Above Swashplate	1	3	2	3	3	4	1	4	53
Integrated into Swashplate	3	4	4	3	1	1	2	1	70
Below Swashplate	3	3	3	3	3	3	1	4	66
Below Main Shaft	4	3	4	3	2	2	4	3	87

Table L.1: Decision matrix for transfer system location versus design criteria

Decision:

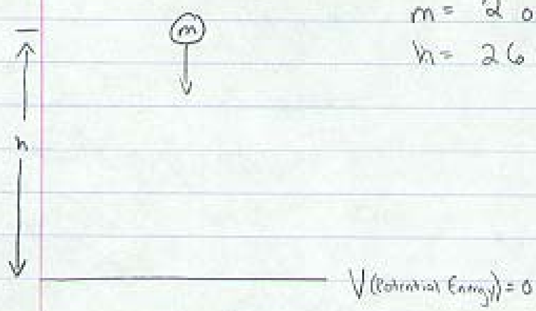
This analysis showed that the best transfer system location is below the main shaft. Therefore, that location will be used in the design of HBEDS.

Appendix M: Ensign-Bickford Specification Test for Detonating Cord End Tip

Test to ignite detonating cord (52 in·oz according to EBA & D)

$m = 2\ oz = 0.056699\ kg$

$h = 26\ in = 0.6604\ m$



conservation of energy

① $V_1 + T_1 = V_2 + T_2$

② $V_1 = mgh$

$T_1 = 0$

$V_2 = 0$

$T_2 = \frac{1}{2} m v_f^2$

③ $\frac{1}{2} m v_f^2 = mgh$

$v_f^2 = 2gh$

$v_f = \sqrt{(2)(32.2)(\frac{26}{12})} = 11.81\ ft/s$

$v_f = \sqrt{(2)(9.8)(0.6604)} = 3.598\ m/s$

④ $T_2 = \frac{1}{2} m v_f^2 = \frac{1}{2}(0.056699)(3.598)^2$

$= 0.367$ Joules ← these two values also can be found from each other with unit conversions

$T_2 = \frac{1}{2} m v_f^2 = \frac{1}{2}(\frac{2}{16})(11.81)^2(\frac{1}{32.2}) = 0.2708\ ft \cdot lb = 52\ in \cdot oz$

Appendix N: Transfer System Glossary of Terms

Cartridge – the entire set of components that provide the necessary impact force to ignite the detonating cord, which runs up the inside of the main mast to the explosive charges. There are four of them and they are housed within the rotor.

Cartridge Cap – a thin wafer of metal that rests on top of the percussion primer and is designed to fail after it has delivered the appropriate force to the detonating cord end tip. By failing, it allows the piston to push past the percussion primer, after which it is free to strike the next percussion primer.

Cartridge Case – a bushing, inside the rotor, that supports the percussion primer.

Detonating Cord – a column of light explosives which transfers a signal from end to end in a short period of time.

Detonating Cord End Tip – a fitting from Ensign-Bickford that is bonded to the beginning of the rotating detonating cords and screws into the top of the rotor. The end of this must be struck with 52 in oz of energy to ignite the detonating cord.

Main Mast – the drive shaft for the main rotor system, on one end it is driven by the engine transmission and the other end drives the four main rotor blades.

Mast Moment Sensor – a strain gauge mounted inside the main mast that provides read-out in the cockpit regarding the moments experienced by the main mast. Several components of the sensor mount below the main mast where the transfer system is design to mount. This is not necessarily found on all helicopters and is an optional accessory on the EC-135.

Oil Seal – a conventional automobile oil seal was used to block out transmission oil from the inner parts of the transfer system.

Percussion Primer – the bullet-like mass which is struck by the piston, transferring the horizontal motion of the piston into vertical motion, striking the detonating cord end tip.

Piston – the component which is pushed into the gap to strike the percussion primer, transferring the signal for detonation to the rotor.

Piston Actuator – a fitting from Ensign-Bickford that is bonded to the end of a line of detonating cord which screws into the stator. Upon detonation, the piston actuator pushes out a piston with a force of 1200 lbs.

Piston Case – a bushing, inside the stator, that supports the piston.

Rotor – the rotating section of the transfer system that attaches to the main mast and houses the cartridges, it is comprised of two pieces, the inner rotor and outer rotor that lock into each other through the use of key slots.

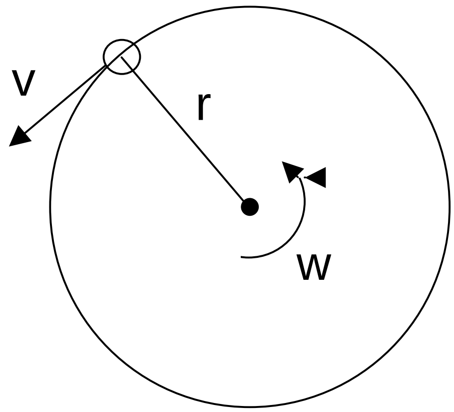
Stator – the stationary section of the transfer system that attaches to the access panel and houses the piston and piston actuator, as well as the oil seal.

Thrust Nut – the large nut that screws onto the base of the main mast and restricts its vertical motion. This component conflicted with the transfer system, so an alternate design was created.

Appendix O: Analysis of Velocity of Rotating Cartridge

Purpose

- To determine the translation velocities of the percussion primers



Variables

- r is the radius that the cartridge rotates about the center axis of the main mast
- w is the normal operating angular velocity of the main mast
- v is the horizontal translational velocity of the percussion primer

Calculations

r = 0.65 inches
w = 400 rpm = 41.89 rad/s

α v | w x r | w * r | 27.23 in/s | 2.27 ft/s

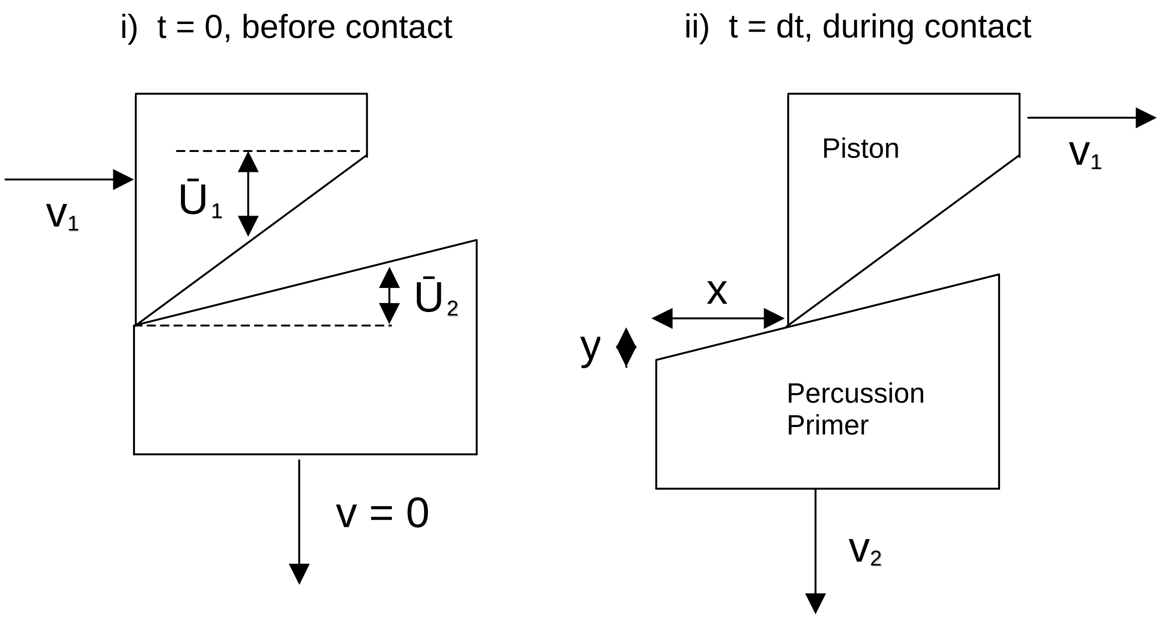
Appendix P: Relative Velocities of Percussion Primer and Piston Actuator

Purpose

- To determine the vertical velocity of the percussion primer given its previously determined horizontal velocity

Diagram

- Diagram is shown from a Cartesian coordinate system rotating with the percussion primer. So while the percussion primer is actually rotating, for the means of this calculation, it will be considered stationary in the x direction, and the piston will be considered to have a velocity of v_1 in the x direction.
- Note that $\bar{U}_1$ and $\bar{U}_2$ are actually equal in the prototype, but they are shown as unequal in this diagram to illustrate the different roles they play in this calculation.



Calculations

1) $x = v_1 t$, $y = v_2 t$

2) $\dfrac{x}{v_1} = \dfrac{y}{v_2}$

3) $\tan\chi_2 = \dfrac{y}{x}$

4) $v_2 = \dfrac{y}{x} v_1 = v_1 \tan\chi_2$

5) $v_1 = 2.27\ ft/s$, $v_2 = v_1 \tan\chi_2 = 0.608\ ft/s$

Conclusions

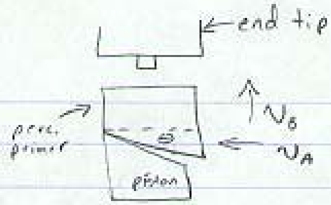
- The relationship between v_1 and v_2 depends only on χ_2

Assumptions

- This analysis is true only if the two surfaces remain in contact

Appendix Q: Kinetic Energy of Percussion Primer

Percussion Primer striking end tip



Assumptions

- energy is conserved
- perc. primer and piston remain in contact
- only mass involved in transfer of energy is perc. primer
- perc. primer strikes end tip just as pin thruster loses contact with perc. primer

must impact 0.367 J

$v_A = 2.3 \text{ ft/s} = 0.7 \text{ m/s}$

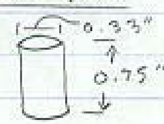
$v_B = v_A \tan\theta$

$T = \frac{1}{2} m v_B^2$ for percussion primer

$= \frac{1}{2} m v_A^2 \tan^2\theta$

$$\frac{\frac{1}{2} m v_A^2 \tan^2\theta}{f_s} > 0.367$$

mass approx



$V = \pi r^2 h = 0.064 \text{ in}^3$

$= 1.05 \times 10^{-6} \text{ m}^3$

$\rho = 7840 \text{ kg/m}^3$ (1080 steel)

$m = 0.0082 \text{ kg}$

$v_A = 0.7 \text{ m/s} \rightarrow v_A^2 = 0.5 \text{ m}^2/\text{s}^2$

$m = 0.0082$

$f_s = 1$

$\theta = 45 \rightarrow \tan^2\theta = 1$ // assume larger θ

$$\frac{\frac{1}{2}(0.0082)(0.5)(1)}{(1)} = 0.0021 \text{ J}$$ = Kinetic energy of primer

∴ cannot rely on energy of primer alone to activate detonating cord

Appendix R: Test to Determine the Force that must be Delivered to the End Tip

Testing performed (2/21/04)

What we know

- Specification test by the manufacturer is to drop a 2oz steel ball from a height of 26in, which imparts 52in-oz of energy to the end tip (0.367J).

What we want to know

- How much energy we are imparting to the end tip from the percussion primer.
- Find the delta t in order to do the analytical calculation using impulse-momentum

How to find the delta t?

- We can use an accelerometer attached to a steel ball, recreating the specification test, and from the data we should be able to gleam a reasonable delta t value.
    - We could not find a functional accelerometer, so we did not use this approach.
- We can use a load cell. By placing a steel plate on a load cell, we can set the load cell to read out the maximum force and recreate the spec test by dropping a steel ball onto the steel plate.
    - The load cell did not have the appropriate time resolution to pick up the impact force with sufficient repeatability to yield any worthwhile data.
- We tried dropping a steel ball from the correct height onto the back of our hand, remembering how it felt, then pressing down on the steel ball with a load cell until we felt the same amount of force, then recording the data from the load cell.
    - This test was actually repeatable, and we felt a force of about 10 pounds across several tests. However this test was useless, because our hand has a different density and composition, yielding a different delta t, than a steel plate would upon impact with a steel ball.

A different solution

- Finally, we tried repeating the specification test with a steel ball dropping onto a steel plate, and observing the diameter of the dent
- We then pressed the steel ball onto the steel plate using the Instron machine until we could reproduce the same size dent under a given load.
    - We could only find a 1.2oz steel ball, so in order to reproduce the same amount of kinetic energy, we dropped it from 70in, rather than 26in. Assume the impact force of this variation from the specification test is not greatly different from the impact force in the specification test.
    - Also assume that a force applied slowly (on the Instron) and a force applied quickly (by dropping the steel ball from 70in) give similar deformation in the steel plate
    - In several tests, on the steel plate, a force of 3500N on the Instron machine was required to reproduce the size of the dent from the steel ball dropped from 70in. On the aluminum plate, a force of 2500N was required to reproduce the size of the dent from the steel ball dropped from 70in.

Results

- Given the two sets of data from the Instron machine, and with an understanding that our experiment is not perfect and has only at best produced an approximate value, we are choosing 3000N (675 lb) as the force we need to impart to the detonating cord end tip.

Appendix S: Cartridge Cap Design

Purpose

- To determine the thickness of the cartridge cap. This value will control the force delivered to the end tip before cartridge cap failure.

Calculations

- The axial force must cause a shear stress above the materials shear strength according to:
  F_{axial} = ů$_s$ x A_{shear}
- Where the area of shear equals the circumference of the end tip times the thickness of the cartridge cap.
  h_{cap} = F_{axial}/(ů$_s$ x $C_{end\ tip}$) = 1012.5lbs/(30000psi x 0.159´ inches) = 0.068in

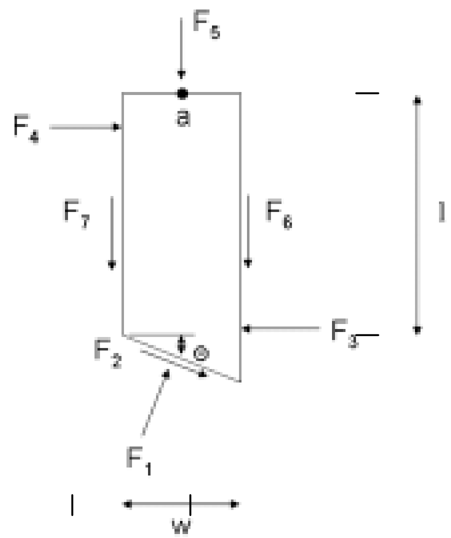
Conclusions

- The end tip will punch out a circle in the cartridge cap, allowing for continued rotation of the rotor.
- The cartridge cap must be 0.068 inches thick if made out of Aluminum 6061-T6 in order to shear at 1012.5 pounds

Appendix T: Forces on the Cartridge when Cartridge Cap Fails

Purpose: To identify the maximum forces experienced by the cartridge components under its maximum load (when the cartridge cap fails). This will allow us to choose the proper type of bushing to serve as the cartridge wall, as well as design the cartridge cap to fail at the correct impact force.

Free Body Diagram: the forces acting on the percussion primer by the detonating cord end tip (F5), cartridge casing/bushing (F3, F4, F6, F7) and piston actuator (F1, F2)



where

- F1 is an unknown that represents the striking force from the piston actuator striking the percussion primer.
- F2 = μ1 * F1, it is the friction force acting on the percussion primer
- F3 is an unknown that represents the normal reaction force from the bottom of the cartridge casing
- F4 is an unknown that represents the normal reaction force from the top of the cartridge casing
- F5 is the force acting on the cartridge cap caused by collision with the detonating cord end tip
- F6 = μ2 * F3, it is the friction force acting on the right side of the cartridge casing
- F7 = μ2 * F4, it is the friction force acting on the left side of the cartridge casing

Assumptions

- F1 and F2 act at a single point on the center of the angled face
- F3 and F4 act at a single point at a distance of L and 0 from point a, respectively
- The sum of forces in the y direction is assumed to be 0 because the percussion primer does not travel very far before striking the end tip (0.1”) and because the mass is small enough so as to render m*a ~= 0

Equations

1) $\_\_Fx | F1\sin\chi 2 F2\cos\chi 4 F3 2 F4 | 0$

2) $\_\_Fy | F1\cos\chi 4 F2\sin\chi 4 F5 4 F6 4 F7 | 0$

3) $\_\_Ma | 4F1(l 2 w/2\tan\chi) 4 F2(l 2 w/2\tan\chi) 2 F3(l) 2 F6(w/2) 4 F7(w/2) | 0$

Simplified

1) $\_\_Fx | F1(\sin\chi 2 \sigma1\cos\chi) 4 F3 2 F4 | 0$

2) $\_\_Fy | F1(\cos\chi 4 \sigma1\sin\chi) 4 \sigma2(F3 2 F4) | F5$

3) $\_\_Ma | F1(l 2 w/2\tan\chi)(\sin\chi 2 \sigma2\cos\chi) 4 F3(l 2 \sigma2(w/2)) 2 F4(\sigma2)(w/2) | 0$

Unknowns: F1, F3, F4

Method: Use Excel to choose different values for µ1, µ2, Ū, l, and w, within geometric and physical property constraints, and then solve 3 equations simultaneously with 3 unknowns. Examine the results and choose values to minimize the normal forces (F3, F4) on the cartridge casing wall.

Excel Output

parameters			**calcs**		
F5	675	lbs	fs*F5	1012.5	lbs
fs	1.5		sin(theta)	0.3	
mu1	0.05		cos(theta)	0.97	
mu2	0.16		tan(theta)	0.27	
l	0.7	in			
w	0.375	in			
theta	15	degrees			

coefficients

eq		F1	F3	F4		b
	1	0.307	-1.000	1.000	=	0.000
	2	0.953	-0.160	-0.160	=	1012.5
	3	0.310	-0.730	0.030	=	0

output

				F2	F5	F6	F7
theta=10	1120.7	373.2	2.2	56.0	1012.5	59.7	0.4
theta=15	1184.2	503.5	14.4	59.2	1012.5	80.6	2.3
theta=20	1269.3	658.7	34.2	63.5	1012.5	105.4	5.5
theta=25	1380.7	848.1	63.8	69.0	1012.5	135.7	10.2
theta=30	1531.5	1087.0	108.4	76.6	1012.5	173.9	17.3
l=1	1182.6	498.6	10.2	59.1	1012.5	79.8	1.6

conclusions: length is unimportant, longer may even be worse, ie:F3

w=0.5	1186.0	509.1	19.3	59.3	1012.5	81.5	3.1

conclusions: width doesn't seem that important either

mu2=.05	1108.6	358.4	-99.5	55.4	1012.5	57.3	-15.9

conclusions: teflon bushing drops F3 some

mu1=.05	1171.0	503.2	143.7	58.6	1012.5	80.5	23.0

conclusions: magnesium or something other coating actually seems to increase F4

Conclusion

- Given the chosen parameters, the forces that allow us to solve the 3 simultaneous equations are (all forces in lbs):

F1	F2	F3	F4	F5	F6	F7
1184.2	59.2	503.5	14.4	1012.5	80.6	2.3

Discussion

- After crunching the numbers, we found that our assumption for F5 basically determines the rest of the force values.
- F4 and F7 are not very large
- The choice of values for parameters l, w, and $\sigma 1$ did not affect the results very much
- Changes in the values for $\sigma 2$ and χ had a relatively strong effect on F3 (the bottom normal force on the casing wall)

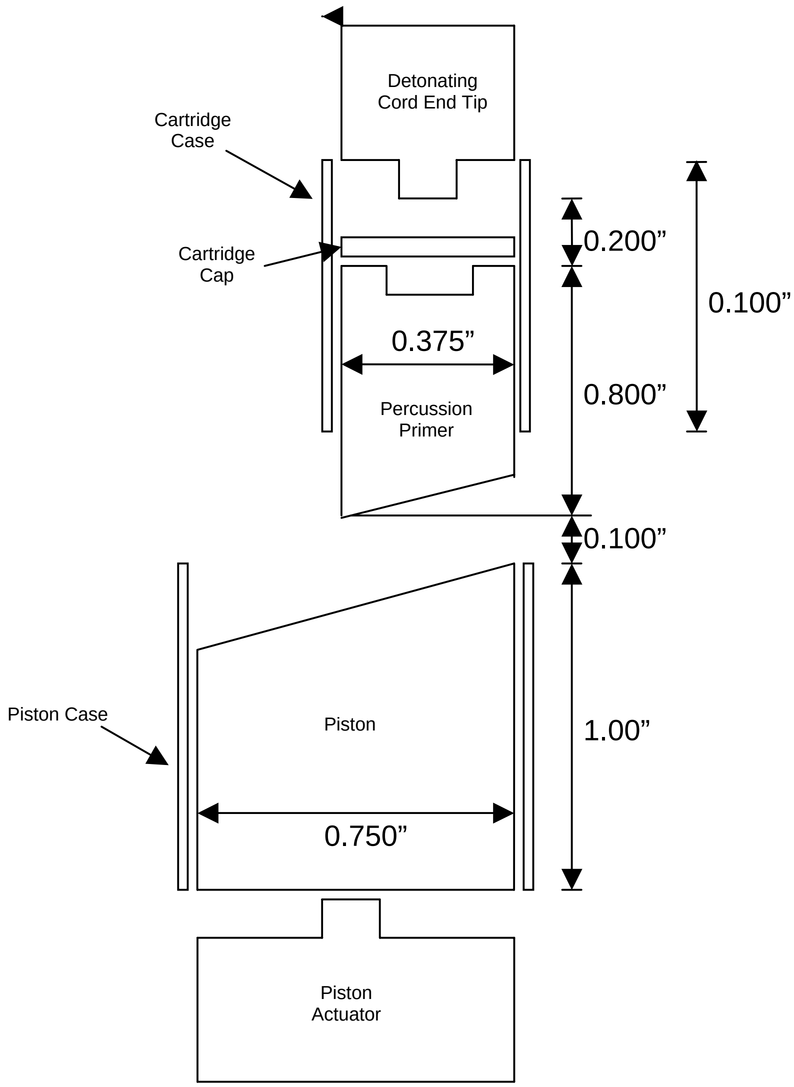
Choice of Parameters

- Length of percussion primer, *l*: 0.7"
  - This is robust enough in size to withstand the forces acting on it and fits within the geometric constraints of the transfer system rotor components
- Width of percussion primer, *w*: 0.375"
  - This is robust enough in size to withstand the forces acting on it and fits within the geometric constraints of the transfer system rotor components
- Surface finish of percussion primer, $\sigma 1$: 0.16
  - This is the value for simple hardened steel on hardened steel contact lubricated with grease. It was found that this variable does not affect the other forces involved very much, although the use of different coatings could make this value as low as 0.05.
- Friction from wall of cartridge, $\sigma 2$: 0.16
  - This is the value for lubricated bronze on steel contact. This value was found to affect the normal force on the casing wall (F3). By dropping the value for $\sigma 2$ to 0.05, which would be standard for Teflon bushings, the value for F3 drops from roughly 500 lbs to 350 lbs. However, bronze bushings were selected because they

can better absorb the impact of 500 lbs than a Teflon bushing can absorb the impact of 350 lbs, before deformation of the bushing will occur.

- Angle of attack on percussion primer, Ū: 15 degrees
    - The smaller this angle was made, the smaller the normal forces acting on the cartridge casing wall. It was determined by balancing lowering the normal forces to an acceptable level and making the angled section of the percussion primer hanging enough into the gap to strike the piston actuator.

Appendix U: Piston and Cartridge Assemblies



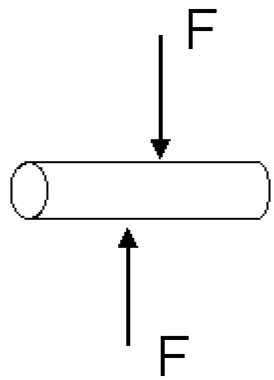
Appendix V: Shear Pin Design

Purpose

- A shear pin will be used to hold the four percussion primers and one piston actuator in place until the detonating cord is ignited, at which point they will shear at 100 lbs of force.

Choose Aluminum because of its relatively low UTS of 8 ksi.

Free Body Diagram



Calculations

(Shear pin failure at 100 lbs)

$$A | Mr^2$$

$$\omega | \frac{F}{A} | 800\,psi$$

$$A | \frac{F}{\omega} | \frac{100}{8000} | Mr^2$$

$$r | 0.063''$$

(Shear pin failure at 250 lbs)

$$A | Mr^2$$

$$\omega | \frac{F}{A} | 800\,psi$$

$$A | \frac{F}{\omega} | \frac{250}{8000} | Mr^2$$

$$r | 0.100''$$

Appendix W: Final Prototype Assemblies

Transfer System

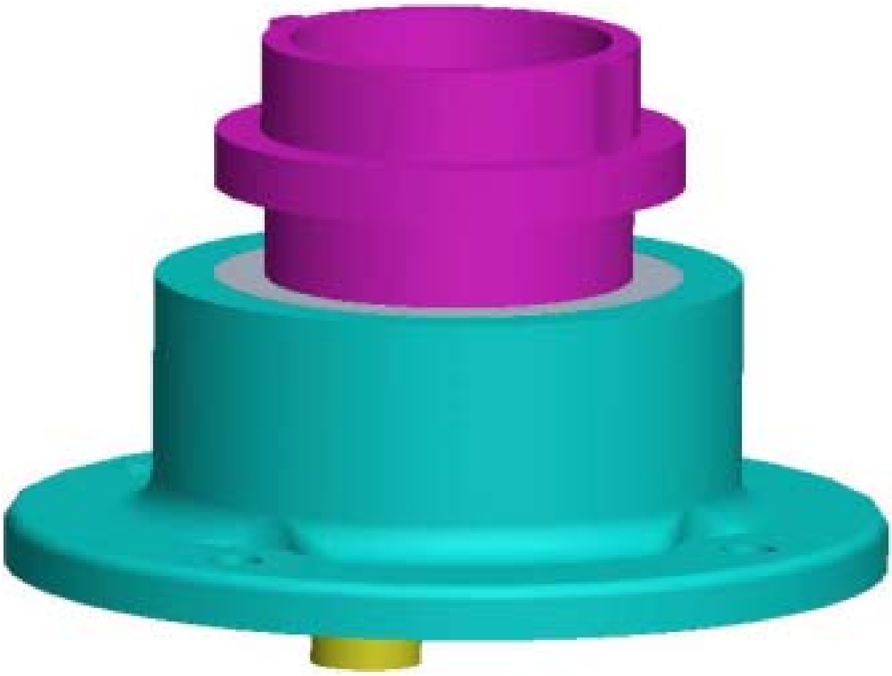


Figure W.1: Transfer System Perspective

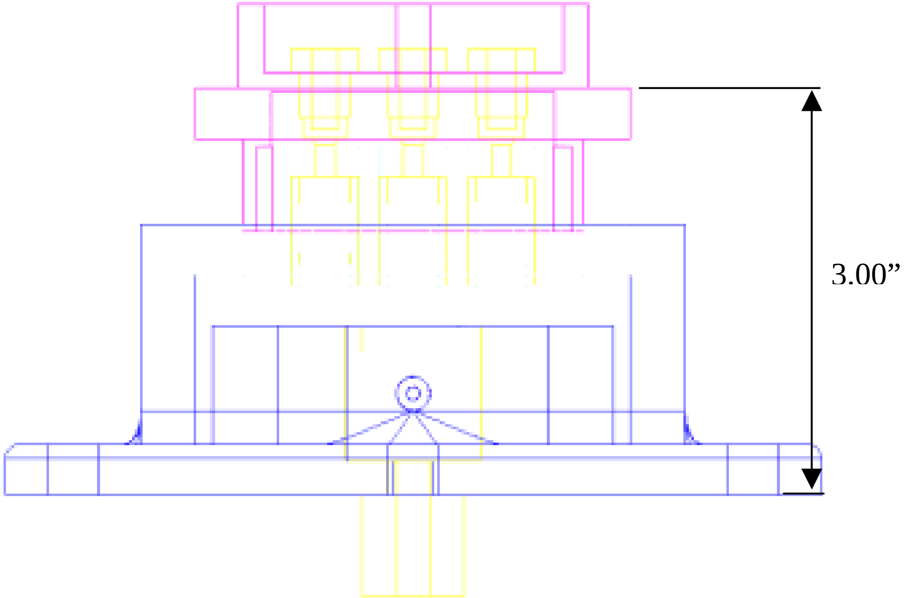


Figure W.2: Transfer System Profile

Rotor

Figure W.3: Rotor Perspective

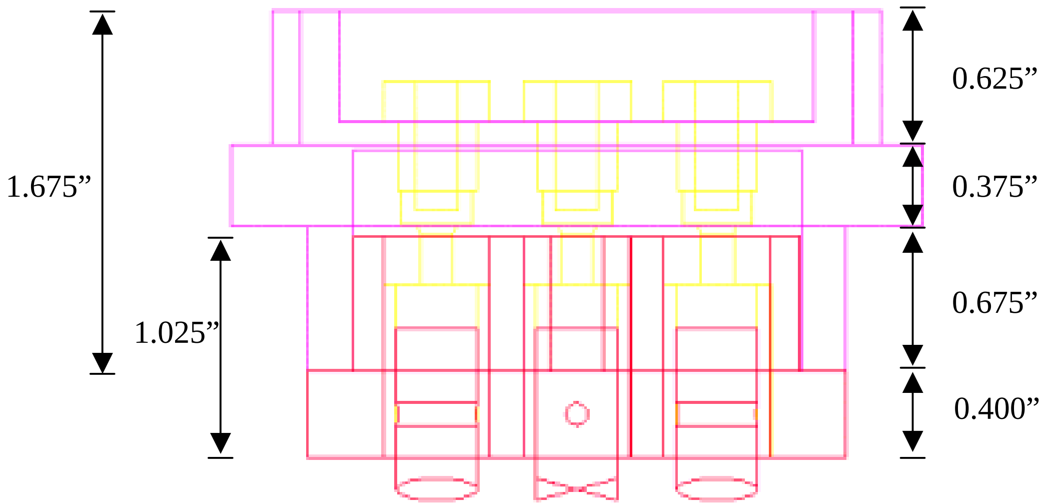


Figure W.4: Rotor Profile

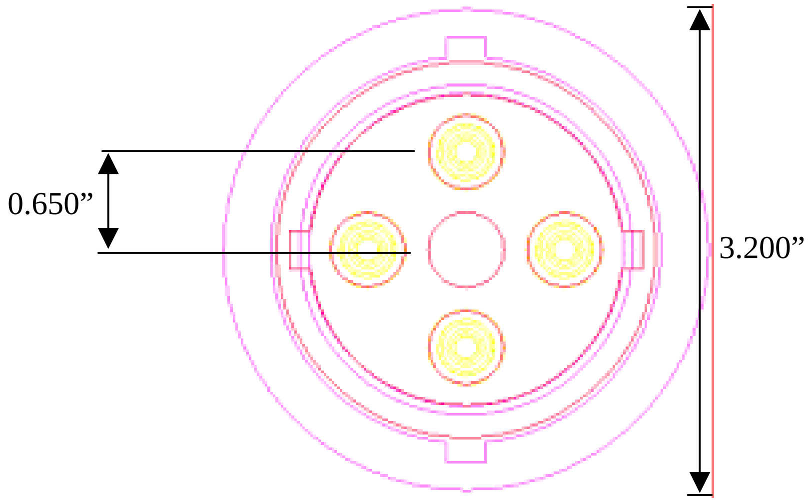
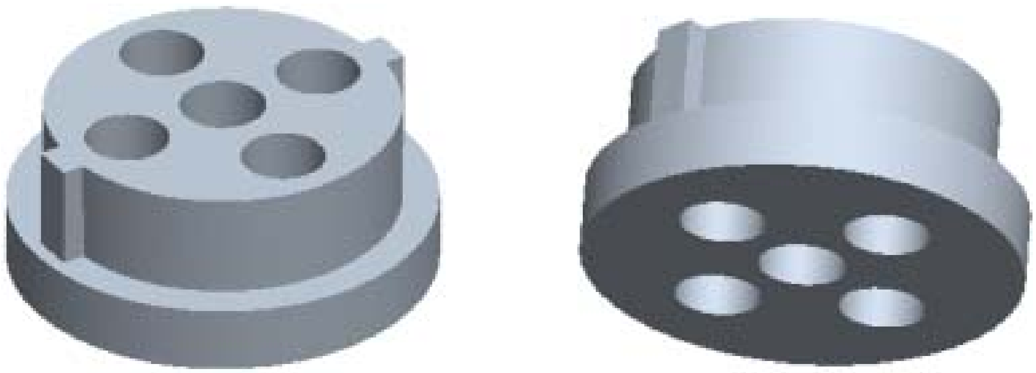


Figure W.5: Rotor Overhead

Rotor Pieces



(top) *(bottom)*

Figure W.6: Inner Rotor Perspectives

(top) *(bottom)*

Figure W.7: Outer Rotor Perspectives

(top – lines to blades) *(bottom – lock nut and striking surface for percussion primer)*

Figure W.8: Outer Rotor With End Tips Attached

Stator

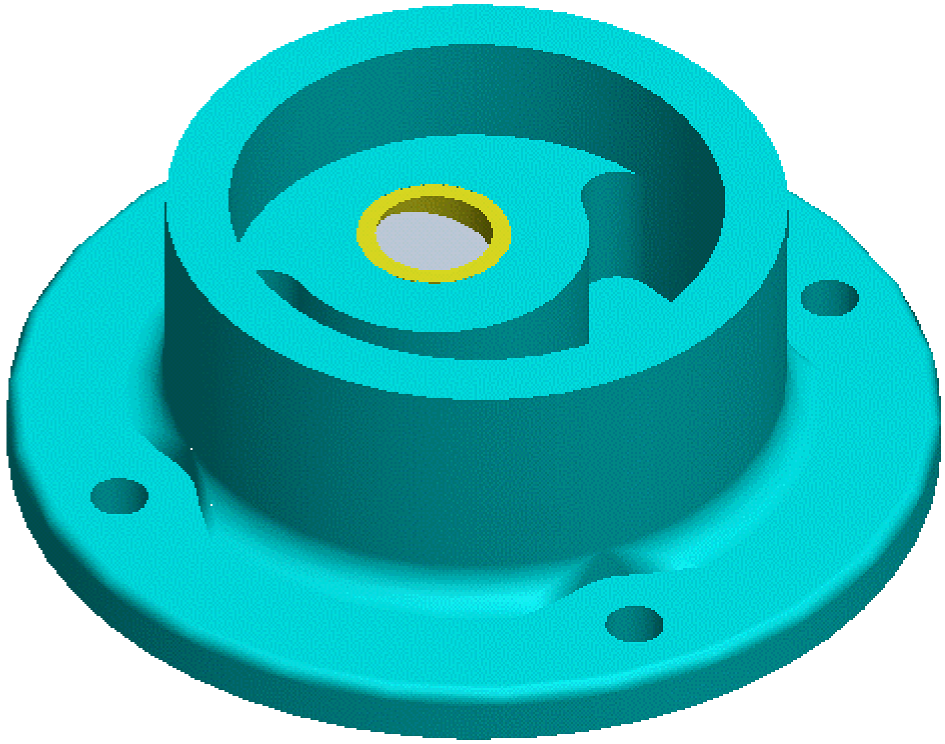


Figure W.9: Stator Perspective

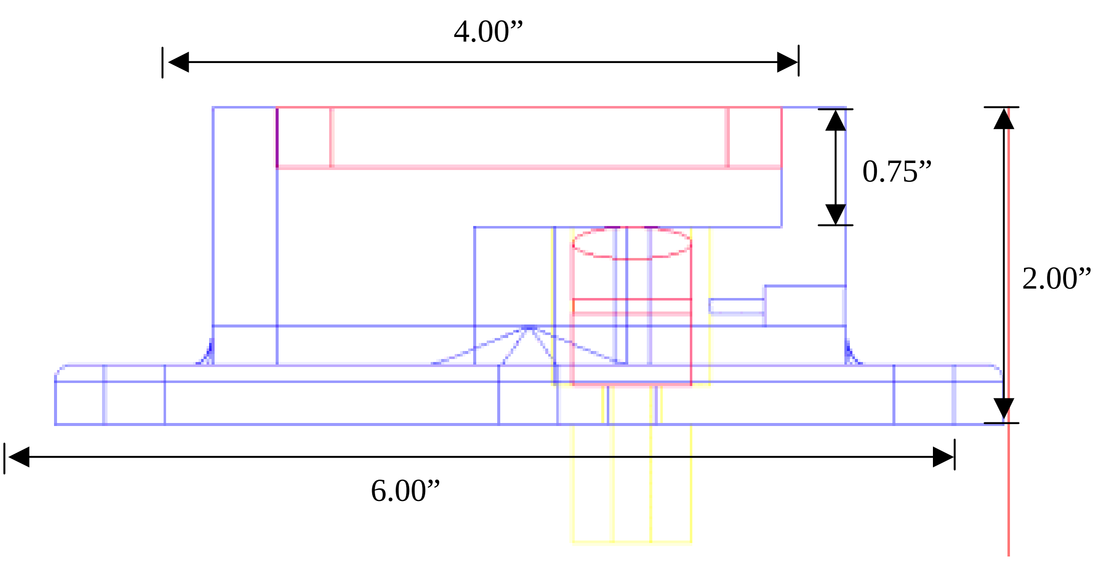
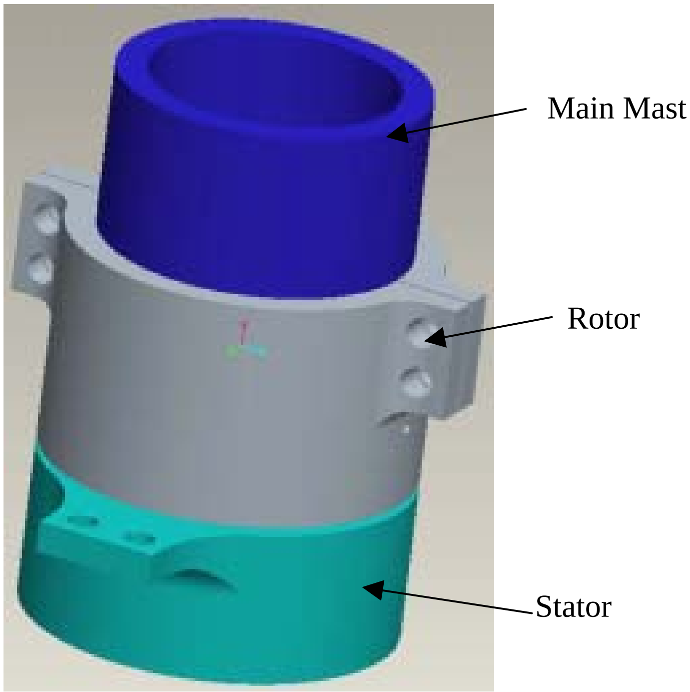
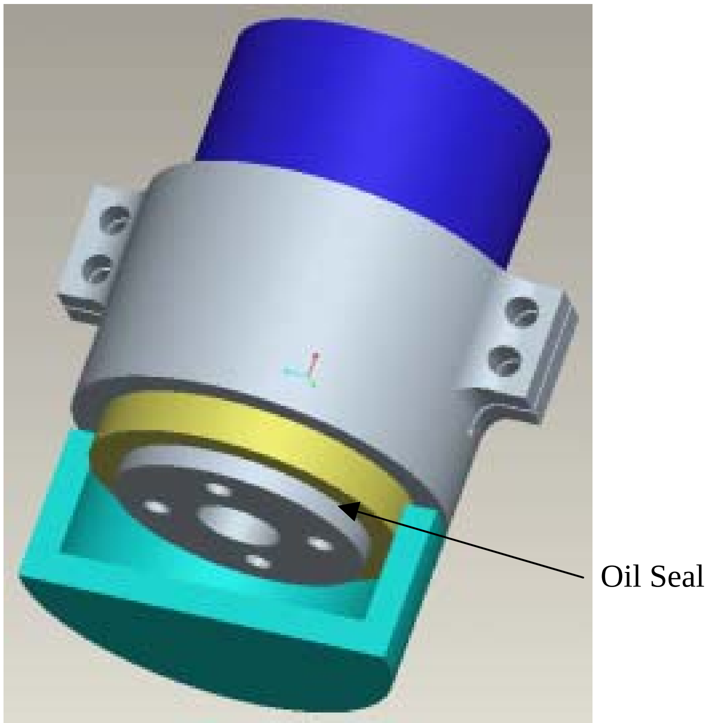


Figure W.10: Stator Profile

Appendix X: Early Design Concepts





Appendix Y: Alignment Tab Analysis

Purpose

- An analysis was performed to determine the necessary size of the alignment tab on the outer rotor ring. These tabs are required to transmit the torque generated due to contact between the piston and firing pin.

Objective

- Determine the minimum length of the alignment slots in order to avoid failure due to shear and compressive stress. Assume the slots will be 0.25 inches wide and 0.125 inches deep.

Assumptions

- Alignment slots can be modeled as simple keys
- The piston applies a 560lb force to the cartridge case
- The cartridge case is 0.75" from the axis of rotation
- The outer diameter of the rotor ring is 2.575"
- The key and rotor ring are made of 2014 aluminum, Sy = 40ksi[160]
- Factor of safety is Ns = 4 because failure of the slots may result in incomplete blade detachment
- Key width is 0.25"
- Key height is 0.125"

Analysis[161]

Applied torque on rotor ring:

$$T = 0.75in \times 560lb = 420in \cdot lb$$

Maximum design shear stress:

$$\tau_{design} = \frac{S_{sy}}{N_s} = \frac{(0.4)(S_y)}{N_s} = \frac{(0.4)(40ksi)}{4} = 4.0ksi$$

Critical length of key to avoid shear failure:

$$l = \frac{2T}{dw\tau_{design}} = \frac{2(420in \cdot lb)}{(2.575in)(0.25in)(40ksi)} = 0.3in$$

Maximum compressive stress:

[160] Yield strength for 6061-T6 aluminum. See <<http://www.efunda.com/materials/alloys/aluminum/show_aluminum.cfm?ID=AA_6061&prop=uts&Page_Title=Aluminum%20Alloy%20AA%206061?>> Accessed Feb 23, 2004.

[161] Analysis based on sample calculation in Machine Elements, p 447.

$$\sigma_{design} = \frac{S_{cy}}{Ns} = \frac{(0.9)(S_y)}{Ns} = \frac{(0.9)(40ksi)}{4} = 9.0ksi$$

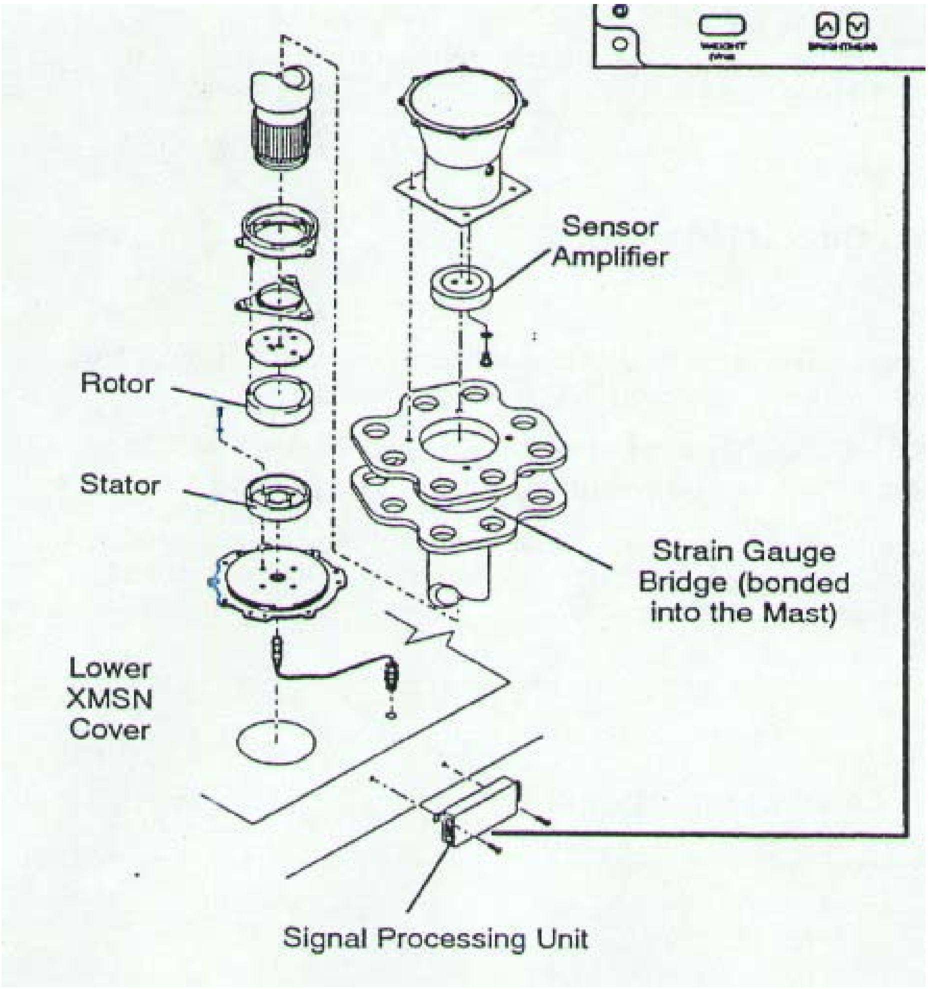
Critical length of key to avoid failure under compressive stress:

$$l = \frac{4T}{dh\sigma_{design}} = \frac{4(420in \cdot lb)}{(2.575in)(0.125in)(9.0ksi)} = 0.6in$$

Conclusion

- Given the aforementioned assumptions and dimensions, the alignment slots must be at least 0.6 inches in length to avoid failure with a factor of safety of 4.

Appendix Z: Mast Moment Sensor Components Diagram



Source: Eurocopter. See Eurocopter Group, Aircraft Maintenance Manual EC-135, Part 1. (1997).

Appendix AA: Transfer System Reliability Calculations

Testing of the concept prototype allowed the team to estimate the reliability of the transfer system design. 100 test runs were performed and no failures were observed. A hypothesis test was then applied:

1. The parameter of interest is fraction of failed runs: p

2. H_O: $p = 0.0275$
   H_1: $p < 0.0275$
   Ŭ= 0.05

3. Test statistic $z_O = (x – n*p_O) / (n*p_O*(1-p_O))$^0.5,
   where $x = 0$, $n = 100$, and $p_O = 0.0275$

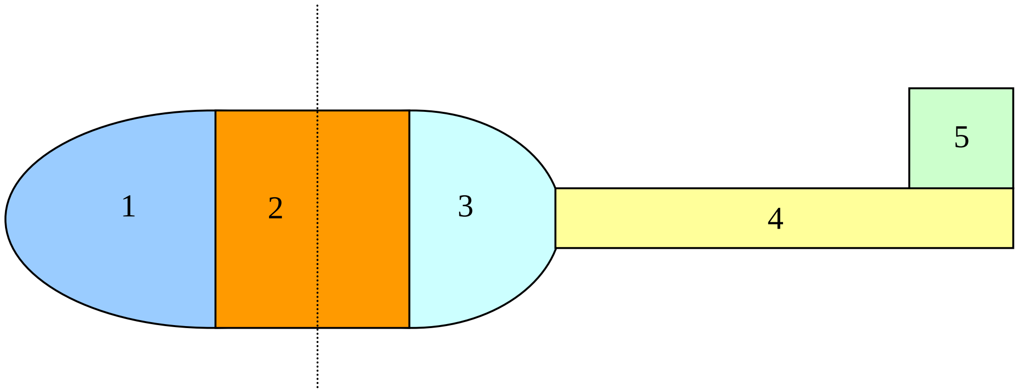
   Reject H_O: $p = 0.0275$ if $z_O < - z_{0.05} = -1.64$

   $z_O = (0 – 100*0.02) / (100*0.0275*0.9725)$^0.5 = -1.68

4. Conclusions: Since $z_o = -1.68 < -z_{0.05} = -1.64$, we reject the null hypothesis.

Rejection of the null hypothesis allowed the team to conclude that the fraction of failed runs is less than 0.0275. The reliability of the transfer system is therefore greater than 97.25%.

Appendix BB: EC-135 Mass Moment of Inertia Calculation



mass balance line

Section 1:
-Contains forward section of fuselage frame, avionics, controls, pilots
-Approximated by solid semiellipsoid: $\left(\frac{x}{2.5m}\right)^2 + \left(\frac{y}{1m}\right)^2 + \left(\frac{z}{1m}\right)^2 \le 1$
-Estimated mass = 380kg

Section 2:
-Contains fuselage frame midsection, transmission, engines, main rotor control systems
-Approximated by solid cube: *length = 2m; width = 2m; height = 2m*
- Estimated mass = 1000kg

Section 3:
-Contains rear section of fuselage frame
-Approximated by solid semiellipsoid: $\left(\frac{x}{1.5m}\right)^2 + \left(\frac{y}{1m}\right)^2 + \left(\frac{z}{1m}\right)^2 \le 1$
-Estimated mass = 90kg

Section 4:
-Contains tail boom structure, tail rotor driveshaft
-Approximated by solid cylinder: *radius = 0.3m, length = 4.75m*
-Estimated mass = 90kg

Section 5:
-Contains tail rotor
-Approximated by solid rectangular parallelepiped: *length = 1.95m; width = 0.2m; height = 1.95m*
-Estimated mass = 25kg

Mass balance about center of Section 2:

$$\sum M_{cm} = 0$$

$$m_1 d_1 - m_3 d_3 - m_4 d_4 - m_5 d_5 = 0$$

$$380kg\left(\frac{3 \cdot 2.5m}{8} + 1\right) - 90kg\left(\frac{3 \cdot 1.5m}{8} + 1\right) - 90kg(4.875m) - 25kg(6.275m) = 0$$

Mass moment of inertia about mass balance line z:

$$I_{zz} = I_{zz1} + I_{zz2} + I_{zz3} + I_{zz4} + I_{zz5}$$

$$I_{zz1} = \bar{I}_{zz1} + md_1^2 = \left(\frac{380kg}{5}\right)\left((1m)^2 + (2.5m)^2\right) + (380kg)(1m)^2 = 930kg \cdot m^2$$

$$I_{zz2} = \bar{I}_{zz2} + md_2^2 = \left(\frac{1000kg}{12}\right)\left((2m)^2 + (2m)^2\right) = 670kg \cdot m^2$$

$$I_{zz3} = \bar{I}_{zz3} + md_3^2 = \left(\frac{90kg}{5}\right)\left((1m)^2 + (1.5m)^2\right) + (90kg)(1m)^2 = 150kg \cdot m^2$$

$$I_{zz4} = \bar{I}_{zz4} + md_4^2 = \left(\frac{90kg}{4}\right)(0.3m)^2 + \left(\frac{90kg}{3}\right)(4.75m)^2 + (90kg)(2.5m)^2 = 1240kg \cdot m^2$$

$$I_{zz5} = \bar{I}_{zz5} + md_5^2 = \left(\frac{25kg}{12}\right)\left((0.2m)^2 + (1.95m)^2\right) + (25kg)(6.275m)^2 = 990kg \cdot m^2$$

$$I_{zz} = (930 + 670 + 150 + 1240 + 990)kg \cdot m^2 = 3980kg \cdot m^2$$