ENGINE NON-CONTAINMENT -- UK RISK ASSESSMENT METHODS

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SUMMARY

In order to establish compliance with recent changes to British Civil Airworthiness Requirements it has been necessary to develop methodology for assessment of catastrophic risks resulting from uncontained turbine engine rotors.

The methodology was developed during the course of the Concorde SST certification programme, utilising an engine failure model for the Olympus 593.

In essence this work is applicable to any aircraft type, but it has been established that some of the data used produces unrealistically pessimistic assessments.

Work continues to develop realistic guideline data for use in these assessments, which can be used for future aircraft design.

1. Introduction

Gordon Gunstone in his paper "Engine Non Containment - The U.K. C.A.A. View" has explained the thinking which has led to the latest British Civil Airworthiness Requirement in respect of engine non-containment hazards.

Alongside this one has had to develop numeric methodology by the use of which compliance with the requirement can be shown. As will be appreciated new requirements cannot be imposed overnight, and in fact the present B.C.A.R. is the culmination of some years of joint work between CAA and the British Aircraft industry, so that the methodology has tended to be developed alongside the developing requirement.

Being a numeric method, somewhat greater precision can be given to answering the question "where should minimising the risk stop?" However it must be emphasised that a numeric answer is an aid to engineering judgement and can never entirely replace it. For example, if an assessment showed compliance with B.C.A.R., but one particular risk, which could be reduced without excessive penalties, constituted a major part of the total risk, it would be expected that design action to reduce this risk would be taken.

A summary of the foregoing appears in Figure 1.

It cannot today be claimed that the methods are perfect and indeed considerably more work is required to establish satisfactory data values in certain areas which require the use of judgements. However it is hopefully of interest to members of the workshop to have some idea of the present position.

2. Background

The current B.C.A.R. is summarised in Figure 2, and employs a relatively simple failure model.

This was not always the case, and the story of the practical development of the new requirement and its associated methodology really began with the Concorde. Here, because of the relatively unorthodox layout of the aircraft, the degree of hazard minimising required for parity with subsonic types was not immediately obvious. Additionally, although the aircraft in its conception in 1962 had accounted for the possibility of turbine rupture, accumulating evidence over the years indicated the necessity for considering compressor debris as well. Not unnaturally argument developed between the constructors and the ARB (as the CAA then was) as to the required precautions. Since numerical methods of airworthiness analysis were a fundamental part of Concorde certification, it seemed logical to extend this to consideration of engine non-containment risks. It was therefore agreed to make an assessment against an engine failure model to be derived by Rolls-Royce as the most probable failure debris based on previous non-containment experience and the knowledge of the Olympus construction. This resulted in the model shown in Figure 3, which took three years and numerous meetings to produce!

The requirement was that the probability of catastrophe should not be worse than 10^{-8} per aircraft hour, and in order to achieve this a number of changes were made to the aircraft, primarily as a result of the inclusion of compressor debris. These changes are shown in Figure 4 and 5 the former indicating the armour plate necessary to prevent penetration of the fuel tanks and the latter showing systems layout and fire precautions modifications.

It will be noted that the model did not include ½ compressor disc pieces, since at the time the model was agreed, no Rolls-Royce axial engine had ever had a major compressor disintegration. Subsequent events, however, led CAA to review the situation and to require an assessment of the effect of the random release of two ½ compressor disc pieces. Since there were insufficient statistics to define the probability of the event, it was not possible to include these pieces in the model, and a new requirement criterion had to be developed. At this stage, a requirement akin to the present BCAR was introduced for the compressor ½ disc pieces, such that the probability of catastrophe per event, averaged across the flight should not be worse than a given number. Originally CAA would have liked to see 1 in 20, but this was not possible to achieve, the actual value being something like half of this. However an assessment, by the same methods and to the same standards, of a number of established aircraft showed that these aircraft had no better probability of catastrophe, and in some cases considerably worse. It was therefore apparent that parity at least with current aircraft types was established.

The final result of this effort, over a period of some six years was a certification report two inches thick and working documentation and drawings occupying over 50 cubic feet.

In retrospect this model was probably much too complicated and the precautions taken would have been similar had today's BCAR model been used, since ½ disc pieces and disc rim fragments dominated the exercise. Nevertheless it did result in the development of methodology which with further refinement can be applied to any aircraft.

3. Methodology

3.1. Basic Work

The initial stages of the assessment consist of the following steps.

a) Establish a hazard tree (Figure 6). This will essentially be the same for all aircraft, but may vary in detail, particularly where methods of operation of flying controls differ.

b) Establish debris size for each stage of the engine (Figure 7).

c) Draw plan view of fly off zone (Figure 8) for each stage, identifying potential risk items (e.g. systems, fuel tanks, other engines etc.)

d) Draw section through fly off zone (Figure 9) establishing risk angles for each item potentially at risk. It is assumed that ⅓ disc pieces will not be stopped, but in the case of the disc rim pieces, structural analysis is required to determine whether at some structural interface the piece will be stopped. The example in Figure 10 shows that engine controls and fuel tank are potentially at risk but that flying controls and electrics are not.

3.2. Data and Assumptions

3.2.1. Flight Phases

It will be remembered that the hazard assessment is averaged throughout the flight, and there will be some risks which are only present during certain phases of flight. Hence it is necessary to break down the flight to well defined phases, and while this breakdown could vary with the aircraft mission, it has been found so far that the three phases shown in Figure 11 are suitable for jet transport types.

3.2.2. Failure distribution by flight phase

In assessing the overall risks it is necessary to consider the percentage of failures occurring in each phase. In practice this can only be established statistically and Figure 12 shows the values obtained from three sources. So far, in BAC's assessments, the Rolls-Royce values have been used, but these are identical with NTSB for the phases in use. CAA's analysis gives a slightly higher weighting to the take-off phase and some re-thinking here may be necessary.

3.2.3. Guidelines

In considering the potential hazards from individual contributory factors, some items can be dealt with as matters of fact. For example in systems areas the design of the aircraft will establish clearly whether a catastrophe can or cannot occur due to the loss of a given system or systems.

In other areas, notably loss of adequate thrust, fire, and structural damage an element of judgement is required. In these cases guidelines have been discussed and provisionally agreed with CAA.

3.2.4. Loss of adequate thrust

Figure 13 shows the probability of catastrophe (i.e. of not being able to land the aircraft safely) for the loss of multiple engines. Apparent inconsistencies will be noted, and these have resulted from CAA Flight Department knowledge of the handling of the particular aircraft types considered. It is thought that for design assessment of new types, a more consistent set of numbers needs to be established.

3.2.5. Fire Hazards

Figure 14 shows the factors considered in establishing fire hazards. In this I_R, the ignition probability is a powerful factor and Figure 15 gives the CAA guideline values.

3.2.6. Structural damage

Figure 16 shows the CAA guideline for the minimum static ultimate strength requirement to be used in considering the size of catastrophic holes in primary structure.

3.3. Calculations

Having completed the basic work of section 3.1. (establishing the risk angle) and assessed the risk factor for each hazard, using where appropriate, the assumptions from section 3.2., it is now possible to draw for each flight phase and each stage a diagram of risk angle versus risk factor as shown in Figure 17. (In practice it will probably be found that one diagram covers several stages, all producing the same angles and factors.)

The individual risks are then summed as shown at the bottom of the figure, using success theory for summing overlapping risks, i.e.

$$F_{1+2} = \left[1 - (1-F_1)(1-F_2)\right]$$

Thereafter the averaging method shown on Figure 18, will result in the mean catastrophic risk to the aircraft across a typical flight mission.

4. Results

In order to validate the above methods and assumptions, BAC have been analysing a range of current aircraft to evaluate the catastrophic risk level due to $\frac{1}{3}$ disc pieces. The results appear on Figure 19, and are indeed surprising, with risks varying from 1 in 6.9 for an underwing narrowbody twin to 1 in 27.8 for a widebody trijet, with only two of the types considered meeting BCAR!

The actual in-service world wide record derived from the number of fatal accidents compared with the number of major disc releases gives a value of approximately 1 in 30. In can be argued therefore that current aircraft on average must in practice be complying with BCAR, and hence the assessments must be pessimistic.

Work is continuing to identify and study the areas of pessimism, with the objective of modifying the guidelines where necessary. As an end result it is hoped to agree a set of realistic ground rules with CAA which will be suitable for future aircraft design assessment.

Reference to Figure 19 will show that the most recurring major contributory factors are structural damage and fires, and hence these are receiving major attention.

With particular regard to critical cut lengths in fuselage structure, work is leading to a more sophisticated analysis of the residual structural strength based on the fracture toughness of the skin material and the nominal axial stress before damage (Figure 20).

Even this may still be pessimistic in meeting the requirement of Figure 16, and perhaps this requirement should be further questioned. Who, for example, on the basis of analysis, would have believed that the aircraft shown in Figure 21 could have suffered this amount of damage and survived - but it did!

5. Conclusions

Methodology has been established to assess the catastrophic risks from uncontained rotor debris, but further work is required to refine the assumptions used so as to bring the results into accord with the known facts. When this is done it should be possible, using agreed standards of assessment, to produce cost effective design precautions against rotor failure on future aircraft types.

Acknowledgements

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- METHODOLOGY DEVELOPED TO MEET NEW C.A.A. REQUIREMENTS.
- GIVES MORE PRECISION TO SAFETY ASSESSMENT-BUT:
- DOES NOT REPLACE ENGINEERING JUDGEMENT.

Figure 1. - Engine Non-containment U. K. Risk Assessment Methods.

DEBRIS TYPE	ACCEPTABLE ✱ CATASTROPHIC RISK LEVEL	N^{O} OF PIECES	SPREAD ANGLE	MASS	REMARKS
ONE-THIRD DISC FRAGMENT	1 in 20	1	± 3°	ONE-THIRD BLADED DISC MASS.	TRANSLATIONAL ENERGY (NEGLECTING ROTATIONAL ENERGY)
DISC RIM PIECE	1 in 60	1	± 5°	GREATER OF 1/20th BLADED DISC MASS OR MASS OF TWO BLADES WITH ROOTS.	TRANSLATIONAL ENERGY (NEGLECTING ROTATIONAL ENERGY)
MULTIPLE ONE-THIRD DISC FRAGMENTS	1 in 10	3	± 3°	AS FOR SINGLE ONE-THIRD DISC FRAGMENT.	APPLICABLE TO DUPLICATED OR MULTIPLICATED SYSTEMS ONLY. ENERGY AS DEFINED FOR SINGLE ONE-THIRD DISC FRAGMENT.

✱ 1. AVERAGE OF ALL DISCS & ALL ENGINES ACROSS TYPICAL FLIGHT PLAN.
2. NO SINGLE DISC MUST HAVE RISK GREATER THAN TWICE THE REQUIRED AVERAGE RISK.

Figure 2. - BCAR Engine Failure Model.

	DEBRIS TYPE	CONTRIBUTION PER 10^6 A/C HOURS		Nº OF PIECES	SPREAD ANGLE	REMARKS
TURBINE	1/3 BLADED DISC	·05	·75	2	± 3°	EQUAL PROBABILITY OVER 360° TRANSLATIONAL ENERGY
	MINOR DISC FRAGMENTS	·20		1	± 5°	RIM PIECE & BLADES WITH SIZE & ENERGY VALUE DEFINED FOR EACH STAGE.
	BLADES (HIGH ENERGY)	·08		2	± 30°	MAX BLADE ENERGY
	BLADES (LOW ENERGY)	·40		1	± 30°	55% OF MAX BLADE ENERGY
	MULTIPLE BLADES	·02		N/3 - 120° SPREAD N/12 - 30° SPREAD	± 30°	ALL BLADES 100% ENERGY
COMPRESSOR	DISC RIM PIECE	·05	·25	1	± 5°	RIM PIECE & BLADES WITH SIZE & ENERGY VALUE DEFINED FOR EACH STAGE
	BLADES (HIGH ENERGY)	·05		2	± 30°	MAX BLADE ENERGY
	BLADES (LOW ENERGY)	·15		1	± 30°	55% OF MAX BLADE ENERGY

Figure 3. - Olympus 593 Failure Model.

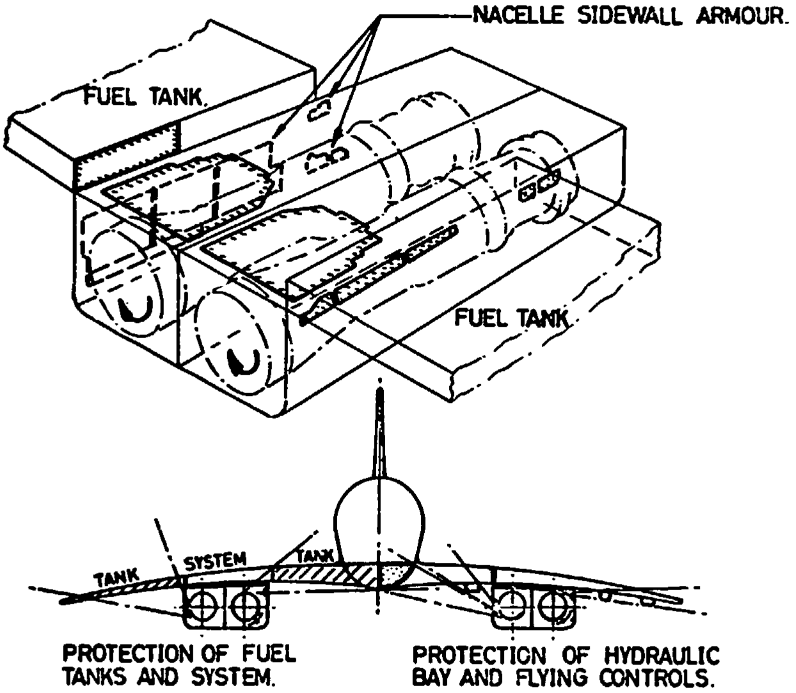


Figure 4. - Concorde-Armour Plate.

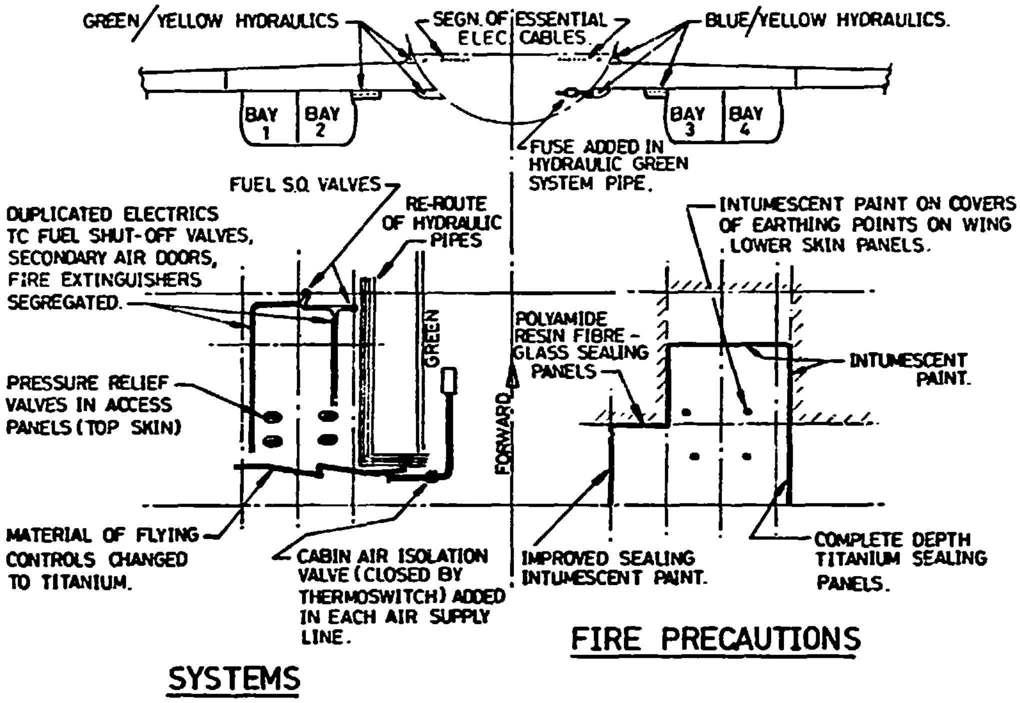


Figure 5. - Concorde - Design Precautions to Minimise Rotor Failure Damage.

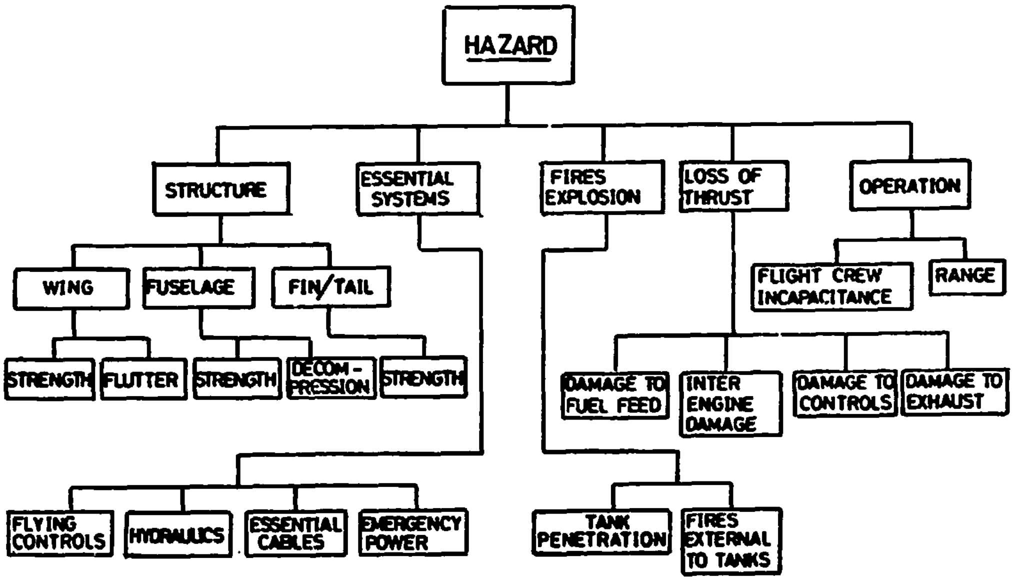
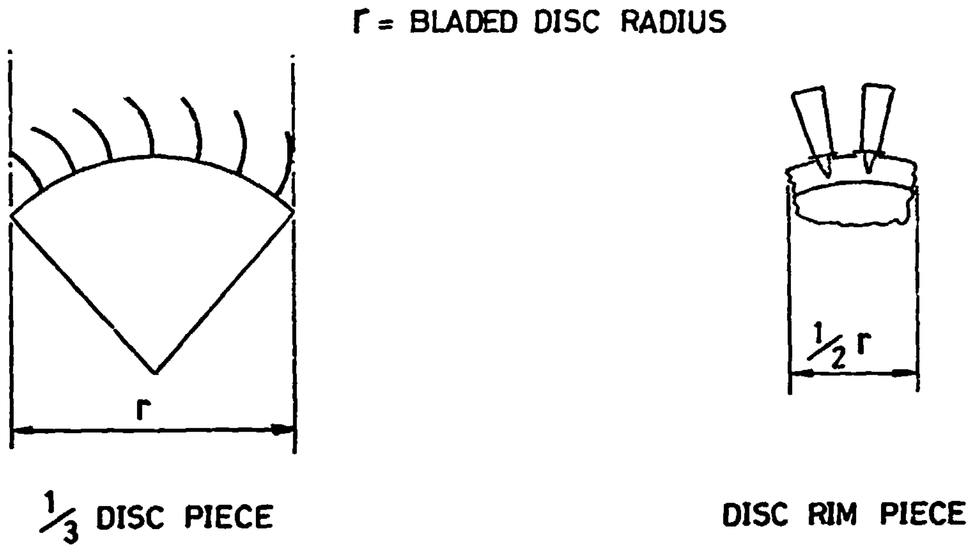


Figure 6. - Engine Rotor Failure - Hazard Tree.



1/3 DISC PIECE

DISC RIM PIECE

Figure 7. - BCAR Debris.

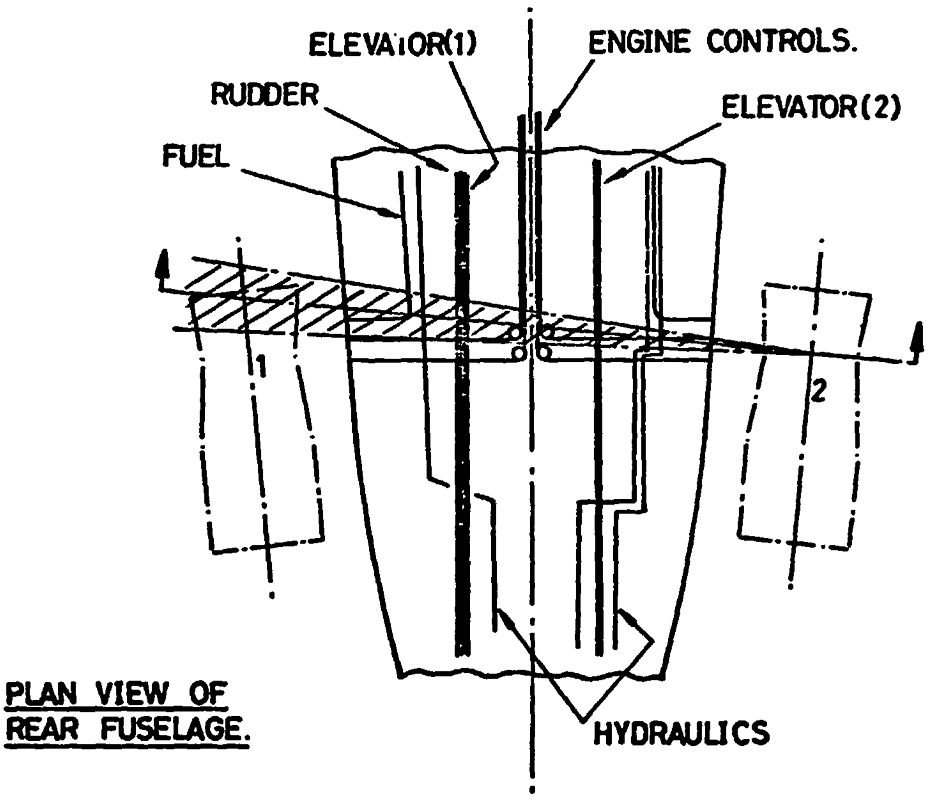
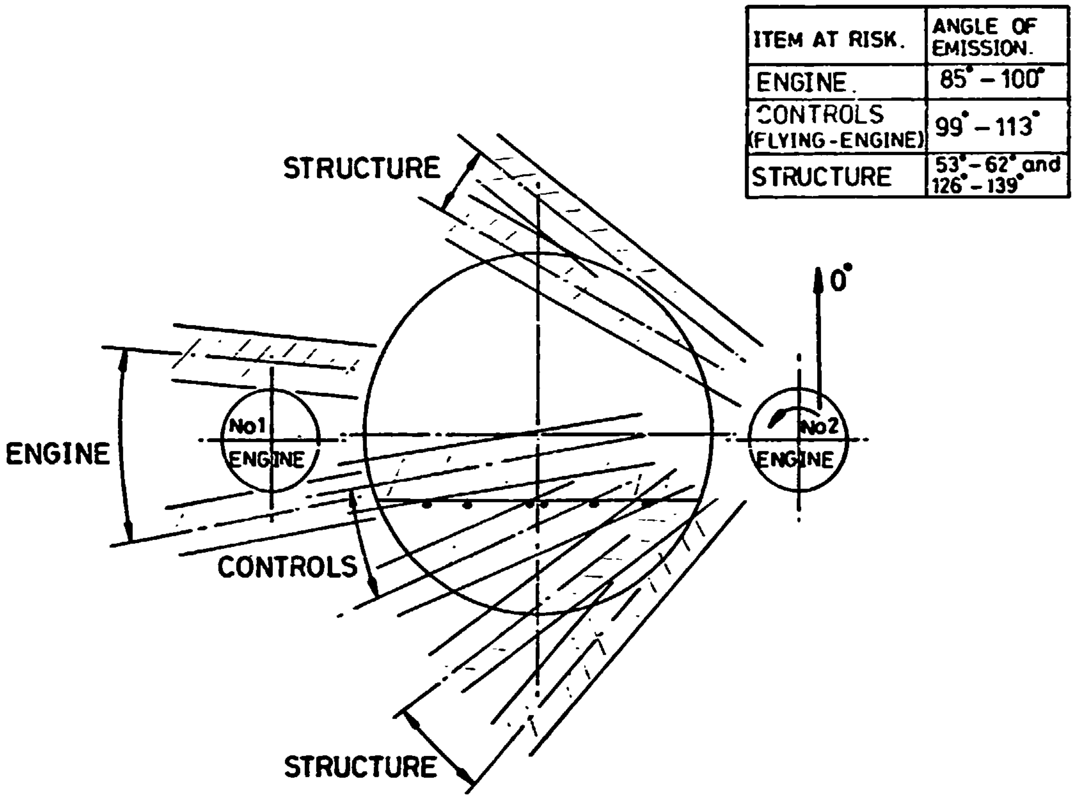


Figure 8. - Typical Fly Off Zone.



ITEM AT RISK.	ANGLE OF EMISSION.
ENGINE.	85° – 100°
CONTROLS (FLYING-ENGINE)	99° – 113°
STRUCTURE	53° – 62° and 126° – 139°

Figure 9. - Debris Trajectories.

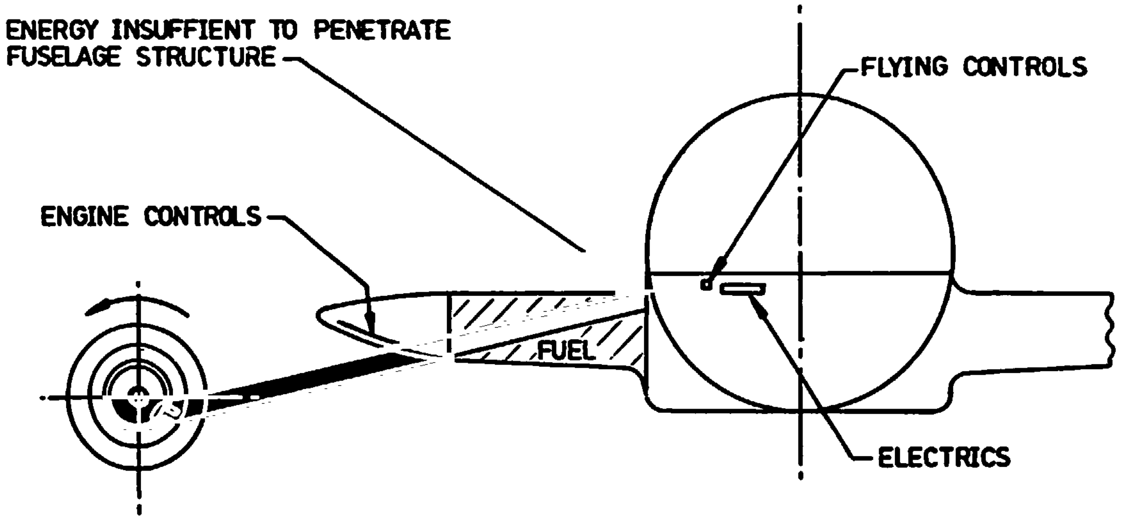


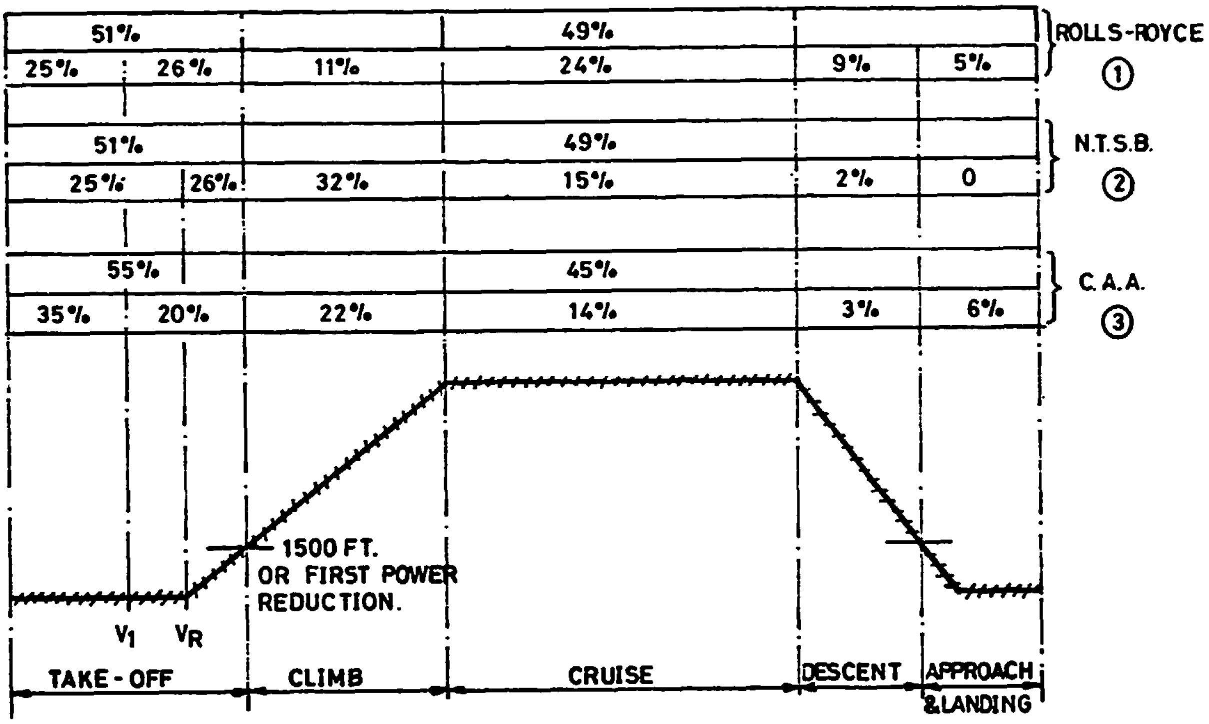
Figure 10. - Structurally Limited Trajectory.

1. TAKE OFF – START OF ROLL TO V_1.

2. TAKE OFF – V_1 TO 1,500 FT.

3. POST TAKE OFF – 1500 FT TO TOUCHDOWN.

Figure 11. - Flight Phase Breakdown.



	TAKE-OFF		CLIMB	CRUISE	DESCENT	APPROACH & LANDING
ROLLS-ROYCE ①	51%		49%			
	25%	26%	11%	24%	9%	5%
N.T.S.B. ②	51%		49%			
	25%	26%	32%	15%	2%	0
C.A.A. ③	55%		45%			
	35%	20%	22%	14%	3%	6%

① ROLLS-ROYCE ENGINES (1954-1970 STATISTICS)

② N.T.S.B. REPORT NTSB-AAS-74-4.

③ CAA - GUNSTON, "ENGINE NON CONTAINMENT - THE UK CAA VIEW."

Figure 12. - Distribution of Uncontained Failures Over Flight Phases.

FLIGHT PHASE	NO OF ENGINES LOST				AICRAFT TYPE
	1	2	3	4	
0 TO V_1	0	0			REAR OR UNDERWING ENGINED TWIN-JET.
V_1 TO 1,500FT	0	·7			
POST 1,500FT	0	·6			
0 TO V_1	0	0	0		REAR ENGINED TRI-JET
V_1 TO 1,500FT	0	·4	·85		
POST 1,500FT	0	0	·75		
0 TO V_1	0	0	0	0	FOUR REAR MOUNTED ENGINES.
V_1 TO 750 FT	0	·8	·8	·8	
750 TO 1500FT	0	·2	·5	·8	
POST 1500 FT	0	0	·2	·7	
0 TO V_1	0	0	N/A	0	FOUR UNDERWING PODDED ENGINES.
V_1 TO 1,500 FT	0	·25	N/A	·7	
POST 1,500 FT	0	0	N/A	·6	

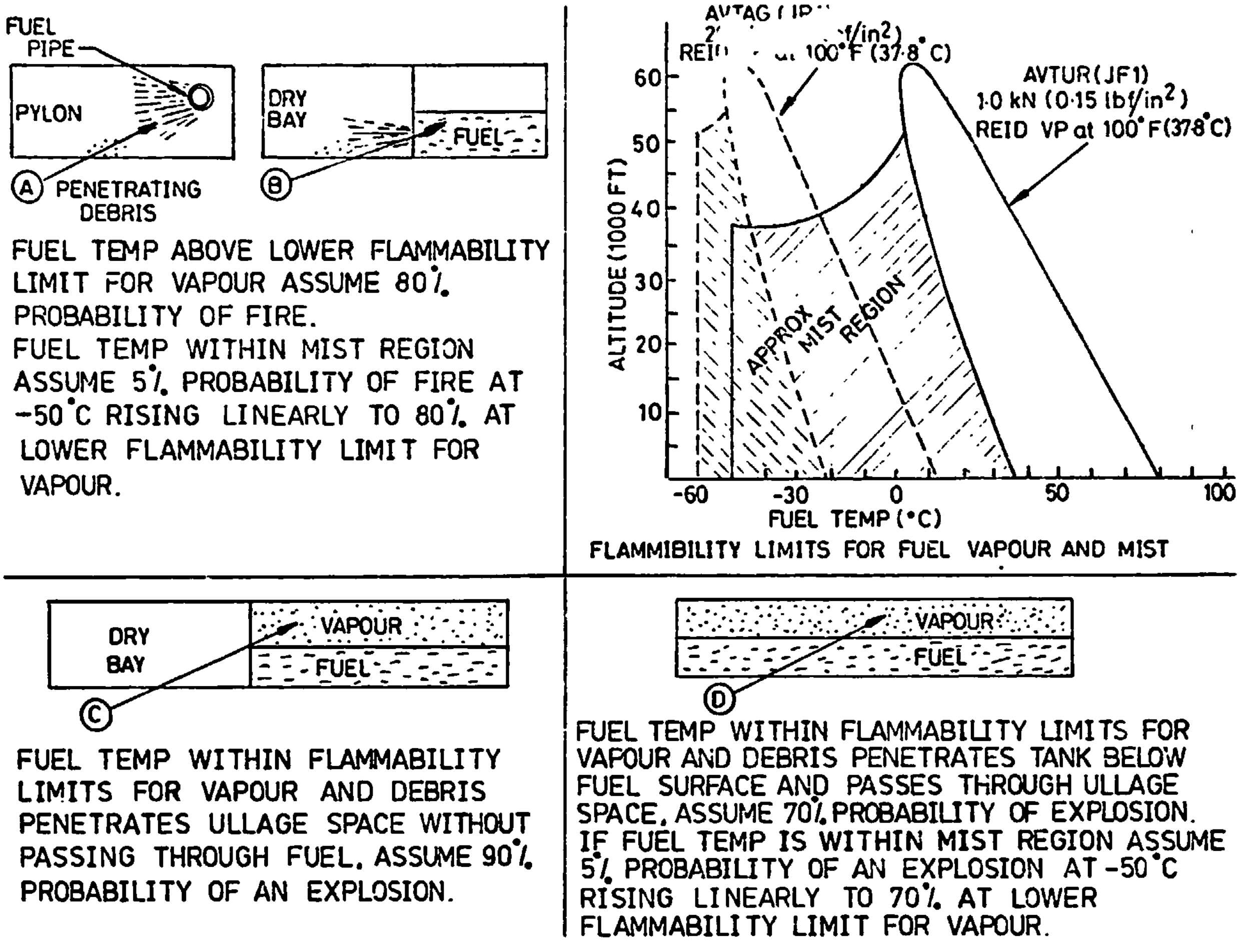
Figure 13. - Risk Factors for Loss of Thrust. (Expressed as a fraction of 1.)

RISK FACTORS / FLIGHT PHASE	T_R	I_R	H_R	L_R	E_R
GROUND ROLL TO V_1					
V_1 TO 1,500 FT					
POST 1,500 FT					

T_R = PROPORTION OF FLIGHT PHASE THAT FUEL IS PRESENT IN PENETRATED TANK.
I_R = IGNITION PROBABILITY.
H_R = PROBABILITY OF FIRE SITUATION BECOMING POTENTIALLY CATOSTROPHIC.
L_R = PROBABILITY OF NOT LANDING SAFELY AND EVACUATING PASSENGERS WITH POTENTIALLY CATASTROPHIC FIRE.
E_R = PROBABILITY OF A CATASTROPHIC EXPLOSION AT INSTANT OF PENETRATION = I_R X STRUCTURAL RESISTANCE TO OVERPRESSURE.

PROBABILITY OF CATASTROPHE = $(T_R \times I_R \times H_R \times L_R) + E_R$

Figure 14. - Risk Factors for Fuel Tank Fire and Explosion.



FUEL TEMP ABOVE LOWER FLAMMABILITY LIMIT FOR VAPOUR ASSUME 80% PROBABILITY OF FIRE.
FUEL TEMP WITHIN MIST REGION ASSUME 5% PROBABILITY OF FIRE AT -50°C RISING LINEARLY TO 80% AT LOWER FLAMMABILITY LIMIT FOR VAPOUR.

FUEL TEMP WITHIN FLAMMABILITY LIMITS FOR VAPOUR AND DEBRIS PENETRATES ULLAGE SPACE WITHOUT PASSING THROUGH FUEL. ASSUME 90% PROBABILITY OF AN EXPLOSION.

FUEL TEMP WITHIN FLAMMABILITY LIMITS FOR VAPOUR AND DEBRIS PENETRATES TANK BELOW FUEL SURFACE AND PASSES THROUGH ULLAGE SPACE. ASSUME 70% PROBABILITY OF EXPLOSION. IF FUEL TEMP IS WITHIN MIST REGION ASSUME 5% PROBABILITY OF AN EXPLOSION AT -50°C RISING LINEARLY TO 70% AT LOWER FLAMMABILITY LIMIT FOR VAPOUR.

Figure 15. - Ignition Risk Factors, I_R.

A. 70% LIMIT FLIGHT MANOEUVERING LOAD.
20 FT/SEC EAS GUST (VERTICAL OR LATERAL) AT Vc COMBINED WITH MAXIMUM CABIN DIFFERENTIAL PRESSURE (PLUS AERODYNAMIC SUCTION).

B. 1·1 (MAXIMUM NORMAL CABIN DIFFERENTIAL PRESSURE AT TIME OF INCIDENT PLUS AERODYNAMIC SUCTION) PLUS 1g FLIGHT LOAD FREEDOM FROM FLUTTER UP TO Vc.

Figure 16. - Minimum Static Ultimate Strength Requirement.

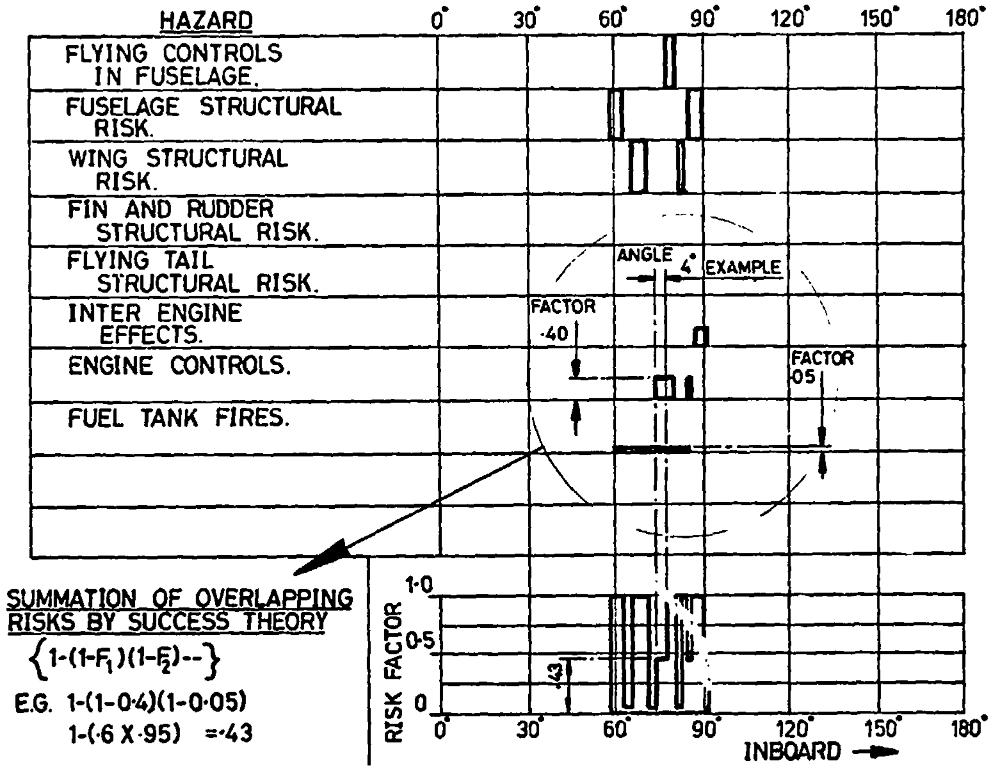


Figure 17. - Hazard Summary Diagram.

FOR EACH ENGINE STAGE IN EACH FLIGHT PHASE

- DERIVE POTENTIALLY CATASTROPHIC ANGLES ($\propto$) FOR EACH HAZARD.
- DERIVE RISK FACTOR (F) FOR EACH HAZARD.
- CALCULATE COMBINED RISK FACTOR (C_{SP}) FOR THE PHASE AND AVERAGE OVER 360° (n RISKS)

$$C_{SP} = D_P \times \left(\propto_1 F_1 + d_2 F_2 \cdots \propto_n F_n \right) \quad D_p = \text{PHASE FAILURE DISTRIBUTION.}$$

THEN

- SUM COMBINED RISK FACTOR FOR THE STAGE OVER THE TOTAL FLIGHT ('P' PHASES) TO OBTAIN OVERALL STAGE RISK (C_S).

$$C_S = C_{SP_1} + C_{SP_2} \cdots C_{SP_p}$$

- AVERAGE ALL STAGES OVER THE TOTAL ENGINE ('S' STAGES) TO OBTAIN MEAN ENGINE RISK (C_E)

$$C_E = \frac{C_{S_1} + C_{S_2} \cdots C_{S_S}}{S}$$

- AVERAGE ALL ENGINES OVER THE AIRCRAFT ('E' ENGINES) TO OBTAIN MEAN AIRCRAFT RISK (C_A)

$$C_A = \frac{C_{E_1} + C_{E_2} \cdots C_{E_E}}{E}$$

Figure 18. - Engine Rotor Failure - Risk Evaluation.

AIRCRAFT TYPE	CATASTROPHIC RISK RATIO	MAJOR CONTRIBUTARY FACTORS.
TWO REAR ENGINES - NARROWBODY	1 IN 23·3	1. LOSS OF ADEQUATE THRUST. 2. FUSELAGE STRUCTURAL DAMAGE.
TWO UNDERWING ENGINES - NARROWBODY	1 IN 6·9	1. FUEL TANK FIRES.
THREE REAR ENGINES - NARROWBODY	1 IN 9·2	1. FUSELAGE/FIN STRUCTURAL DAMAGE 2. FIRE. 3. LOSS OF ADEQUATE THRUST.
FOUR REAR ENGINES - NARROWBODY	1 IN 12·7	1. LOSS OF ADEQUATE THRUST.
FOUR UNDERWING ENGINES - NARROWBODY	1 IN 15·8	1. WING STRUCTURAL DAMAGE. 2. FUSELAGE STRUCTURAL DAMAGE.
ONE REAR, TWO UNDERWING ENGINES - WIDE BODY	1 IN 27·8	1. FUSELAGE STRUCTURAL DAMAGE. 2. WING STRUCTURAL DAMAGE.
FOUR UNDERWING ENGINES WIDE BODY	1 IN 15·9	1. WING STRUCTURAL DAMAGE. 2. FUSELAGE STRUCTURAL DAMAGE.

ALL TYPES - WORLDWIDE STATISTICS	APPROX. 1 IN 30	—

Figure 19. - Summary of BAC Assessments for Single 1/3 Disc Piece.

AN APPROXIMATION OF CRITICAL CRACK LENGTH FOR CATASTROPHIC CIRCUMFERENTIAL FUSELAGE DAMAGE IS GIVEN BY THE FOLLOWING, AND MAY BE USED FOR CRACKS OF UP TO 100 INCHES IN LENGTH.

$$\text{CRACK LENGTH} \quad 2a_c = \frac{2}{\pi}\left(\frac{1{\cdot}74\, K_c}{\sigma}\right)^2$$

WHERE K_c = FRACTURE TOUGHNESS OF SKIN MAT$^{\underline{L}}$.

σ = NOMINAL AXIAL STRESS BEFORE DAMAGE UNDER CRITICAL LOADING CASE

Figure 20. - Catastrophic 1/3 Disc Fuselage Damage.

Figure 21. - Fuselage Damage - BAC 1-11.

DISCUSSION

John Meaney, Rohr

I have a question on the armor plate slide that you showed on the Concorde. What material is that and what total weight impact was it, and what was the largest energy magnitude that your're trying to absorb?

J.C. Wallin, BAC

The material was titanium. We looked at a number of different materials including non-metallics and so on, and found in the end that titanium was the lightest that we could use. For our testing the fragment that we dealt with was a full energy single blade which in the failure model was the equivalent (in energy terms) of a disk ring piece plus a couple of blades, (which having penetrated the casing, will have lost some energy).

From the point of view of armor design, the single blade was a critical piece because, of course, you had the highest impact pressure (acting on the small area). We designed on that criterion. The actual weight we added to the airplane was something of the order of a thousand pounds. I said earlier (when I was commenting on I think it was Ken Forney's talk this morning) it could well be that in the case of an airplane of this particular configuration that the extra containment within the engine to cope with a rim-and-three-blades piece might have been more cost-effective. But I think that is applicable only to this configuration of airplane.

J. Meaney, Rohr

What titanium metal alloy was used? For these pieces that you tested, what weights and velocities were used?

J.C. Wallin, BAC

The material is commercially pure titanium. The biggest piece we had to deal with was an LP 1 blade, which was five pounds in weight, with a velocity of 680 fps.

J. Gausselin, Rockwell International

In 1972 you people conducted tests, firing projectiles into fuel tanks, to simulate the fan blades you were talking about. These were preliminary tests and the conclusions were preliminary. You may be doing more testing. I haven't seen anything further in this program. Are you doing anything further and if so, where can the results be obtained?

J.C. Wallin, BAC

At the time we had to deal with the fuel tanks because we thought that blades being fired into fuel tanks (where the blade passed through the fuel before it got into the vapor space), was probably not a very high ignition risk. So we started doing these tests to try to generate some data to prove our case if you like. Now, in point of fact what we came up with was that within the first six firings, we generated four explosions, due to titanium blades nicking structure. We had been looking at the prime ignition source as being the blade temperature. What we found was that when we fired the blade into a representative tank, as soon as the blade hit the structure inside the tank, even though it passed through the fuel in the first place, we actually generated sparks of sufficient magnitude to set off the explosion. At that point we abandoned our original line of thinking and, therefore, abandoned the tests. I think in that respect, even if we had been right in our original thinking, the cost of the testing we would have had to have done to prove our case would have been so high that we would probably have abandoned it anyway. This was because we would have needed to do it a thousand times or so with no ignition to prove the case statistically. Since we could, in fact, get explosions in the tank if titanium blades were being fired into it, we faced up to the facts and decided to develop our armor for the tanks.

One other thing that we found in general, both in the case of firing into tanks and also doing our armor testing, was that a lot of the information which you get from ballistic firings (typical of military projectiles) is totally irrelevant to the engine burst case where one is dealing with non-uniform shapes and sharp corners. With things of that sort, the results can be very different from those derived from bullet firings.