

## TYPES OF ROTOR FAILURE AND CHARACTERISTICS OF FRAGMENTS

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INTRODUCTION

There are three obvious ways of reducing the hazard of non-contained engine failure. One is to find ways of preventing the types of failure that lead to non-containment, another is to make the engine casings strong enough to prevent the release of high-energy debris, at least in harmful directions, and a third is to design the aircraft in such a way that the probability of high-energy debris creating a hazard is acceptably low.

The prevention of primary failure, particularly of the type that may escalate to non-containment has always been a natural aim in engine design and development and it will continue to be so. Prevention of non-containment by providing engine casings strong enough to contain the highest energy fragments would require an increase in engine weight that is generally regarded as quite unacceptable and would create problems of thermal lag in the casings and substantially increased loads in the engine mountings. Limited strengthening of casings, especially local strengthening designed to prevent the release of debris in harmful directions, might offer some advantage provided that containing larger or more numerous bodies did not cause greater problems downstream.

The remaining action open to the engine manufacturer is to provide the aircraft designer with the most accurate information available upon the probability of non-contained failure and upon the type of debris a given engine is capable of releasing. This information can be taken into account, along with all other constraints, when the positioning of engines and the location of vital services are being determined for a new aircraft. In the case of established aircraft, a re-appraisal of current precautions against non-containment can be conducted with a view to making any adjustments that might improve on the current level of safety.

In this presentation I propose to concentrate upon the types of non-contained rotor failure experienced in U.K. engines and upon the characteristics of fragments released, including their size, shape, weight, velocity, energy and direction. Developments in the prevention

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of rotor failure and in the technique of containment or deflection of fragments comes up for discussion later at this meeting, therefore they are not included here.

**SAFETY RECORD**

Although non-contained failures account for only a small proportion of aircraft accidents, their spectacular nature makes non-containment an emotive subject. Anyone who has been near a turbine engine when it has produced a non-contained failure will know why. It is an alarming experience. The explosive release of energy appears to have enormous destructive potential. Yet in nearly all cases of non-contained engine failure in commercial service the aircraft landed safely and no one was hurt.

This record is partly due to aircraft/engine layout geometry which, to varying degrees in different aircraft types, minimises the chances of a fragment from the engine striking a vulnerable part of the aircraft. It is also partly due to the ability of the aircraft to withstand the impact or to deal with the consequences of any damage caused by the impact in all but the most serious cases. Less than one non-containment in 10 has caused injuries or affected the airworthiness of the aircraft. This is in 146 million hours of service operation.

To put the part played by non-containment in aircraft accidents into perspective for U.K. engined aircraft, FIG.1 lists the known causes of

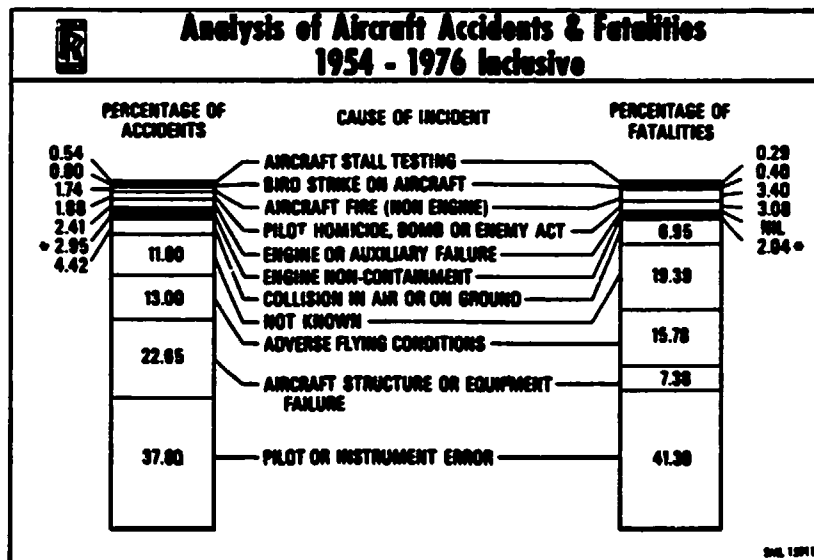


FIG.1

aircraft accidents (defined as involving damage to wing, fuselage or vital services) expressed in the left hand column as a percentage of total accidents and in the right hand column as a percentage of total fatalities. It illustrates that non-contained engine failure accounted for 2.95% of accidents and 2.04% of fatalities from the beginning of commercial flying to the end of 1976. These are not large numbers but it is clear that research and development to eliminate non-containment or to minimise its effect must continue at high priority.

**FAILURE RATE**

In a machine based upon high energy rotating masses carried inside relatively lightweight casings, a degree of risk of non-contained failure is bound to exist. The level of that risk does not appear to have changed very much since the early days of gas turbine flight. FIG.2 illustrates that during the initial three years of gas turbine

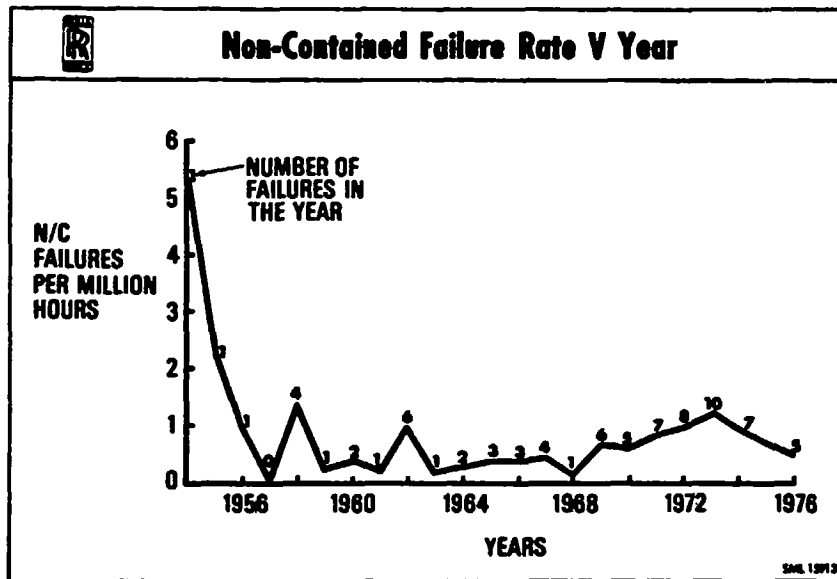


FIG.2

operation there was one Category D (i.e. not contained within engine or cowling) failure per year. The rate looks high because the running time was low. Thereafter the rate was generally below 0.5 per million engine hours. In spite of the progressive elimination of the causes

of earlier non-containments, engines continued to find new ways of producing non-contained failure. The hump in the curve in the 1969 to 1973 period was not due to the introduction of new engines, it was the result of a crop of new modes of failure appearing on long-established engines.

It would be unrealistic to expect the rate of non-contained failure to be appreciably better than 0.5 per million hours in the foreseeable future, the constant demand for higher engine efficiency and reduction in weight involves increasingly arduous engine conditions and the development of new materials without any substantial background of service experience. These factors tend to offset the benefits derived from the elimination of the causes of past non-contained failures. Further, it should be remembered that the figure of 0.5 is an average for all engines and there could be considerable variations in the rate between different engine types.

#### TYPES OF ROTOR FAILURE

In this presentation we are concerned with the fragments released by engines when non-contained engine failure occurs, rather than with the causes of failure, and for this purpose the types of rotor failure, as affecting the shape of fragment, can be divided into three categories.

1. Low cycle fatigue (LCF)
2. LCF with superimposed high cycle fatigue (HCF)
3. Failure due to overheating and/or overspeeding

#### LOW CYCLE FATIGUE

Cracks which propagate to eventual failure at a rate related to flight cycles and not to total running time are categorised as LCF failures. The resulting fracture surfaces can be expected to exhibit fatigue striations indicating an extension of the crack for each flight cycle after crack initiation. For the purpose of this study the category includes LCF failures initiated by defects in material, manufacture or assembly, as well as those that occurred where no such defects existed.

FIG.3 shows the types of rotor failure known to have been caused predominantly in LCF. Diagram A shows a failure from an origin in the

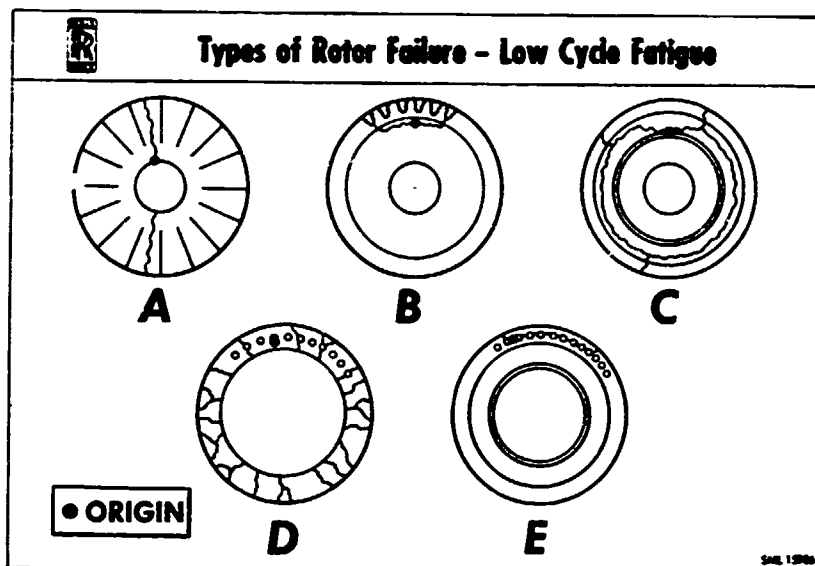


FIG.3

hub of a disc. This mode of failure, which can release the most potentially destructive fragment an engine is capable of producing, is fortunately extremely rare because the cyclic life of a given disc can be predicted with reasonable accuracy in terms of disc bore life, when based upon calculation and the results of rig and engine cyclic tests carried out at appropriate levels of stress in the disc bore. Occasionally a disc has failed from the hub in service but all such failures have been traced to defects in the disc material or processing.

The measures taken to eliminate them make similar problems less likely to occur in the future. But it is impossible to guarantee that there will never be another failure from a disc hub.

Diagrams B and C illustrate LCF failures from an origin in the disc diaphragm. This failure can be initiated in a region of high radial stress when some additional factor has increased the stress beyond a tolerable level. For example, natural concentration of stress in a disc neck can be unacceptably increased by the presence of machining

marks or handling damage or by the unintentional axial displacement of the disc hub relative to the rim. As a result, a crack may initiate and develop into the disc rim (Diagram B) or propagate right round the disc to release the entire disc rim either in one piece or in series of lengths (Diagram C).

Diagram D is a type of failure of which only one has occurred. A compressor drum carrying pin-fixed blades cracked from an origin in the bore of a pin hole. The crack ran into the bore of the drum which proceeded to break-up into a large number of pieces.

Diagram E shows a type of LCF failure experienced on discs with pin-fixed blades. Cracks propagated from hole to hole in one of the two flanges on the disc rim eventually releasing blades and a local piece of disc flange.

#### LCF WITH SUPERIMPOSED HCF

Under engine conditions all rotor discs are subject to some degree of alternating stress superimposed upon the speed-related steady stress. The steady stress is reasonably predictable but the level of alternating stress has to be arbitrarily assumed at the design stage on the basis of previous experience and measurement on other discs. Its level depends upon the dynamic characteristics of the bladed disc and the likely magnitude and frequency of the exciting forces. When alternating stresses are low enough for the cycles to failure to be related only to flight cycles, the failure mode is labelled LCF. When the superimposed alternating stresses are high enough to propagate fatigue cracks at a rate related only to the number of alternating cycles, it is a case of HCF. But this is an over simplification because both LCF and HCF play a part in most disc fatigue failures, one or the other being predominant during the whole or part of the crack propagation process. FIG.4

Diagram F shows an early alum centrifugal impeller with a fatigue origin in a region of high alternating stress created by a vibration mode in the impeller. The 'striation count' method of inspecting fractures had not been developed at the time but it is likely that, as the crack propagated inward, the initial predominance of HCF was superseded by LCF as the crack moved into the hub region which is little affected

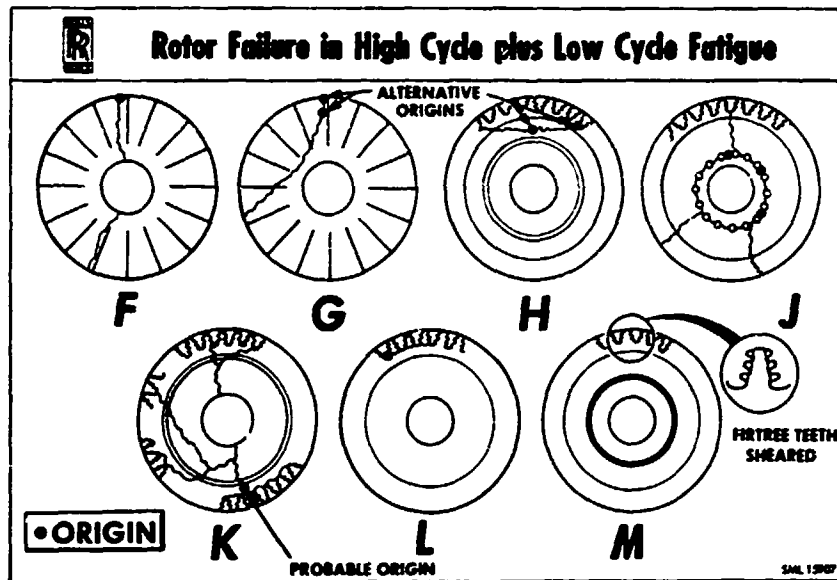


FIG.4

by impeller vibration but is subject to a high steady hoop stress. The crack proceeded to propagate into the bore, to release a large sector of the impeller.

Diagram G illustrates an impeller failure initiated in a similar way but in this case the crack turned circumferentially under the influence of low cycle radial stress combined with the high cycle bending stress arising from the impeller vibration mode. The crack eventually ran outwards and released a relatively light piece of disc, compared with the previous case. Similar cracks developed in compressor and turbine discs with dovetail or firtree fixings (Diagram H).

Diagram J shows a more serious type of failure, predominantly in HCF. Cracks initiated in the ring of holes in the disc hub, run around their pitch circle and radially outwards through the disc rim, releasing three large sectors of disc but leaving the hub, inboard of the holes, in position in the engine. This failure and other similar less severe failures occurred when the wake created by local blockage of nozzle guide vanes excited diametral-mode resonance in the bladed disc. Similar vibration can be caused by the disturbance created when a nozzle guide

vane is missing, or when a fuel burner becomes blocked, or even when a local rub occurs, say an axial rub on the blade tip shroud, and such failures may release a substantial piece of disc. The cure is to design low diametral mode resonances out of the running range because disc failures in such modes tend to release large fragments. Disc failures in higher diametral modes, say 5D and over tend to release much smaller fragments and they are also more difficult to excite.

Another way in which high levels of alternating stress have been generated in discs is the repeated deflection of a bladed disc in an umbrella mode due to engine surge. Each surge causes a cycle of stress unrelated to flight cycles by contributing to the accumulation of fatigue. The result can be the detachment of the disc rim resulting in the release of pieces of disc rim with blades, as in the case of LCF failure in the disc neck.

Diagram K shows a turbine disc nearing time-expiry which was judged to have been exposed to a degree of high-cycle alternating stress for a long period due to a minor blade vibration problem. Fatigue cracks predominantly in LCF but with indications of superimposed HCF, developed in the bottom of a large number of disc grooves. Disc failure occurred shortly before the full service life of the disc had been achieved. One of the cracks propagated inwards far enough to become critical and the disc broke into six pieces, the largest fragment being almost half a disc.

Diagram L is an example of disc failure in blade-excited fatigue in which a group of disc lobes failed in the neck and released the lobes together with the corresponding group of blades. Diagram M shows a case in which fir-tree teeth on the disc failed and released blades. In both types of failure the largest fragment likely to be released by the engine is a single complete blade.

#### DISC FAILURE DUE TO OVERHEATING (FIG.5)

Three types of disc failure have occurred as a result of loss of material properties due to overheating. The causes were:-



- (a) Loss of cooling air
- (b) Rub against a static part
- (c) Internal oil fire

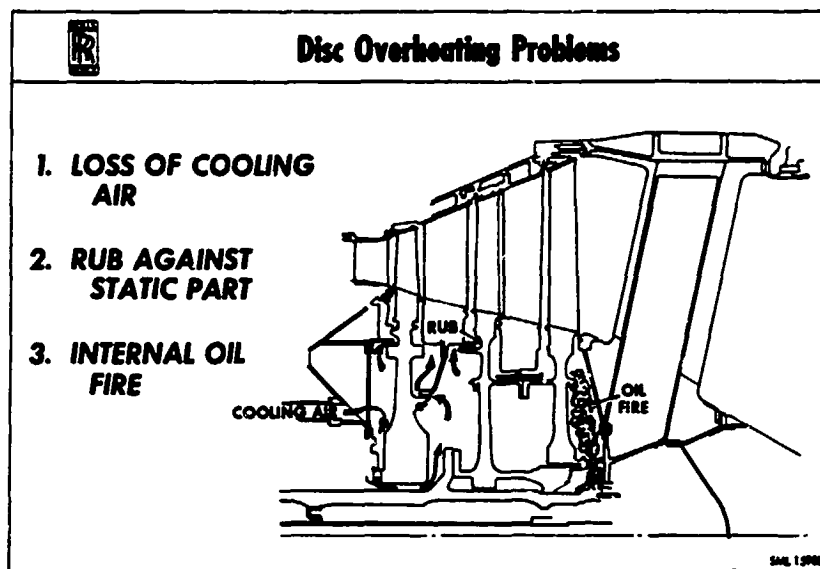


FIG. 5

Disc failures under these headings have occurred only in turbines. Turbine discs in UK engines are traditionally cooled by enveloping them in cool air which exhausts into the gas annulus fore and aft of the disc. It has the dual purpose of cooling the discs and of preventing the ingress of hot gas into spaces surrounding them. On rare occasions this system has been disrupted by loss of cooling air pressure, in a typical case due to the failure of an external cooling air supply pipe and in another due to the loss of interstage seals following turbine blade failure. In both cases the result is overheating of the disc due to the inflow of hot gas into spaces adjacent to it. The form of failure depends upon the design of disc and blades. In some cases the overheated disc stretches and releases all its blades and the largest fragments released are single complete blades. In other cases the disc fails first in the neck, releasing the disc rim with blades attached and the largest fragments are pieces of disc rim with blades. The latter failure is much more serious, in terms of the

likely energy of the largest fragment released, than the loss of blades alone, the fragments being capable of cutting through the engine casings throughout the entire circumference of the engine and proceeding to inflict heavy damage on any aircraft parts in the line of flight.

Disc failures due to axial rubs were typically rubs between the disc diaphragm and a stationary component such as a static seal. This causes overheating of the diaphragm at the seal diameter and the release of the portion of the disc outboard of the rub which includes the entire disc rim and some of the diaphragm. The result is similar to the previous case.

The third cause of overheating, the oil fire, again results in stretching of the disc which either releases the blades or fails in the diaphragm.

**MULTIPLE BLADE RELEASE (FIG.6)**

In addition to disc overheating, multiple turbine blade release has been brought about in two other ways -

- (a) Shelling-out of blades
- (b) Overspeed of turbine

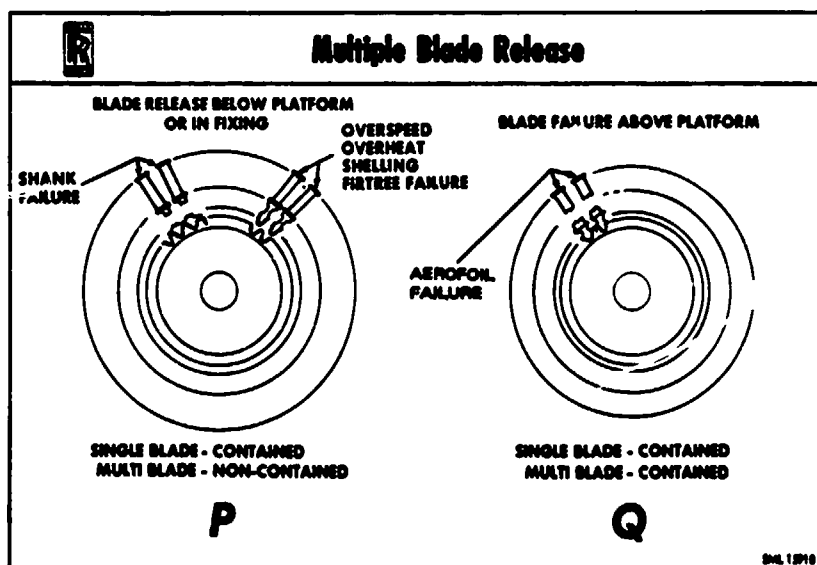


FIG.6

If sufficient tangential force be applied to a blade it will bend over or break, or it will be wrenched out of its fixing. The result depending upon the relative strengths of blade and fixing. In some cases the fixing will fail first so that an obstruction in the blade path or a heavy rub against adjacent vanes will cause the complete row of blades to shell out of a disc. If such a failure be non-contained the largest single fragments to be released by the engine are likely to be single complete blades.

In the event of turbine overspeed to failure the result is that either the disc bursts, probably from the bore, or it stretches sufficiently to release its blades. The outcome depends upon factors such as the ductility of the disc material, the fineness of the firtree teeth and the stress distribution in the disc. Clearly, the release of the blades is preferable to the disc burst in terms of the destructive potential of the fragments released, but multiple blade release provides the greater probability of striking any vulnerable aircraft item in the general plane of the rotor.

The requirement that engine casings shall be capable of containing a single blade released from immediately above its fixing, determines the minimum strength required in the casings. If the casings just meet this requirement we would not expect two adjacent blades released together to be contained but we might expect two blades  $180^{\circ}$  apart, and perhaps four or more blades,  $90^{\circ}$  or less apart, released simultaneously, to be contained up to the point where the bulge in the

casing caused by one blade did not encroach upon the bulge created by the next. The energy of a contained blade is used up in stretching and bulging the casing and if a second blade attempts to use up energy in the same bulge the casing is likely to fail. In virtually every case of multiple turbine blade release from below the platform the blades have been non-contained, even where casings have been substantially thicker than the minimum required for single blade containment because of structural or pressure requirements. Multiple blades released from above the platform, in the aerofoil, normally have been contained, presumably because of their light weight compared with complete blades. It would be useful to know how strong a casing would have to be to contain the multiple release of complete blades.

The release of all blades from a disc does not normally result in their emerging uniformly from the engine in 'Catherine Wheel' style but rather in the release of groups of blades through random arcs of casing, typically as shown in FIG.7, presumably because the first blades to

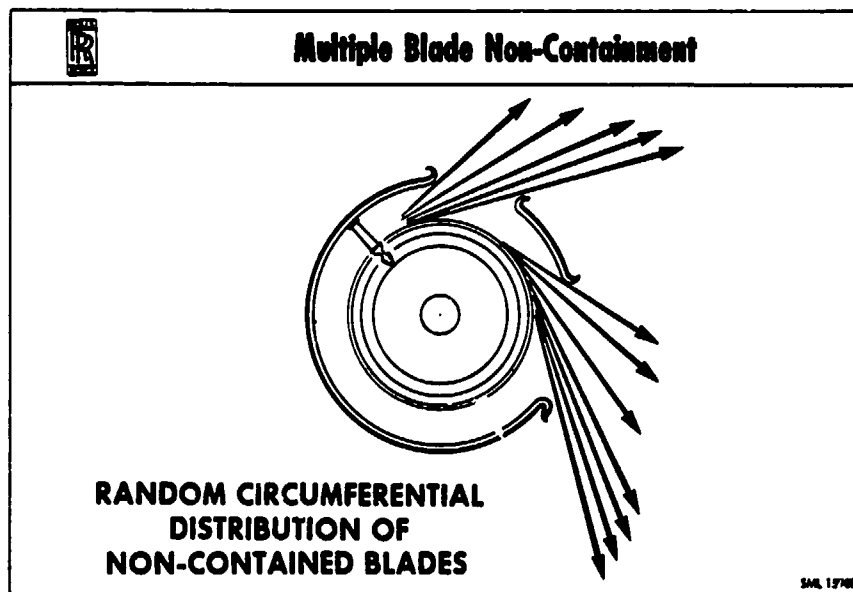


FIG.7

touch the casing tend to interfere with following blades. The result, from the aircraft point of view, is that the assumption must be made that the engine may throw complete blades either singly or in groups, and a number of impacts may occur almost simultaneously within a small target area.

CHARACTERISTICS OF ROTOR FRAGMENTS

At an early stage in the evolution of the design of a new engine the approximate diameters, speeds and weights of compressor and turbine rotors can be defined. From the information generated by all non-containment incidents, these three parameters can be used to predict the range of fragments the new engine could conceivably release, including weight, size, shape, velocity and direction, together with the probability of release of given fragments. The prediction should give the aircraft designer the best chance of minimising the possible effect of non-containment upon aircraft safety.

An analysis of all UK engine failures not contained within engine casings or cowlings, since turbine engine flying began in 1953 is given below.

SHAPE OF FRAGMENT

Diagram R in FIG.8 shows the shape of fragments released when a compressor

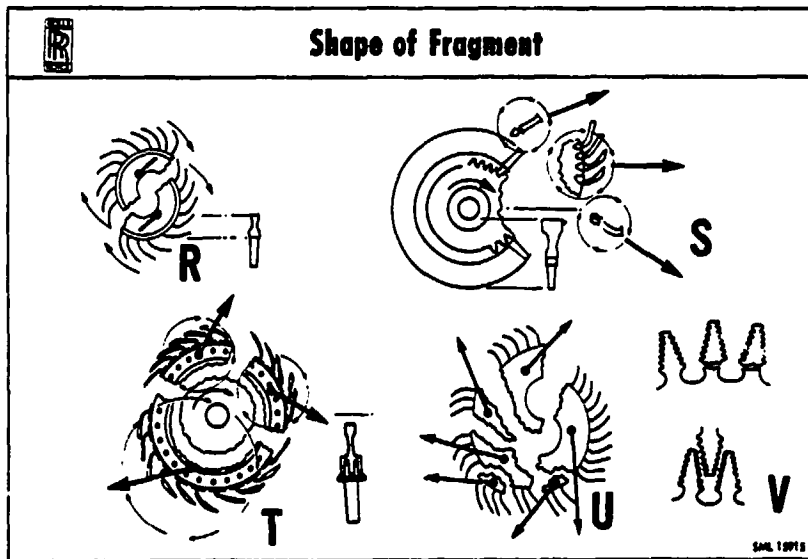


FIG.8

disc fails through the bore. It could equally well be a turbine disc. The origin of failure might be anywhere along the line of fracture in the fatigue case or it might be from the bore in the overspeed case. Two sectors of rotor are released with very high energy, capable of slicing through almost any aircraft structure in their path, each rotating about its own c of g and travelling along a line tangential to the circle described by its c of g before release.

Diagram S shows a failure where the fragment released comprises a group of blades held in a piece of disc, additional separate blades are released at the same time. This type of failure is likely to be the result of low or high cycle fatigue or a combination of both. The fragment again rotates about its own c of g and travels along the appropriate tangential line. It has a much less energy than a half disc and it may strike its target in any attitude probably the most damaging being when a jagged piece of disc rather than the relatively flexible blades, make first contact.

Diagram T shows the case where the complete rim of a disc is released in a number of lengths. This type of failure can be the result of fatigue cracks in the diaphragm propagating circumferentially right round the disc. A failure with similar results is the circumferential failure of a disc diaphragm due to overheating caused by a local rub on the diaphragm say by a static air seal or due to general overheating due to loss of disc cooling air. This type of failure can cut an engine in half in the case of a disc with a heavy rim section. But rims of light section, when released from discs, have often been contained by the casings, notably in the case of H.P. compressor disc rims. In other incidents the rim has penetrated the casing locally and unwrapped itself to emerge from the engine in a straight line, like a spear.

Diagram U shows the fatigue break up of a disc into a number of irregular fragments. This type of failure has been observed particularly in the case of discs reaching the end of their fatigue life. It presents some formidable fragments, distributed around the engine.

Diagram V shows other types of fatigue failures in blade fixings, including failure through the firtree neck and failure of the firtree

teeth. These failures release one or more blades which may or may not be contained, but the largest fragment released is a single blade.

The failure of a turbine disc due to overspeed, say due to shaft failure, will produce a type of failure dependent upon the disc design. In some cases the disc will fail from the bore and release sectors at higher velocity than the normal maximum but in most engines the design aim is to release blades rather than allow the disc to fail in the ultimate overspeed case.

SIZE OF FRAGMENT

With regard to the size of fragments, the maximum dimension of a missile affects the probability of its striking a given part of the aircraft and an analysis of fragment sizes has been carried out.

FIG.9 shows a breakdown of all non-containments in terms of number of

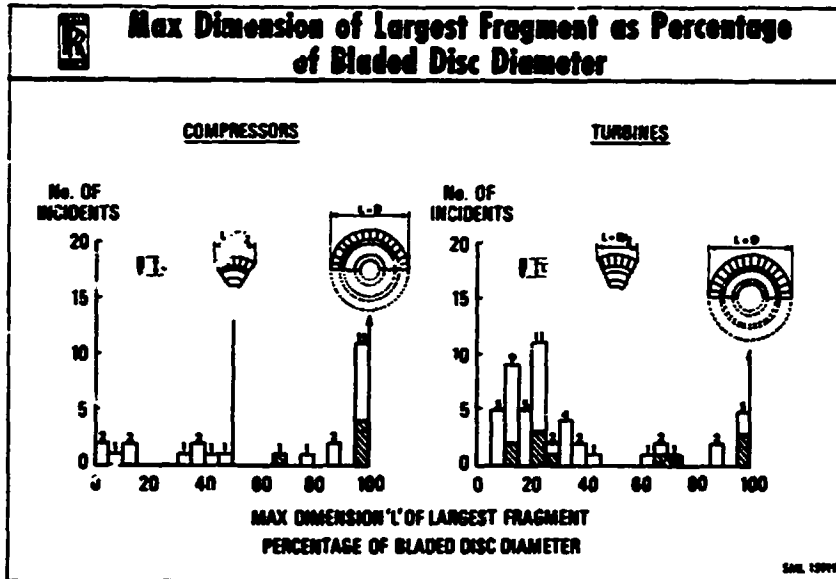


FIG.9

incidents against the maximum dimensions of the largest fragment expressed as a percentage of the bladed disc diameter, ignoring the effect of bent-over blades which is unpredictable. Compressors and turbines are shown separately. It can be seen that for compressors,

fragments with a maximum dimension equal to the overall diameter of the bladed disc, i.e. a half-disc and above, less the effect of bent blades, tend to predominate. The shaded areas in the figure show the incidents that caused injuries or affected the airworthiness of aircraft. Not surprisingly the large fragments did the most damage, not the least because, in the case of compressors, large fragments were released more frequently than small ones.

In the case of turbines, about twice as many non-containsments overall have occurred (although in recent years compressors and turbines have produced approximately equal numbers of non-containsments) and the tendency has been for turbines to release small fragments more often than large. The small pieces include single blades or part blades or small pieces of disc with blades attached.

Clearly, large fragments are more likely to damage the aircraft and, based upon the limited number of incidents for which fragment sizes are known, this tendency is confirmed. But small fragments have been released in far more incidents than large and they have caused service aircraft problems in a greater total number of cases.

WEIGHT OF FRAGMENT

FIG.10 shows the number of incidents in which the heaviest fragment

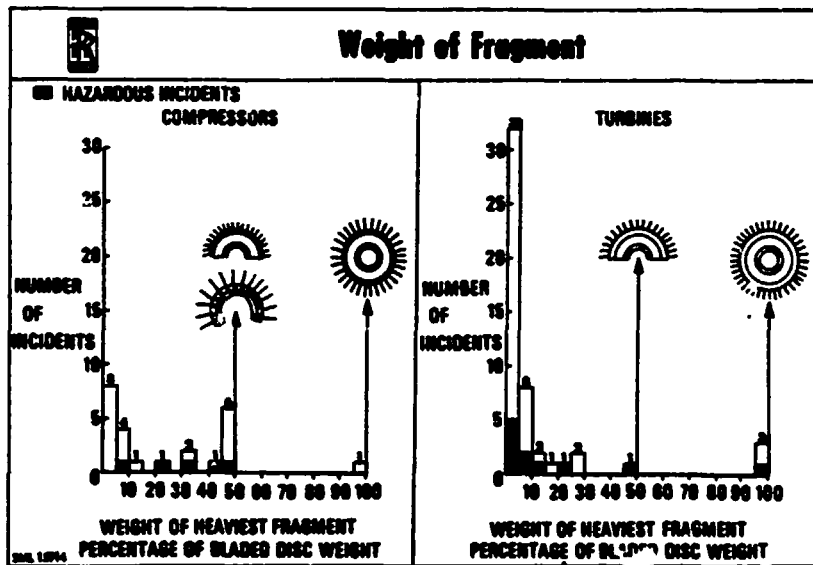


FIG.10



released was a given percentage of the bladed disc weight. The weights are taken in 5% steps. The heaviest fragment is chosen because it has the greatest destructive potential of all the fragments released in a given incident. In this plot the heaviest fragment in a non-containment in which all the blades in a disc are released, is taken as a single blade.

The shaded areas show the number of incidents in which injuries were caused or the airworthiness of the aircraft was affected. In the case of compressors the release of fragments weighing up to 5% of the bladed disc weight was not, in this experience, responsible for creating any hazard. Incidents involving the release of heavier fragments weighing more than 5% of bladed disc, proved to be hardous or non-hazardous in a random way, probably because the aircraft/engine layouts provide favourable odds against single heavy fragments striking a vital part of the aircraft.

In the case of turbines, of the total of 50 incidents in which the weight of fragments released is recorded, 32 involved the release of fragments weighing not more than 5% of their bladed disc weight and 5 of the 32 caused sufficient damage to affect the airworthiness of the aircraft. Larger fragments in the range 10 to 50% of the bladed disc weight appear in only 7 incidents but, as might be expected with larger fragments, they proved more likely than small fragments to affect airworthiness and this they did in 3 of the 7 incidents. Looking more closely at the manner in which the aircraft was affected in these events we find that the incidents involving the release of fragments weighing no more than 5% of the bladed disc weight were all cases of multiple blade release, two causing damage to aircraft hydraulics, one damaging an adjacent engine, one starting an extensive fire and one causing cabin depressurisation. In the case where the heaviest fragment released weighed 50% of the bladed disc the result was penetration of the fuselage and of a wing tank causing a fire. In one case of full disc release the pressure hull was punctured and an adjacent engine was damaged but in the other two cases damage was not serious.

On this evidence heavy fragments present an occasional serious threat and lighter fragments present a less serious but more frequent threat capable of causing enough damage to create an aircraft hazard in some cases. This experience involves some of the older aircraft and the results might be different with later designs, but it shows that there are two vital factors affecting airworthiness in the non-containment case, the first is the aircraft/engine layout and the way it affects the probability of damage to vital parts of the aircraft and the second is the number of fragments released in a non-contained failure. Clearly there is a need to pay a lot more attention to the problem of multiple blade release.

VELOCITY OF FRAGMENT

In designing armour or deflectors to provide protection against missiles, it is important to have some knowledge of the likely approach velocity of the missile as this will determine the type of armour or deflector required. FIG.11 gives the maximum rim speeds of rotors in UK engines.

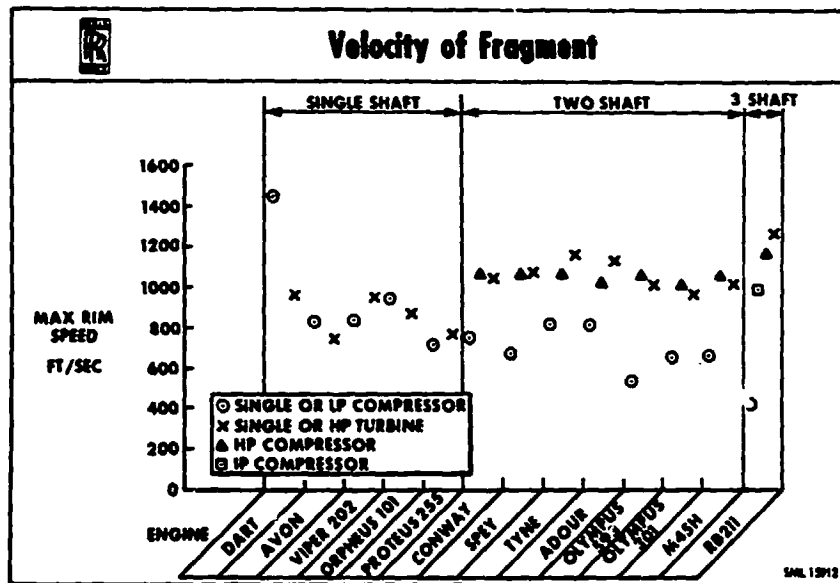


FIG.11

Rim speeds were chosen because a fragment is released at approximately the tangential velocity of its centre of gravity at the instant of

release and the centre of gravity of a rim piece with blades attached is likely to be near the radius of the rim and travelling at rim speed. Corrections can be made for fragments with centres of gravity at smaller or larger radii. Note that the velocities lie between about 400 and 1300 ft/sec. which is within the range that can be stopped or deflected by conventional armour like steel or titanium plate, and does not require the more exotic armour developed against missiles with much higher approach velocities. It will be shown later that non-contained fragments weighing above about 6% of the bladed disc weight are likely to emerge from an engine with a tangential velocity equal to the tangential velocity of the c of g of the fragment at the instant of release from the disc.

ENERGY OF FRAGMENT (FIG.12)

A fragment released from a rotor has kinetic energy along its line of flight plus rotational energy about its own c of g. Plotting the

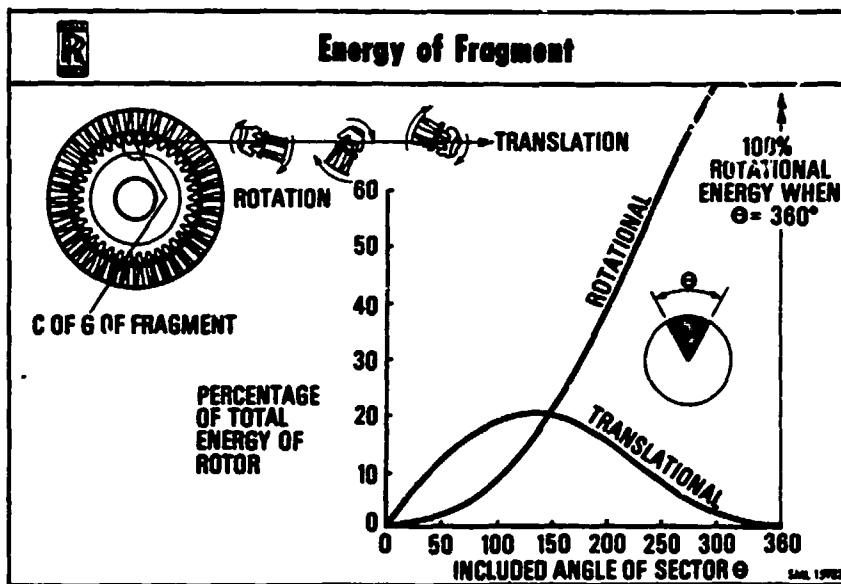


FIG.12

translational and rotational components of energy for a disc sector against the included angle of the sector shows that translational energy reaches a peak when the sector angle is about  $134^\circ$ . But the rotational

energy increased with sector angle until at  $360^{\circ}$  we have a full disc with all its energy in rotation and none in translation.

Engine experience and tests on armour and deflectors used against rotor fragments show that translational energy is the more important factor in the case of fragments comprising up to four blades and a piece of disc. Rotational energy may have a greater effect in the case of large fragments involving half a disc or more but this has yet to be established by test. Another point to note about the shape of the curve of translational energy is that any sector angle between  $90^{\circ}$  and  $180^{\circ}$  has energy within 10% of the maximum. Evidently a fragment of near-maximum translational energy would be produced if a rotor released anything between a quarter and a half of a disc.

In passing through an engine casing, a fragment uses up energy in damaging itself and the casing. Recent containment tests in which representative fragments were released from a rotating arm inside an engine casing showed that a fragment with an energy level just beyond the containment capability of the casing lost 90% of its translational energy in getting through the casing. But when a portion of rotor, comprising four blades and a piece of disc weighing 6.5% of the bladed-disc weight, was released inside a casing designed to contain a single blade, the fragment passed through the casing without measurable loss of translational energy. It was thought at the time that the energy expended by the fragment in bursting through the casing was too small to be measured in terms of fragment velocity before and after penetration. But on further study of high-speed films of the fragment passing through the casing, it was observed that although no translational energy was lost there was a 10% to 20% loss of rotational energy and this would account for the energy used up in damaging the fragment and the casing. There is no evidence that this loss of rotational energy would reduce potential damage to the aircraft.

It is notable that when complete discs were released, usually as a result of heavy unbalance due to blade or other failure, in the majority of cases no serious aircraft damage was sustained. Any disc released with virtually all its energy in rotation is unlikely to develop more than a small amount of translational energy, say by being thrown sideways by

friction between rotor and static parts. The main danger of a free disc is its ability to act as a cutter, capable of severing vital services in its path.

DEFLECTION OF FRAGMENTS BY CASING

When a fragment passes through an engine casing it tends to be deflected from its path. The deflection is equally likely to be in an axial or in a circumferential direction as shown in FIG.13. Observations of

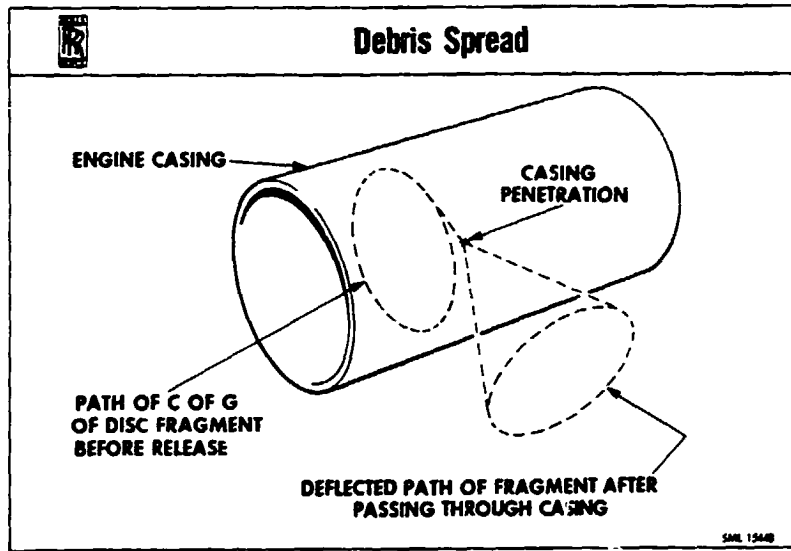


FIG.13

damage to surroundings caused by actual non-containment incidents show that heavy fragments tend to remain within  $\pm 5^\circ$  of the plane of the rotor FIG.14. Much greater deflections have been recorded with lighter

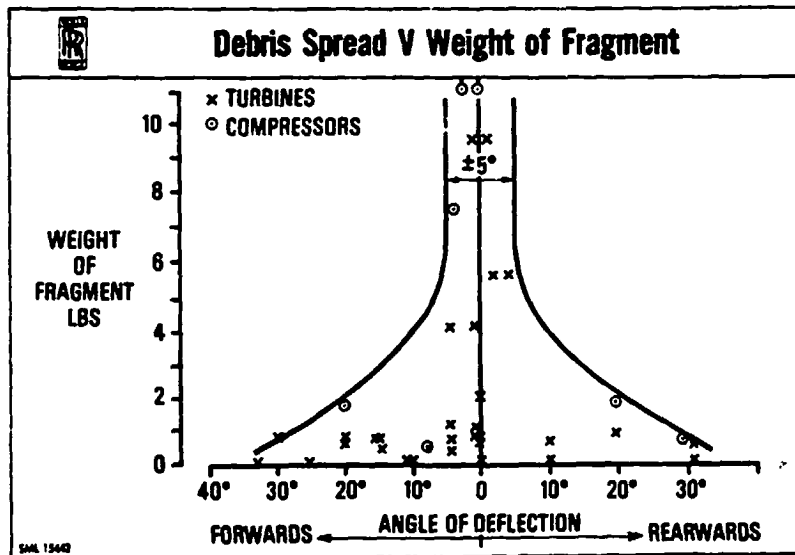


FIG.14

fragments but those deflected by more than  $33^\circ$  appear to have lost virtually all their energy.

If we assume that in striking the casing, a fragment loses the component of velocity perpendicular to its final line of flight, this does not wholly account for the loss of translational energy observed in practice when deflection exceeds  $33^\circ$ . There must be another factor and this is likely to be the decelerating impulse induced by friction between fragment and casing. We can derive this frictional factor from the knowledge that the final velocity is virtually zero when deflection exceeds  $33^\circ$ . FIG.15 shows the translational energy of fragments for

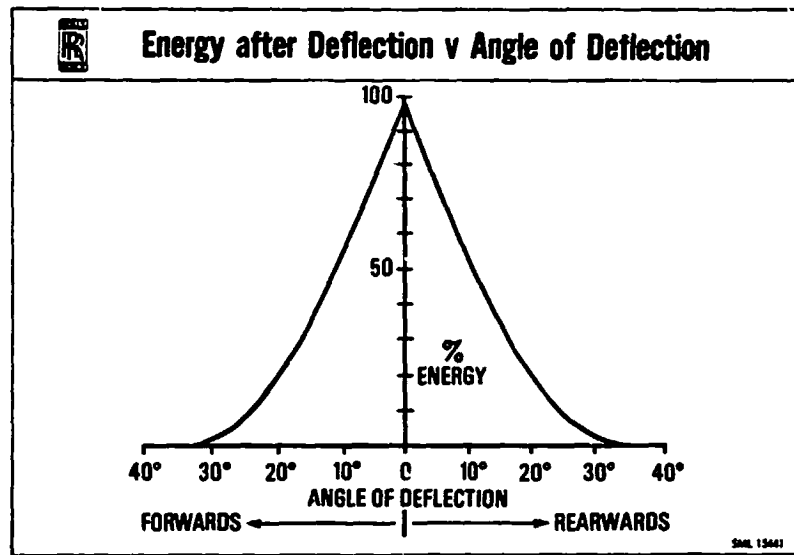


FIG.15

various degrees of deflection derived in this way. From the aircraft point of view the potential spread of debris is as shown in FIG.16.

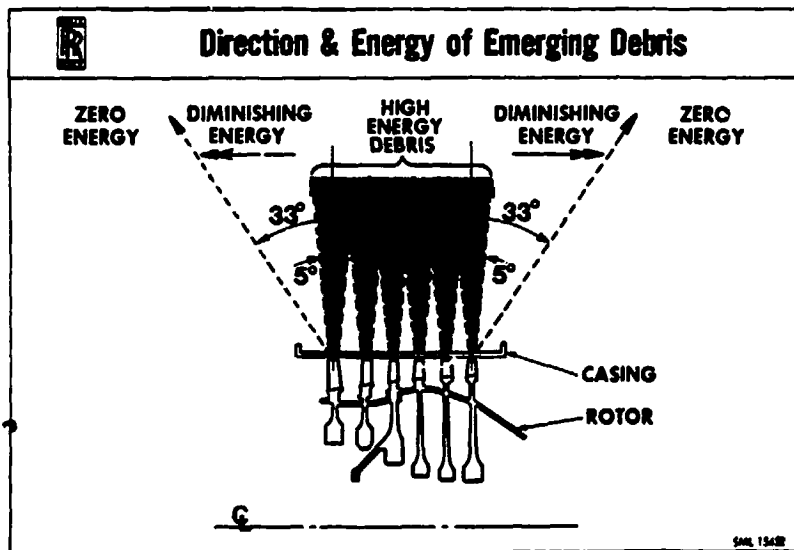


FIG.16

The distribution of energy can be established for a given engine. High energy fragments emerge within  $\pm 5^\circ$  of the plane of the rotor, fragments deflected beyond  $5^\circ$  have energy that diminishes with angle of deflection and fragments deflected by more than  $33^\circ$  have zero energy.

#### SUMMARY AND CONCLUSIONS

1. The rate of non-contained engine failure in UK engined aircraft has remained sensibly constant at 0.5 per million engine hours for the past 20 years. The progressive elimination of tangible causes of non-containment has been offset by the development of new modes of failure. To reduce the rate of non-contained failure, or even to hold it down to the present level, requires work on the prevention of rotor failure to be continued at high priority. In addition, research and development in the field of containment of high-energy debris should continue to be pushed ahead and measures taken in aircraft design to minimise the hazard of non-containment should begin to reflect a more complete knowledge of the characteristics of fragments likely to be released by a given engine.
2. Types of rotor failure leading to non-containment include low and high cycle fatigue, disc material and processing defects, disc overheating due to rubs or loss of cooling air and disc overspeeding due to shaft failure or engine overspeed. It is not possible to guarantee the permanent elimination of them all.
3. Rotors are capable of breaking up in a wide variety of ways, producing non-contained debris ranging from maximum energy sectors to single blades or part blades. Complete discs have been released in some cases of shaft or bolt failure, sometimes precipitated by the primary failure of another rotor.
4. Large heavy fragments released by an engine are naturally more prone to damage the aircraft than small fragments and the damage tends to be more extensive. But small fragments are also capable of doing enough damage to create airworthiness problems, they are released more frequently than large fragments and because

of the greater number released per non-containment, the probability of impact on a vulnerable item in the aircraft is increased. Multiple blade release has proved to be particularly damaging and this type of non-containment calls for special attention.

5. The velocities at which engine fragments are released fall within the range that can be arrested or deflected by armour developed to provide protection against low velocity projectiles. There would be no advantage in using advanced armour developed for use against very high speed projectiles.
6. Large fragments, certainly those weighing over 6% of the bladed disc weight, tend to escape from the engine without losing any of the translational velocity they possessed at the instant of their release from the disc. But they lose a small proportion of their rotational energy. Small fragments lose some translational energy in getting through the casing unless they escape through a previously created hole.
7. Large fragments tend to emerge from the casing within  $\pm 5^\circ$  of the plane of the rotor but small fragments can be substantially deflected axially and circumferentially and they lose energy in the process. They appear to lose virtually all translational energy if deflected more than about  $33^\circ$ .
8. From these results the distribution of possible fragments and the energy with which they are likely to emerge from any given engine can be predicted with reasonable accuracy and used in assessing the threat to the aircraft.

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## DISCUSSION

### H. Rubel, Lockheed-Georgia

Thank you for a very enlightening discussion. I have a question on the very last statement that you made with regard to multiple blade release and I wonder if the turbine blade release you referred to is associated with the retention of the turbine blade and not necessarily with the difference inherent between compressor and turbine. What I have in mind is your Fig. 6 -- how many of these cases, five, were category three and four (if I may use the SAE Ad Hoc Committee terminology) and were due to overspeed or overheat causing shelling of the fir tree because of the retention having small teeth? Specifically, in the designs discussed because the teeth were very fine, a slight overspeed causing yielding of the disk would permit the whole blade to come out. By the same token, if there were a fatigue failure and the retention was very fine, the impact from the failed blade could cause other blades to snap out or unlatch. Whereas, in America, we have gone to two or three fir trees and, normally, have a failure above the attachment in the first fir tree or airfoil. With this type of failure (similar to the compressor), energy is used up in breaking all the other blades. So, the question I raise is, do you really need to beef up the turbine case for multiple blade release or should we prevent the unlatching of the multiple blades?

### D. McCarthy, Rolls-Royce

Our experience is that breaking up blades absorbs very little energy. We design blades so that in the event of a blade being bent over it will break in the shank or in the aerofoil before it breaks in the fir tree fixing. Some of our turbine discs are designed with fine fir tree teeth so that, in the event of overspeed, the disc releases its blades before bursting speed can be reached. This blade-release is achieved only after very substantial plastic growth of the disc, just short of ultimate failure. The situation is quite different under normal running conditions when the fir tree teeth are fully engaged and the difference between fine and coarse fir tree teeth is like the difference between fine and coarse screw threads.

Our reference to blade "shelling" in early engines covers cases where blades were successively wrenched out of their fixings by a tangential force, like shelling peas. Later blade fixing designs do not have this problem.

Turbines tend to release blades more frequently than do compressors because turbines are open to overspeeding or overheating whereas compressors, in general, are not.

### H. Rubel, Lockheed-GA

Energy can be used up in breaking blades. Is it better to have blades break off before releasing? Should we put more weight into the aircraft to protect against multiple release or should we work on preventing multiple release?

D. McCarthy, Rolls-Royce

We should be doing both. There are some things the engine man can do to avoid known problems but he can never guarantee that non-containment has been entirely eliminated. The aircraft man should protect vulnerable items in his aircraft and he should not ignore small fragments.

In Mr. McCormick's paper the statistics showed that in a total of eleven serious (SAE definition) accidents, six were due to the release of disc sectors but no less than five others were due to impact from small fragments. I suggest that the aircraft man cannot afford to ignore the cases involving the release of small fragments.

S. Sattar, P&W

One question I had concerns fan blades. Could you comment on those designs where one has the same mode of failure below the platform at the dovetail where some designs tend to result in multiple blade loss failures and others don't? Have you in your studies come across some significant parameter (say there's something about a particular airfoil configuration or airfoil geometry) that makes one more prone to a multiple blade loss failure than others, assuming that both fail below the platform?

D. McCarthy, Rolls-Royce

We have experience of a fan blade failure in the root releasing the blade which leaned upon the adjacent following blade and caused it to fail in the fixing due to asymmetrical loading. The process did not go beyond the release of the two blades. The problem was overcome by strengthening the fir tree teeth and by improving the circumferential support of the blades at the platform. It was later demonstrated that a failed fan blade no longer dislodged its neighbour, nor any other blade in the rotor.

Alan Weaver, P&W

You showed fragment impact velocities between 400 and 1200 feet per second in your armor design work. Are these blade tip or disk rim velocities?

D. McCarthy, Rolls-Royce

Rim velocity is plotted because the centre of gravity of a rim-piece with blade attached is approximately at the rim radius. A factor could be used in the case of a fragment with a centre of gravity at a different radius.

J.C. Wallin, BAC

Damage depends on the way that engines actually can break up (or have broken up). From the point of view of the assessment methods that I was describing earlier, we consider one-third disk piece, or a piece of rim with a couple of blades. If we take blade shelling, the assessment would be the same as if you were using a one-third disk. Indeed, the one-third disk might be a bit over-pessimistic, so I don't think there's an inconsistency here. The one particular inconsistency that one sees is perhaps the question of the blades which will come out over a 33 degree fore and aft sector and which in the CAA model we don't take account of. Again, I think that one perhaps doesn't

have to take account of that because the energy gets lower as you move away from the five degrees. One hopes that there won't be single articles in the way of a single blade that could in fact lose the airplane. I'm quite sure that if we did Concorde over again today (and bear in mind we're talking about airframe design that's really fifteen years old) we would not put a flight control system in, where all three hydraulic systems came together at a single point. I'm sure my colleagues in the aircraft design industry would agree, we just wouldn't do that today. So in that case you don't really need to consider the single-blade effect because you wouldn't have single vulnerable articles.

D. McCarthy, Rolls-Royce

In the case of multiple blade release, some of the blades are deflected in passing through the engine casing. The likely spread of emerging debris has been indicated, together with the likely energy of the fragments. These factors affect the provision necessary in the aircraft. Beside affecting the extent of the target area, the amount of deflection given to a fragment may be important in determining the angle at which to mount a deflector to ensure that all fragments that strike it will be deflected in a harmless direction.

J.H. Gerstle, Boeing

Do you have any data on the range of residual velocities that the fragments have in the case of multiple releases?

D. McCarthy, Rolls-Royce

In the event of multiple blade release, the blades that first strike the casing can lose as much as 90% of their energy in penetrating the casing. The remaining blades tend to come out through the hole or holes created by the first impacts. A few blades may emerge with full energy, having come through the casing without touching it. But the majority will lose energy in sliding round inside the casing and the measured residual translational energy in these blades, when they emerge from the casing, is not more than 55% of their original energy.

J.H. Gerstle, Boeing

Would you suspect that the rotational energy lost would be a function of the fragment type -- that a rim fragment would lose a greater fraction of the rotational energy than a pie-shaped fragment?

D. McCarthy, Rolls-Royce

We have released a fragment consisting of four blades and a piece of disc from a rotor rotating at full speed inside a casing designed to contain a single blade. On that test we measured a zero loss of translational energy and a 10% to 20% loss of rotational energy in the fragment when it emerged from the casing. Presumably the rotational energy was absorbed in bending the blades and damaging the casing. We would expect the corresponding loss of rotational energy in the case of non-containment of a high energy disc sector to be proportionally less, because the casing has limited energy-absorbing capability.

In the case of a small fragment like a single blade, its rotational energy after release is unpredictable.

J.H. Gerstle, Boeing

I might just remark on a very slender piece of evidence that we have from some films taken at the Naval Air Propulsion Test Center involving impact against a Kevlar shield by a rotor disk burst with six equal-size fragments, the portions of rotational and translational energy loss were roughly comparable. This surprised us.

D. McCarthy, Rolls-Royce

Were you using a metal drum with a Kevlar wrapping?

J.H. Gerstle, Boeing

Yes.

D. McCarthy, Rolls-Royce

So the angles would be somewhat different from the case of going through a casing close to the blade?

J.H. Gerstle, Boeing

That's correct.