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REPORT ON AIRCRAFT ENGINE CONTAINMENT

INTRODUCTION AND BACKGROUND

On April 23, 1973 the Safety Standardization Advisory Committee of the SAE Aerospace Council requested the Propulsion Division to initiate a technical study of aircraft gas turbine non-containment. This request was reviewed with the Aerospace Council and the Propulsion Division was directed to establish an Ad Hoc Committee.

The committee was established on May 5, 1975 and a preliminary work statement was drafted. The first meeting of the committee was held on July 31, 1975 and the work statement was agreed to as follows:

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.

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 January 31, 1977 to the Propulsion Division. An extension may be granted by the Propulsion Division if required.

The committee decided that commercial helicopter operations were so small, in comparison to fixed wing aircraft operations, that their inclusion in this study was not warranted. General aviation was not considered as it was beyond the scope of this committee.

Committee Membership and Activity: As stated in the Statement of Work for the committee: "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."

The individuals forming the committee were selected from companies in the fields of airline operation (Pan American, Trans-World and United), airframe design (Beech, Boeing, Lockheed and McDonnell Douglas), engine design (AiResearch, Allison, General Electric, Pratt & Whitney, and Rolls-Royce), and the FAA.

INTRODUCTION AND BACKGROUND (Continued)

The committee established a schedule of meetings consistent with the submission of the report to the Propulsion Division in January 1977. The submission of the final report was moved to May 1977 by the SAE Aerospace Council. Nine meetings were held between July 31, 1975 and February 1977.

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1. SCOPE:

The study shall be directed to commercial aircraft service and include engine experience in both fixed wing aircraft and helicopters covering the time period from 1962 to the present.

1.1 Purpose:

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

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

Finally, evaluate or determine means for evaluation of the penalties imposed on aircraft systems to achieve greater levels of containment or recommend alternatives to containment.

2. SUMMARY:

The committee examined the nature and consequences of turbine engine non-contained rotor failures which occurred during 417 million engine hours on commercial aircraft powered by Allison, General Electric, Pratt & Whitney and Rolls-Royce turbine engines during certificated air carrier service for the period January 1, 1962 through December 31, 1975. Information obtained from U.S., NTSB, FAA, and U.K. CAA reports was cross-checked and supplemented with certain manufacturers' data and used as the basis for this examination. The results of the study are presented in statistical and graphical forms, and are discussed in the body of the report.

The committee considered only those events where fragments exited the nacelle because fragments which are contained within the nacelle do not have potential for damage to the aircraft. These failures, which occurred at a rate of 0.66 per million engine flying hours, were categorized as follows:

TABLE 1 - Non-Contained Failure Summary[1]

Consequences of Failure[1]	Disks and Spacers	Blades Only	Total	Failure Rate Per Million Engine Hours
1. Nacelle Damage Only	47	48	95	0.23
2. Minor Aircraft Damage	71	60	131	0.31
3. Significant Aircraft Damage	34	10	44	0.11
4. Severe Aircraft Damage	4	1	5	0.01
Total	156	119	275	0.66

[1] See Section 4 for definitions.

2. (Continued):

The non-contained failure events have been classified by cause, engine section and flight mode; the details are given in the text. 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 current state-of-the-art. Although the probability of major aircraft accident caused by non-contained failure is remote, this must be considered an important element of overall aircraft system safety and the committee therefore recommends continued effort to reduce this hazard.

3. CONCLUSIONS, OBSERVATIONS, AND RECOMMENDATIONS:

3.1 Conclusions:

3.1.1 A total of 275 non-contained engine failures occurred in 417 million engine hours resulting in a rate of 0.66 events per million hours. Of these, 0.54 events per million hours caused minor or no damage to the aircraft; 0.11 events per million hours caused significant damage; and 0.01 events per million hours caused severe damage.

3.1.2 Engine non-containment was a factor in 0.33 percent of all fatalities, 2.62 percent of all accidents and 1.05 percent[1] of all hull losses which have occurred in commercial aircraft from all causes.

3.1.3 Although the probability of a major aircraft accident caused by an engine rotor burst is extremely low, it must be considered an important element of overall aircraft safety and continued effort to reduce the hazard from engine rotor burst is warranted.

3.1.4 Causes of failure were classified in 15 categories. No single cause contributed more than one quarter of the total failures. High-cycle fatigue, low-cycle fatigue and material defects together accounted for one half of the total disk and spacer failures.

3.2 Observations:

3.2.1 The greatest potential for reduction of significant damage to the aircraft caused by non-contained rotor failures lies in continued major efforts by the engine manufacturer 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 of non-contained engine fragments.

3.2.2 The majority of non-containment occurrences which involved significant or severe damage to the aircraft were due to release of fragments of such large size and energy as to make containment impractical within the current state-of-the-art.

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[1] Corrected from “0.05 percent” to “1.05 percent” April 1978.

3.3 Recommendations:

Recommendations are made as follows that:

3.3.1 A data retrieval system be set up to collect detailed data including failure cause (primary or secondary) for non-contained rotor events.

3.3.2 Continuing, and in some areas, augmented efforts to reduce the frequency of bird ingestion at airports be carried out.

3.3.3 Research be carried out to provide better understanding of aerodynamic excitation, mechanical excitation and interactions of blade/rotor/stator systems leading to improved design criteria for normal and off design engine operations. This research should also include the effect on the engine and the installed engine system of potential engine and system malfunctions and external influences.

3.3.4 Continued research and major efforts to improve the sensitivity and reliability of NDI (Non Destructive Inspection) methods be carried out.

3.3.5 Research be carried out to provide an improved capability for understanding the dynamics of engine rotor systems subsequent to blade loss, to permit establishing effective design criteria and practice to minimize the effects of blade loss and to reduce the sometimes extensive secondary damage that results.

3.3.6 Continuing research and development on damage tolerant blade designs be carried out.

3.3.7 Engine burst characteristics be better defined in terms of fragment sizes and energies, fragment population and dispersion angles.

4. DEFINITIONS:

4.1 Definition of Non-Containment:

Non-containment failure of an aircraft turbine engine was defined for the purposes of this study as any failure which results in the escape of rotor fragments through the nacelle cowling or through panels which isolate the propulsion installation from the remainder of the aircraft structure. The term rotor includes rotating structural 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. It should be noted that aircraft certified under F.A.R. Part 25 are capable of continued safe operation after loss of power/thrust from one engine during any phase of flight.

4.1 (Continued):

Fragments of disks, spacers, and/or blades which are released from turbine engines can represent a hazard because of the potential for injury or damage to aircraft structures or systems. There is, however, a clear distinction in the risk of aircraft accident associated with cases where fragments are contained within the propulsion system/nacelle and the instances where fragments have enough energy to penetrate the propulsion system cowling or skins. This distinction is drawn because the fragments contained within the propulsion system do not represent a hazard to personnel, airframe structures or systems. The propulsion system is designed to confine the fire or damage which might result from such a failure.

4.2 Definition of Aircraft Damage:

The committee agreed that a hazard from a noncontained engine failure results when damage occurs to critical aircraft structure or systems, other than the affected nacelle. To assess the resulting aircraft damage and to determine the areas of greatest concern, a means of classifying the severity of the damage was developed. The severity of aircraft damage, as judged from a relative standpoint, is based upon the consequence and the damage that actually occurred. Damage severity was classified into four categories and is defined as follows:

Category 1. Damage limited 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

4.2 (Continued):

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

5. ANALYSIS OF DATA:

5.1 Data Base:

The statement of work defined the committee's basic task as, "to gather and analyze available service data on aircraft propulsion turbine engine rotating part noncontained failures on public record." Service data was obtained from NTSB, FAA and United Kingdom CAA reports for the time period of January 1, 1962 through December 31, 1975. In addition, to provide more details, certain manufacturers' data were used to supplement the information provided in the government reports.

The committee considered those events where fragments exited the nacelle, because of the potential damage to the aircraft. Thus, the data were limited to events that met the committee's definition of non-containment as presented in 4.1. The data include non-contained rotor failures which occurred during 417 million engine hours of commercial airline service for aircraft powered by Allison, General Electric, Pratt & Whitney, and Rolls-Royce turbine engines. Two hundred seventy-five non-contained events were identified, including 156 events that involved disks and spacers, and 119 events that involved only blades. The pertinent data for these events are included in Appendix B.

5.2 Damage Classification:

In approaching the study, the committee agreed that the greatest concern relative to turbine engine rotor failures involves events that constitute the greatest hazard to the aircraft and its occupants. 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 4.2. The committee realizes that the classifications are somewhat subjective and involve arbitrary judgments as to the exact classification of certain events. However, the committee concluded that the relative severity of damage can be reasonably well classified and that a difference of judgment in a few events in the large data base would not significantly change the general conclusions.

5.3 Organization of Data:

The statement of work identified three major areas of investigation for the committee to pursue in the analysis of the service data on turbine engine rotor failures. The areas of investigation were: (1) to determine the rates of past occurrences, (2) to classify incidents by cause, and (3) to assess the resulting aircraft damage.

5.3.1 Rate of Past Occurrences: The service data were analyzed to evaluate trends and failure rates for each year of the study as a function of engine type, i.e., turbo-prop, turbojet, low bypass fan jet and high bypass fan jet. In addition, to show the trends relative to the more serious consequence, the rates for events that resulted in Category 3 and 4 damage severity were identified. These data are included in Figures 1 through 1D.

5.3.2 Causes of Rotor Failures: The non-contained events were classified by engine section, flight mode, and by cause of failure to isolate the probable causes of the majority of the events, as shown in Tables 2 through 4B. In addition, the rate for events that resulted in Category 3 and 4 damage severity is shown with the cause of failures in Tables 5 through 5B.

5.3.3 Resulting Aircraft Damage: The aircraft damage resulting from engine rotor failures was classified by damage severity (see 4.2) and by fragment type (blade or disks and spacers) to identify the type of fragments that were responsible for the more severe damage. These data are presented in Figure 2.

The penalties associated with increased containment to reduce the damage severity were estimated in terms of the increase in aircraft weight required to retain its performance level. The results of this study are included in 7.3. Alternatives to increased containment to reduce the hazard of non-contained rotor fragments are discussed in 7.1 and 7.2.

5.3.4 Additional Tasks: In addition to the items in the statement of work, the committee elected to include two additional tasks. First, to estimate the benefits in reducing the damage severity with increased containment and second, to put the consequence of engine rotor failures in perspective relative to other causes of aircraft accidents.

The benefits of increased containment were assessed by estimating the number of Category 3 and 4 damage severity events where the hazard to the aircraft would have been substantially reduced by the addition of a specified amount of containment. Containment which would be adequate for containment of a weight equivalent to three blades and the two included posts was considered in making the judgment. The estimated fragment weight for each event used in this study is listed in the data summary, Appendix B, and is the estimated weight of the largest fragment expelled unless otherwise noted. The largest fragment will usually represent the greatest hazard to the aircraft. In some events, however, particularly those involving multiple blade expulsion, the total weight of the expelled fragments is noted because this total weight is important to the judgment as to whether the fragments would have been contained by containment adequate for 3 blades plus 2 posts. In general, the 3 blades/2 post containment is judged to be adequate to contain the fragments if their weight is lower than the weight of 3 blades and 2 posts for the stage where the failure occurred. The results of this study are shown in Figure 3.

The contributions of non-contained turbine engine rotor failures to the total number of aircraft accidents from all causes is shown in Figure 4. The number of fatalities, accidents, and hull losses in which a rotor failure was involved is compared to the total number of fatalities, accidents, and hull losses that have resulted from all causes.

5.4 Current Practices:

Design and certification practices relevant to the subject of containment are discussed in Appendix A.

6. SERVICE DATA:

6.1 Tables:

TABLE 2 - NON-CONTAINED FAILURES CLASSIFIED BY FRAGMENT TYPE:

Table 2 shows failures according to fragment type and engine section for all severity categories and for severity 3 and 4 categories. This shows that over 75% of Category 3 and 4 events are attributed to disk and spacer failures and that well over half of categories 3 and 4 events are attributed to fan and compressor disk and spacer failures.

TABLE 3 - NON-CONTAINED FAILURES CLASSIFIED BY FLIGHT MODE:

Table 3 shows the number of events, failure rate, and percentage of failures occurring at take-off, climb, cruise, descent, and ground run. This table shows approximately 2/3 of the total events are at take-off and climb.

TABLE 4 - NON-CONTAINED FAILURES CLASSIFIED BY CAUSE:

All rotor failures are classified as to the basic cause of failure in Table 4. These causes are shown as either “primary”, that is failures resulting from an initial deficiency or abnormality in the part which failed or as “secondary”, that is, the failure which resulted in non-containment was the result of an initiating abnormality elsewhere in the engine. The relatively large percentage of failures for which the cause is unknown in this list is the result of including blade failures which in many cases were of such minor consequence that they were not well documented.

TABLE 4A - NON-CONTAINED DISK AND SPACER FAILURES CLASSIFIED BY CAUSE:

Table 4A is a similar classification and analysis for disk and spacers only. These failures inherently tend to be more severe and, therefore, a much higher percentage of these events are classifiable as to cause. It is noted that four failure causes, high cycle fatigue (primary), material defects, rubbing against static parts, and low cycle fatigue, account for 60% of the events.

TABLE 4B - NON-CONTAINED BLADES FAILURES CLASSIFIED BY CAUSE:

Table 4B is a similar classification and analysis for blades only. As stated previously the relatively large percent of failures for which the cause is unknown is the result of failures which in many cases are of such minor consequence that they are not well documented.

6.1 (Continued):

TABLE 5 - NON-CONTAINED FAILURES CLASSIFIED BY CAUSE - SEVERITY CATEGORIES 3 AND 4:

The causes of failures for events that resulted in Category 3 and 4 damage severity are shown. Material defects, high cycle fatigue, low cycle fatigue and rubbing against static parts account for over half of severity Category 3 and 4 events.

TABLES 5A AND 5B - DISKS, SPACERS AND BLADE FAILURES CLASSIFIED BY CAUSE - CATEGORIES 3 AND 4:

Tables 5A and 5B classify the data in Table 5 for disks and spacers, and blades respectively. Since the majority of Category 3 and 4 failures involve disks, the major causes are similar to those in Table 5.

TABLE 2 - Non-Contained Failures Classified by Fragment Type

Fragment Type	Number of Failures All Categories	Number of Failures Category 3 and 4	Failure Rate Per Million Hours All Categories	Failure Rate Per Million Hours Category 3 and 4	Percent of Failures All Categories	Percent of Failures Category 3 and 4
Fan Disk, Spacer	23	12	0.055	0.029	8.4	4.4
Fan Blade	32	2	0.077	0.005	11.6	0.7
Compressor Disk, Spacer	77	17	0.185	0.041	28.0	6.2
Compressor Blade	22	2	0.053	0.005	8.0	0.7
Turbine Disk, Spacer	56	9	0.134	0.022	20.4	3.3
Turbine Blade	65	7	0.156	0.017	23.6	2.5
Total Non-Contained	275	49	0.66	0.119	100.0	17.8

January, 1962 - December, 1975: 417 Million Engine Hours

TABLE 3 - Non-Contained Failures - Disks, Spacers, and Blades Classified by Flight Mode

Flight Mode	Number of Failures	Failure Rate Per Million Hours	Percent of Failures	Rank
Take-Off	129	0.309	46.9	1
Climb	52	0.125	18.9	2
Cruise	35	0.084	12.7	4
Descent	9	0.022	3.3	5
Thrust Reverse	4	0.010	1.5	7
Ground Run	8	0.019	2.9	6
Unknown	38	0.091	13.8	3
Total Non-Contained	275	0.660	100.0	–

January, 1962 - December, 1975: 417 Million Engine Hours

TABLE 4 - Non-Contained Failures - Disks, Spacers, and Blades
Classified by Cause

Cause of Failure	Primary or Secondary Failure	Number of Failures	Failure Rate per Million Hours	Percent of Failures
Unknown	--	58	0.139	21.1
High Cycle Fatigue	Primary	52	0.125	18.9
Rubbing Against Static Parts	Secondary	28	0.067	10.2
Material Defects	Primary	25	0.060	9.1
Foreign Object Damage	Secondary	15	0.036	5.5
Overtemperature	Secondary	15	0.036	5.5
Low Cycle Fatigue	Primary	15	0.036	5.5
Other	--	14	0.034	5.0
Manufacturing Defects	Primary	14	0.034	5.0
Shaft and Shaft Retention Bolt Failure	Secondary	13	0.031	4.7
Overhaul Procedures	Primary	11	0.026	4.0
High Cycle Fatigue	Secondary	10	0.024	3.6
Mis-Assembly	Primary	3	0.007	1.1
Combination of HCF and LCF	Primary	1	0.002	0.4
Overspeed	Secondary	1	0.002	0.4
Total Non-Contained		275	0.659	100.0

January, 1962 - December, 1975: 417 Million Engine Hours

TABLE 4A - Non-Contained Failures - Disks and Spacers
Classified by Cause

Cause of Failure	Primary or Secondary Failure	Number of Failures	Failure Rate per Million Hours	Percent of Failures
High Cycle Fatigue	Primary	44	0.108	28.8
Material Defects	Primary	19	0.046	12.2
Rubbing Against Static Parts	Secondary	16	0.038	10.3
Low Cycle Fatigue	Primary	15	0.036	9.6
Unknown	--	16	0.036	9.6
Other	--	11	0.026	7.1
Overhaul Procedures	Primary	9	0.022	5.8
High Cycle Fatigue	Secondary	8	0.019	5.1
Overtemperature	Secondary	7	0.017	4.5
Manufacturing Defects	Primary	3	0.007	1.9
Mis-Assembly	Primary	2	0.005	1.3
Foreign Object Damage	Secondary	2	0.005	1.3
Shaft and Shaft Retention Bolt Failure	Secondary	2	0.005	1.3
Combination of HCF and LCF	Primary	1	0.002	0.6
Overspeed	Secondary	1	0.002	0.6
Total Non-Contained		156	0.374	100.0

January, 1962 - December, 1975: 417 Million Engine Hours

TABLE 4B - Non-Contained Failures - Blades Only
Classified by Cause

Cause of Failure	Primary or Secondary Failure	Number of Failures	Failure Rate per Million Hours	Percent of Failures
Unknown	--	42	0.106	37.0
Foreign Object Damage	Secondary	13	0.031	10.9
Rubbing Against Static Parts	Secondary	12	0.029	10.1
Manufacturing Defects	Primary	11	0.026	9.3
Shaft and Shaft Retention Bolt Failure	Secondary	11	0.026	9.3
Overtemperature	Secondary	8	0.019	6.7
High Cycle Fatigue	Primary	8	0.014	5.0
Material Defects	Primary	6	0.014	5.0
Other	--	3	0.007	2.5
Overhaul Procedures	Primary	2	0.005	1.7
High Cycle Fatigue	Secondary	2	0.005	1.7
Mis-Assembly	Primary	1	0.002	0.8
Low Cycle Fatigue	Primary	0	--	--
Combination of HCF and LCF	Primary	0	--	--
Overspeed	Secondary	0	--	--
Total Non-Contained		119	0.284	100.0

January, 1962 - December, 1975: 417 Million Engine Hours

TABLE 5 - Non-Contained Failures - Disks, Spacers, and Blades
Classified by Cause
(Severity Categories 3 and 4)

Cause of Failure	Primary or Secondary Failure	Number of Failures	Failure Rate per Million Hours	Percent of Failures
Material Defects	Primary	11	0.026	22.4
High Cycle Fatigue	Primary	6	0.014	12.2
Unknown	--	6	0.014	12.2
Low Cycle Fatigue	Primary	5	0.012	10.2
Rubbing Against Static Parts	Secondary	4	0.010	8.2
Other	--	4	0.010	8.2
Overhaul Procedures	Primary	4	0.010	8.2
Overtemperature	Secondary	4	0.010	8.2
Shaft and Shaft Retention Bolt Failure	Secondary	2	0.005	4.1
Combination of HCF and LCF	Primary	1	0.002	2.0
Overspeed	Secondary	1	0.002	2.0
Foreign Object Damage	Secondary	1	0.002	2.0
Total Non-Contained		49	0.117	100.0

January, 1962 - December, 1975: 417 Million Engine Hours

TABLE 5A - Non-Contained Failures - Disk and Spacer Only
Classified by Cause
(Severity Categories 3 and 4)

Cause of Failure	Primary or Secondary Failure	Number of Failures	Failure Rate per Million Hours	Percent of Failures
Material Defects	Primary	10	0.024	26.3
High Cycle Fatigue	Primary	6	0.014	15.8
Low Cycle Fatigue	Primary	5	0.012	13.2
Overhaul Procedures	Primary	4	0.010	10.5
Rubbing Against Static Parts	Secondary	3	0.007	7.9
Other	--	3	0.007	7.9
Unknown	--	3	0.007	7.9
Overtemperature	Secondary	1	0.002	2.6
Combination of HCF and LCF	Primary	1	0.002	2.6
Overspeed	Secondary	1	0.002	2.6
Foreign Object Damage	Secondary	1	0.002	2.6
Total Non-Contained		38	0.089	100.0

January, 1962 - December, 1975: 417 Million Engine Hours

TABLE 5B - Non-Contained Failures - Blades Only
Classified by Cause
(Severity Categories 3 and 4)

Cause of Failure	Primary or Secondary Failure	Number of Failures	Failure Rate per 10^6 Hours	Percent of Failures
Overtemperature	Secondary	3	0.007	27.3
Unknown	--	3	0.007	27.3
Shaft and Shaft Retention Bolt Failure	Secondary	2	0.005	18.2
Material Defects	Primary	1	0.002	9.1
Rubbing Against Static Parts	Secondary	1	0.002	9.1
Other	--	1	0.002	9.1
Total Non-Contained		11	0.025	100.0

January, 1962 - December, 1975: 417 Million Engine Hours

6.2 Figures:

FIGURE 1 - NON-CONTAINED FAILURES - DISKS, SPACERS, AND BLADES:

Figures 1 through 1D show the annual rate (events per million engine hours) of all non-contained rotor failures for each year 1962 through 1975, as well as events in severity categories 3 and 4.

Figure 1 includes all turbine engine types, while Figures 1A through 1D present similar data for turboprop, turbojet, low bypass and high bypass engines separately, using the applicable service hours in each year for each engine type.

Figure 1, for all engine types, does not show a significant trend. Category 4 events occurred in four of the fourteen years.

FIGURE 1A - NON-CONTAINED TURBOPROP FAILURES - DISKS, SPACERS, AND BLADES:

Figure 1A shows the failure rate by years for turboprop engines classified by severity category. Although there is a general upward trend in the Category 1 and 2 failure rate since 1968 there is as yet no statistically valid trend in the Category 3 and 4 rates. There were three Category 3 and one Category 4 failures in 1975 distributed among three turboprop engine types. The Category 3 rates shown in 1967, 1970 and 1972 represent 1 failure each year, distributed between two engine types.

FIGURE 1B - NON-CONTAINED TURBOJET FAILURES - DISKS, SPACERS, AND BLADES:

Figure 1B presents data for turbojet engines; a discernible trend is not apparent. No Category 4 events occurred in the period covered, and no particular significance is attributed to year 1968 when a low rate occurred. There was inadequate information to establish a rate for 1975.

FIGURE 1C - NON-CONTAINED LOW BYPASS TURBOFAN FAILURES - DISKS, SPACERS, AND BLADES:

Figure 1C presents data for low bypass turbofans. One Category 4 event occurred in each of two of the fourteen years covered. It should be noted that low bypass turbofan engines account for 59% of the total engine hours included in the committee’s investigation.

FIGURE 1D - NON-CONTAINED HIGH BYPASS TURBOFAN FAILURES - DISKS, SPACERS, AND BLADES:

Figure 1D presents data for the high bypass engines introduced since 1970 and is the only one of Figures 1A through 1D which shows the introduction into service of an engine type over the time period covered. An initial high rate seen in the first year is the result of one event and a small number of engine hours. The number of engine hours per year for this engine class has grown from .58 to 5.73 million hours per year in the period shown, and the data sample available covers too short a period for any meaningful comment with respect to trends. One Category 4 event occurred in each of two of the six years covered.

6.2 (Continued):

FIGURE 2 - NON-CONTAINED ROTOR FAILURE EVENTS:

Figure 2 shows the total number of events and the number of events attributed to disks and spacers only classified by severity category. In Categories 1 and 2, which represent virtually no hazard to the aircraft, the disks and spacers represent approximately one half of the total events. In Categories 3 and 4 it can be seen that the major portion of these events are the results of disk and spacer failure.

FIGURE 3 - EFFECT OF INCREASED CONTAINMENT - SEVERITY CATEGORIES 3 AND 4:

This chart shows that the increased containment for three blades and two posts was judged to be incapable of containing the fragments of any of the five Category 4 events. The increased containment was judged to be capable of containing the fragments of only one of the 43 Category 3 events and possibly capable of containing the fragments of eight additional Category 3 events. The basis for this evaluation is given in 5.3.

FIGURE 4 - INVOLVEMENT OF NON-CONTAINED ROTOR FAILURES IN TOTAL ACCIDENTS, HULL LOSSES AND FATALITIES:

Figure 4 shows the total number and percentage of fatalities, accidents, and hull losses for the time period of this study where there was engine rotor non-containment involved in the event. Out of 11,690 fatalities due to all causes, 39 fatalities occurred where non-containment was involved. It should be noted that non-containment was not judged to be the cause of the accident by the responsible investigating agency in all of the cases where it was involved. However, these cases are included because non-containment was reported to be a factor.

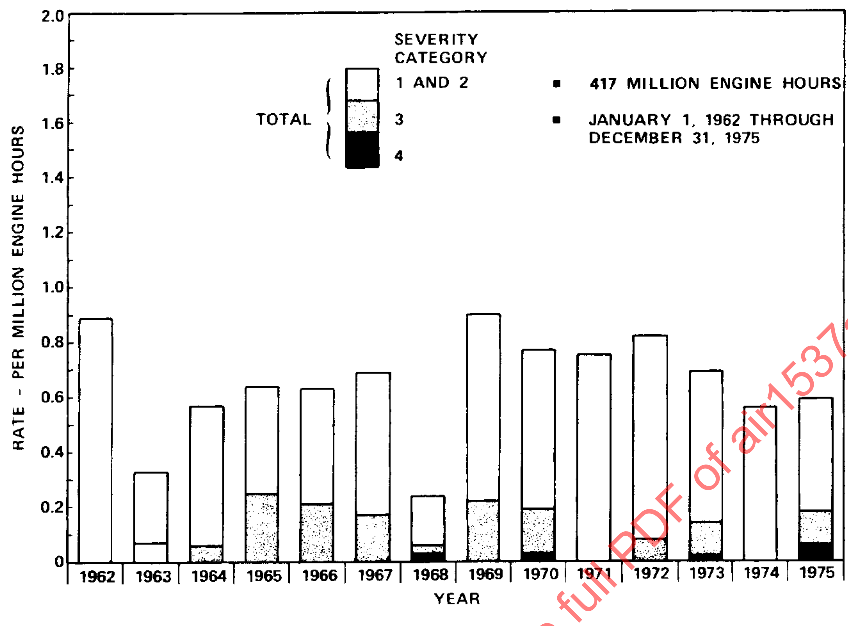


FIGURE 1 - Non-Contained Failures - Disks, Spacers, and Blades

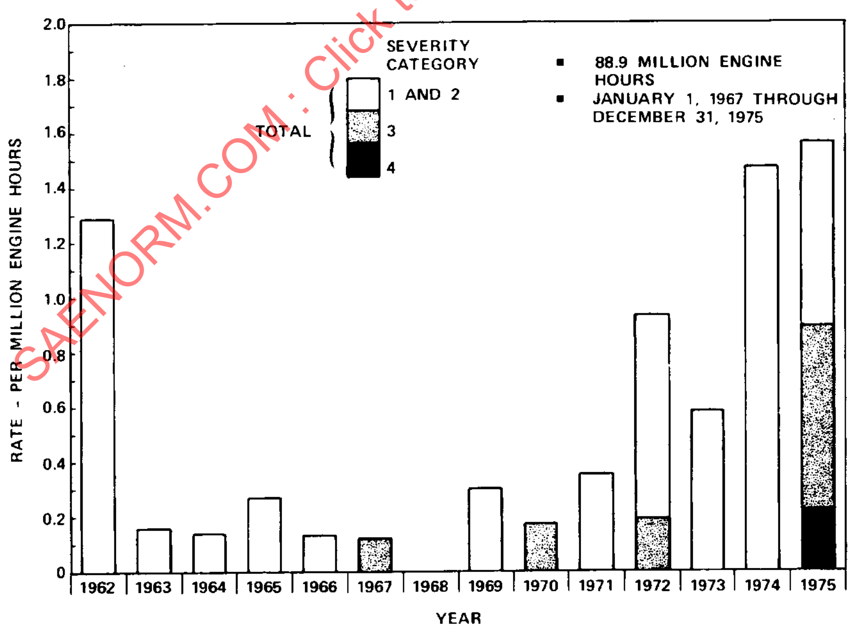


FIGURE 1A - Non-Contained Turboprop Failures - Disks, Spacers, and Blades

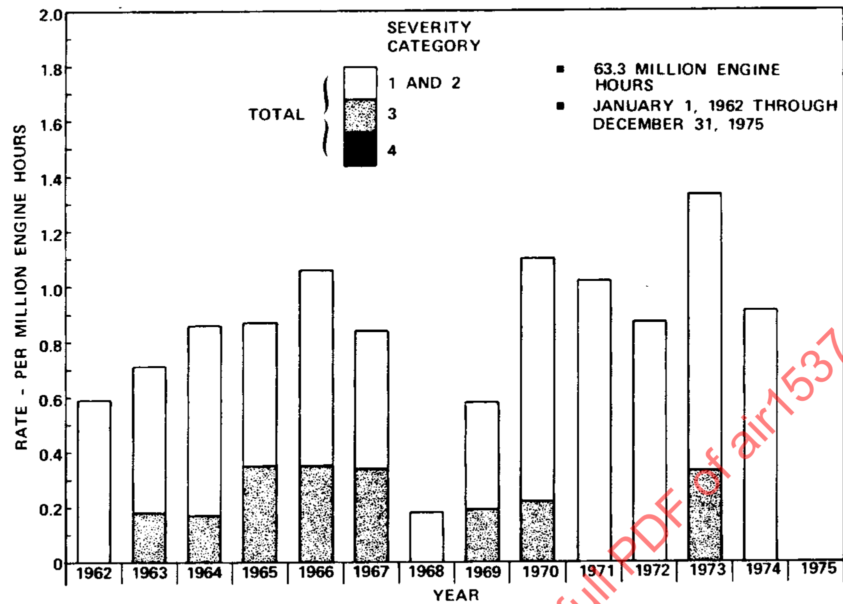


FIGURE 1B - Non-Contained Turbojet Failures - Disks, Spacers, and Blades

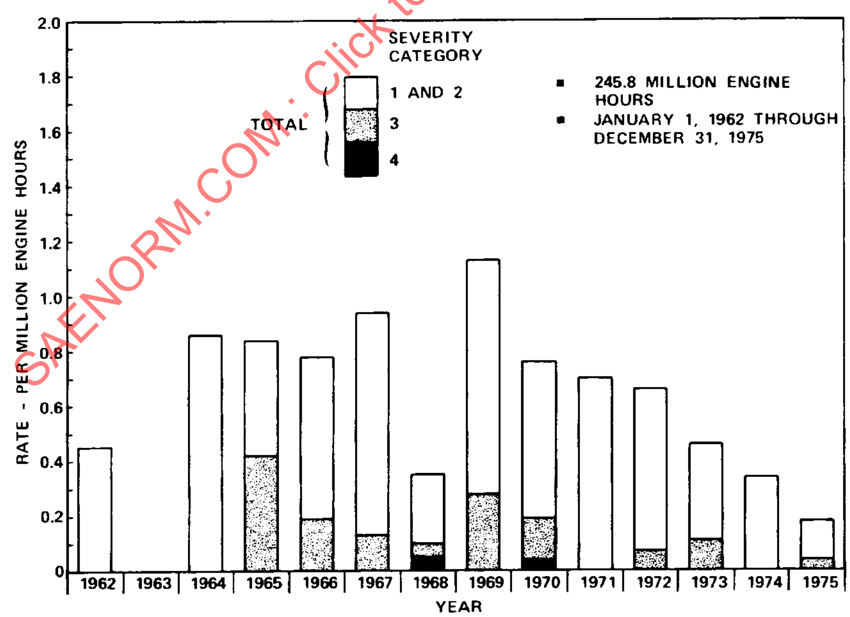


FIGURE 1C - Non-Contained Low-Bypass Turbofan Failures - Disks, Spacers, and Blades

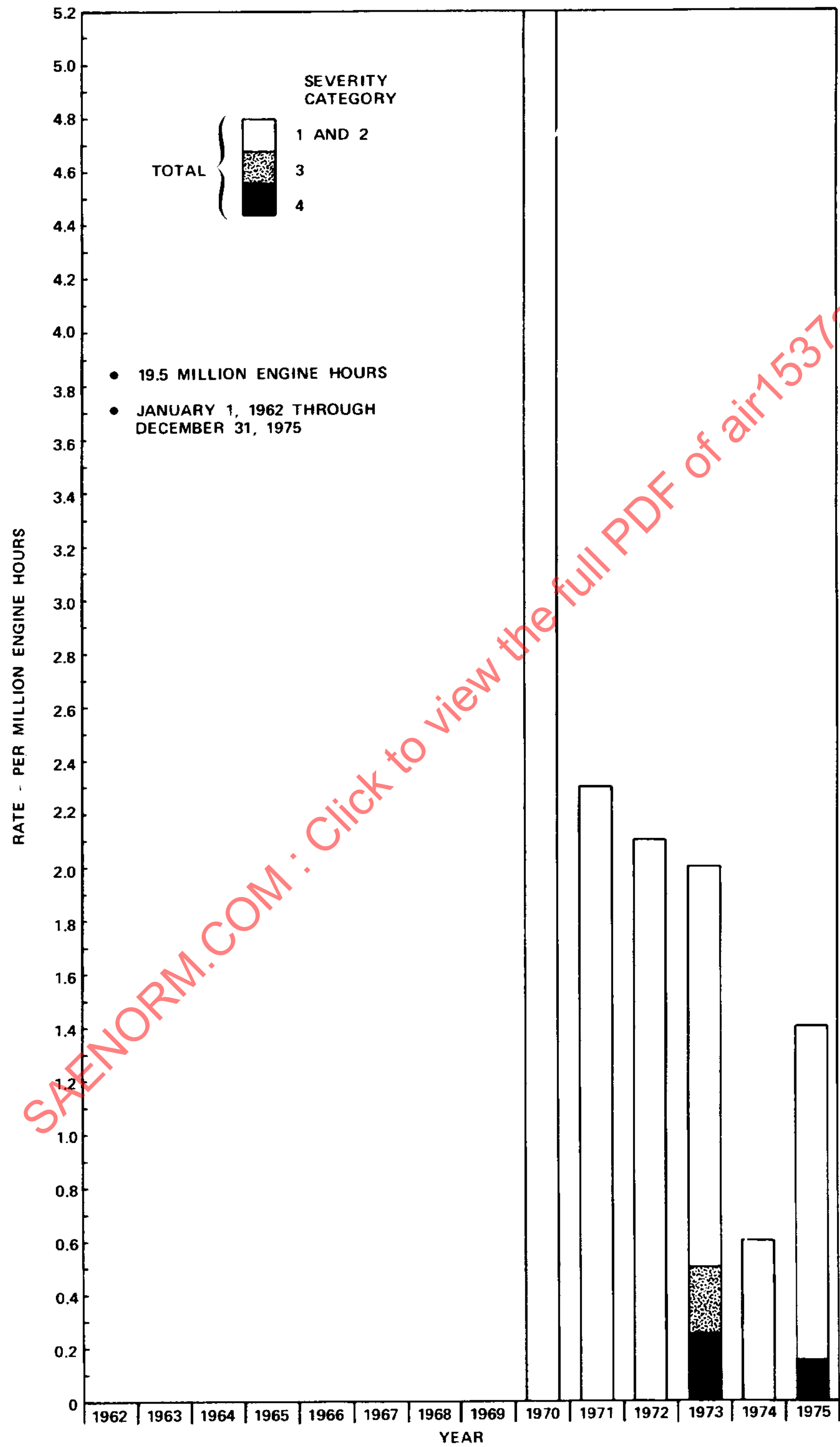


FIGURE 1D - Non-Contained High-Bypass Turbofan Failures - Disks, Spacers, and Blades

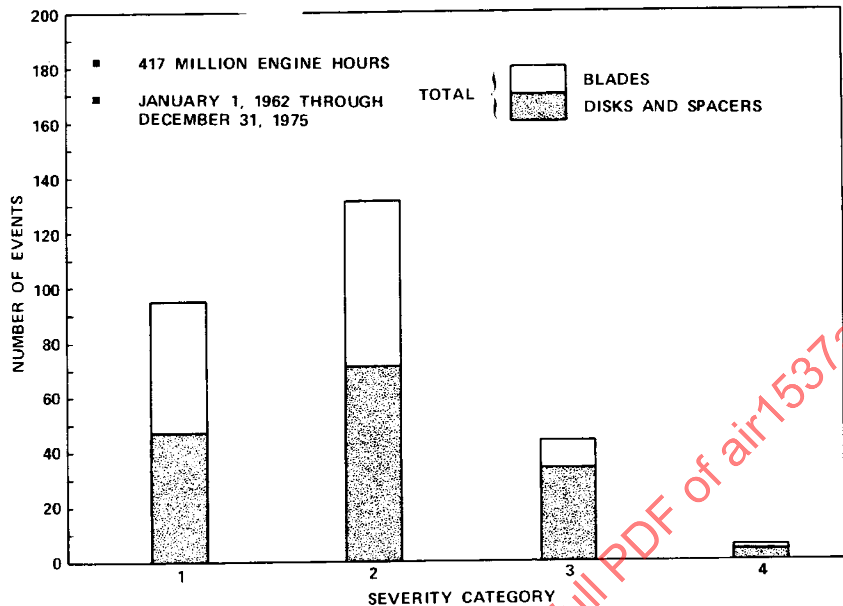


FIGURE 2 - Non-Contained Failures by Severity Category

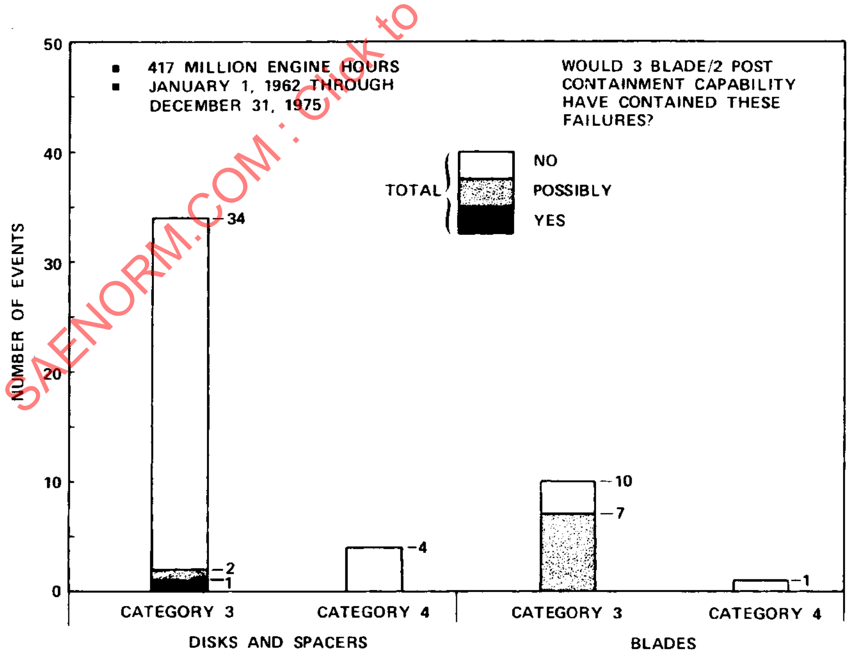
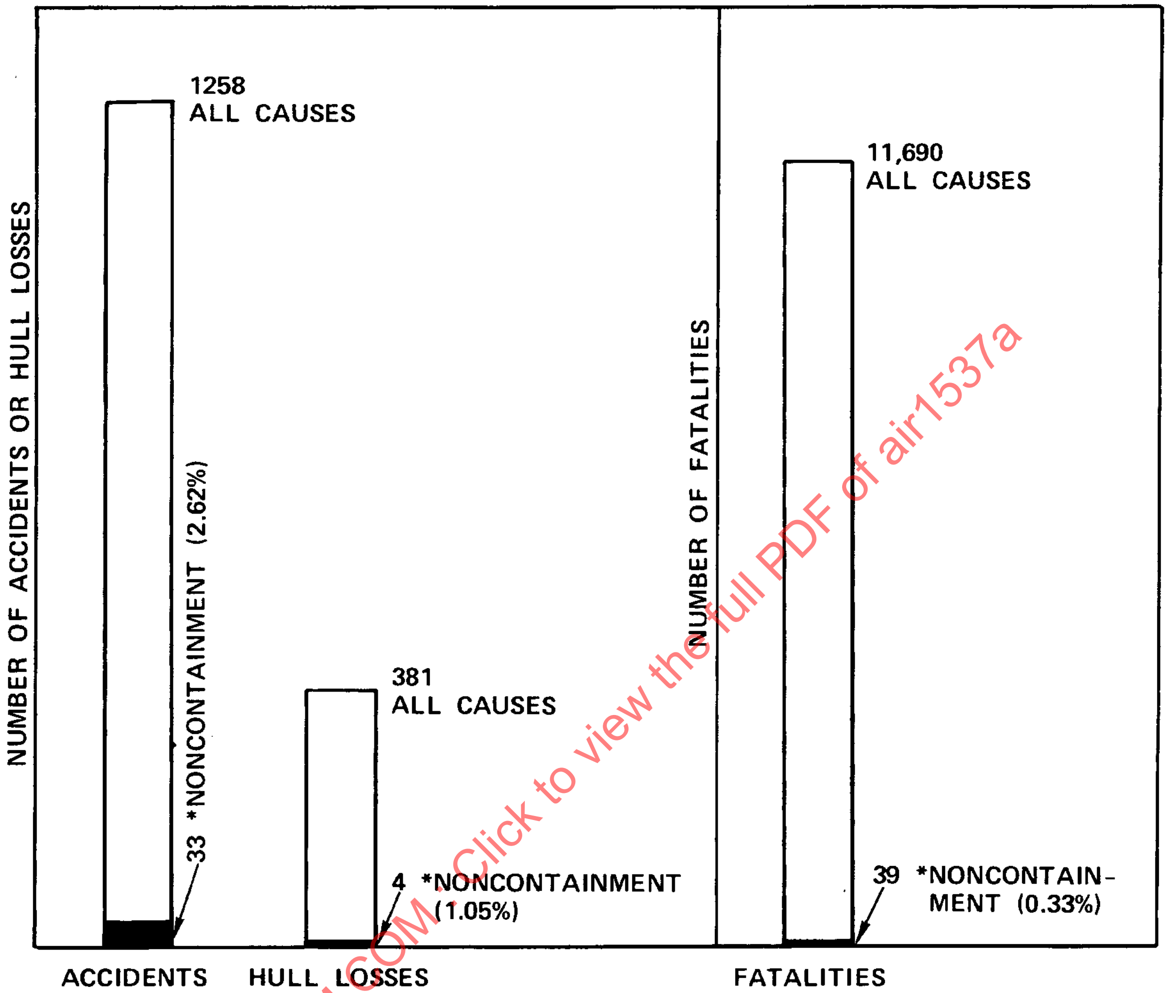


FIGURE 3 - Effect of Increased Containment Capability for Severity of Categories 3 and 4



NOTE: OBTAINED FROM THE WORLD AIRLINE ACCIDENT SUMMARY PREPARED BY THE UK CAA, COVERING ALL TURBINE POWERED AIRCRAFT POWERED BY DETROIT DIESEL ALLISON, GENERAL ELECTRIC, PRATT & WHITNEY, AND ROLLS ROYCE FOR THE PERIOD JANUARY 1, 1962 TO DECEMBER 31, 1975.

*BASED ON DATA DEVELOPED BY THIS COMMITTEE WHERE ENGINE NONCONTAINMENT WAS INVOLVED.

FIGURE 4 - Total Aircraft Accidents, Hull Losses and Fatalities Where Engine Non-Containment was Involved

7. POTENTIAL FOR IMPROVEMENT:

As shown in Figure 4, the probability of an aircraft accident caused by an engine rotor burst is low. This is, however, an important element of overall aircraft safety and continued major effort to further reduce the frequency and hazard of rotor failure is warranted. In addition to safety considerations, the industry has substantial economic incentives to avoid the costs associated with rotor failure.

7.1 Engine Design:

While an improvement may be achieved, the probability of rotor failure cannot be reduced to zero because of the variety of possible causes for rotor failure. Figure 3 shows that increasing casing containment capability (3 blades/2 posts) would not have materially reduced the hazard to the aircraft in the events which were investigated by this committee. This is discussed in more detail in 7.3 of this report.

An examination of the causes for component failure given in Tables 4, 4A, and 4B, and the flight mode during which events occurred, Table 3, shows the areas where efforts to reduce rotor failure frequency may be most fruitfully applied. Following then, are comments relative to the factors that are important to the reduction of blade, disk, or spacer failure probability for each of the causes listed in Table 4, also where appropriate, possibilities and recommendations for improvement are noted:

High Cycle Fatigue has been shown to be a primary or secondary cause of failure in 22.5% of all events. During engine design and development, manufacturers conduct test programs to determine vibratory stresses in rotor components under a wide range of engine operating conditions. As part of the normal analysis and test process, maximum stresses are calculated and measured in order to establish vibratory stress margins. Current regulations require manufacturers to show that adequate vibratory stress margins exist and that components are free of harmful vibration. In service, high cycle fatigue failures may occur as a consequence of the engine operating with a malfunction which does not force engine shut-down, and may occur in a random fashion producing failures in a manner that is not easily reproduced in the test cell. It is important that instrumented testing be conducted, in so far as practicable, to simulate aircraft operating conditions and that vibratory stress in components that are critical to rotor integrity be determined when the engine is operating with statistically probable malfunctions which would not necessarily force engine shutdown. Therefore, research should be carried out to provide better understanding of aerodynamic excitation, mechanical excitation and system interactions of blade/rotor/stator systems leading to improved design criteria for normal and off design engine operations. This research should also include the effect on the engine and the installed engine system of potential engine and system malfunctions and external influences.

Unknown Failure Cause applied to 21.1% of the events -- the percentage in this category is sufficiently large to justify improved procedures for reporting and analysis of non-contained rotor failure events to avoid delayed or inadequate problem recognition and corrective action. It is noted that most of these events were in severity category 1 or 2 which do not represent a significant hazard to the aircraft.

7.1 (Continued):

Rubbing Against Static Parts was a secondary cause of failure in 10.2% of the events. A basic requirement of sound engine design is the prevention of rubbing of primary rotor structure as a consequence of an engine failure. Rubs, when they occur, should occur in a manner which cannot cause disk or shaft failure, and should occur in regions which have been designed to accept rub.

Material Defects account for 9.1% of the events. Proper materials specifications and process controls, in conjunction with sensitive modern inspection techniques have been shown to be effective in reducing the incidence of material defects as a cause of disk burst. Improved material specifications, for example, triple vacuum melted titanium forgings, with closely controlled chemistry and processing, is given credit by engine manufacturers for providing a very high degree of freedom from non-contained disk failures caused by material defects.

Foreign Object Damage (FOD) caused 5.5% of the total non-contained failure events. As would be expected, and shown in Table 4A, none of the disk or spacer failures were caused by FOD -- Table 4B shows that these failures represented 10.9% of the total number of blade failure events. Engine manufacturers are currently engaged in the development of damage resistant designs and design criteria for engine blading with particular emphasis on the blading at the front end of the engine. Progress in these areas together with continuing aggressive efforts to reduce FOD sources, especially bird control in the vicinity of airports, can be expected to achieve a reduction in FOD-caused non-containment events. Steps taken to prevent cowl penetration by fan blade fragments forward of the fan containment case would diminish the potential for these incidents to FOD other engines on the aircraft. The following recommendations are made:

a. Continuing research and development on damage tolerant blade designs should be carried out.

b. Continuing, and in some areas, increased efforts to reduce bird flocks at airports thereby reducing frequency of bird ingestion should be carried out.

Overtemperature was identified as a secondary cause of failure in 5.5% of the events. Failure mode analysis and, where feasible, demonstration should be employed to show that cooling system malfunction will not lead to disk overheating and failure, and that oil system failures or malfunctions will not cause oil accumulation in a zone where fire could occur that would lead to disk overheating.

Low Cycle Fatigue (LCF) is a primary cause of failure in 5.5% of the events. The methods by which service life for rotor components are to be established are clearly identified in the relevant regulations. The process requires a detailed definition of engine operating conditions and a determination of component speed and temperature transients throughout the operating spectrum. The cyclic strain which occurs in critical rotor components, particularly in areas of strain concentration, must then be evaluated and shown to be consistent with material capability, with an appropriate allowance of engine-to-engine variation and tolerances in parts, material capabilities and operating conditions.

7.1 (Continued):

Manufacturers in recent years have developed greatly improved analytical tools, testing and measurement capability, and an improved understanding of material fracture mechanics. This should reduce the number of LCF related failures in newer designs, and permit earlier and more positive resolution of problems occurring in current engines. The statistical nature of the problem is well understood and is evaluated during analysis and materials testing.

Manufacturing Defects and Misassembly account for 6.1% of the events. Continuing care, vigilance and quality control, etc. in manufacturing should keep the frequency of these incidents to a low level. It is important to examine designs to avoid the need for exceptionally critical, difficult to measure, manufacturing processes or controls.

Shaft and Shaft Retention Bolt Failure account for 4.7% of the events. From a design viewpoint, the recommendations and actions listed under high cycle fatigue and low cycle fatigue above can be applied in this area to assure adequate margins for all conditions of engine operations.

Overhaul Procedures were listed as the cause in 4.0% of the events. Completeness of instructions, quality control, personnel training, adequacy of inspection, etc., are the obvious actions to be taken in this area. Sensitivity and care in analyzing the condition of overhaul parts is of great importance in detecting problems, e.g., LCF, HCF, rubs, wear, fretting, overtemperature, etc., which must be recognized and corrected to attain satisfactory long life and freedom from noncontained disk failures.

Combination of HCF and LCF Fatigue (High Cycle and Low Cycle) was the cause of failure in only one event. This is, however, an important potential failure mechanism and is an area of substantial research and development effort in metallurgy and the mechanics of the materials in the industry.

Overspeed was the cause of failure in only one event. Speed limiting provision, as necessary, to prevent destructive overspeed must be incorporated in the basic engine design by a control with very high reliability. Provision must also be made to limit overspeed which might result from shaft failure by providing for engagement, rubbing and destruction of blading or other means.

Related Research - The importance of basic research to improve the understanding of materials behavior and analytic test techniques to improve structural integrity and life prediction has received increasing recognition by both industry and Government agencies.

A substantial and continuing number of Government sponsored development programs are being carried out by the industry to develop understanding and technology in these critical areas. Some examples of current programs are:

7.1 (Continued):

An improved turbine disk design to increase reliability of aircraft engines.
Cyclic behavior of aircraft turbine disk alloys.
Experimental analysis of blade instability.
Instrumentation programs.
LCF life prediction assessment program.
A cost effective evaluation of gas turbine disk residual life.
Structural life prediction and analysis technology.
High performance turbine engine component stress state simulation program.
Damage tolerant design data for propulsion systems.
Evaluation of cyclic behavior of aircraft turbine disk alloys.
Application of advanced fracture mechanics to crack growth in turbine disks.
Experimental determination of unsteady blade element aerodynamics in cascades.
Development of turbine engine structural design criteria.
Non Destructive Inspection (NDI) methods.

Additional recommendations are also made as follows:

a. Research and Development effort and design studies to identify safer disk design approaches is endorsed and is desirable.

b. Continued research and major effort to improve the sensitivity and reliability of NDI (Non Destructive Inspection) methods is strongly endorsed. This has important potential for improving the reliability of material quality assurance, as well as providing greater accuracy and reliability in the identification of cracks or defects in service hardware.

c. Fail-safe disc design.

d. Crack-stopper disc design.

e. That research be carried out to provide an improved capability for understanding the dynamics of engine rotor systems subsequent to blade loss, to permit establishing effective design criteria and practice to minimize the effects of blade loss and to reduce the sometimes extensive secondary damage that results.

7.2 Aircraft Design:

The excellent safety record established by modern aircraft relative to the hazard attributable to non-contained engine fragments as shown in Figure 4, limits the potential for improvement and requires that proposed changes to existing design procedures to minimize this hazard be carefully evaluated to ensure that meaningful gains in flight safety will be achieved by such changes and that unnecessary system penalties are avoided.

7.2 (Continued):

The majority of non-contained occurrences that resulted in severe aircraft damage released fragments of such a large size and energy as to make their containment within the nacelle, or by "shadow containment" in the aircraft structure impractical as a means of reducing the risks to the aircraft, i.e., with current and projected technology, the added weight necessary to insure full containment is impractical (see 7.3). Continued emphasis on the proven design practices to minimize the hazard of non-contained engine fragments has the greatest potential for improved flight safety. As a result of substantial design efforts, a high degree of flight safety is provided with minimal effects on aircraft performance, weight and cost. Continued development of these proven principles, including consideration of the location of engines and critical systems, use of redundant systems with sufficient physical separation and use of dual-load path structure can continue to provide acceptably high levels of flight safety. In addition, where configuration peculiarity requires it, consideration should be given to protection of critical components with energy absorption materials. In order to improve the application of current design practices to new airplane configurations, studies should be conducted to improve the understanding of engine burst characteristics, resulting aircraft damage and to develop lightweight protection for critical aircraft components. Engine burst characteristics should be better defined in terms of fragment sizes and energies, fragment population, and dispersion angles. The relationship of fragment characteristics and aircraft damage potential should be better understood to allow the best application of current procedures. The development of lightweight protection for critical components will allow more versatility in aircraft configurations.

A key requirement for any program to decrease aircraft vulnerability to non-contained rotor failures is development of a better understanding of details relating to incidents in aircraft service. Improvements in the "incident" reporting is required by the airlines, manufacturers, and government agencies to establish a uniform and adequate data base of engine burst characteristics and resulting aircraft damage.

7.3 Increased Containment Capability:

To complement the study of the benefits of increased containment (Section 5.3 and Figure 3), an assessment was made of the penalties associated with increased containment. The assessment included an estimate of the increase in engine weight required for containment of a fragment mass equivalent to three blades and the two included posts expelled from any stage of the engine.

An analysis of the required additional weight of engine casings needed on a large high bypass ratio fan engine (40,000 to 50,000 lb thrust) was made by three engine manufacturers independently. The mean figure of the increase in weight per engine was 400 lb (182 kg) (about 5%) for the additional containment capability and did not take into account any additional strengthening of the engine case, shafting, or mountings to withstand the out-of-balance forces arising from a rotor having three adjacent blades missing.

7.3 (Continued):

The weight penalty incurred by an aircraft using such engines with greater containment capability is greater than the increase in engine weight. If mission (payload/range) and airport operations (take-off distance, etc.) and structural margins are to be maintained on a large widebodied aircraft, the change in aircraft operating weight (excluding engines and pods) would require a gross weight factor of about 3. If mission requirements only were to be maintained, a gross weight factor of 1.6 would apply (i.e., to maintain aircraft range but to permit an increase in field length). Thus for a large 3-engined wide-bodied aircraft, the additional aircraft weight increase could be about 3600 lb (1634 kg) (or a total of 4800 lb (2179 kg) including engine weight increase) for restoration of mission, airport operation and structural margins. Similarly, the total increase for restoration of mission only would be 3100 lb (1407 kg). This overall weight penalty appears difficult to justify in light of the modest benefit of this level of increased containment indicated in Figure 3.

Since non-containment events could be eliminated if engines and/or nacelles could be designed to contain all rotor failures, the committee also considered the weight penalties of complete containment, including segmental disk failures through the bore (the “tri-hub” mode). One engine manufacturer has estimated that for a large high bypass turbofan engine, the weight increase for the containment alone would be of the order of 50% of the basic engine weight. This is obviously not a practical consideration.

APPENDIX A

1. CURRENT PRACTICES:

Sections 1.1 through 1.3 of this Appendix briefly discuss design criteria currently used to minimize non-contained engine rotor failure and resultant aircraft damage. Section 1.1 describes the design and test practices required by FAA Regulations while Sections 1.2 and 1.3 specify the approaches used by the manufacturers to comply with these requirements.

1.1 FAA Regulations and Certification Procedures:

The FAA Regulations approach the problem of turbine engine rotor failures in three ways. First, design and test requirements are imposed for the purpose of ensuring the integrity of the rotor to the maximum extent practical. Second, containment requirements are imposed for the purpose of providing some containment capability. Finally, because complete containment of high energy fragments is impracticable, design requirements are imposed on transport type aircraft to minimize the hazard to the aircraft from non-contained rotor fragments. Each of these items is discussed in more detail below.

1.1.1 Engine Certification: The engine design and test requirements are covered in the United States Code of Federal Regulations, Title 14 Aeronautics and Space, Part 33, Airworthiness Standards; Aircraft Engines. Section 33.14 Start-Stop cyclic stress (low-cycle fatigue) presents the low-cycle fatigue requirements. Section 33.27 Turbine, compressor, and turbo-supercharger rotors covers the overspeed requirements. The overspeed required is 120% of the maximum limiting rpm if the rotor is tested on a rig, or 115% of its maximum limiting rpm if on an engine. Section 33.83 Vibration test includes the following requirement: The vibration stresses of the rotors, rotor shafts, and rotor and stator blades may not exceed the endurance limit stress of the material from which these parts are made.

1.1.2 Containment Requirements: Section 33.14 Durability requires that the engine design and construction must minimize the development of an unsafe condition of the engine between overhaul periods, and the design of the compressor and turbine rotor cases must provide for the containment of damage from rotor blade failure.

1.1.3 Aircraft Certification: The regulation relating to aircraft is covered in the United States Code of Federal Regulations, Title 14, Aeronautics and Space, Part 25 Airworthiness Standards; Transport Category Airplanes, Subpart E, Powerplant, Section 25.903 Engines. Section 25.903, subparagraph (d) (1) reads: "For turbine engine installations design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure..." Methods for meeting this requirement include: (1) location of the engines relative to each other and to critical portions and components of the airplane; (2) locations and separation of critical components and redundant systems; and (3) the strategic location of protective armor and deflectors.

1.2 Engine Design Considerations:

There are three major engine design considerations that are relevant to the subject of rotor containment. They deal with the design and the structural integrity of the rotors themselves, the design of the engine cases to contain blades, and the design of the engine cases, major static support structures and the rotor shafts to withstand the loads generated by the loss of a full blade.

1.2.1 Rotor Design Considerations: Four major design criteria are satisfied to assure a long life for the design. These include prevention of rupture due to overspeed, minimum dimensional changes, acceptable structural dynamics and prevention of failure by low cycle fatigue. To prevent a rotor rupture due to any inadvertent overspeed, the rotor stresses are limited to be able to tolerate at least a 20% overspeed above the engine redline. This design criteria is directly related to the Federal Aviation Regulation 33.27 which requires a 20% rotor overspeed demonstration in a rig or 15% in an engine.

The second design consideration relates to the dimensional growth of the part. This design criteria requires that the rotor over its full certified life does not grow excessively.

To assure that the rotor will not experience excessive vibratory high cycle fatigue stresses, certain dynamic design criteria are satisfied. A fully bladed rotor should be designed to avoid the lower engine order resonances being in the expected operating range. The major excitations from the engine manufacturers experience include the low order excitations as well as the excitation due to the number of struts of support structures in front of and behind the stage.

The other important design consideration related to the dynamics is flutter. The stages are designed to avoid all known kinds of flutter based on the engine manufacturer’s empirical data base and analytical techniques.

The last major design criteria relates to the low cycle fatigue capability of the rotor. The rotor is designed to provide the required long life to prevent cracking of the rotor over its certified life. This design consideration is related to the FAA Regulation 33.14.

Engine Case Design to Contain Blades: The engine cases are designed to meet the FAA containment requirements, FAR 33.19. The design of compressor and turbine rotor cases must provide containment from rotor blade failures.

Design Considerations to Absorb Transient Blade Loss Loads: In addition to containing the failed blade within the engine cases, the entire engine structure must be able to sustain the resulting rotating imbalance loads caused by the missing blade as well as the impact load of the blades striking the containment case. These blade loss loads may become the limiting loads for an engine component such as a major bearing support structure. The blade loss loads are suddenly applied to the engine structure and the engine response to these loads is dependent upon the dynamics of the engine as well as the rotational speed at which the blade is lost, the size of the blade, available damping and the location of the missing blade. This design criterion is directly related to the FAA Regulation 33.77 and 33.19.

1.3 Aircraft Design Considerations:

The following is a discussion of the aircraft design considerations and the requirements to provide an acceptable standard of safety for a non-contained engine rotor failure.

1.3.1 The FAR 25.903 (d) (1) states: “Design precautions must be taken to minimize the hazard to the airplane in the event of an engine rotor failure or of a fire originating within the engine which burns through the engine case.” The design objective is to locate the engine and airframe systems to isolate the effects of the rotor failures so as to minimize the hazard.

The engine installation of contemporary Air Carrier transport aircraft are designed to provide and/or permit isolation of the effects of engine failures to meet the requirements of FAR 25.903(b). To comply, an analysis is made of the design arrangement of the critical systems in the plane of each stage of the engine rotor with the assumption that a third of a disk has sufficient energy to penetrate completely through the aircraft structure. The critical systems include but are not limited to fuel system, hydraulic system, electrical system, flight controls, engine controls and primary structure, and the analysis should consider the routing of piping and control cables, system redundancy and isolation.

1.3.2 Some of the design details that are considered to minimize the hazard due to rotor failures are as follows:

a. Mount the fuel system fire shutoff valve on the fuel tank wall, out of the possible fragment path, to minimize the fuel spillage due to a severed engine fuel feed pipe. Route the fuel pipes within the fuel tanks as much as possible to keep the flammable fluids away from the leading edges of the wing (for wing mounted engines). Install flammable fluid shutoff valves so that operation of the valve is not affected with a power plant or engine mounted structural failure (resulting from a non-contained engine failure).

b. Route the hydraulic piping with the systems isolated from each other, so that a rotor failure does not affect all hydraulic systems.

c. Separate mechanical control cables in the plane of the engine rotors to minimize the effect on the flight and engine control systems following a rotor failure.

d. Design the aircraft structure to be redundant with the capability of sustaining substantial damage under repeated and fail-safe loads. Also, evaluate by analysis or test the damage tolerance of the structural elements to ensure the structural integrity following the penetration of a rotor segment.

1.3.3 The above isolation is implemented in accordance with several other sections of FAR 25. Independent supply to/from each engine and independent shutoff provisions are required for fuel, hydraulics, bleed air and electrical power by FAR's 25.953(a), 25.831, and 25.1351(b)(2).

Separate throttle controls and ignition switch circuits are provided in accordance with FAR's 25.1143(b) and 25.1143(a).

For those rotor failures that are contained within the nacelle, the designated fire zones of certified aircraft, which includes the propulsion system have to comply with FAR's 25.1181 through 25.1205. This means that the following or equivalent provisions are provided:

a. Fire Isolation - firewalls, shrouds or equivalent means isolate each designated fire zone from the rest of the aircraft.

b. Fire detection.

c. Fire extinguishing.

d. Drainage - to prevent accumulation of flammable fluids.

e. Pressure relief - to limit structural damage in the event of an explosion.

APPENDIX B
SUMMARY OF NON-CONTAINED ROTOR FAILURES FOR COMMERCIAL AIRCRAFT JANUARY 1962 - DECEMBER 1975

The events tabulated in the Appendix are non-contained rotor failures which occurred during operation of aircraft powered by Allison, General Electric, Pratt & Whitney, and Rolls-Royce turbine engines during certified air carrier service for the period January 1, 1962 through December 31, 1975. These events are identified according to the item ejected, engine station from which the ejected item originated, flight regime at the moment of failure, cause of failure and severity category. Weight of the ejected fragments (or largest fragment), and weight of 3 blades and 2 posts from the affected engine stage is noted for Category 3 and 4 events. A notation is also presented of the SAE Ad Hoc Committee on Aircraft Turbine Engine Containment judgment as to whether the ejected fragments would have been contained by containment adequate for 3 blades and 2 posts.

The severity of aircraft damage, as judged from a relative standpoint, is based upon the consequence and the damage that actually occurred. Damage severity is divided into four categories and defined as follows:

Category 1. Damage limited 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