

REPORT ON AIRCRAFT ENGINE CONTAINMENT

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CONTENTS

	PAGE NO.
1. INTRODUCTION AND BACKGROUND	3
1.1 Purpose, Scope, Committee Representation	3
1.2 Committee Membership and Activity	4
1.3 Aerospace Information Report (AIR 1537) Summary	4
2. DEFINITIONS	5
2.1 Definition of Non-Containment	5
2.2 Definition of Aircraft Damage	6
3. SUMMARY OF RESULTS.	8
4. CONCLUSIONS, OBSERVATIONS AND RECOMMENDATIONS	10
5. DATA SUMMARIES.	17
5.1 Data Organization	17
5.2 Commercial Transport Engine Data - Tables and Figures	19
5.3 General Aviation Engine Data - Tables and Figures	25
5.4 Rotorcraft Engine Data - Tables and Figures	28
6. POTENTIAL FOR IMPROVEMENTS	35
6.1 Aircraft Damage Data - Flight Safety Record	35
6.2 Engine Design	36
6.3 Aircraft Design	39
6.4 Other Considerations	40

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CONTENTS (Cont'd.)

	<u>PAGE NO.</u>
7. REGULATIONS AND PRACTICES	41
7.1 FAA Regulations and Certification Procedures	41
7.2 Containment Requirements	44
7.3 Transport Category Aircraft Powerplant Installation	44
7.4 General Aviation Powerplant Installation	44
7.5 Aircraft Design and Certification	45
8. TABULATION OF NON-CONTAINED ROTOR FAILURES	46

1. INTRODUCTION AND BACKGROUND:

- 1.1 Purpose, Scope, Committee Representation: On August 2, 1983; the Federal Aviation Administration (FAA) requested an update of the previous SAE technical study (AIR 1537) covering aircraft gas turbine engine non-containment. The FAA request also asked for expansion of the data base to include helicopter operation. This request was reviewed by the Aerospace Council, and the Propulsion Division was subsequently directed to establish an Ad-Hoc Committee.

The Committee was established and held its first meeting March 22, 1984. A preliminary work statement was drafted as follows:

- A. Purpose: To gather and analyze service data on aircraft propulsion turbine engine rotating part non-containment failures on record, assess the resulting aircraft damage, and determine the rate of past occurrences based on these data.

In addition, to classify incidents by cause and consequence, to identify areas of greatest concern, and to recommend areas for greatest potential improvement.

- B. Scope: The study shall be directed to include all certified turbine engine experience in civil aircraft service covering the time period from January 1976 through December 1983.
- C. Committee Representation: The Committee shall be composed of individuals competent and authoritative in the fields of airline operation, airframe and engine design, and able to make significant contributions to this study.
- D. Committee Report: The Committee is to release the results of the study to the SAE Aerospace Council after approval of the Aerospace Propulsion Division. The Committee shall submit its report June 1, 1985 to the Propulsion Division. An extension may be granted by the Propulsion Division if required.

While the previous SAE Committee report, AIR 1537, focused solely on fixed wing commercial engine experience, the current Committee decided that the scope should be expanded to collect the data relating to helicopter and general aviation operations. The inclusion of helicopter experience was prompted by the FAA request to anticipate the projected substantial increase in commercial use of helicopters within the next decade. For completeness, general aviation experience, including commuter airlines, was considered significant enough to include in the current committee's activities. At the direction of the Aerospace Council, all three classes of engines have been treated in a single report. It is expected that the data, conclusions and recommendations of this report will be accepted as a standard reference by anyone dealing with turbine engine rotor non-containment.

- 1.2 Committee Membership and Activity: The individuals forming the Committee were selected from companies in the field of airline operation (Delta Air Lines), airframe design (Bell, Boeing, Lockheed, Sikorsky), engine design (Allison, AVCO-Lycoming, Garrett, General Electric, Pratt & Whitney, Pratt & Whitney Canada, Rolls-Royce, Turbomeca) and the FAA.

The Committee established a schedule of meetings with the goal of submitting a report to the Propulsion Division in June of 1985. Starting in March, 1984, meetings were held approximately every two months, but due to the expanded scope of the effort and the complexity of the issues involved, the report was subsequently submitted to the SAE Aerospace Council on April 1, 1987.

- 1.3 Aerospace Information Report (AIR 1537) Summary: As indicated above, a previous Ad Hoc Committee had studied the subject of gas turbine engine non-containment. Their report, AIR 1537, was issued in October, 1977. In that report, data were presented relative to non-containment of commercial fixed wing aircraft gas turbine engines between the time period of January 1962 through December 1975. The study included experience covering 417 million engine hours of turboprop, turbojet, and turbofan engine operation. More than half the experience was generated by low bypass turbofan engines, and only the initial service experience of high bypass turbofan engines was covered by this time period. No rotorcraft or general aviation engine was included.

Overall, the non-containment failure rate in that time period was 0.66 failures per million engine hours. Of these failures, less than 20% resulted in significant or severe aircraft damage. Engine non-containment was a factor in 0.22% of all fatalities, 2.62% of all accidents, and 1.05% of all hull losses which occurred in commercial aircraft service from all causes in that time period. No single cause contributed to more than one-quarter of the total non-contained failures, although high cycle fatigue, low cycle fatigue, and material defects together accounted for one-half the total number of disk and spacer failures.

Penalties imposed on aircraft systems to achieve greater levels of containment were evaluated in terms of weight. The Committee concluded that the majority of non-containment occurrences which involved significant or severe damage to the aircraft were due to release of fragments of such size and energy as to make the additional mass required for containment impractical within the then current state of the art. Although the occurrence of aircraft accidents caused by non-containment failures is infrequent, non-containment must be considered an important element of overall aircraft system safety, and the Committee therefore recommended continued efforts to reduce this hazard. The greatest potential for reduction of significant damage to the aircraft caused by non-containment rotor failures was considered to be the continued major efforts by the engine manufacturers to improve engine design, manufacturing, and quality control to reduce the number of rotor bursts, and by the airframe manufacturer to minimize the hazard to the aircraft caused by non-containment engine fragments.

2. DEFINITIONS: Fixed wing aircraft engines have been treated in two classes; engines powering an aircraft with a maximum passenger capacity not in excess of 19 persons or a cargo capacity not greater than 6000 lbs. have been classified as general aviation engines. All other engines are considered commercial transport engines.

In this report the following conventions are observed:

- a) Use of "hours" refers to engine operating hours, unless otherwise specified. Use of "cycle" refers to a flight initiated by engine start-up and concluded at engine shutdown.
- b) Where an "overall" failure rate is stated, the cumulative rate at the end of the 8-year (1976 - 1983) report period applies. Yearly rates are also presented and some comparisons are made between the "overall AIR 1537" (i.e., cumulative 1962 - 1975) and the "current period overall" or cumulative 1976 - 1983 data. For general aviation and rotorcraft, there were no data from the prior period.

2.1 Definition of Non-Containment:

- 2.1.1 Commercial Transport and General Aviation Engines: Non-contained failure of a fixed wing aircraft turbine engine was defined for the purpose of this study to be the same as in AIR 1537, i.e., any failure which results in the escape of rotor fragments through the nacelle cowling or through panels which isolate the powerplant installation from the remainder of the aircraft structure. The term rotor includes rotating components such as disks, spacers and blades.

Rotor failures of primary importance in this study are those which release fragments of sufficient energy to constitute a potential hazard to the aircraft through damage to other systems or structure outside the affected propulsion system. This is based on the fact that multi-turbine powered aircraft are capable of continued safe operation after loss of power/thrust from one engine during any phase of flight. In addition, this distinction is drawn because fragments contained within the propulsion system, even when engine cases are penetrated, do not represent a hazard to personnel, airframe structures or systems. The powerplant installation is designed to confine the fire or damage which might result from such a failure.

- 2.1.2 Rotorcraft: For the purpose of this study, a non-contained failure for a rotorcraft engine was defined as any rotor failure which resulted in the escape of rotor fragments through the engine casing or the inlet structure. In rotorcraft installations, engines are mounted in close proximity to other critical aircraft systems such as power shafting, electrical systems, flammable fluid lines and, in many twin engine rotorcraft, the second engine. Unlike most fixed wing installations, the powerplant system is usually integral with the helicopter as opposed to an isolated system contained in a nacelle. For these reasons, the definition of a non-contained failure for rotorcraft engines differs from that for fixed wing aircraft.

- 2.1.3 Exclusions: For commercial transport and general aviation engines where rotor fragments were released and did not penetrate the powerplant installation, i.e., inlet or exhaust nacelle outer skin, but did pass out of the exhaust or were propelled forward out of the air intake entry, the events were not included because in most cases added containment would be of no benefit and retaining devices are not practical.

As pointed out earlier, this study addresses rotor failure where high energy fragments are released. Not considered are secondary failures such as contained failures producing imbalance resulting in vibratory failure of bolts or exhaust cone attachments, liberating exhaust cones or portions thereof, or where the vibratory imbalance caused separation of bolted joints leading to the release of pressurized gases/air resulting in the liberation/separation of cowl access panels or cowl doors.

2.2 Definition of Aircraft Damage:

- 2.2.1 Commercial Transport and General Aviation: A hazard from a non-contained engine failure results when damage occurs to critical aircraft structure or systems other than the affected nacelle or when there are personal injuries. To assess the resulting aircraft damage and to determine the areas of greatest concern, the same severity classification as was defined in AIR 1537 has been maintained. The severity of aircraft damage, as judged from a relative standpoint, is based on the consequences and the damage that actually occurred. For example, fuel tank puncture events were not judged by what could have occurred, i.e., fire, but were judged on the actual consequences. If, however, an event resulted in the aircraft being exposed to circumstances outside its certified limits, then it was considered serious enough to be classified as significant aircraft damage.

The four damage severity classifications are defined as follows:

Category 1. Nacelle Damage, where damage from escaping fragments was confined to the affected nacelle.

Category 2. Minor Aircraft Damage, defined as damage that has little effect on aircraft performance, such as:

- a. Nicks, dents and small penetrations in aircraft structure.
- b. Slow depressurization.
- c. Controlled fires.

Category 3. Significant Aircraft Damage, as listed below, with the aircraft continuing flight and making a safe landing.

- a. Damage to primary structure or systems.
- b. Uncontrolled fire.
- c. Rapid depressurization.
- d. Loss of thrust on an additional engine.
- e. Minor injuries.

Category 4. Severe Aircraft Damage, as listed below:

- a. Crash landing.
- b. Loss of the aircraft.
- c. Critical injuries.
- d. Fatalities.

It is apparent from these definitions that Categories 1 and 2 present no hazard to the welfare and safety of the aircraft passenger. Thus, in analyzing the service data, Categories 3 and 4 were emphasized in order to determine the areas of greatest concern.

2.2.2 Definition of Rotorcraft Damage: Hazard from a non-contained engine failure results when damage occurs to aircraft structure or systems or there are personal injuries. To assess the resulting damage and to determine the areas of greatest concern, a means of classifying the severity of damage was developed. The severity of rotorcraft damage, as judged from a relative standpoint, is based upon the consequence and the damage that actually occurred. Consideration was given to the fact that rotorcraft are designed to autorotate to the ground safely in a power-off situation.

Damage severity was classified into four categories and is defined as follows:

Category 1. Damage limited to affected engine, such as:

- a. Continued safe flight.
- b. Successful power-off or reduced power landing.

Category 2. Minor aircraft damage, defined as damage that has little effect on aircraft performance, such as:

- a. Nicks, dents and small penetrations in aircraft structure.
- b. Slow depressurization.
- c. Controlled fires.
- d. Successful power-off or reduced power landing.

Category 3. Significant aircraft damage, as listed below, with the rotorcraft making a safe landing.

- a. Damage to primary structure or systems.
- b. Uncontrolled fire.
- c. Rapid depressurization.
- d. Loss of power on an additional engine.
- e. Minor injuries.

Category 4. Severe aircraft damage, as listed below:

- a. Crash landing.
- b. Loss of the aircraft.
- c. Critical injuries.
- d. Fatalities.

3. SUMMARY OF RESULTS:

- 3.1 The current study involved collating data from the period 1976 through 1983 on the nature and consequence of turbine engine non-containment rotor failures. Experience on commercial transport aircraft, general aviation aircraft and rotorcraft powered by engines from Allison, AVCO Lycoming, Garrett, General Electric, Pratt & Whitney, Pratt & Whitney Canada, Inc., Rolls-Royce and Turbomeca were considered. A total of 351.2 million engine hours of service experience was accumulated by commercial transport operations, 80.1 million engine hours by general aviation, and 35.1 million engine hours for rotorcraft. An eight-year period has been considered (compared with 14 years previously).

During the current study period, commercial transport hours of operation are only 16% lower than for the previous study, but the percentage of commercial operating hours related to high bypass ratio engines rose from 5% in the previous study to 23% of the total for the current study. Overall, the non-containment failure rate during the current study period for commercial transport engines was relatively stable at 0.58 failures per million engine hours. Of these failures, 12.3% resulted in significant or severe aircraft damage, a significant reduction from the 17.8% of AIR 1537. Engine non-containment was a factor in 1.6% of all fatalities and 1.3% of all hull losses which occurred in the period 1976 - 1983. These results are low, as were those reported previously in AIR 1537 (See Section 1.3).

For the period 1976 - 1983, the non-containment failure rate for general aviation engines was 0.42 events per million engine hours, and 14.7% of these failures resulted in significant (Category 3), but not severe (Category 4) aircraft damage. General aviation engine non-containment was not a factor in fatalities or hull losses that occurred in the period. No comparative data exist for general aviation engines in AIR 1537.

For rotorcraft, the overall engine non-containment rate was 2.22 events per million hours for the period 1976 - 1983. Of these failures, 38.5% resulted in significant or severe (Categories 3 and 4) aircraft damage. Engine non-containment was a factor in 3.2% of all rotorcraft fatalities for that time period and 11.3% of all hull losses, including those wherein the aircraft was lost for other reasons after completing a safe auto rotation. No comparative data exist for rotorcraft in AIR 1537.

- 3.2 Information on non-contained events was obtained mainly from the engine manufacturers since their records of time accumulated and non-containment events were the most comprehensive. These were supplemented by and cross-checked against data provided by airlines, aircraft manufacturers, and the FAA.
- 3.3 The results of the analysis of these data are presented in both tabular and graphical form generally following the formats used in the previous report (AIR 1537). Some changes, however, have been introduced. (See Sections 4 and 5).

- 3.4 For commercial transport operations and general aviation, only those events where rotor fragments exited the nacelle were defined as non-contained (consistent with AIR 1537). For these aircraft types, it is clear that those fragments retained within the nacelle do not represent a hazard to the aircraft. For rotorcraft, however, any fragment exiting the engine case represents a potential hazard to the aircraft and all such events have been defined as non-contained.

It must be stressed that comparisons between data for each of the three engine classes must not ignore the above differences in installation and associated non-containment definitions. These will account for part of the general difference between the rotorcraft overall engine hourly failure rate (2.22 events per million engine hours) and that of general aviation (0.42 events per million hours) even though some basic engine types are used in both classes of operation and all engines are certificated to the same Federal Aviation Regulations (FAR 33). The differences in the above definitions do not, however, affect the statistics for events causing significant or severe aircraft damage.

The impact of the operational procedures used on single and twin engined rotorcraft and of the significantly higher cyclic usage per hour of most rotorcraft were also considered. The effects of this cyclic usage provide an alternate basis of comparison for the data and explain some of the apparent differences between the hourly failure rates of the different classes.

Beyond differences in the installations, associated definitions and cyclic usage, the data also reflect differences in effects of operational influences upon the three engine classes.

In general, the higher percentages of events occur at those conditions where the engines are at high power (See Table 5.1). For commercial transports, these conditions are take-off and climb. For general aviation, these conditions are take-off, climb, and cruise. Most general aviation aircraft have take-off power needs that do not approach the maximum rated power of the engines, and maximum rotor speeds and temperatures are only attained at altitude cruise for optimum altitude performance. For rotorcraft, the distribution of events with operating conditions is more uniform because of specific problems with a single engine model which makes up more than half the rotorcraft data base.

- 3.5 It should be recognized that data presented in this report are often dominated by a single engine type in each of the three engine classes being discussed. One commercial engine type represents 40% of the total commercial transport engine hours; one engine type represents 53% of the total general aviation engine hours; and one engine type represents 62% of the total rotorcraft engine hours. With this situation, some statistics are skewed by an individual engine's experience and are not representative of the entire class of engines involved.

3.6 The overall data base included 315 non-contained rotor failure events which occurred during 466.4 million engine hours of civil aircraft service. These involved equipment types as follows:

	Operating Hours (X10 ⁻⁶)	Operating Cycles (X10 ⁻⁶)	No. of Events	Events/10 ⁶ Hrs	Events/10 ⁶ Cycles
Commercial Transport	351.2 (417)*	267.5	203 (275)*	0.58 (.66)*	.76
General Aviation	80.1	80.1	34	0.42	.42
Rotorcraft	35.1	87.7	78	2.22	.89
Total	466.4		315		

*Numbers in parentheses were reported in AIR 1537

It has been concluded that neither the hourly failure rate nor the cyclic failure rate alone is a fully adequate basis for comparison and that both should be considered before drawing any conclusions.

3.7 Non-containment events have been classified by cause, component and flight mode; full details are provided in the text and accompanying tables. The causes have been divided into two categories which differ from those used in AIR 1537.

These are: (a) the initiating cause
(b) The cause of failure of the part exiting the nacelle/engine.

This change was introduced to identify aspects of engine design, manufacture and/or operation responsible for the non-containment failures and to direct attention to any aspect which accounted for a significant proportion of those failures. In this way, it could be ascertained if additional measures to increase engine containment capability are required or whether resources could be more effectively directed at reducing the potential hazard from non-contained failures by alternative means.

3.8 Engine non-containment is seldom linked to fatalities or hull losses for commercial fixed wing aircraft. The statistics on rotorcraft show non-containment to be a factor more frequently associated with them, but often the non-contained initiating event was not the primary cause of the hull loss and, in some cases, subsequent fatalities.

3.9 This report does not re-examine the size or weight distribution of fragments since this was adequately handled in the previous report (AIR 1537), and accurate information on fragment weight is seldom available from damage reports.

4. CONCLUSIONS, OBSERVATIONS AND RECOMMENDATIONS:

4.1 Conclusions and Observations:

4.1.1 Commercial Transport Engines:

- 4.1.1.1 The general conclusions and observations made in the previous SAE review (AIR 1537) of commercial transport aircraft engine non-containment remain valid.
- 4.1.1.2 The rate of non-contained failures causing more than minor aircraft damage is very low at less than one event per ten million engine hours.
- 4.1.1.3 The overall rate of non-containment engine events has decreased approximately 12% during the current study period relative to AIR 1537, from 0.66 to 0.58 events per million hours (See Table 5.2), indicating the continuing improvement in turbine engine durability.
- 4.1.1.4 The average non-containment rate for high bypass ratio engines was about 2.5 times that of low bypass ratio engines. For significant or severe aircraft (Categories 3 and 4) damage events, however, they were approximately equal.
- 4.1.1.5 The introduction of the high bypass ratio (HBPR) engine which incorporated larger numbers of stages and exposed them to higher temperatures and pressures initially showed a higher non-containment rate than the more mature low bypass ratio (LBPR) engines. Despite the impact of these HBPR engines on the overall statistics, the cumulative rate from 1962 of non-contained engine events for all damage categories has decreased by approximately 6% (from 0.66 to 0.62 events per million hours - See Figure 5.2.5) since the AIR 1537 study.
- 4.1.1.6 The cumulative non-containment rate of the HBPR engines has dropped to approximately 2.5 times that of LBPR engines, but if fan blade events are excluded, to a value of 1.3 times that of LBPR engines. (See Section 5.2)

HBPR engine non-contained events relating to fan blade loss are running at a rate significantly higher than the LBPR engine rate. Loss of HBPR fan blades from ingestion allows some debris to travel forward as there are no inlet vanes and thus introduces a failure mechanism not characteristic of LBPR engines. These events do not usually cause significant aircraft damage. They will, however, increasingly influence the future overall statistics as the HBPR engine proportion of the total commercial fleet operation becomes more dominant (see paragraph 4.2.1 Commercial Transport).

- 4.1.1.7 The overall non-containment failure rate for disks and spacers during this period has decreased by approximately one-third since the AIR 1537 study. This is significant since these parts typically represent the highest energy threat to the aircraft.
- 4.1.1.8 Ingestion related events (bird strikes, FOD) ranked as the highest single cause of non-containment events (22%). This compares with 5.5% during the previous study. This is due to the increased exposure of the HBPR engines.
- 4.1.1.9 The majority of non-containment events (87%) occur during take-off and climb, only 8% occur at cruise (See Table 5.2.2).

- 4.1.1.10 Loss of blades caused the most frequent non-containment events, however, none of these caused severe (Category 4) aircraft damage. 94% of the blade non-containment events resulted in no more than minor (Categories 1 and 2) aircraft damage.
- 4.1.1.11 There has been an appreciable decrease (43%) in rate for those events causing significant (Category 3) aircraft damage (from 0.11 to 0.06 events per million engine hours) since AIR 1537. The rate of events causing severe (Category 4) aircraft damage has remained low.
- 4.1.1.12 Engine non-containment was a factor in 1.6% of all fatalities and 1.3% of all hull losses which have occurred in commercial fixed wing aircraft from all causes.

4.1.2 General Aviation (G.A.) Engines:

- 4.1.2.1 There are no general aviation data in AIR 1537 with which to compare the current data. Since general aviation engines are certified to the same regulations as commercial transport engines and are operated similarly, comparison with commercial transport engines is appropriate.
- 4.1.2.2 General aviation non-containment statistics compare favorably with commercial transport experience and have a lower rate in every damage category with an overall rate 73% of the commercial rate based on hours and 56% of the commercial rate based on cycles. The lower rate of the smaller general aviation engines is partially due to having fewer rotating parts and lower cycle pressures and temperatures.
- 4.1.2.3 Non-containments have not been a serious safety problem in the general aviation fleet. There have been no events causing severe (Category 4) aircraft damage. No events have been reported to be a factor in hull losses or fatalities. There have only been five events causing significant (Category 3) aircraft damage, all of which have been in turboprops and these resulted in only minor injuries from fragments as opposed to leading to fires or primary structural damage.
- 4.1.2.4 While the fan and compressor sections combined accounted for 63% of the non-containments of commercial transport engines, general aviation engines had only one such event which represents less than 3% of the events in this class. General aviation turbine section non-containments which dominate the statistics of this class were in themselves dominated by overspeed events (68% of the total) of a particular model turboprop engine and were usually the result of a power train failure. These events have shown a dramatic and consistent reduction in rate of occurrence over the reporting period, (See Figure 5.3.4). This reflects modifications to that engine model introduced into service to eliminate the problem.

The remaining general aviation non-containments are relatively few (11 in 80 million hours) with half of these being attributed to manufacturing defects with no clear pattern predominating.

4.1.2.5 Regarding containment following ingestion events, the data indicate that current design practices for general aviation turbine engines are adequate.

4.1.2.6 General aviation non-containment events can be divided into two distinct groups; a) failures which reduced the structural integrity of the turbine components, i.e., over-heating, rubbing, inherent defects, etc.; b) failures of the power train of the engines which exposed the turbine rotor to extreme conditions, i.e., overspeed.

4.1.3 Rotorcraft Engines:

4.1.3.1 There are no rotorcraft aviation data in AIR 1537 with which to compare the current data. Although rotorcraft engines are certified to the same regulations as contemporary general aviation and commercial transport engines, they are installed and operate in a significantly different environment, directly contributing to the high proportion of non-containment events found in the data that were associated with significant damage. However, a comparison of engine experience made on the basis of cyclic usage, shows similar rates of non-containment for the three classes of engines in spite of different non-containment definitions.

4.1.3.2 The yearly rate of rotorcraft non-containment events has decreased from 3.4 incidents per million engine hours in 1976 to 1.5 per million engine hours in 1983. The cumulative rate improved from 3.4 per million in 1976 to 2.3 per million during this period.

4.1.3.3 The rate of non-containment failures causing more than minor rotorcraft damage is less than one event per million engine hours.

4.1.3.4 For those resulting in significant rotorcraft damage (Categories 3 and 4), 37% reflected failure to execute a safe autorotation where hazardous terrain was not a factor, indicating either low altitude operation or lack of pilot training in emergency procedures.

4.1.3.5 While the overall rate of non-containment events for twin-engine powered rotorcraft was lower than for single engine rotorcraft (1.68 per million hours vs. 2.44 per million hours), the rates for more than minor damage were approximately the same (0.79 per million hours for the twin and 0.88 per million hours for single engine installations). These more severe events were dominated by one engine type.

4.1.3.6 For all damage categories of civil engine rotorcraft configurations, either single or twin engines, the turbine component is by far the main source of non-contained events. These events were predominantly related to non-contained disk fragments (74.4%).

4.1.3.7 For rotorcraft, the cruise flight mode accounts for 34.6% of all non-containment events followed closely by the descent mode which accounts for 24%. Unlike the commercial transport engines, the take-off mode (23%) is not dominant.

- 4.1.3.8 Significant and severe aircraft damage events (Categories 3 and 4) formed a higher percentage of the total compared with other engine classes.

	<u>Commercial</u>	<u>General Aviation</u>	<u>Rotorcraft</u>
% Events in Category 3	10.8	14.7	20.5
% Events in Category 4	1.5	0	18.0

This can be attributed to several factors, the most important being that a) rotorcraft engines are typically installed close to other critical systems and aircraft structures, often another engine, and, b) autorotation is frequently not successfully executed.

The higher rates in Category 3 and 4 events for rotorcraft are attributed, in part, to the intended operation of the aircraft. Unlike multi-engine fixed-wing aircraft, rotorcraft, by intent, often operate at low altitudes over hazardous, rough terrain where any engine or major system malfunction may preclude a safe autorotation and result in aircraft damage.

- 4.1.3.9 For rotorcraft, there was only one event of exhaust-exiting debris producing serious damage to the aircraft.
- 4.1.3.10 Engine non-containment was a factor in 3.2% of all fatalities and 11.3% or rotorcraft hull losses which have occurred from all causes.

4.1.4 General:

- 4.1.4.1 General aviation engines had the lowest non-containment failure rate (0.42 events/million hrs.), 27% lower than the commercial transport rate, with no fatalities or severe (Category 4) aircraft damage events.
- 4.1.4.2 Non-containment events were a factor in a very small number of the total number of aircraft accidents.
- 4.1.4.3 Disk failures have been the foremost cause of non-containment fragments causing severe (Category 4) aircraft damage. For events causing severe aircraft damage, 88% were due to disks, of which 20% were commercial transport, 0% general aviation and 80% rotorcraft. For those events causing significant (Category 3) aircraft damage 70% were due to disks of which 40% were commercial transport, 10% general aviation, and 50% rotorcraft.
- 4.1.4.4 The cause of non-containment events was identified in most cases studied. This resulted in only 14.3% of the events being labeled "unknown" compared to 21.1% in the previous AIR 1537 study. In general, "unknown" events result when there is total destruction or non-recovery of the failed part.

- 4.2 Recommendations: It must be noted that many of the engine certification requirements have changed since the engines involved in this study entered service. In some instances, the new requirements reflect the experience which makes up the statistics in this data base. Therefore, the following recommendations are directed primarily toward engines yet to be certified.
- 4.2.1 Commercial Transport: Inlet cowl penetrations by fan blade fragments forward of the fan containment case are not characteristic of LBPR engines but represent a significant percentage of the total non-contained events of high bypass ratio engines. While these events typically produce minor damage, one of these events caused Category 3 damage and steps should be taken to diminish the potential hazard from these incidents by improvements in either engine or inlet design, whichever is more efficient.
- 4.2.2 General Aviation: Since the type of failure which dominated the general aviation non-containment statistics is currently addressed by design practices and FAA rules, it is recommended that no changes to the practices and rules as they pertain to general aviation non-containment be made.
- 4.2.3 Rotorcraft:
- 4.2.3.1 Rotorcraft engine design practices include a fault analysis in accordance with FAR 33.75(b). This analysis should be conducted early in the engine design to assure that all foreseeable engine failures which could result in a non-contained event are minimized.
- 4.2.3.2 The percentage of rotorcraft disk and spacer failures wherein the initiating cause was low cycle fatigue (21.8%) is relatively high. The entire life management system for rotorcraft engines, including design duty cycles, engine operational severity and maintenance/recording procedures, should be critically reviewed.
- 4.2.3.3 Rotorcraft design practices should be expanded to include a rigorous hazard analysis conducted early in the installation design cycle. This analysis (similar to that required by JAR 25.903 (d) (1)) should consider rotor bursts from all stages of the engine and their effect on critical systems, structure, and other engines. Results should assure that the probability of a catastrophic event is minimized.
- 4.2.3.4 Since the data reflected numerous instances in which a safe autorotation was not executed when terrain or low altitude operation were not factors, consideration should be given to increasing rotorcraft pilot autorotation training. Such training should improve the overall flight safety record for rotorcraft.
- 4.2.4 General:

- 4.2.4.1 A further review of non-contained events should be carried out in the 1990/91 time period to monitor any changes that might have occurred as a result of changes in engine/aircraft design and utilization. Individual manufacturers should continue to maintain adequate incident follow-up activity to be prepared for that review, including an incident data base that is supplemented periodically with new findings as they become available.
- 4.2.4.2 Since bird ingestion related events are a major percentage of the total non-contained events, increased efforts to control bird flocks and clear runways at airports is needed (See Sections 6.2.1 and 6.4.1).
- 4.2.4.3 As observed in AIR 1537, there is still no evidence that additional containment capability for disks in general is required. No further change to containment certification requirements is recommended.
- 4.2.4.4 Efforts to improve material processing and manufacturing control of disks and spacers to reduce still further severe non-contained failures must be continued (See Section 6.2.5.3).
- 4.2.4.5 Periodic review of the mission cycle effects imposed on rotors due to speed and temperature transients experienced in actual usage will also lead to improvements (See Section 6.2.5.1).
- 4.2.4.6 During the data collection phase of this study, it was apparent that the manufacturers and government regulatory agencies had extensive data bases concerning non-contained failures. Two areas of concern were uncovered:
 - a. While the engine manufacturer, aircraft manufacturer, and regulatory agency had data bases, it was difficult to correlate information between them. The difference in data was usually due to the sources of information and the technical orientation of the data base manager (i.e., aircraft manufacturer vs. engine manufacturer, etc.). Future efforts to compare data could be made easier by adoption of a standard format for recording non-contained rotor failure information.
 - b. In some instances where non-contained events occurred, the data base may have listed "unknown causes" or may be missing critical information. The "unknown causes" situation is discussed in paragraph 6.4.3. The second area, missing, incomplete, or inaccurate information, was seen predominantly in the rotorcraft area and somewhat in general aviation. This is probably due to the operating environment of the aircraft. The commercial transport category (operators under FAR 121, 125, 135) have well-defined record keeping requirements. General aviation and rotorcraft generally operate differently with respect to maintenance and record keeping requirements (i.e., maintenance of aircraft or engines may be done by independent repair/overhaul facilities rather than the operator). To ensure complete information, manufacturers and regulatory agencies should pursue programs to ensure complete reporting of incidents and teardown findings.

5. DATA SUMMARIES:

5.1 Data Organization:

The data and analysis are presented separately for each of the three classes of aircraft, and, to the extent that it is appropriate to do so, selected data for different classes are presented together. For ease of data location and for an orderly presentation, there are three sections, i.e. commercial transport engines, general aviation engines, and rotorcraft engines.

- 5.1.1 Data Base: For this study, the scope, when compared with the previous AIR 1537 report which covered only commercial transport engines, was extended to encompass all the certified turbine engines, including general aviation fixed-wing and civil rotorcraft. Data from the USSR, China, and Eastern Europe were not available. Service data for the period January 1, 1976 through December 20, 1983 were obtained through the committee members from records supplied by the manufacturers and government agencies.

The AIR 1537 report covered the period January 1962 through December 30, 1975. In order to facilitate continuity of the data record and observation of ongoing trends, this report for the January 1976 through December 1983 period has a similar format in data presentation. Where there are differences, they are in response to the needs of the broadened scope of this study.

In the analysis of the service data on turbine engine rotor failures, the charter of this committee identified three major areas of investigation for study. These areas of investigation are: 1) to determine the rates of past occurrences, 2) to classify incidents by cause, and 3) to assess the resulting aircraft damage.

- 5.1.2 Damage Classification: Consistent with the approach taken in AIR 1537, the greatest concern relative to turbine engine failures involved those events which constituted a hazard to the aircraft and its personnel. The relative hazard to the aircraft was identified by classifying the severity of the resulting aircraft damage and the consequence according to the definitions in Section 2.2.

- 5.1.3 Aircraft Classification: Use of three classes of aircraft, i.e., commercial transport, general aviation and rotorcraft as natural classification groups facilitated orderly data-gathering, analysis and presentation. The committee judged each a separate group of interest with general differences in environment and operational usage. Further, each of the three groups is actually separate in terms of the characteristics of its data base for the following reasons.

The commercial transport engines have the best documented records and most reliable data base by virtue of the fact that the majority of these aircraft operate in the generally consistent, controlled environment of scheduled commercial air carrier service with an orderly structure of record-keeping. The previous AIR 1537 report was limited to this group.

The group referred to as "general aviation", although also comprised of fixed-wing aircraft, is used in transport commuter service, executive aircraft, air taxi and other miscellaneous applications, - often by owners/operators with only one or two aircraft. Although the commuters are generally in an airline-type operating and maintenance environment, some of these aircraft are widely dispersed around the world in remote areas. Data collection for these aircraft is less complete.

Rotorcraft as an aircraft class operate in the widest range of environments where records of operation and maintenance action are often significantly less complete. Although there are a few rotorcraft which operate in an airline-type passenger service (this is a growing application), the majority of helicopters are in a highly variable-duty service including police, EMS/rescue, backwoods logging, offshore supply and replenishment, and corporate transportation, and they frequently see high cyclic rate utility service. Compared with engines in commercial transport and general aviation service, rotorcraft engines are subjected to extensive cyclic usage, involving a larger number of thermal and mechanical transients in a given period of time having a strong influence upon engine rotor part life. Further, rotorcraft engine arrangement and aircraft construction are such that in most rotorcraft engine installations, there are greater system vulnerabilities to escaping rotor fragments, highlighting the need for innovative design solutions to minimize engine case penetrations. Additionally, the rotorcraft class is the only one in which a majority of the aircraft is single-engine powered.

- 5.1.4 Presentation of Data: The data for each of the three classes of aircraft are first presented separately. The results of the analysis of these data are presented in both tabular and graphical form following as closely as practicable the formats used in AIR 1537.

The data included 315 non-contained rotor failures which occurred during 466.4 million engine hours of operation in non-military service. These involved equipment types as follows:

	<u>Operating Hours ($\times 10^{-6}$ Hrs)</u>	<u>No. of Events</u>
Commercial Transport	351.2	203
General Aviation	80.1	34
Rotorcraft	35.1	78
	<u>466.4</u>	<u>315</u>

Events were classified by further breakdowns, presented in the accompanying tables and figures:

- Engine type (turbojet, turbofan, turboprop, turboshaft)
- Flight mode (takeoff, climb, hover, cruise, etc.)
- Severity category (Category 1 through 4 - see Section 2.2)
- Rotating part category (blade, disk, spacer)
- Engine component (fan, compressor, turbine)
- Originating cause (HCF, FOD, LCF, etc.)
- Consequence (failure mechanism for the exiting part)
- Broad cause categories (environmental, mechanical, manufacturing, etc.)



Table 5.2 shows the overall summary data for each engine class and damage category for January '76 through December '83. The numbers in parentheses are the corresponding values from the previous (AIR 1537) report period, and are shown for comparison. Since the AIR 1537 data were limited to the first class, i.e., commercial transport engines, there are no general aviation or rotorcraft comparison data for the period prior to January 1, 1976 and for these, the long-term trend data are not available in this data base.

- 5.2 Commercial Transport Engine Data - Tables and Figures: A total of 203 non-contained events comprised the data base for commercial transport engines during the current period. These data consisted of experience from four transport engine types, i.e., turbojet, turboprop, low bypass ratio turbofan and high bypass ratio turbofan. The summary totals of operating hours, cycles, non-contained failure events and hourly rates for each type during this period were as follows:

Commercial Transport Engine Non-Contained Rotor Failures
1976 - 1983

	Millions		Events			Events per Million Hr.		
	Hours	Cycles	All Cat.	Cat. 3	Cat. 4	All Cat.	Cat. 3	Cat. 4
Turbojets	7.1	3.6	6	2	1	0.85	0.28	0.14
Turboprops	35.9	35.9	10	1	1	0.28	0.03	0.03
LBPR Turbofan	226.1	201.4	95	14	0	0.42	0.06	0
HBPR Turbofan	82.1	26.6	92	5	1	1.12 (.56)*	0.06	0.01
TOTAL	351.2	267.5	203	22	3	0.58	0.06	0.01

***Failure Rate Excluding Fan Blades**

The turbojets had the lowest number of operating hours, but a comparatively high failure rate. The turboprop had the lowest overall rate. The high bypass ratio turbofan had the highest non-contained rate; 46 of the total 92 events (50%) were fan blade separation events, primarily Category 1 and 2 events. Excluding the fan blade events, the rate of high bypass ratio turbofan core section non-containment is comparable to the low bypass ratio turbofan rate.

For the more serious failures, i.e., Categories 3 and 4, the turbojets have by far the highest rate and the turbofans the lowest, even with fan blades included. This may be explained on the basis that turbojets represent earlier technology and turbofans, as a newer design class, include the benefits of lessons learned from that earlier experience.

From Table 5.2, it is seen that the failure rate for commercial transport engines Category 3 events (0.063 per M hours) is 43% lower than the 0.11 events per M hours of the previous report, but Category 4 events (0.01 per million hours) show no change from the 0.01 events per million hours of the previous report.

Table 5.2.1: Commercial Transport Non-Contained Failures Classified by Fragment Type

Table 5.2.1 shows failures according to fragment type and engine location. This shows that 72% of Category 3 and 4 events are attributed to disk and spacer failures and that half of Categories 3 and 4 events are attributed to fan and compressor disk and spacer failures. The other 28% were caused by blades - 12% by turbine blades and 16% by fan blades.

The highest contributor to the total non-contained events was the fan; 88 of the total 203 events (43%) in all severity categories occurred in the fan. Of Category 3 and 4 severity, 7 of total 25 events (28%) occurred in the fan. The blades of the fan are the highest single component, contributing 36.5% of the total, however, only 2% of the Category 3 and 4 events resulted from fan blade loss. This shows that although the high exposure of the fan produces many non-contained events due to blade separation, these have not been of serious consequence to the aircraft.

Category 3 and 4 events make up 12.3% of the total; this is a significant reduction from the AIR 1537 report period (17.8%).

For Category 3 and 4 events, the dominating events were compressor disk (3.4% overall) and turbine disk (3.0% overall) failures; together they caused 52% of the total Category 3 and 4 events.

Comparison with AIR 1537 shows that the non-containment failure rate for disks and spacers during this period has decreased by nearly one-half, from 0.37 events per million hours to 0.23 events per million hours.

Tables 5.2.2 and 5.2.3: Commercial Transport Non-Contained Failures Classified By Flight Mode and Component

Table 5.2.2 shows the number of events, failure rate, and percentage occurring at various flight modes. This table shows that 87% of the total events occurred at takeoff and climb. Since these flight phases correspond to a high rotor speed and high temperature condition this is consistent with expectations.

Table 5.2.3 is a further breakdown of the data in Table 5.2.2. It shows the distribution of events by component as well as flight mode, and the dominance of takeoff and climb is shown to be independent of the component that produced the non-contained part.

Takeoff and climb failures, at 87% of the total, are increased from 66% of the total in the previous report. This increase of 21% may be attributed to the progressive evolution of the fleet toward a larger percentage of high bypass turbofan engines. The increase can be traced to a higher frequency of non-contained events due to bird ingestion and FOD which is consistent with the larger frontal area and exposure presented by the fan of the high bypass ratio engines.

Table 5.2.4: Commercial Transport Non-Contained Failures Classified by Initiating Cause/Result - Disks, Blades and Spacers

Every rotor failure was classified by cause and result, i.e., (a) the basic initiating cause which progressed into or resulted in the separation failure of a rotor component, and (b) the failure process within the exiting part itself.

In some cases the initiating cause (such as a classic fatigue failure) was within the part itself and thus, was the same as the failure process. One example of the other kind, i.e., a failure resulting from an initiating abnormality elsewhere, would be a bearing failure or loss of lubrication which progressed into a rubbing failure of a rotating spacer.

The process involved in the component was selected from one of the following:

- Fracture (due to impact or overstress)
- High cycle fatigue
- Low cycle fatigue
- Overtemperature (loss of properties)
- Overspeed (Loss of load or control failure)
- Rubbing against static parts

"Unknown" as a cause was fairly high at 14.%, however, this is an improvement over the 21% "unknown" in the previous report period. Although further improvement appears possible, it will never reach zero "unknown" because some of the events result in liberation of the broken parts over water, difficult terrain or ground cover, making location and recovery of a primary fracture surface for analysis very difficult or impossible.

It should be noted that of the 29 total unknown events, 9 are disks and spacers; 19 are blades and one is unknown.

Table 5.2.5: Commercial Transport Non-Contained Failures Classified By Initiating Cause/Result - Disks Only

Because of the severity of damage resulting from most disk failures, this is one of the most important data tables of the study. As previously noted in Table 5.2, of 52 total disk failures, 15 events or 29% were in Category 3 or 4, i.e., significant or severe aircraft damage. Of the 52 disk failures, 32 events, or 62% were initiated by fatigue, fretting or defects. Of the 15 Category 3 and 4 disk events, 8 or 53% were initiated by fatigue, fretting or defects (see Table 5.2.9). This is a consistent percentage compared to 57% of the total in the previous report period (disks and spacers) indicating a fairly mature technology with unchanging cause factors.

Table 5.2.6: Commercial Transport Non-Contained Failures Classified By Initiating Cause/Result - Spacers Only

Table 5.2.7: Commercial Transport Non-Contained Failures Classified By Initiating Cause/Result - Blades Only

Table 5.2.8: Commercial Transport Non-Contained Failures Classified By Initiating Cause/Result - Disks, Blades, and Spacers, Damage Categories 3 and 4 Only

Table 5.2.9: Commercial Transport Non-Contained Failures Classified By Initiating Cause/Result - Disks Only, Damage Categories 3 & 4 Only

Table 5.2.10: Commercial Transport Non-Contained Failures Classified By Initiating Cause/Result - Disks Only, Damage Categories 3 & 4 Only

Table 5.2.11: Commercial Transport Non-Contained Failures Classified By Initiating Cause/Result - Blades Only, Damage Categories 3 & 4 Only

Tables 5.2.8 through 5.2.11 present the more serious events, i.e., Categories 3 and 4 for large commercial transport engines. Of these 25 serious events, 5 events, or 20%, are of unknown cause. These include 3 disk and 2 blade failures.

Table 5.2.12: Commercial Transport Non-Contained Failures Classified by Broad Categories of Initiating Cause - Disks, Blades and Spacers

Table 5.2.13: Commercial Transport Non-Contained Failures Classified By Broad Categories of Initiating Cause - Disks Only

Tables 5.2.4 through 5.2.7 provide a detailed breakdown by 16 different initiating causes. This degree of detail is useful and will be of value to those interested in pursuing understanding to this level of detail. However, other methods or presentation, though containing less detail, may also provide significant insight. To this end, these data were gathered into coherent logical groupings of originating influences as follows:

- | | |
|-----------------------------|--|
| - Environmental: | Birdstrike
Foreign object damage
Corrosion/erosion |
| - Mechanical: | Rubbing against static parts
Low cycle fatigue
High cycle fatigue
Fretting
Bearing Distress
Loss of lubrication |
| - Manufacture and Material: | Manufacturing defects
Material defects |
| - Human factors: | Maintenance
Misassembly
Operational procedures |
| - Other | All causes not listed above |
| - Unknown | Cause not determined |

The results presented in Tables 5.2.12 and 5.2.13, afford a simplified view of the driving influences which produced the rotor failures, in particular the Category 3 and 4 events. It is readily seen that of these more serious events, 14 of 25 total events (56%) and 8 of 15 disk events (53%) originated within the domain of design, manufacture and life management of disks, a significant observation relative to state of the art in the air transport industry.

In terms of overall Category 3 and 4 consequence, the environmental influence is low, i.e., one FOD and one corrosion/erosion event. Of the total 48 environmentally-influenced events, the other 46 were of minor (Categories 1 and 2) consequence; of these, 30 were birdstrikes. Consideration of the indirect, or subsequent operational consequences of the power loss from these fan failures, although potentially severe, is beyond the scope of this study.

The Tables 5.2.12 and 5.2.13 help to highlight those areas where effort may be applied to yield an improvement in the damage statistics of non-contained rotor failures.

Figure 5.2.1: Commercial Transport Annual Engine Hours

The annual engine hours have decreased each year, since the 1979 peak. Part of this decline may be attributed to the influx of more two and three engine transport aircraft in the worldwide fleet. The data shows a 30% decrease in annual hours of low bypass ratio engines and also a continued decline in turbojet operations as the airlines undergo fleet modernization replacing older, less fuel-efficient equipment. High bypass ratio turbofan hours per year have more than doubled during this report period.

Figure 5.2.2: Commercial Transport Annual Engine Cycles

Similar to the decline in annual hours, annual cycles decreased 32% from the 1979 peak due to the decrease in low bypass ratio engine operations. The number of high bypass ratio engine cycles per year more than doubled during this report period. Presently the high bypass ratio engines worldwide operate, on the average, 3.1 hours per cycle, and the low bypass ratio engines average 1.1 hours per cycle.

Figure 5.2.3: Commercial Transport Annual Non-Contained Failure Rates - Hourly Basis

Figure 5.2.4: Commercial Transport Annual Non-Contained Failure Rates - Cyclic Basis

Figures 5.2.5 and 5.2.6: Commercial Transport Cumulative Non-Contained Failure Rates - Hourly and Cyclic Basis

The eight-year cumulative rate for commercial transport engines as of 1983 compared with the 21-year rate (including the last report period) shows a continued improvement. The non-contained events rate for all severity categories decreased somewhat in this eight year period, a cumulative 7% decrease as of 1983 year end. However, the Category 3 and 4 events occurred at a fairly constant rate without significant improvement.

Figures 5.2.7 and 5.2.8: Commercial Transport Cumulative Non-Contained Failure Rates - Hourly Basis

The influence of the introduction into the fleet of the high bypass ratio turbofan engines is illustrated in Figure 5.2.7. The initial failure rate is distorted by the statistics associated with a low number of service hours. The effect on overall fleet statistics was minimal. It can be seen that the LBPR, turbojets, and turboprops failure rates have shown a constant, slightly improving trend, reflecting the product maturity of this equipment. It establishes that this standard is unlikely to change with current technology, even after many years of operation.

Also shown in Figure 5.2.7 is the influence that HBPR turbofan fan blade and spinner failures have had on the total statistics. It can be seen that without the fan blades and spinner failures the HBPR engine experience would have been similar to that of the rest of the fleet of commercial transport engines. This implies that the core experience of HBPR turbofan engines is already on a par with the standard set by the older, more mature engines. For example, the overall uncontained failure rate of HBPR less fan blades and spinner was 0.46 per million hours compared to the overall rate of 0.42 per million hours for the LBPR turbofan.

Figure 5.2.8 shows that the failure rate of the HBPR fan blades and spinners has remained relatively constant since 1979. Loss of HBPR fan blades from ingestion allows some debris to travel forward, as there are no inlet vanes, and thus introduces a failure mechanism not characteristic of LBPR turbofan engines. These events do not usually cause significant aircraft damage (only 1 event caused Category 3 damage). They will, however, increasingly influence the future overall statistics as the HBPR engine proportion of the total fleet becomes more dominant. (See Figure 5.2.1). At the end of 1983 the HBPR engines comprised 23% of the commercial transport fleet hours, compared to 5% at the end of 1975 (AIR 1537).

Figures 5.2.9 and 5.2.10: Commercial Transport Turboprop Annual Non-Contained Failure Rates - Hourly and Cyclic Basis

Of all the engine types, the turboprop failure rates were the lowest in non-contained failure rates during this period. There were a total of 10 failure events; these included one Category 2 (turbine blade overtemperature) and one each in Categories 3 and 4, both failures of a centrifugal compressor impeller. The turboprop hours comprised 10% of the total fleet hours during this period.

Figures 5.2.11 and 5.2.12: Commercial Transport Turbojet Annual Non-Contained Failure Rates - Hourly and Cyclic Basis

The failure rates for the turbojet fleet were similar to the rates reported in AIR 1537. The fleet age is increasing and the number of hours being flown is decreasing. During this seven year period, there were only a total of six events. There were 2 Category 3 failures (compressor disks) and one Category 4 (compressor disk). Five of the six events were caused by high cycle fatigue.

The number of turbojet flight hours was low as was the number of events; any event results in large change in computed failure rate. The turbojet hours were only 2% of the fleet total.

Figures 5.2.13 and 5.2.14: Commercial Transport Low Bypass Ratio Annual Non-Contained Failure Rates - Hourly and Cyclic Basis

Low bypass ratio engine hours comprised 64% of the commercial transport fleet total during this period and the failure rate was fairly steady. Of the total events, 15% were Category 3 failures.

Figures 5.2.15 and 5.2.16: Commercial Transport High Bypass Ratio Annual Non-Contained Failure Rates - Hourly and Cyclic Basis

The high bypass ratio engine hours comprised 23% of the commercial transport fleet total during this period. Of the total 92 non-contained events, 7% were Category 3 and 4; there were 5 Category 3 and one Category 4 events. The HBPR failure rate overall was the highest, at 1.12 per million for all categories.

5.3 General Aviation (GA) Engine Data - Tables and Figures:

A total of 34 non-contained events comprised the general aviation engine data on non-contained rotor failures during this 1976-1983 period. These data consisted of experience from three engine types, i.e., turbojet, turboprop, and turbofan. The summary totals of operating hours, which are coincident with cycles, non-contained failure events and hourly rates for each type during this period were as follows:

General Aviation Engine Non-Contained Rotor Failures,
1976 - 1983

	Millions	Events			Events per Million Hr.		
	Hours	All Cat.	Cat. 3	Cat. 4	All Cat.	Cat. 3	Cat. 4
Turbojets	09.4	1	0	0	0.11	0	0
Turboprops	55.4	31	5	0	0.56	.09	0
Turbofans	15.3	2	0	0	0.13	0	0
TOTAL	80.1	34	5	0	0.42	.06	0

The tables and figures follow generally the same breakdown and format as the data presented in AIR 1537, (Sections 6.1 and 5.2).

The turbojets, all older design engine types, had the lowest number of operating hours, and a comparatively low failure rate. The turboprop has the highest failure rate; 31 of the total 34 events. These failures are dominated by gearbox problems inducing overspeed events in an older model engine (23 of the 31 non-containments). If these events are excluded, the turboprop has roughly the same failure rate as the other G.A. engine types.

The most serious failures, i.e., Category 3, occurred in the turboprops. This may be explained on the basis that some turboprops represent the earliest technology; turboprops as a newer design class include the benefits of lessons learned from the earlier experience.

Table 5.3.1: General Aviation Non-Contained Failures Classified By Fragment Type

Table 5.3.1 shows non-containments according to fragment type and engine section. Ninety-seven percent of all failures were associated with the turbine blades and disks. The largest percentage of the total non-contained events were turbine blades; 22 of the total 34 events (65%) in all severity categories were turbine blades. Of Category 3 severity, two of the five events were turbine blades with the other three being turbine disks.

Table 5.3.2: General Aviation Non-Contained Failures Classified By Flight Mode

Table 5.3.2 shows the number of events, the failure rate, and percentage occurring at takeoff, climb, cruise, descent, etc. Although this table presents a different pattern of events to that of the commercial transport (CT) category (Table 5.2.2) it, in fact, demonstrates the same expected relationship between events, high rotational speed, and high operating temperatures. The differences are in the proportion of events occurring at take-off (GA 17.6%, CT 52.2%), climb (GA 26.5%, CT 34.5%) and cruise (GA 32.4%, C.T. 7.9%) (See Table 5.1). The principal reason for the difference is that, except in commuter use, most GA engines do not reach maximum speed and temperature until they are at altitude cruise. The installed power is usually greatly in excess of that needed for take-off and in operation is limited to some fraction of the engine's thermodynamic capability. Thus the sequence - take-off, climb, cruise, - in fact corresponds to increases in speed and temperature while gross power or thrust is constant or, at altitude, reduced.

Table 5.3.3: General Aviation Non-Contained Failures Classified by Flight Mode and Component

Table 5.3.3 is important as a further breakdown of the data in Table 5.3.2 because it reveals that the power turbine was involved in 76% of the events occurring at climb or cruise. The dominance of the power turbine is the direct result of various power train problems. Many of these originated through wear, fatigue, or lack of lubrication, and the final failure was more dependent on time exposure than load level. In a typical GA mission, more than two-thirds of the flight time is spent at climb or cruise power.

Table 5.3.4: General Aviation Non-Contained Failures Classified By Initiating Cause/Result - Disks, Blades and Spacers

Every rotor failure was classified by cause and result, i.e., (a) the basic initiating cause which progressed into or resulted in the separation failure of the rotor component, and (b) the failure process within the exiting part itself.

The process involved in the component was selected from one of the following:

- Fracture (due to impact or overstress)
- High cycle fatigue
- Low cycle fatigue
- Overtemperature (loss of properties)
- Overspeed (loss of load or control failure)
- Rubbing against static parts

In some cases, the initiating cause was within the part itself and thus, was the same as the failure process. One example of the other kind, i.e., a failure resulting from an initiating abnormality elsewhere, would be a reduction gearbox failure which progressed into a power turbine overspeed and release of turbine blades.

Table 5.3.5: General Aviation Non-Contained Failures Classified By Initiating Cause/Result - Disks Only

Because of the severity of damage resulting from most disk failures, this is one of the most important data tables of the study. Of 12 total disk failures, eight events or 67% were secondary failures (i.e., the initiating abnormality existed elsewhere), three were unknown and only one was a known primary disk failure.

Table 5.3.6: General Aviation Non-Contained Failures Classified By Initiating Cause/Result - Blades Only

Most of the blade non-containments, 19 of 22 events, were the result of reduction gearbox failures followed by a power turbine overspeed and subsequent release of multiple blades at a high overspeed.

Tables 5.3.7, 8 and 9: General Aviation Non-Contained Failures Classified By Initiating Cause/Result - Disks, Blades and Spacers, Damage Category 3 Only

Tables 5.3.7 through 5.3.9 present the more serious events, i.e., Category 3 for the general aviation engines. There were no Category 4 events. Of these total five serious events, none originated in the non-contained parts, four were caused by a primary failure in the reduction gearbox, and one was caused by a static part failure which resulted in a heavy rub on the disk.

Figure 5.3.1: General Aviation Annual Engine Hours

In the general aviation fleet engine hours and cycles have essentially a one to one correspondence. The annual engine hours have shown a general increasing trend. The annual hours have more than doubled during this report period with only the turbojets showing a reduction in usage.

Figure 5.3.2: General Aviation Annual Non-Contained Failure Rates

The yearly GA failure rate has decreased significantly in this eight-year period, the 1983 non-containments being only 14% of the 1976 non-containments. This can largely be attributed to the elimination of a problem in one particular engine model.

Figure 5.3.3: General Aviation Cumulative Non-Contained Failure Rates - Hourly Basis

The eight-year cumulative rate for general aviation engines as of 1983 shows a continued improvement. The Category 3 events rate improved consistent with the overall rate improvement. There were no Category 4 events.

Figure 5.3.4: General Aviation Annual Non-Contained Failure Rates vs. Overspeed Caused Non-Contained Failure Rates - Annual Basis

This figure illustrates the previously mentioned reduction in the frequency of overspeed events.

- 5.4 Rotorcraft Engine Data - Tables and Figures: A total of 78 events comprise the rotorcraft engine data on non-contained rotor failures during the 1976-1983 time period. These data consisted of both single and twin-engine powered rotorcraft. The summary of operating hours, cycles, non-contained events and rates for both single and twin engine civil aircraft during this period were as follows:

Rotorcraft Non-Contained Rotor Failures, 1976 - 1983

	Millions		Events	Events		Events per Million Hr.		
			All	Category	Category	All	Category	Category
	Hrs	Cycles	Cat.	3	4	Cat.	3	4
Single	25.0	62.5	61	11	11	2.44	0.44	0.44
Twin	10.1	25.2	17	5	3	1.68	0.50	0.30
Total	35.1	87.7	78	16	14	2.22	0.46	0.40

In contrast with the prior categories of aircraft, rotorcraft reflect a higher percentage of incidents assigned to the Category 3 and 4 damage assessments based upon the operation of the vehicle. As indicated in Section 3, however, the incidents attributed to non-contained failure events represent a small percentage of overall rotorcraft accidents (see also Section 6.1.2). While rotorcraft are designed to safely autorotate to the ground in a power-off situation, there are factors which can nullify these characteristics. These include:

- Low altitude operation over hazardous, rough terrain negating the opportunity to execute a safe autorotation;
- Failure of the pilot to execute a safe autorotation when terrain was not a factor indicating either low altitude operation or a situation beyond the capability of the pilot - possibly from lack of training in emergency procedures. Of the 30 events resulting in significant damage (Category 3 and 4), 11 events (36.7%) reflected failure to successfully execute a safe autorotation where terrain was not a factor.
- Damage to other critical aircraft systems (e.g., tail rotor drives, control linkages, fuel lines, etc.) due to close proximity of the subject engine thus impacting safe rotorcraft operation or resulting in increased likelihood of fire.

In general, hull losses for rotorcraft were more frequently associated with the loss of power rather than the non-contained event, particularly for the large data base of single-engine helicopters. It should be noted that rotorcraft are by far the majority of single engine turbine-powered aircraft operating in the civil market. For certain twin engine installations, a power-off condition has occurred when the second engine was damaged by fragments from the failed engine.

While the twin-engine rotorcraft, predominantly newer engine and aircraft designs, experienced a lower overall incident rate than the single-engine rotorcraft (1.68 versus 2.44 events per million hours), the more serious incident rates, Categories 3 and 4, occurred at nearly the same frequency. The eight Category 3 and 4 twin-engine non-contained events all represented disk failures with the attendant release of high energy fragments. Further, five of these events occurred in aircraft operating at low altitude, three resulted in damage to the second engine, three experienced damage to critical aircraft electrical systems, two resulted in severed or critically damaged tail rotor drives, and four experienced severed fuel lines and fire on board the aircraft. These incidents, like the entire rotorcraft data base, were dominated by an engine that represents early design technology. As a result of these consequences, the safety potential of certain twin-engine rotorcraft was not fully realized. Design changes have been introduced into service by the engine and airframe manufacturer to reduce the frequency and consequences of non-contained events in corresponding twin-engine rotorcraft installation.

It should be noted that for rotorcraft there was only one documented event of exhaust-exiting debris producing serious damage to the aircraft. This event has not been included in the statistics.

Table 5.4.1: Rotorcraft Non-Contained Failures Classified By Fragment Type

Table 5.4.1 shows failures according to fragment type and engine location. Disks and spacer failures represent 77% of all non-contained events and 93% of events resulting in Category 3 and 4 incidents. Blades represented 21.8% of the released fragments - 15.4% in the compressor and 6.4% in the turbine, but only 3.0% in the Category 3 and 4 events. Category 3 and 4 events make up 38.5% of the total.

The highest contributor to the total non-contained events was the turbine section - 62 of the total 78 events (79.5%) in all severity categories. Of Category 3 and 4 severity, 27 of a total of 30 events (90%) occurred in the turbine, highlighting the need to focus on the turbine section, principally the disk, for design improvement/protection.

The compressor blades represent 15.4% of all events, but were not a factor in Category 3 or 4 incidents.

Table 5.4.2: Rotorcraft Non-Contained Failures Classified By Flight Mode

Table 5.4.2 shows the number of events, failure rates, event ranking and percentages for each of the flight modes. The take-off and descent flight modes accounted for 47.4% of the reported incidents while the cruise mode was 34.6%. This high number of incidents in the descent mode is attributable to the turbine disk rim segment failures on the dominant engine in the population. In this engine, the high pressure turbine disk rim realized its maximum tensile stress in descent due to disk thermal gradients in this flight regime, increasing the likelihood of fatigue.

High cycle fatigue modes dominate the incidents at cruise power where the engine operates for the majority of each flight. Take-off power, representing 23% of the events, is typically the first opportunity for many of the other contributing factors such as manufacturing defects, engine mis-assembly, low cycle fatigue, or any condition resulting from an engine overtemperature during the starting sequence, etc. to produce an incident. Since this flight regime corresponds to the engine's first exposure to a high speed or high temperature condition, the percentage of failures during take-off are consistent with expectations.

Table 5.4.3: Rotorcraft Non-Contained Failures Classified By Flight Mode and Component

Table 5.4.3 is a further breakdown of the data contained in Table 5.4.2 and reveals that the events occurring during rotorcraft descent represent 24% of the total and all are turbine components. Further, while the cruise mode represents 35% of the events, these incidents are evenly distributed between the compressor and the turbine components.

Table 5.4.4 Rotorcraft Non-Contained Failures Classified By Initiating Cause/Result - Disks, Blades and Spacers

Every rotor failure was classified by cause and result, i.e., the basic initiating cause which progressed into or resulted in the separation failure of the component, and (b) the failure process within the exiting part itself.

The process involved in the component was selected from one of the following:

- Fracture (due to impact or overstress)
- High cycle fatigue
- Low cycle fatigue
- Overtemperature (loss of properties)
- Overspeed (loss of load or control failure)
- Rubbing against static parts

In some cases, the initiating cause was within the part itself and thus, was the same as the result. One example of the other kind, i.e., a failure resulting from an initiating abnormality elsewhere, would be a bearing failure or loss of lubrication which progressed into a rub failure of a rotating part such as a spacer.

"Unknown" as a cause was at 12.8%, at approximately the same value of the other engine categories.

Further, for rotorcraft, the data was sorted into broader categories dealing not only with the "resulting cause" but also the "initiating cause", i.e., what events or actions contributed to the non-contained event. In addition to those causes that are characteristically mechanical in nature or design-related, consideration was given to effects related to maintenance and operational procedures. For rotorcraft, these latter two effects contributed to 17.9 and 16.7% of the non-contained events, respectively. Of the 78 events, 22 (28%) were turbine overspeed incidents.

Table 5.4.5 Rotorcraft Non-Contained Failures Classified By Initiating Cause/Result - Disks and Spacers Only

Because of the severity of damage resulting from most disk and spacer failures, disks and spacers were examined separately. Of a total of 60 failures, 28 events, or 46.6% caused rotorcraft damage in Categories 3 or 4 i.e., significant or severe aircraft damage. Note that of the 60 events, only 2 were spacer failures. (See Table 5.4.1).

The leading mechanism for the release of a disk or spacer was a loss of load or an overspeed condition; 20 of the 60 failures (33%) were the result of an overspeed event for a variety of initiating causes.

The leading cause for disk failures was engine operational procedures and represented 21.6% of the disk events and 16.7% of all rotorcraft events. The majority of these resulted from a turbine overtemperature and subsequent disk failure.

Corrective action has already been instituted on the part of manufacturers to reduce the number of events attributed to the overtemperature mode. Improved engine starting procedures and engine overtemperature indicators have been successfully employed along with the more recent introduction into the civil fleet of improved engine electronic controls, some with automatic starting capabilities.

There is a relatively large percentage of low cycle fatigue failures. It is recognized that the operational utility of rotorcraft creates an opportunity for a varied, often ill-defined, mix of high cyclic usage for rotorcraft engines, and that remote deployment may restrict or compromise maintenance practices. The comparison of fatigue events in rotorcraft to the other class of engines suggest that improvements could be made in the life management of rotorcraft engine rotating hardware.

Table 5.4.6: Rotorcraft Non-Contained Failures Classified By Initiating Cause/Result - Blades Only

While rotorcraft non-contained events involving blades represents 21.8% of the total number of events, there is a more limited number of initiating causes. Maintenance represents a fairly high percentage for blades, 47%. Most of these were high cycle fatigue failures which initiated from corrosion pitting on airfoils (inadequate cleaning). All failures from corrosion pitting and the release of a compressor blade were Category 1 or 2 damage severity.

Table 5.4.7: Rotorcraft Non-Contained Failures Classified by Initiating Cause/Result - Disks, Blades and Spacers, Damage Categories 3 & 4 Only

The largest initiating cause for the more consequential Category 3 and 4 events is "unknown" (20%). This is due predominantly to the inability to retrieve the hardware necessary to affix a cause. In many of these events, the rotorcraft was not available for inspection after the incident or the relevant data were never reported. As in Table 5.4.5, overspeed as a result of several initiating events was involved in 47% of the failures.

Table 5.4.8: Rotorcraft Non-Contained Failures Classified By Initiating Cause/Result - Disks and Spacers, Damage Categories 3 & 4 Only

Of the 28 disk failures in damage Categories 3 and 4, 13 (46%) were the result of an overspeed condition of the turbine component, 8 of the power turbine and 5 of the high pressure turbine. The turbine overspeeds were the result of a loss of load and several failure modes were evident, e.g., gear shaft failures on the power output train, coupling shaft failures, etc., caused by a variety of factors such as fatigue, corrosion, mis-assembly and bearing failure. Note that 27 of the 28 events were disk failures; only one was a spacer failure. (See Table 5.4.1).

Table 5.4.9: Rotorcraft Non-Contained Failures Classified By Initiating Cause/Result - Blades Only. Damage Categories 3 & 4 Only

Tables 5.4.7 through 5.4.9 present the more serious events for rotorcraft. In the total population of events, almost all the serious damage category incidents are attributable to disks or disk segments--only one incident each for a blade and a spacer.

Table 5.4.10: Rotorcraft Non-Contained Failures Classified By Broad Categories of Initiating Cause - Disks, Blades and Spacers

Table 5.4.11: Rotorcraft Non-Contained Failures Classified By Broad Categories of Initiating Cause - Disks and Spacers.

Tables 5.4.4 through 5.4.9 provide a rather detailed breakdown by 16 initiating causes. This degree of detail is useful, but, in the case of three vastly different classes of aircraft whose utility, operation and support are so dissimilar, less detail might provide additional information. Accordingly, these data for rotorcraft were collected into coherent logical groupings of broader categories of originating influences as follows:

Mechanical -	Rubbing against static parts Low cycle fatigue High cycle fatigue Fretting Bearing distress Loss of lubrication
Human Factors -	Operational Procedures Maintenance Misassembly
Environmental -	Foreign object damage Corrosion/Erosion
Manufacturing and Material	Material Defects Manufacturing Errors
Other	All causes not listed above
Unknown	Cause not determined

The results presented in Tables 5.4.10 and 5.4.11 for all rotorcraft failures afford a simpler view of the circumstances surrounding the rotor failures. For rotorcraft, there are two predominant causes - mechanical or design related incidents accounting for 33.3% of failures and human factors accounting for 34.6%. As expected, this trend is repeated for disks and spacers which comprised 76.9% of the rotorcraft incidents. Unlike commercial transport aircraft, the environment is a relatively low factor at 7.7%. This is an expected result since the majority of rotorcraft utilize protective screens over the engine air intake or a by-pass inlet arrangement.

In Categories 3 and 4 the disk/spacer components are the major items accounting for 28 events of the 30. For these failures, mechanical factors comprised 33.3% of the data while human factors contributed to 31.7% and unknowns were at the relatively high level of 15%.

SINGLE VERSUS TWIN ENGINE ROTORCRAFT

Table 5.4.12: Rotorcraft Non-Contained Failures Classified By Fragment Type - Single Versus Twin Engine Aircraft

Table 5.4.12 compares the non-contained rotorcrafts events by fragment type for the single and twin engine aircraft. The distribution by component is very similar for the two installations, with turbine disks being the dominant component: 72.1% for singles and 70.6% for twins. Because of the domination of the rotorcraft fleet by a single engine model, this result is consistent with expectations. While this one engine contributed fewer hours on a relative basis to the twin engine helicopter population, the failure incidents were biased by that engine.

Table 5.4.13: Rotorcraft Non-Contained Failures Classified By Initiating Cause - Single Versus Twin Engine Aircraft

Table 5.4.13 contrasts the leading causes for non-contained events between single and twin engine powered aircraft. For twins, the leading two causes are bearing failures (29.4%) and manufacturing defects (17.6%) while, as discussed earlier, the highest single engine aircraft failure rate is attributable to operationally induced (21.3%) failures. This, in part, reflects the new technologies incorporated in the later twin engine aircraft and engines. The operational effects have been minimized either by more sophisticated procedures and controls or by de-sensitizing the engine design to these consequences.

Table 5.4.14 Rotorcraft Non-Contained Disk Failures By Initiating Cause - Single Versus Twin Engine Aircraft, Damage Categories 3 & 4 Only

Table 5.4.14 compares the Category 3 and 4 disk failures for single versus twin engine rotorcraft. Bearing failures and corrosion/erosion on twin engine rotorcraft were the predominant mode accounting for 11.8% of the failures each. Failures of unknown origin were the highest cause for single engine rotorcraft at 8.2%.

Figure 5.4.1, 2: Rotorcraft Annual Engine Hours, Cycles

The annual engine hours for rotorcraft have increased continuously during the 1976-1983 period. The twin engine hours have increased steadily since 1977. Similarly, the annual cycles on rotorcraft engines have increased over this time period. These trends reflect the increasing use of rotorcraft into a wider variety of applications, i.e., corporate and private ownership, utility and cargo carriers, and off-shore operators.