ROTOR BURST PROTECTION PROGRAM: EXPERIMENTATION TO PROVIDE GUIDELINES FOR THE DESIGN OF TURBINE ROTOR BURST FRAGMENT CONTAINMENT RINGS*

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ABSTRACT

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Presented are the results of a program of rotor burst containment experimentation that provides guidelines for the design of optimum weight turbine rotor disk fragment containment rings. These guidelines were derived by establishing the relationships between a measure of the ring's capability to contain fragment energy with respect to it's weight (the specific contained fragment energy - SCFE - derived by dividing the rotor burst energy by the weight of ring required to contain this energy) and other significant ring and rotor variables such as the: rotor tip diameter; number of rotor fragments; and ring radial thickness and axial length. The experiments consisted mainly of bursting 14 and 31 inch diameter turbine rotors into encircling containment rings made from centrifugally cast 4130 steel. Rules are given for achieving optimum weight ring designs.

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SUMMARY

The program of parametric rotor burst containment experimentation being reported was developed and conducted by the Naval Air Propulsion Test Center (NAPTC) under National Aeronautics and Space Administration (NASA) sponsorship. The program was structured to develop guidelines for the design of optimum weight turbine rotor disk fragment containment rings. The design guidelines were generated by experimentally establishing the relationship between a specific energy variable that provides a measure of ring containment capability, and several select variables which characterize those configurational aspects of the containment rings and rotor fragments that significantly influence the fragment containment process.

The program consisted of a series of rotor burst containment experiments in which rotors of two different diameters were modified to burst at their respective design speeds into various numbers (2, 3 and 6) of pie-sector shaped fragments. These fragments impacted rings made from 4130 cast steel that encircled the rotors at a radial clearance of 0.5 inches (0.0127 m). The ring axial lengths were varied in three discrete steps of 1/2, 1, and 2 times the rir axial length of the rotors used. The radial thicknesses of the rings were varied until fragment containment was achieved, thus establishing the weight of ring required. The results of test provided the guidelines necessary to design an optimum weight steel containment ring for small rotors. The optimum weight ring was 8.6 lbs (3.9 kg) for a 14 inch (0.356 m) diameter rotor having a burst energy of 10^6 in-lbs (3511.6 J) at its design speed of 20,000 rpm (2094 rad/s). This weight decreased slightly with the number of fragments generated at burst in the range of from 2 to 6. The results also indicated that the weight of steel ring required to contain the pie-sector fragments from an average size commercial engine turbine rotor (31 inch (0.787 m) diameter) having a burst energy of 10 X 10^6 in-lbs ([illegible]16 J) would be in excess of 168 lbs (76.2 kg) for 2 and 3-fragment bursts and in the neighborhood of 150 lbs (68 kg) for a 6-fragment burst. Unlike the small rotor containment ring characteristics, the weight of ring required to contain these larger rotors was clearly dependent on the number of fragments generated at burst.

It was also found that a composite ring made from boron carbide backed with filament wound fiberglass in an epoxy matrix contained the fragments from the small rotor burst at a weight reduction of 30% compared to steel. This represents a significant weight reduction configuration that warrants further exploration.

It would appear from the results of this effort that the steel rings required to contain the fragments generated by the burst of an average size turbine rotor (the larger of the two rotors tested) from a commercial engine would be heavy for aircraft application. However, the use of optimally configured composite rings for fragment containment and partial rings for fragment deflection, which are systems that show great promise for light-weight protection, should be thoroughly investigated.

INTRODUCTION

This is a report on the Rotor Burst Protection Program (RBPP), which is sponsored by the National Aeronautics and Space Administration (NASA) and conducted by the Naval Air Propulsion Test Center (NAPTC). The objective of this program is to develop guidelines for the design of devices that will be used on aircraft to protect passengers and the aircraft structure from the lethal and devastating fragments that are generated by gas turbine engine rotor bursts.

Presented in this report are the results of a parametric test program that was conducted by the NAPTC to provide guidelines for the design of turbine rotor fragment containment rings. This program was a sequel to, and to a large extend guided by, the exploratory testing that was conducted by NAPTC and reported in reference (a).

CONCLUSIONS

1. Regarding the containment of typical, relatively small (14 inch (0.356 m)) diameter, axial flow turbine rotors that burst at their design speeds into various numbers of pie-sector shaped fragments having a total energy of approximately 10^6 in-lbs (3511.6 J):

a. Containment of these fragments can be achieved using rings described as follows:

(1) Rings made from 4130 cast steel weighing 8.6 lbs (3.9 kg).

(2) Laminated rings consisting of boron-carbide backed with fiberglass weighing 6.02 lbs (2.71 kg).

b. Optimum weight for the steel containment ring configuration was achieved when the ring axial length was made equal to that of the rotor; making the ring twice or half as long as the rotor axial length resulted in containment rings that were heavier and therefore less than optimum with respect to weight.

c. With the steel ring axial length at it's optimum value with respect to weight, the ring thickness and therefore its weight is, for practical purposes, independent of the number (ranging from 2 to 6) of equal pie-sector shaped rotor fragments generated at burst.

2. Regarding the containment of typical relatively large (31 inch (0.787 m)) axial flow turbine rotors that burst at their design speeds into various numbers of pie-sector shaped fragments having a total energy of approximately 10 X 10^6 in-lbs (35116 J):

a. Rings made from relatively brittle 4130 cast-steel weighing in excess of 168 lbs (76.2 kg) will be required to contain 2 and 3 fragment rotor bursts. A ring of the same material weighing in the neighborhood of 150 lbs (68 kg) will be required to contain a 6-fragment burst.

b. The optimum weight of 4130 cast-steel ring required for containment is dependent on the number of pie-sector shaped fragments generated at burst in the range of from 2 to 6 fragments. The weight will increase as the number of such fragments decreases.

RECOMMENDATIONS

1. Experimentation and analysis should be continued on a limited basis to establish the baseline or reference steel ring weight required to contain 2 and 3 fragment large rotor bursts.

2. Because the weight of steel rings required to contain the pie-sector shaped burst fragments from an average size commercial engine turbine rotor appears to be excessively high, the following two facets of rotor burst protection should be further investigated and design guidelines developed:

a. The use of multi-layered, multi-material rings for containment applications, and

b. The use of partial rings to control the trajectories of rotor burst fragments (directing them away from the more vital areas of the aircraft into the less or negligibly sensitive areas) as a means of providing a "degree" of protection at reduced weight.

PROGRAM DESCRIPTION

A. Concept Development

1. The program of parametric turbine rotor fragment containment testing that is being reported was structured to develop empirical guidelines for the design of minimum weight turbine rotor disk fragment containment rings made from a monolithic metal.

The empirical design guidelines were generated by experimentally establishing the relationship between a variable that provides a measure of containment ring capability and several other variables that both characterized the configurational aspects of the rotor fragments and containment ring; and had been found from exploratory testing to have had significant influence on the containment process.

The variable that provided this measure of containment ring potential or capability was termed the Specific Contained Fragment Energy (SCFE) and was derived by dividing the rotor fragment energy at burst by the ring weight required to contain this energy. The SCFE was the dependent variable of test.

2. The four ring and rotor characteristics that were chosen for test because of their suspected influence on the containment process, and varied during test to establish what this influence was (as measured by the SCFE) were as follows:

a. The ring inner diameter. Two diameters, one approximately twice as large as the other (31.64 and 15 inches) were used for test with rotors having correspondingly larger and smaller tip diameters (the CWJ65 and GET58 engine turbine rotors having tip diameters of 30.64 (.778 m) and 14 (0.356 m) inches, respectively). The burst energies of these rotors at their nominal design speeds were 10 X 10^6 and 10^6 in-lbs (35116 and 3511.6J) for the larger and smaller rotor, respectively. Burst fragment energy (speed) was held constant from test to test as a function of rotor size; the larger rotor having the higher energy.

b. The ring axial length. Three lengths were used that corresponded to 1/2, 1 and 2 times the rim axial lengths of the large and small rotors which were nominally 1.25 and 1 inch (.032 and .0254 m), respectively.

c. The number of rotor fragments generated at burst. The rotors were modified to fail at their respective design speeds of 8,500 rpm (890. rad/s) (J65 rotor) and 20,000 rpm (2094 rad/s) (T58 rotor) and produce pie-sector shaped fragments having included angles of 60° (1.0472 rad), 120° (2.0944 rad) and 180° (3.1416 rad). These were termed 6, 3 and 2-fragment rotor bursts, respectively.

d. The ring radial thickness. The ring thickness was varied until fragment containment was achieved for the different combinations of ring (rotor) diameter; ring axial length; and number of rotor fragments.

The resultant test matrix for this test program is shown in Figure 1; and the procedure for ring thickness variation to achieve containment is shown schematically in Figure 2.

3. Other variables which would, in some way, influence the magnitude and orientation of the forces that create the deformations and displacements of the ring and rotor fragments, and therefore govern the containment process are as follows:

a. The mechanical properties of the rotor and ring materials.

b. The fragment velocities.

c. The fragment masses and mass distributions.

d. The rotor-to-ring radial tip clearance.

e. The rotor tip-to-hub diameter or radius ratio.

Although these factors would significantly influence the containment process, with the exception of the ring material used for containment, the variability of these factors, as a function of rotor size, are constrained within relatively narrow limits by the dictates of rotor aerothermal and structural design. For all practical purposes then, for a given rotor size, these factors would be essentially invariate and the results generated by the experiments conducted would be generally applicable to all turbines as a function of rotor size. This would be so because the experimental scheme presented incorporates, either purposely through the variables of test or inherently because actual rotors are used, all of the factors that could (with the exception of ring material properties) significantly influence the rotor fragment containment process.

Although the mechanical properties of the materials used to make a containment ring can vary widely and are considered to be important factors in containment ring design, the ring material used in most of the tests conducted was the same from one test to another. The material was 4130 cast steel. This was done to generate a baseline for materials comparison in subsequent tests, and to establish the effects of the other variables on the containment process exclusive of material influences. Later when these effects are firmly established, the influence of ring materials will be more fully explored. In fact, during the tests conducted the use of composite rings as containment devices were cursorily investigated.

B. Design Guidelines Synthesis

1. The conceptual functional relationship between the dependent (SCFE) and independent (t, ALR, NF, ID) variables of test are presented conceptually in Figure 3. Once these relationships are established through test, they provide all the information that is needed to design an optimum weight steel ring for a turbine rotor fragment containment application. Given these relationships, the procedure would be as follows:

a. Three basic things would have to be known about the rotor to proceed with the design analysis:

(1) The kinetic energy (KE_R) of the rotor at burst

(2) The rotor tip diameter, and

(3) The rotor rim axial length.

These are characteristics that are usually known or can be easily calculated by a designer.

b. The relationships between the SCFE, the number of fragments and rotor diameter, with the ratio of ring to rotor rim axial length as the parameter, provide an indication of the worst combination of burst conditions for the size rotor being considered; i.e., the lowest SCFE. For a given analysis, this value of SCFE would be obtained from the curves in Figure 3 (or equations derived from regression analyses of the data points developed through test) for the size rotor being considered; the number of rotor fragments that result in producing the most adverse containment condition with respect to weight of ring (the lowest SCFE value in the SCFE-NF plane; and the optimum ring to rotor rim axial length ratio ($L_{RG}/L_{RT} \equiv ALR$)), which is represented by the highest contour line. The SCFE value that is obtained by this exercise is divided into the total anticipated energy of the rotor to yield the optimum (lowest) weight steel ring that will be required to contain the fragments. This procedure is expressed in equation (1).

$$(1) \quad W_t = \frac{KE_R}{SCFE}$$

The weight so derived is then used in the following equation (2) which expresses the thickness of ring required for containment as a function of all the other known dimensional variables.

$$(2) \quad t = \left[R_i^2 + \frac{W_t}{\rho \pi L_{RG}} \right]^{\frac{1}{2}} - R_i$$

Of course the value of weight derived in equation (1) can be substituted in equation (2) to yield perhaps a more useful form; equation (2a)

$$(2a) \quad t = \left[R_i^2 + \frac{KE_R}{\rho \pi L_{RG}\ SCFE} \right]^{\frac{1}{2}} - R_i$$

where

t = ring radial thickness required for containment

R_i = ring inner radius, which, for practical considerations, equals the rotor tip radius because rotor-to-casing operational clearances and considerations of minimum ring weight dictate that the ring and rotor radius be equivalent as possible.

L_{RG} = ring axial length: Derived by the multiplication of the optimum ALR (parameter of highest contour in Figure 3) and the rotor rim axial length L_{RT}.

c. This data synthesis and design analysis would provide the lightest weight steel ring configuration (ID, radial thickness, and axial length) that would be needed to contain the fragments generated by a turbine rotor burst of known size and energy. The analysis is generally applicable to axial flow turbines from aircraft gas turbine engines because, as mentioned previously, of the inherent operational and configurational similarities between turbines of a given size.

C. Test Procedures and Methods of Analysis

1. Test Procedures

Testing was conducted in the NAPTC Rotor Spin Facility (RSF), the detailed capabilities and description of which are contained in reference (b). The test set-up and procedures were basically the same for each test conducted: Rings being evaluated for their containment capability as measured by the SCFE were sandwiched between rigid steel plates and positioned so that they concentrically encircled rotors that were vertically suspended (plane of rotation horizontal) in the spin chamber from the output shaft of the air turbine motor used to spin the rotors to their burst speed. This set-up is shown in Figure 4. The radial tip clearance between the rotor and ring was maintained at 0.50 inch (1.27 cm). The two different size rotors described previously were modified, as shown in Figure 5, to fail into 2, 3 and 6 pie-sector shaped fragments at their nominal operational design speeds.

During test, the spin chamber was evacuated to a vacuum pressure of 10mm Hg to minimize the drive power required to accelerate the rotors to burst speed.

2. Methods of Analysis

Because of the nature of the test program conducted, the analysis of results was relatively straight forward; it depended on two things:

a. Whether or not the ring being subjected to test contained the rotor fragments generated.

b. And if it did contain, what was the associated ring SCFE (by definition no SCFE could be derived for a ring that did not contain the fragments).

As previously mentioned, the SCFE for a ring is derived by dividing the rotor fragment burst energy by the ring weight required for containment. For the tests conducted, two axial flow turbine rotor configurations having different tip diameters (14 and 30.64 inches) bursting at their respective operational design speeds (20,000 and 8,500 rpm) were used. Therefore, from test to test, the rotor burst energy was held constant as a function of rotor size. However, variations in burst energy for a given rotor size did occur during test because of small unpredictable variations in rotor burst speed. These variations stemmed from such factors as: material property scatter; dimensional tolerance differences; flaws or cracks (scrap turbine rotors from high time military engines were used); and other such inherent and induced rotor to rotor anomalies. To account for these "experimental" variations in analyzing the burst test results, the policy was adopted whereby results which had a speed variation greater than ± 2.5% of the design burst speed were not used for analytical purposes; i.e., assessment of a ring's SCFE. The reason for not using the results of a low burst speed (and therefore low energy) test is obvious: It would mistakenly give a lower and therefore erroneously conservative SCFE value for a particular ring configuration. The reason for rejecting the results of a higher burst speed was more subtle and was based on the fact that materials exhibit strain rate sensitivity. Under singularly optimum conditions, it might be possible to derive an erroneously high SCFE from a higher than "rated" burst speed because of a favorable material rate sensitivity. This would indicate that a lighter than required ring would be suitable for containment when in fact at rated speed it would not.

3. In this report, the results of analysis will be presented graphically by indicating the range of SCFE based on the acceptable speed variation (± 2.5%) and the SCFE based on the actual burst speed.

4. The other element beside speed that established the rotor energy at burst was the mass moment of inertia of the two turbine rotors used for test. The values of inertia for each rotor were determined experimentally using the well known torsional pendulum method (reference c).

RESULTS AND DISCUSSION

A compendium of the pertinent test and calculated data used in this report are presented in Appendix A.

The results of test are presented in plotted form in Figures 6, 7, 8, 14 and 15. These plots are actually plane sections of the conceptual three dimensional (variable) plot shown in Figure 3, but in these instances using the test data developed. The intent here is to clearly show, where possible, the functional relationship between the SCFE and the significant test variables: inner ring diameter (ID_R); number of fragments (NF); and ring axial length (ALR).

a. SCFE - NF Relationship for Small Rotors; Figure 6. It can be seen from these curves that for small rotor containment the SCFE is for all practical purposes independent of the number of pie-sector shaped fragments generated at burst. This indicates that rings of the same weight would be required for containment regardless of the number of fragments generated at rotor burst in the range of from 2 to 6 fragments and having a total (translational and rotational) energy content of approximately 10^6 in-lbs. A corollary to this would be that a worst fragment number condition for small rotor containment with respect to ring weight does not exist.

b. SCFE - ALR Relationship for Small Rotors; Figure 7. The relationship shown in this Figure indicates that an optimum value for ring axial length exists. For the size rotor tested, an optimum lightweight ring for containment is derived when the axial length of the ring is made equal to that of the rotor; that is where ALR = 1.

c. SCFE - ID_R Relationship for 2, 3 and 6 Fragment Bursts at ALR = 1; Figure 8. First of all, these relationships are incomplete except for the 6-fragment data because the radial thickness required for large rotor containment of the 2 and 3-fragment bursts exceeded that which was available from inventory (4130 cast steel circular rings with an ID of 31.64 inches (0.804 m) and having a maximum radial thickness of 4.1875 inches (.106 m)). The relationship shown in Figure 8 indicates that the amount of fragment energy that a pound of ring material can contain decreases when the rotor size and energy content increases; that is for the same ring to rotor axial length ratio, ring material, and number of fragments generated at burst, the containment capability of the larger ring, as measured by the SCFE (on a contained energy per unit weight basis) is lower than a small ring. This indicates that the practice of extrapolating small rotor containment ring results to large rotor containment ring applications would be very tenuous. To provide some feel for the ring and fragment distortions that normally accompany the containment process, the post-test conditions of rings and rotors from several selected tests (both contained and uncontained) are shown photographically in Figures 9 through 13.

d. SCFE - NF Relationship for Large Rotor Containment at ALR = 1; Figure 14. The relationship in this figure, though not definitive because containment was not achieved for the 2 and 3 fragment burst, indicates that the SCFE is dependent on the number of fragments (NF) generated at burst. This differs from the small rotor results, which indicated that the SCFE and NF were almost independent. The trend of this relationship indicates that the capability of a ring increases as the number of fragments generated increases or in other words, as the number of fragments generated at burst decreases the containment situation with respect to ring weight become more adverse, i.e., more weight is required.

e. SCFE - ALR Relationship for Large Rotor Containment of 2-Fragment Bursts; Figure 15. Only limited tests were conducted to explore this relationship because trends indicated that the weights of ring required for containment were becoming very high. Figure 15 tends to show that an optimum axial length might exist in the neighborhood of ALR = 1. This is consistent with the results of the small rotor results, which because of the abundance of test data, was more conclusive in indicating an optimum ALR = 1.

f. General Observations and Results:

(1) Comparison Between Large and Small Rotor Containment Ring Deformation/Displacement Characteristics During Fragment Impact: Figure 16 shows high-speed photographic results that depict the mechanics of large and small rotor containment in which a 3-fragment rotor burst is involved. It can be seen from these data that the gross deformations and displacements experienced by the steel rings are quite independent of size. In fact, in a general sense, the deformation/displacement characteristics for the large and small rotor containment rings are approximately identical. On the basis of this data, it was anticipated that a functional relationship between SCFE and rotor diameter/ring ID could be experimentally derived and be generally applicable.

(2) Exploratory Tests of a Small Rotor Composite Containment Ring: Data for these tests can be found in Appendix A under test numbers 143, 144, 183 and 208. These tests were conducted using the smaller T58 engine turbine rotors modified to burst into three fragments at their design speed of 20,000 rpm and impact concentrically, encircling rings that were made from three types of materials or material configurations: (a) filament wound fiberglass in an epoxy matrix; (b) circular boron carbide segments backed by filament wound fiberglass in an epoxy matrix; and (c) a segmented, hardened 4130 steel ring backed by filament wound fiberglass in an epoxy matrix. The fiberglass and steel-fiberglass rings did not contain the fragments; however, the boron carbide-fiberglass ring did contain at a weight savings of 30% over an optimally configured steel ring subjected to identical burst conditions. Post-test photographs of these rings are shown in Figures 17 through 19. On the basis of these exploratory tests, it appears that composite rings may serve to reduce the weight penalty associated with rotor disk fragment containment. To determine what these weight reductions might be, will require an extensive program of experimentation using multi-layered material rings.

REFERENCES

1. REPORT - Mangano, G. J., "Rotor Burst Protection Program - Phases VI and VII; Exploratory Experimentation to Provide Data For The Design of Rotor Burst Fragment Containment Rings", Naval Air Propulsion Test Center, NAPTC-AED-1968 of March 1972

2. REPORT - Martino, A. A. and Mangano, G. J., "Turbine Disk Burst Protection Study", Final Phase II-III Report on Problem Assignment NASA DPR #R105, Naval Air Propulsion Test Center, NAPTC-AEL-1848 of February 1967.

3. TEXT - Freberg, C. R. and Kemler, E. N., "Elements of Mechanical Vibration", John Wiley & Sonce, Inc., New York, 1949 (Page 23).

		ID 15			ID 32		
		NF 2	NF 3	NF 6	NF 2	NF 3	NF 6
ALR 1/2	t_1						
	t_2						
	t_3						
	t_4						
ALR 1	t_1						
	t_2						
	t_3						
	t_4						
ALR 2	t_1						
	t_2						
	t_3						
	t_4						

WHERE: ALR = RING TO ROTOR RIM AXIAL LENGTH RATIO (NUMBER DENOTES RATIO)

ID = RING INNER DIAMETER (SUBSCRIPT DENOTES NOMINAL DIAMETER IN INCHES)

t = RING RADIAL THICKNESS (SUBSCRIPT REFERS TO NO. OF TRIALS TO ESTABLISH CONTAINMENT THICKNESS)

NF = NO. PIE SECTOR SHAPED ROTOR FRAGMENTS (SUBSCRIPT DENOTES NO. FRAGMENTS)

Figure 1. - Small/Large Rotor Containment Test Matrix.

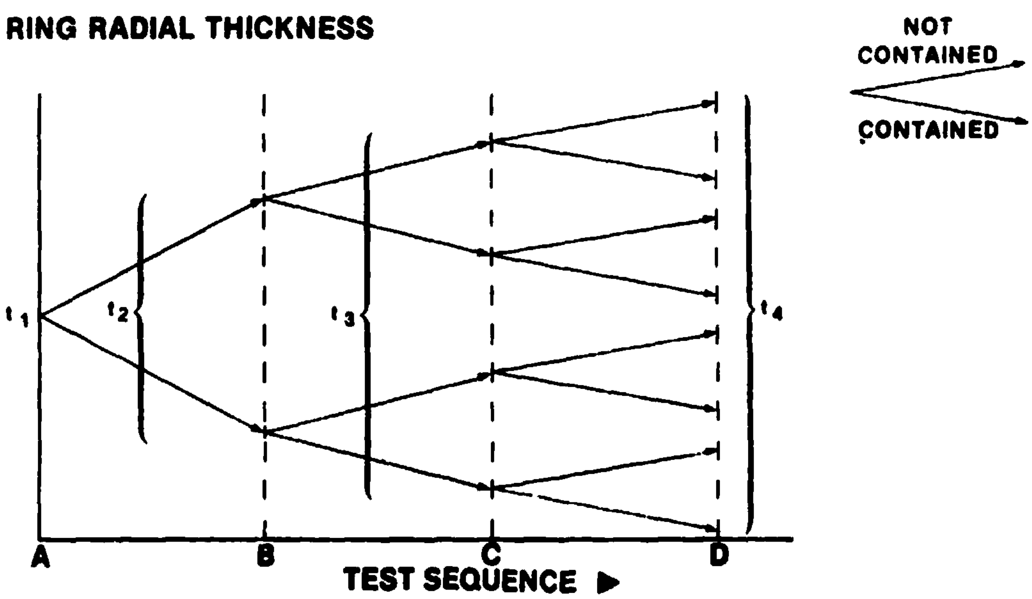


Figure 2. - Ring Thickness Variation Scheme.

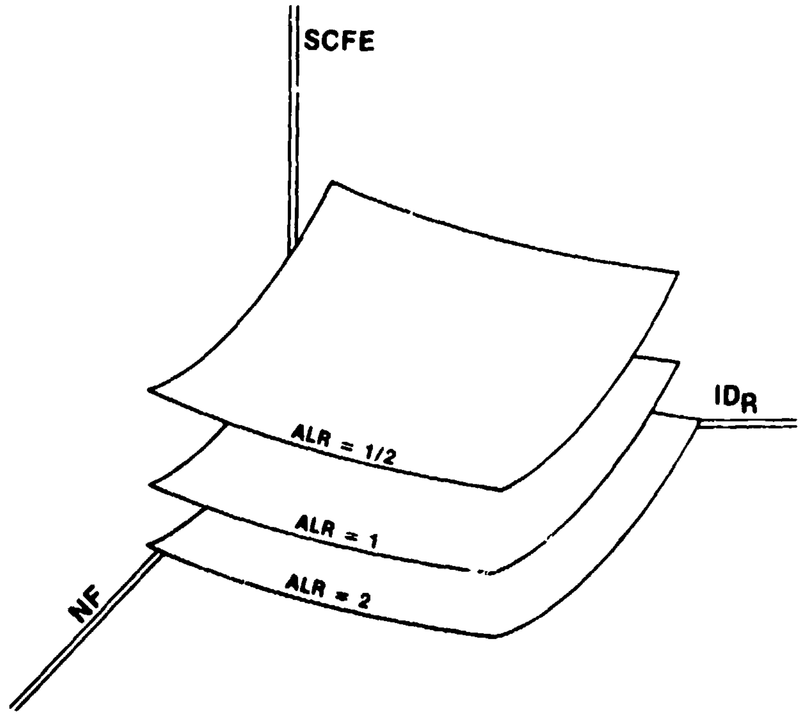


Figure 3. - Conceptual Relationships Between Containment Program Test Variables.

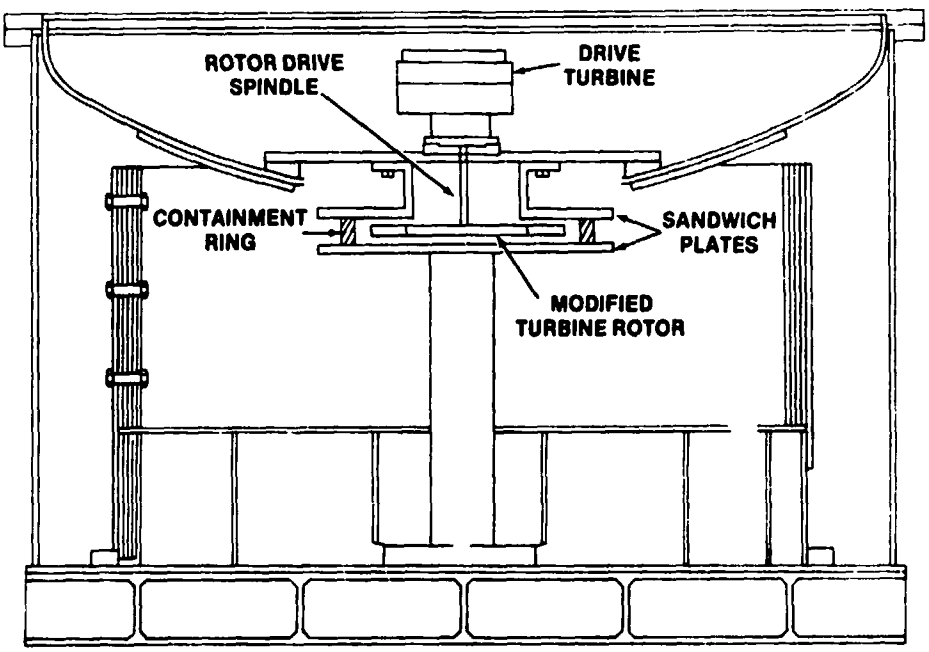


Figure 4. - Typical Containment Test Set-Up.

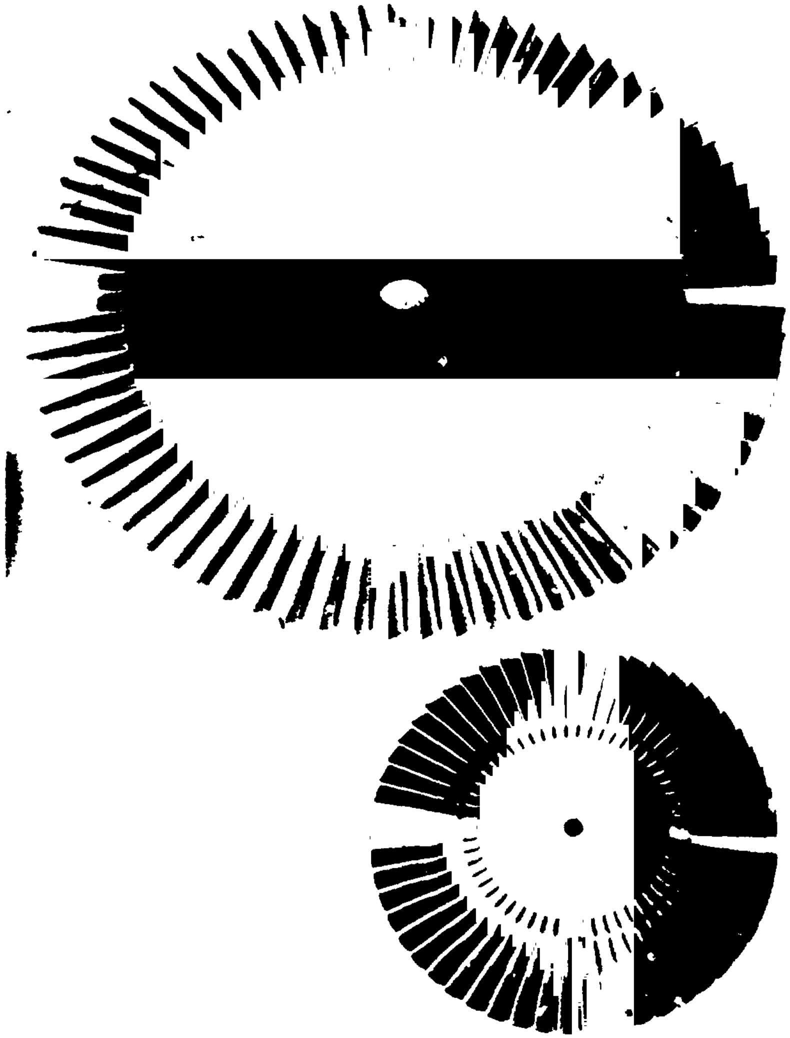


Figure 5. - Typical Rotor Modifications For Containment Tests.

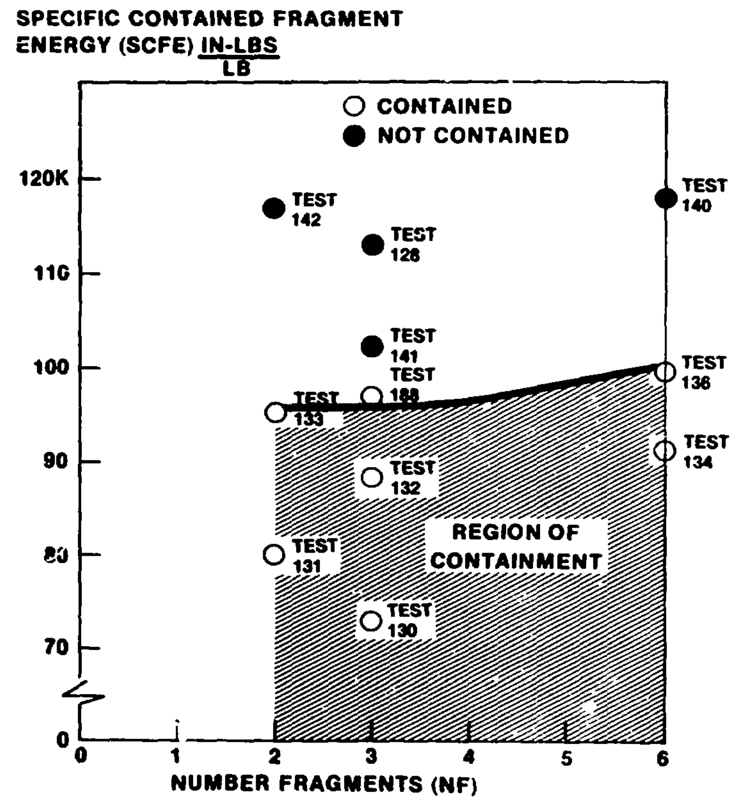


Figure 6. - SCFE-NF Relationship For Small Rotor Containment.

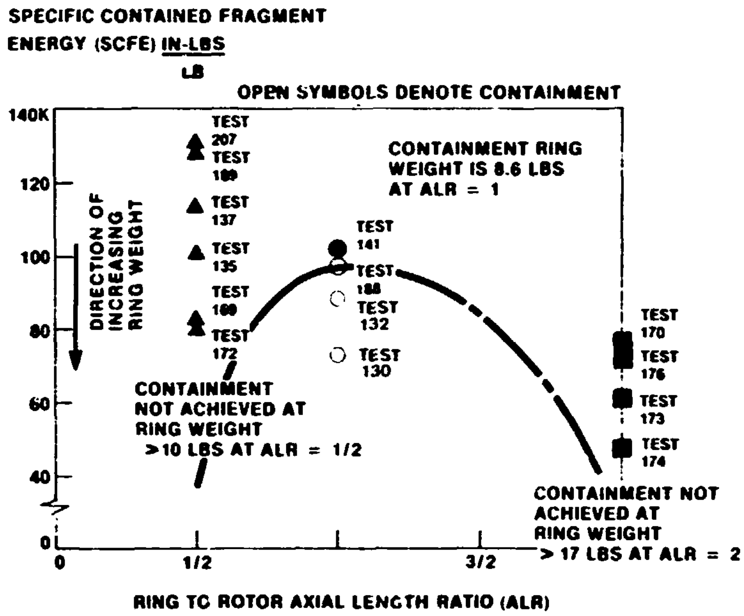


Figure 7. - SCFE-ALR Relationship For Small Rotor Containment.

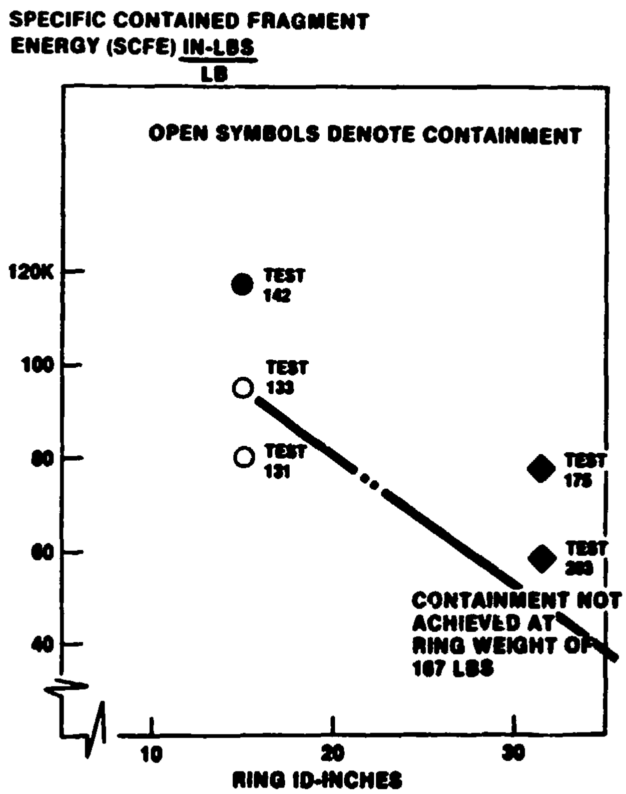


Figure 8. - SCFE-ID_R Relationship.

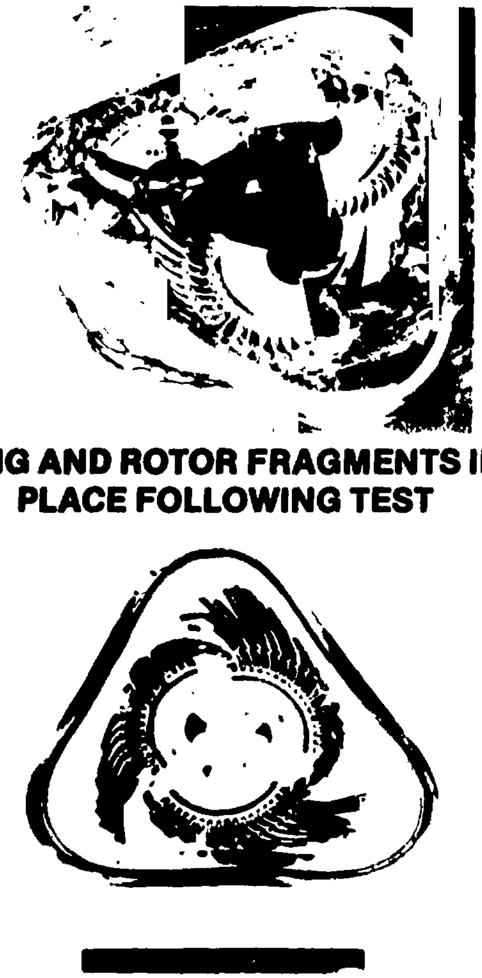


Figure 9. - Small Rotor 3 Fragment Containment Post Test Results.

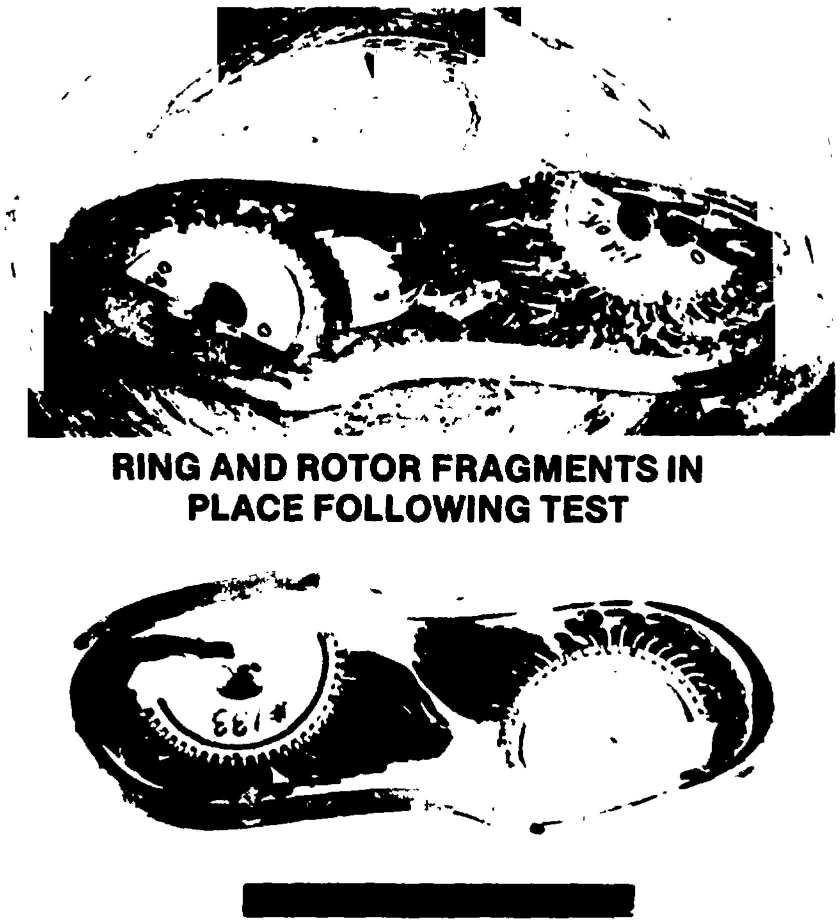


Figure 10. - Small Rotor 2 Fragment Containment Post Test Results.

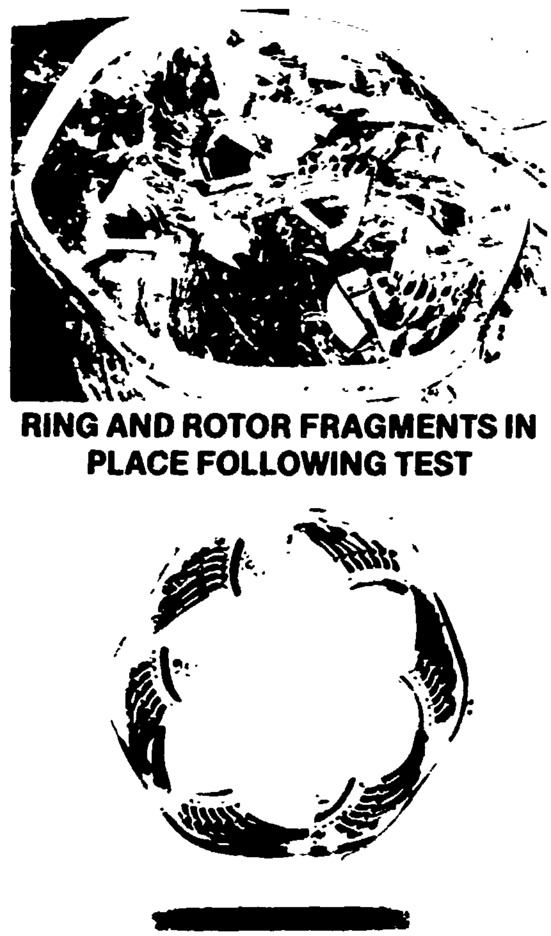


Figure 11. - Small Rotor 6 Fragment Containment Post Test Results.

Figure 12. - Small Rotor 2, 3 and 6 Fragment Containment Post Test Results.

Figure 13. - Large Rotor 2, 3 and 6 Fragment Containment Post Test Results.

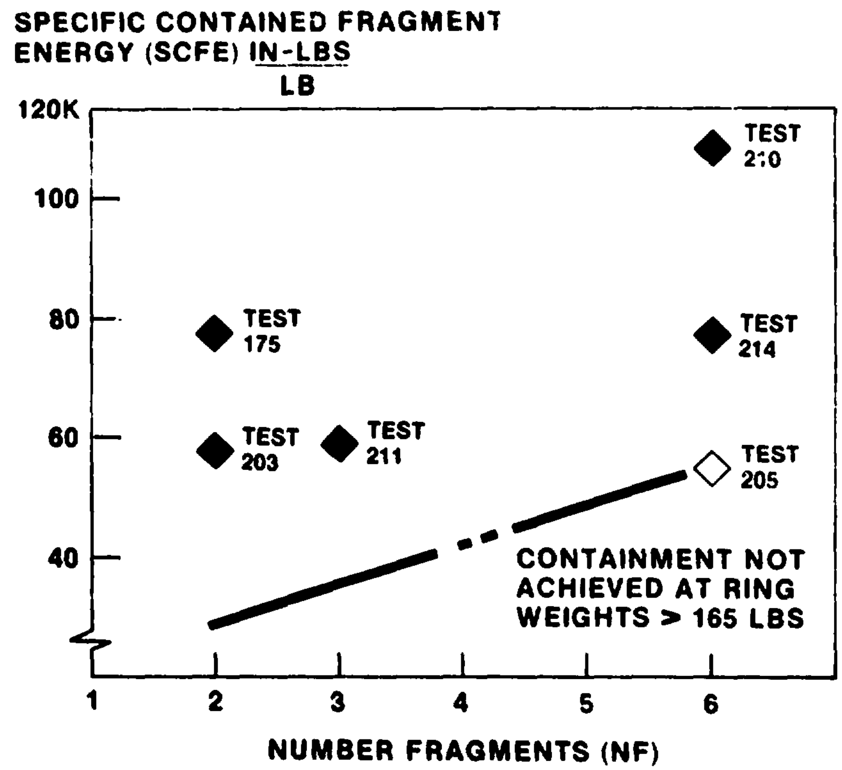


Figure 14. - SCFE-NF Relationship For Large Rotor Containment.

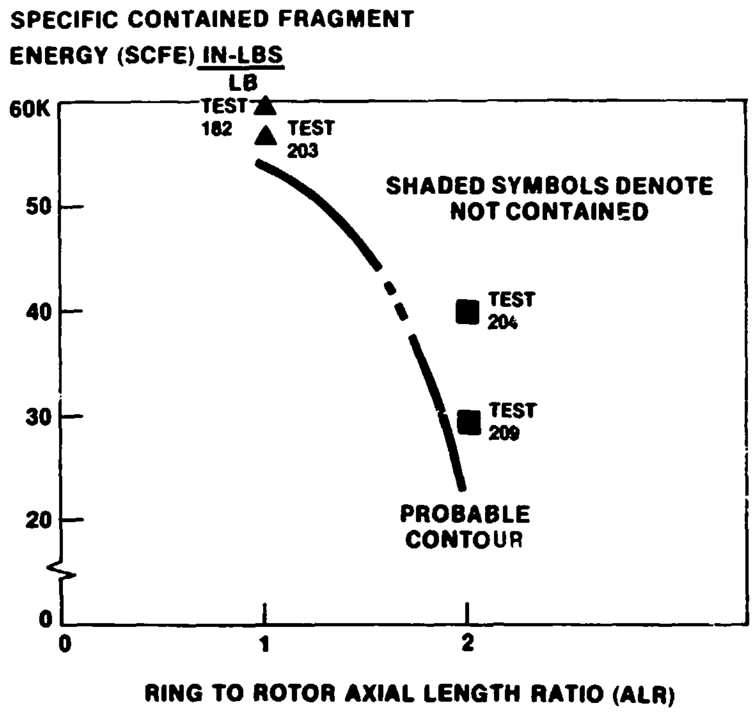


Figure 15. - SCFE-ALR Relationship For Large Rotor Containment 4130 Cast Steel Ring (NF = 2).

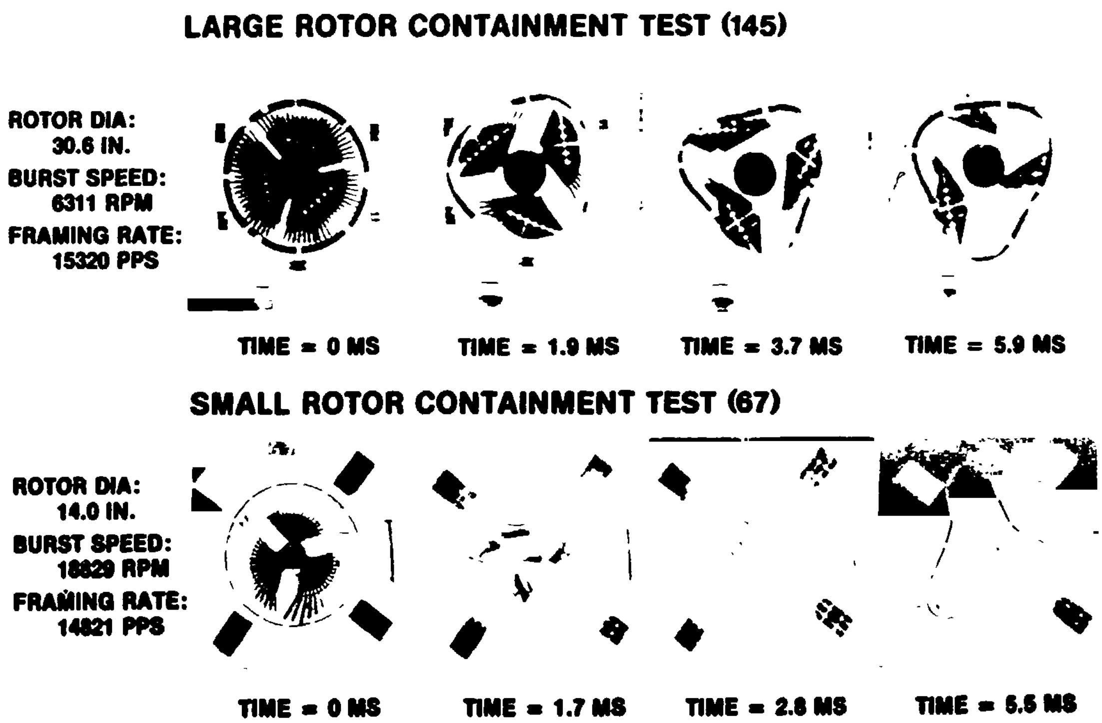


Figure 16. - Rotor Burst Fragment Containment Ring Deformation Characteristics.

Figure 17. - Small Rotor 3 Fragment Containment With A Fiberglass Ring Post Test Results.

Figure 18. - Small Rotor 3 Fragment Containment With A Boron Carbide/Fiberglass Composite Ring Post Test Results.

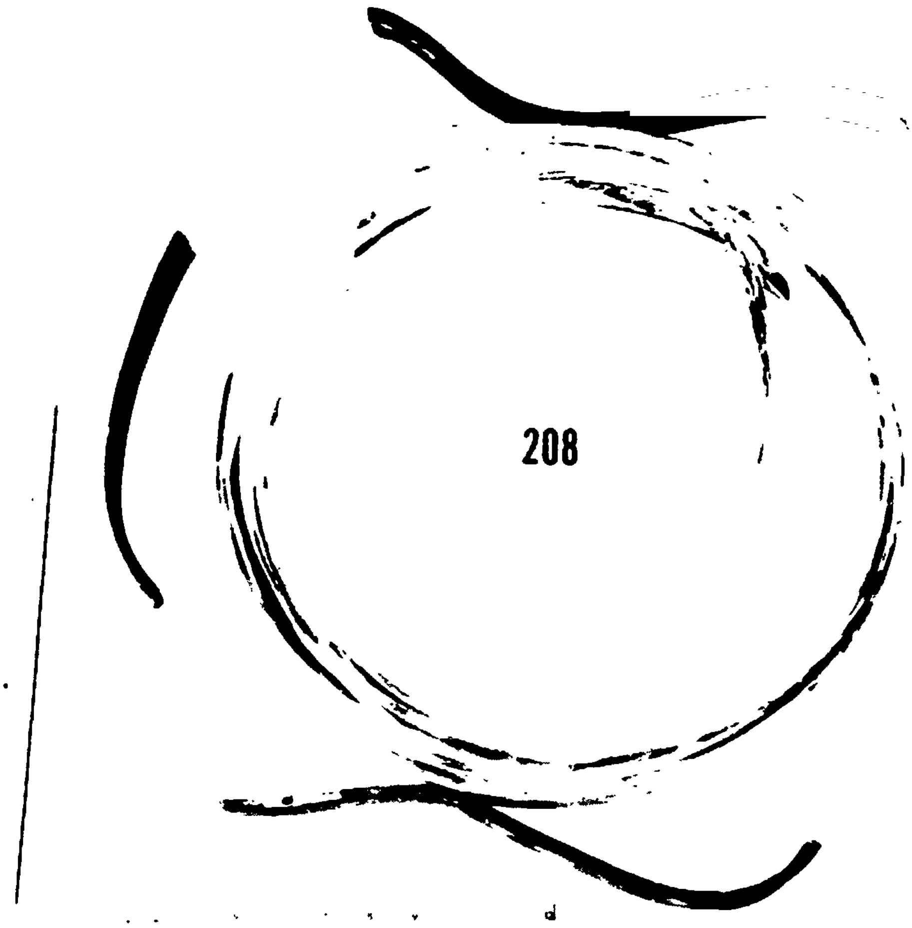


Figure 19. - Small Rotor 3 Fragment Containment With A Steel/Fiberglass Composite Ring Post Test Results.

APPENDIX A

Rotor Burst Protection Program Experimental

Test Data Compilation

DATA COMPILATION NOTES:

(1) GE T58 Engine Power Turbine Rotor - Refer to Figure A-1 for dimensional and physical details.

(2) SRCT Ring Diameter = 15.0 inches.

(3) NF - Centrifugally cast 4130 steel billet produced by National Forge Company, refer to Figure A-2 for stress-strain char.

(4) ACIPCO - Centrifugally cast 4130 steel billet produced by ACIPCO, refer to Figure A-3 for stress-strain char.

(5) Fiber Glass - Composite ring manufactured by Eshbaugh Corporation; construction - E-glass roving in an epoxy resin matrix.

(6) B/C-Glass - Composite ring manufactured by Reflective Laminates/ Fansteel; construction - Boron Carbide segments backed with E-glass tape in an epoxy resin matrix (see Figure A-4).

(7) STL-Glass - Composite ring; construction-4130 plate steel segments backed with E-glass roving in an epoxy matrix (see Figure A-5).

(8) Curtiss-Wright J65 Engine Stage 2 Turbine Rotor; Refer to Figure A-6 for dimensional and physical details.

(9) LRCT Ring Diameter = 31.64 inches.

(10) Centrifugally cast 4130 steel billet produced by ACIPCO. Refer to Figure A-7 for stress-strain char.

(11) C - Contained
NC - Not Contained

SMALL ROTOR[1] CONTAINMENT TESTS (SRCT):

	RING DATA (2)				ROTOR DATA			RESULTS	
TEST NO.	AXIAL LENGTH IN	RADIAL THICKNESS IN	WEIGHT LBS	MATERIAL	NO. FRAGMENTS	BURST SPEED RPM	BURST ENERGY IN-LBS	SCFE IN-LBS/LB	CONT. COND.
129	1.0	0.560	7.68	NF[3]	2	18,630	722,424.0	94,065.6	NC
131	1.0	0.750	10.44	NF	2	20,022	834,413.6	79,924.7	C
133	1.0	0.625	8.63	NF	2	19,899	824,193.1	95,503.3	C
142	1.0	0.5625	7.77	NF	2	20,889	908,242.4	116,890.9	NC
126	1.0	0.250	3.41	NF	3	19,754	799,831.1	234,554.6	NC
127	1.0	0.375	5.14	NF	3	19,720	797,080.2	155,074.0	NC
128	1.0	0.507	7.0	NF	3	19,665	792,640.2	113,234.3	NC
130	1.0	0.750	10.49	NF	3	19.416	772,694.3	73,660.1	C
132	1.0	0.625	8.67	NF	3	19,342	766,815.6	88,444.7	C
138	1.0	0.625	8.62	NF	3	21,363	935,433.0	108,518.9	C
139	1.0	0.561	7.76	NF	3	18,897	731,937.4	94,321.8	NC
141	1.0	0.561	7.78	NF	3	19,719	796,999.4	102,442.1	NC
188	1.0	0.625	8.72	ACIPCO[4]	3	20,347	848,572.5	97,313.4	C
134	1.0	0.625	8.60	NF	6	20,056	786,168.2	91,414.9	C
136	1.0	0.5625	7.69	NF	6	19,775	764,292.8	99,387.9	C

SMALL ROTOR(1) CONTAINMENT TESTS (SRCT):

	RING DATA (2)				ROTOR DATA			RESULTS	
TEST NO.	AXIAL LENGTH IN	RADIAL THICKNESS IN	WEIGHT LBS	MATERIAL	NO. FRAGMENTS	BURST SPEED RPM	BURST ENERGY IN-LBS	SCFE IN-LBS/LB	CONT. COND.
140	1.0	0.500	6.89	NF	6	20,420	814,963.7	118,282.1	NC
135	0.5	1,200	8.53	NF	2	20,437	869,362.2	101,561.0	C
137	0.5	1.075	7.71	NF	2	20,559	879,772.7	114,108.0	(a)
168	0.5	1.402	10.17	NF	3	19,164	752,766.9	74,018.4	C
169	0.5	1.352	9.81	NF	3	20,000	819,976.0	83,575.5	NC
172	0.5	1.394	10.18	NF	3	19,978	818,073.3	80,360.8	NC
177	0.5	0.868	6.20	NF	3	19,103	747,982.4	120,642.3	C
178	0.5	0.883	6.13	NF	3	20,975	901,762.5	147,106.4	NC
207	0.5	0.874	6.16	ACPICO	3	19,880	810,067.1	131,504.4	NC
189	0.5	0.885	6.33	ACPICO	3	19,933	814,392.1	128,655.9	NC
170	2.0	0.375	10.81	NF	3	20,243	839,920.0	77,698.4	NC
173	2.0	0.497	13.57	NF	3	20,206	836,852.5	61,669.3	NC
174	2.0	0.6105	17.01	NF	3	20,032	822,501.8	48,354.0	NC
176	2.0	0.432	11.96	NF	3	20,559	866,347.6	72,437.1	NC
143	1.0	1.50	6.03	B/C-GLASS(6)	3	19,058	744,462.5	123,459.8	C

(a) CONTAINMENT QUESTIONABLE - UNDETEMINED

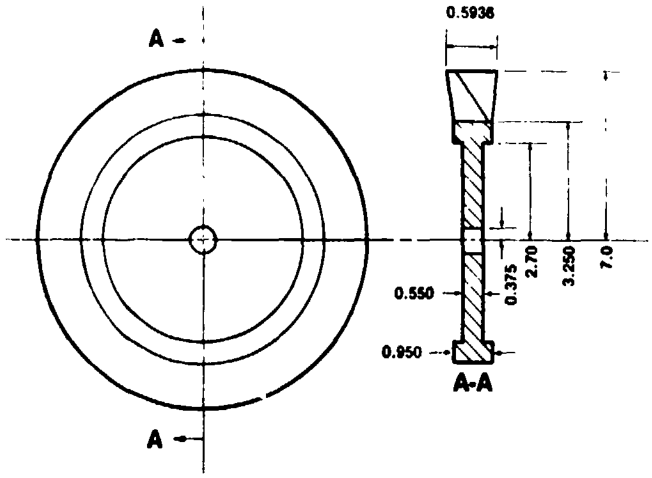
SMALL ROTOR(1) CONTAINMENT TESTS (SRCT):

	RING DATA (2)				ROTOR DATA			RESULTS	
TEST NO.	AXIAL LENGTH IN	RADIAL THICKNESS IN	WEIGHT LBS	MATERIAL	NO. FRAGMENTS	BURST SPEED RPM	BURST ENERGY IN-LBS	SCFE IN-LBS/LB	CONT. COND.
144	1.0	1.375	5.9	FIBER GLASS(5)	3	21,826	976,419.6	165,494.9	NC
208	1.0	.183	6.88	STL-GLASS(7)	3	19,556	783,877.6	113,935.7	NC
183	1.0	1.388	5.4	FIBER GLASS	3	20,680	876,575.4	161,135.2	NC

LARGE ROTOR[8] CONTAINMENT TESTS (LRCT):

	RING DATA (2)				ROTOR DATA			RESULTS	
TEST NO.	AXIAL LENGTH IN	RADIAL THICKNESS IN	WEIGHT LBS	MATERIAL	NO. FRAGMENTS	BURST SPEED RPM	BURST ENERGY IN-LBS	SCFE IN-LBS/LB	CONT. COND.
167	1.25	2.750	105.0	ACIPCO[10]	2	8,044	8,649,195	82,373.2	NC
175	1.25	3.250	125.5	ACIPCO	2	8,581	9,842,544	78,426.6	NC
180	1.25	1.800	70.5	ACIPCO	2	7,798	8,119,958	115,176.7	NC
181	1.25	1.939	74.0	ACIPCO	2	8,592	9,867,795	133,348.5	NC
182	1.25	4.000	160.0	ACIPCO	2	8,416	9,541,828	59,636.4	NC
203	1.25	4.1875	166.6	ACIPCO	2	8,500	9,657,585	57,968.6	NC
211	1.25	4.183	168.25	ACIPCO	3	8,614	9,918,373	58,950.2	NC
205	1.25	4.231	168.75	ACIPCO	6	8,316	9,243,994	54,779.2	C
210	1.25	2.500	95.0	ACIPCO	6	8,764	10,266,808	108,071.6	NC
214	1.25	3.250	123.0	ACIPCO	6	8,458	9,562,381	77,743	NC
204	2.5	3.000	232.0	ACIPCO	2	8,270	9,142,011	39,405	NC
209	2.5	4.225	330.0	ACIPCO	2	8,499	9,655,313	29,259	NC

FIGURE A-1



TYPE ROTOR: T-58 POWER TURBINE (MODIFIED, UNSLOTTED)
ROTOR WEIGHT: 11.8 LBS (AVG.)
ROTOR INERTIA: 151 LB-IN^2 (NOMINAL)

	DISK	BLADES
MATERIAL:	A-286	SEL-5
PROPERTIES:		
SU	157K psi	136K psi
SY	110K psi	118K psi
EU	12%	12%
HD	313 BHN	313 BHN

FIGURE A-2

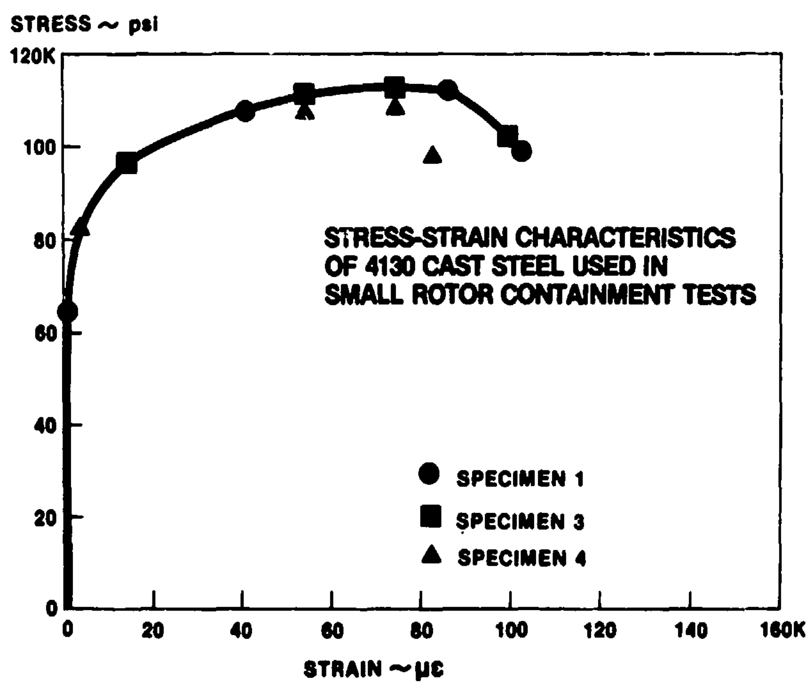


FIGURE A-3

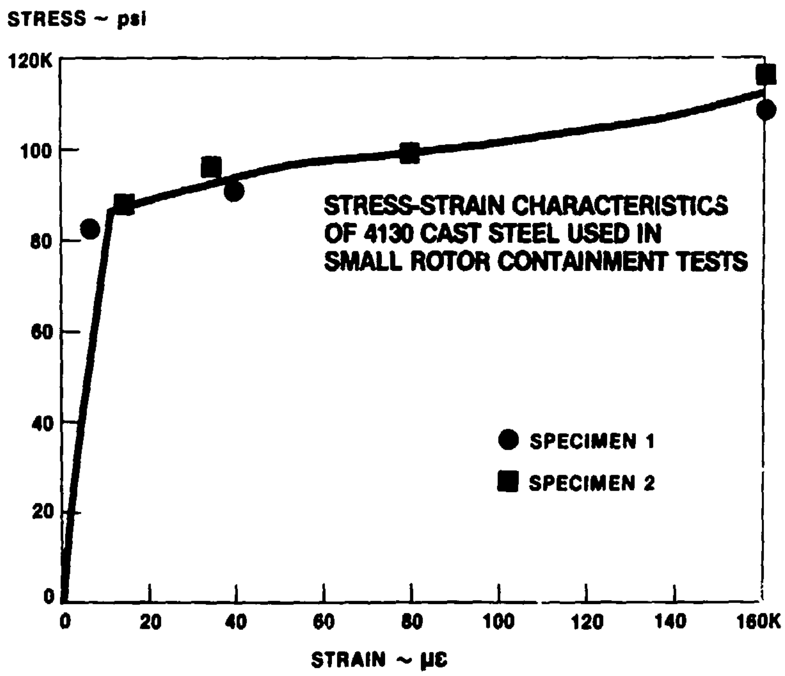


FIGURE A-4

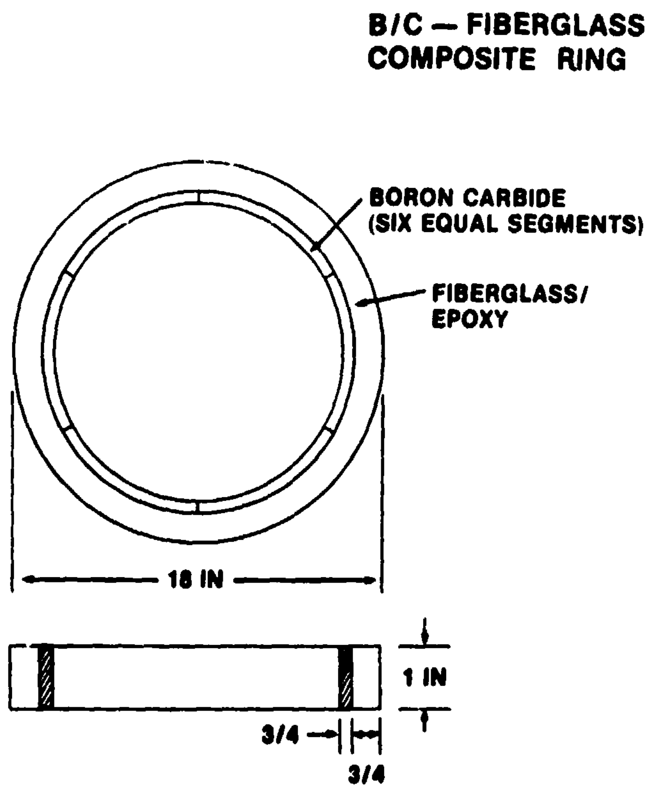


FIGURE A-5

STL-FIBERGLASS COMPOSITE RING

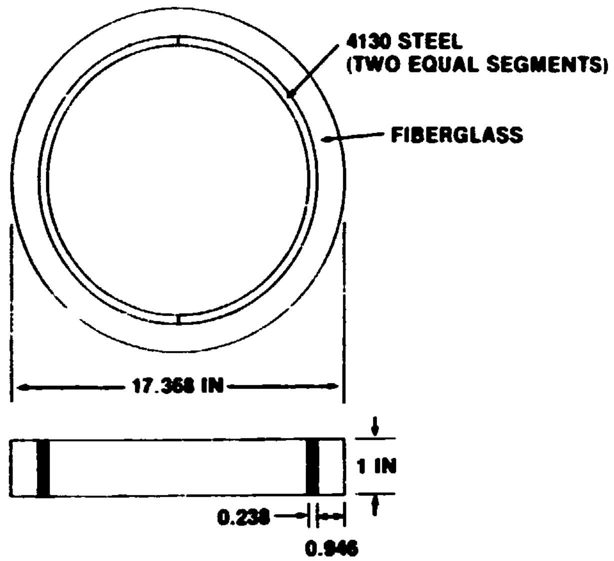
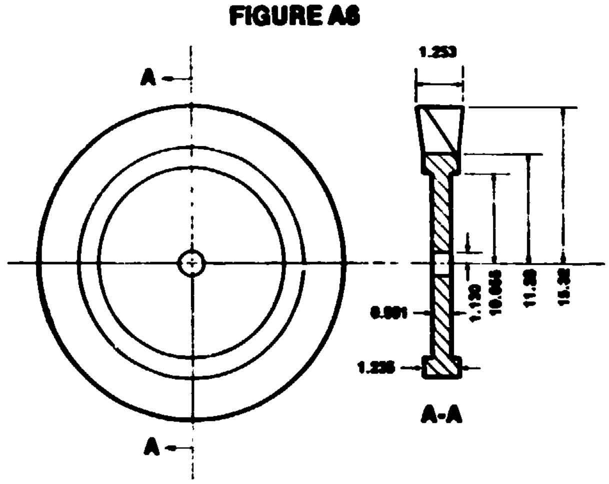


FIGURE A6



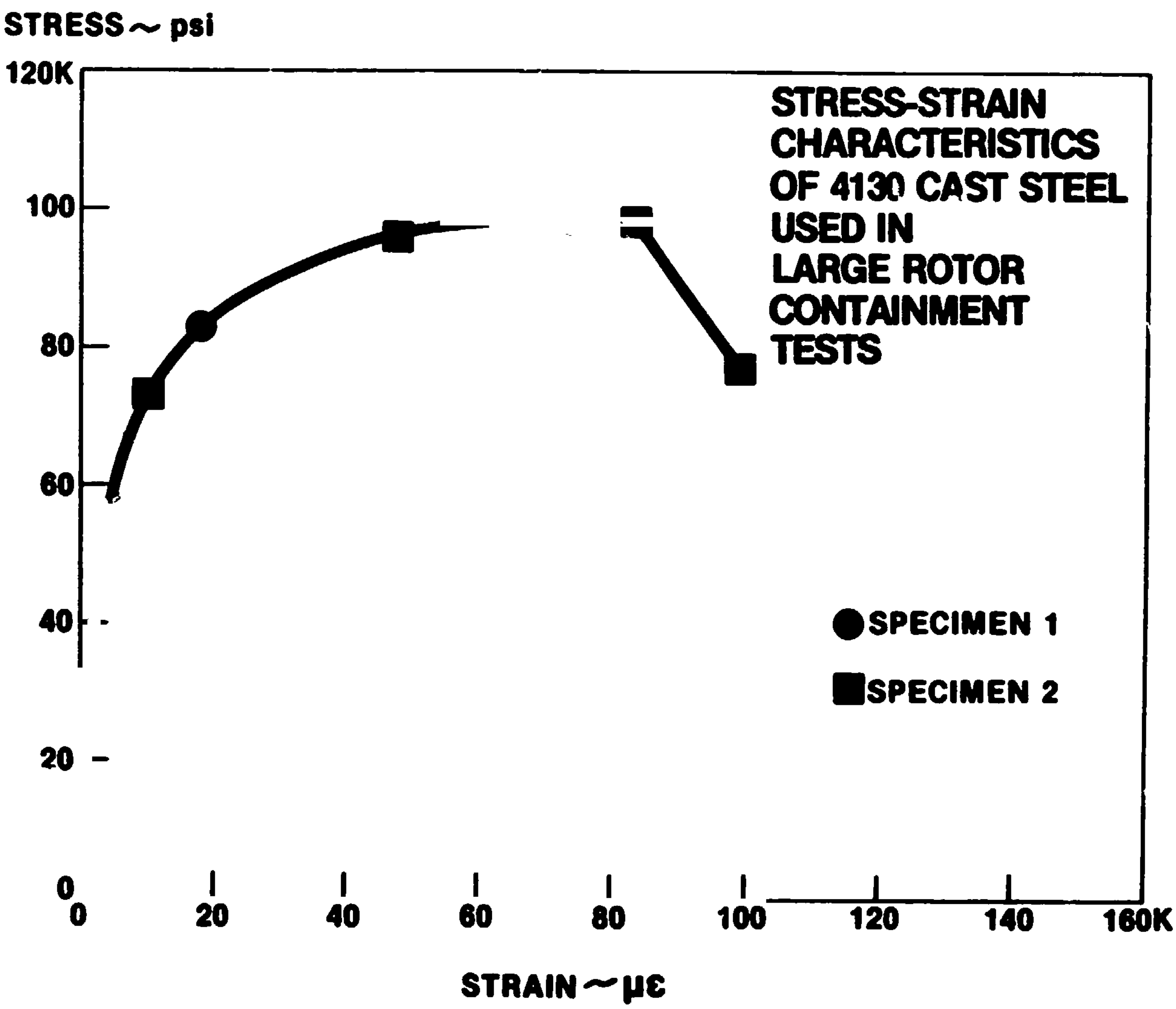
TYPE ROTOR: J-65 SECOND STAGE TURBINE (MODIFIED, UNSLOTTED)

ROTOR WEIGHT: 127.75 LBS (APPROX.)

ROTOR INERTIA: 9410 LB-IN^2 (NOMINAL)

	DISK	BLADES
MATERIAL:	17-22A FERRITIC STEELS	INCONEL 700
PROPERTIES:		
SU	142K PSI	148.5K PSI
SY	126.5K PSI	132K PSI
EU	18%	18%
HD	311 BHN	311 BHN

FIGURE A-7



MOTIVATION FOR RBPP STEMS FROM THE ROTOR FAILURE SITUATION IN COMMERCIAL AVIATION.

POWERPLANT

12-27-76	Orig-Open	RAL	7230	CV-580-31	73102	01107023

TEXT:

BIL. On arrival, crew reported the left engine oil quantity went to zero. Feathered the left prop. Maintenance found metal in the engine tail pipe. Replaced left engine.

SPECIFIC PART CAUSING PROBLEM

Engine		Metal in tailpipe	[illegible]
			025[illegible]
	ALLEN	501D13H	501671

12/26/76	ORIG OPEN	UAL	7200	DC-10-10	1802U	01107024

TEXT DEN-NO. 2 ENGINE FLAMED OUT ON TAKEOFF. FOUND METAL IN SCREEN. REPLACED [illegible]

UNDER INVESTIGATION

SPECIFIC PART CAUSING PROBLEM

ENGINE		FLAMEOUT	NO. 2 POSN
	GE	CF6-6	451368

12/26/76	Orig.Open	MIAS	72-30	B720-022	7207U	01107025

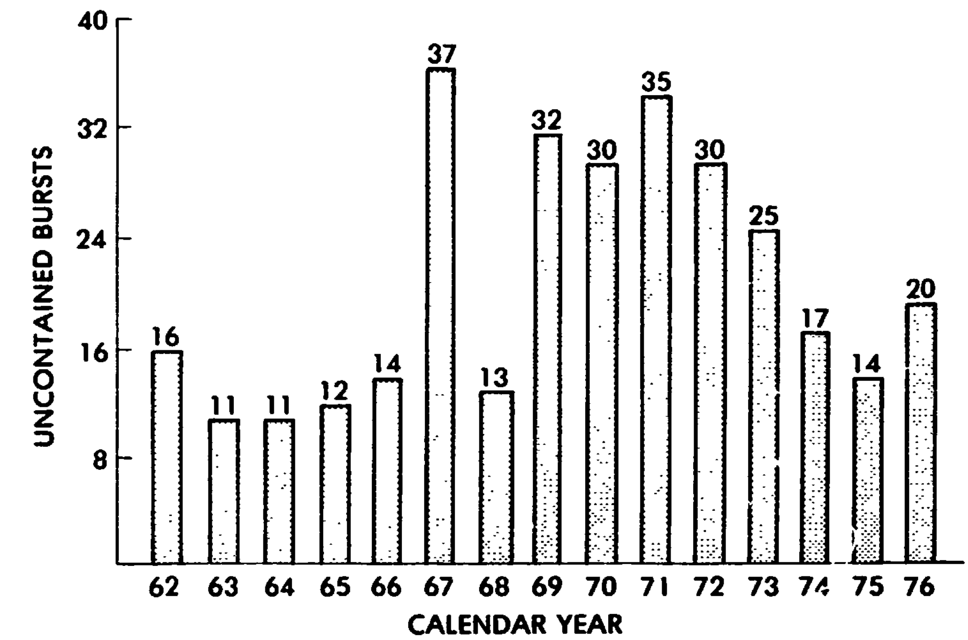
TEXT

DTW: Aborted takeoff DTW due to suspected #4 engine compressor stall on power application. Cause under investigation.

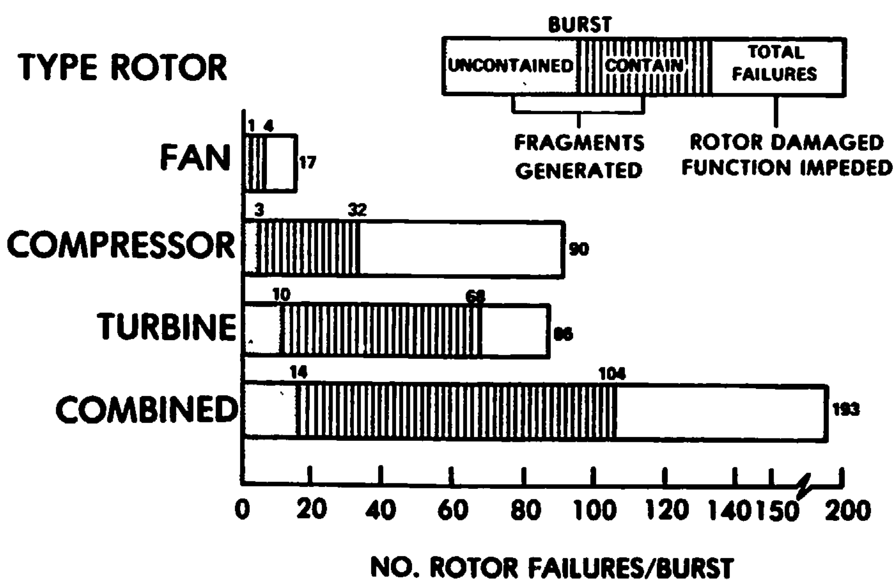
SPECIFIC PART CAUSING PROBLEM

COMPRESSOR		STALLED	NO. 4 ENGINE
Engine	PWA	JT3C-7	632977

THE INCIDENCE OF UNCONTAINED ROTOR BURSTS IN U. S. COMMERCIAL AVIATION 1962 – 1976



INCIDENCE OF ROTOR FAILURE/BURST IN U. S. COMMERCIAL AVIATION 1975

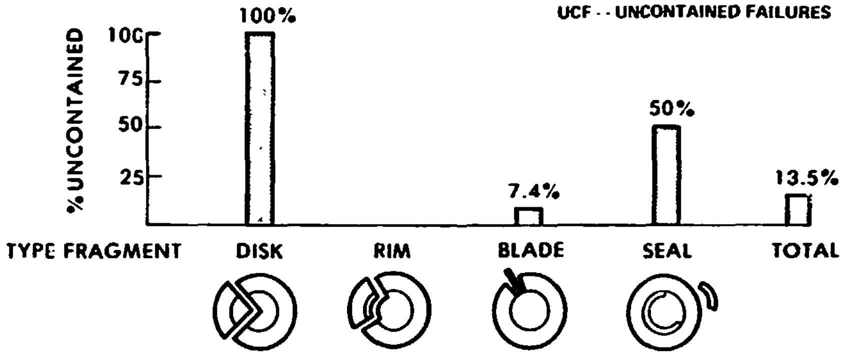


COMPONENT AND FRAGMENT TYPE DISTRIBUTIONS FOR CONTAINED AND UNCONTAINED ROTOR BURSTS(1)—1975

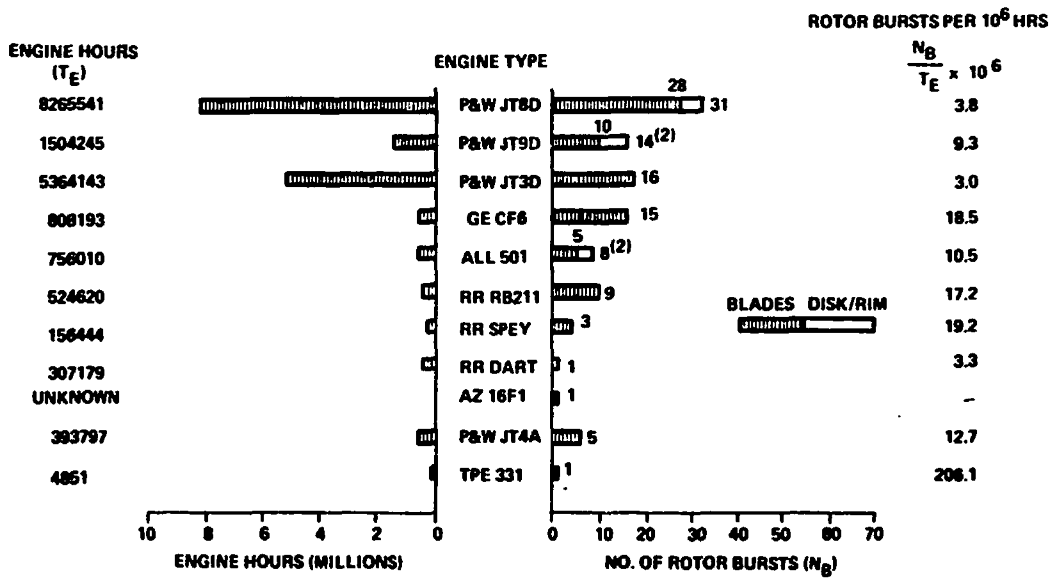
ENGINE ROTOR COMPONENT	TYPE OF FRAGMENT GENERATED								TOTALS	
	DISK		RIM		BLADE		SEAL			
	TF	UCF	TF	UCF	TF	UCF	TF	UCF	TF	UCF
FAN	0	0	0	0	4	1	0	0	4	1
COMPRESSOR	1	1	1	0	30	2	0	0	32	3
TURBINE	5	5	1	0	60	4	2	1	68	10
TOTALS	6	6	2	0	94	7	2	1	104	14

(1) FAILURES THAT PRODUCED FRAGMENTS

TF - - TOTAL FAILURES
UCF - - UNCONTAINED FAILURES

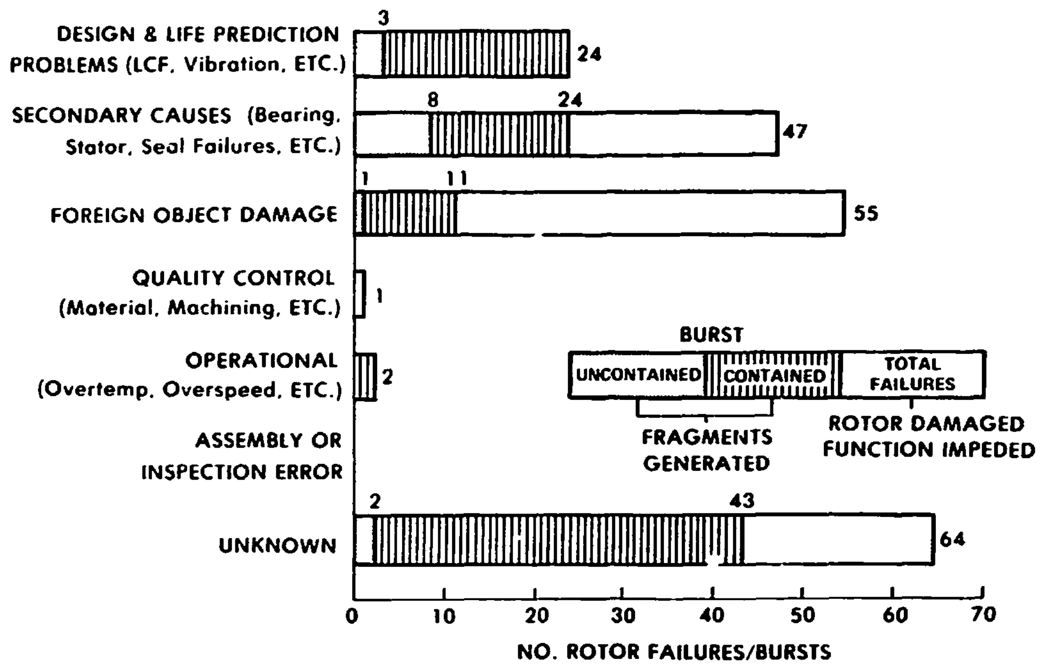


THE INCIDENCE AND RATE OF ROTOR BURST(1) IN U.S. COMMERCIAL AVIATION ACCORDING TO ENGINE TYPE AFFECTED — 1975

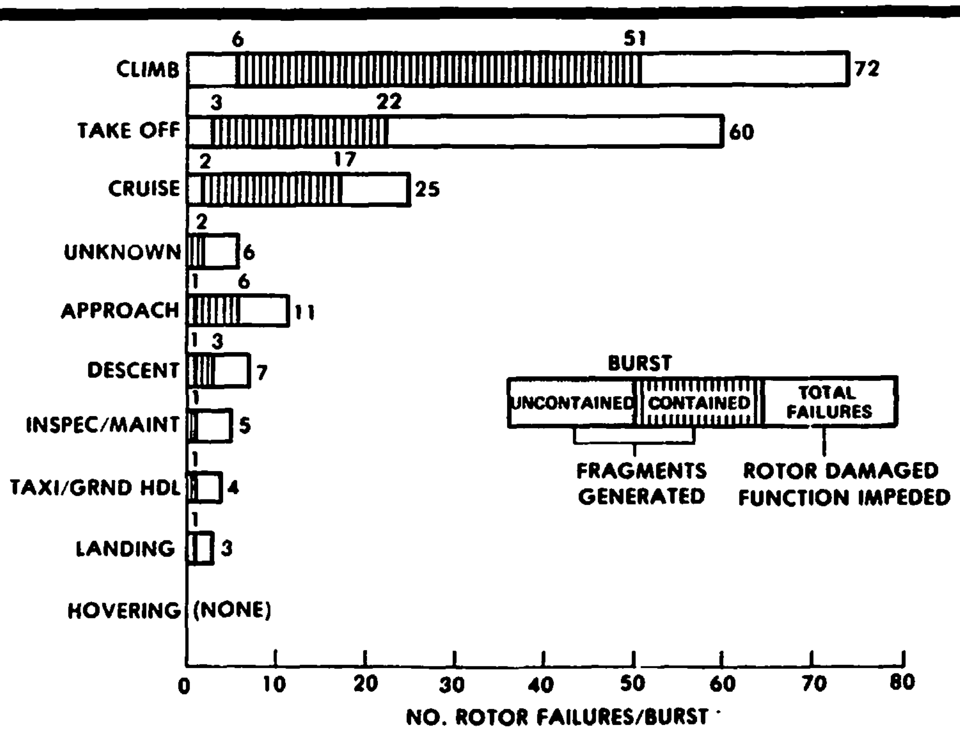


(1) Failures that produced fragments
(2) 1 Seal Burst included in Disk/Rim compilation

ROTOR FAILURE/BURST CAUSE CATEGORIES — 1975



FLIGHT CONDITION AT ROTOR FAILURE/BURST — 1975



SUMMARY ANALYSIS OF ROTOR BURST
INCIDENCE AND RATE FOR 1975

FACTS:

- TOTAL NO. ENGINE SHUTDOWNS - 2305
- NO. ROTOR FAILURES - 193
- NO. ROTOR BURSTS (1) - 104
- NO. UNCONTAINED ROTOR BURSTS - 14
- A/C FLIGHT HOURS - $6x10^6$
- ENGINE FLIGHT HOURS - $19.2x10^6$

ANALYSIS:

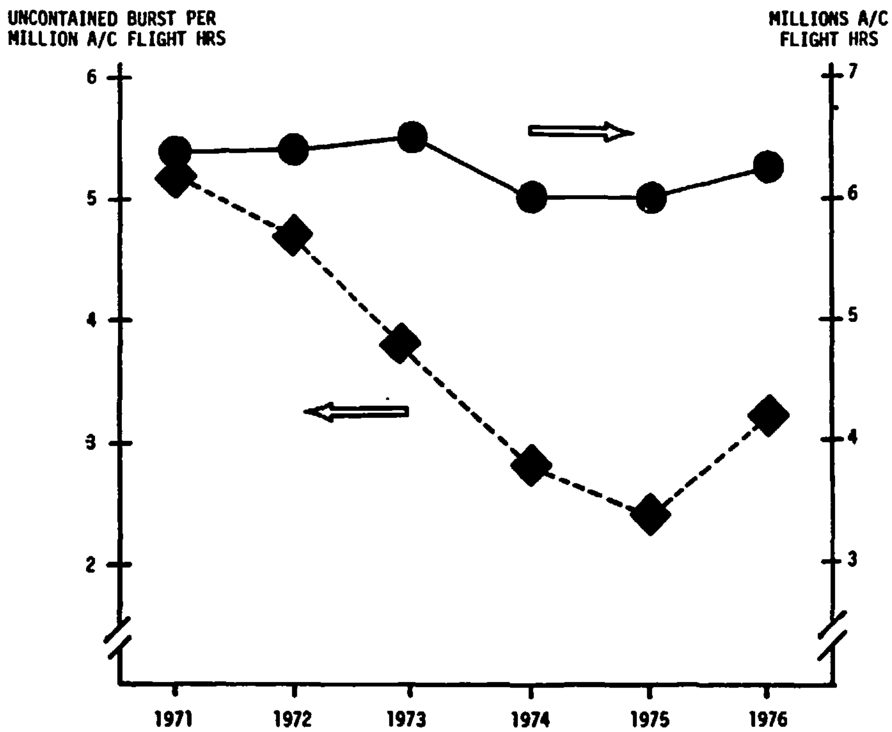
- PERCENT ROTOR FAILURE INDUCED ENGINE SHUTDOWNS - 8.4%

	PER 10^6 A/C HRS	PER 10^6 ENGINE HRS
• ROTOR FAILURE RATE	32	10
• ROTOR BURST RATE	17	5.4
• UNCONTAINED ROTOR BURST RATE	2.3	.73

(1) FAILURES THAT GENERATED FRAGMENTS

DATA ON AIRCRAFT FLIGHT HOURS AND UNCONTAINED ROTOR

BURST RATE, U.S. COMMERCIAL AVIATION 1971-1976



DISCUSSION

J. Meaney, Rohr

First, was the Kevlar ring made with epoxy binding? Second, did you ever test these rings with radial supports; don't you feel that not having radial supports could be unconservative inasmuch as you allow the ring to deform to a much greater manner than if it were part of a "long" container?

G.J. Mangano, NAPTC

In answer to the first question, the Kevlar that we used was a fabric wound on a diagonal with no binder. A thin inner aluminum cylinder was used to provide shape.

Concerning the second question, some preliminary tests in which we purposely added radial constraints were conducted. We found that it wasn't a weight-effective configuration. That is, it weighed more than a freely-supported ring that provided the same degree of containment for identical burst conditions.

J. Meaney, Rohr

Well, the point I was trying to get at was that some of the rings that you showed that actually contained the fragments were greatly deformed. But if the ring had a "large axial length" and was supported on casing or bracket structure, would not this support influence the containment ability?

G.J. Mangano, NAPTC

That was why we went through the exercise of trying to determine the optimum ring axial length with respect to weight. An optimum was found when the axial length ratio between the rotor axial length and the ring axial length was one. Ratios of one-half, one, and two were investigated for a one-inch wide rotor. We evaluated the effect of axial length on the containment process and found an optimum with respect to weight at a rotor to ring axial length ratio ratio of one.

R. Bristow, Boeing

I would like to make a comment on that last question. A Kevlar shield must deform quite a bit more than a steel shield, and we were worried about how some of the aircraft structure might restrain the Kevlar shield such that the fragment punches a hole or chews its way through. We put some honeycomb material behind the Kevlar on some of our tests to simulate the sound suppression material. On some of these, we had two layers of sixteenth inch aluminum with honeycomb in between, so that the whole honeycomb panel was about an inch thick. The Kevlar did not fail under that condition; it blew the honeycomb apart and continued to expand. These were ballistic type impact tests, not engine rotor burst impacts.

B.L. Koff, GE-Cincinnati

These disk impact tests were conducted by bursting a rotor between two steel plates and having the segments impact on a steel ring. In an actual engine, that ring cross-section is not held rigidly and would roll and let the disk segments slip by. As a result, it would take three or four times the ring weight if the axial length effect is included to achieve containment, because in the engine the disk is not guided between two solid steel plates. The disk moves radially outward but the fragment could twist the ring and deflect right past it. That's one point.

The second point is that if you're talking about containing turbine disks, it seems that you should only experiment with materials (if you're going to pack it down tight around the rotor) that can take the temperature environment in the turbine section of the engine.

G.J. Mangano, NAPTC

Yes, I agree. These tests are somewhat abstract; they are not intended to provide final design information, but rather to explore containment ring behavior under conditions of actual engine rotor fragment attack. Because this was a first attempt at providing general design guidelines, it didn't take into account more specific variables such as engine mounting effects, temperature effects, etc.

S. Sattar, P&W

To follow up the previous question -- in an engine, you may not get an axisymmetric failure where fragments are trying to load the ring in a hydrostatic pressure manner. Quite often the fragments want to apply not only hydrostatic pressure on the ring, but want to twist it. If you had supported the containment ring in the manner that the engine sees it, quite often I think a Kevlar ring which might be very effective to contain pressure, may buckle under the very large torque loads that these pieces will impart. An engine rotor may not burst perfectly; all the pieces may not be released. You might lose maybe one-third of it in pieces, and the other two-thirds might stay on the rotor. I wonder if you'd like to comment on that.

G.J. Mangano, NAPTC

High-speed photo results taken of the containment process and examination of the rings after testing indicate that ring loading by a symmetrical rotor burst is not hydrostatic. In fact, highly local and considerable bending of the ring occurs outwardly at the disk impact sites and inwardly at points approximately midway between the impact sites. A symmetrical three-fragment burst, for example, will cause six local bending sites: three inward and three outward. For two-, three-, and six-fragment symmetrical bursts, the loading is symmetrical to be sure but is far from being what can be considered hydrostatic. This is evident from Figs. 9, 10, 11, and 16 of our paper. As the numbers of fragments involved in the burst increases much beyond six, the ring loading would tend to be hydrostatic, but within the scope of our experience, highly fragmented disk bursts in service tend to be the exception rather than the rule.

I have no direct experience with the mechanics of asymmetric burst containment, but it would seem that this type of failure would more likely load larger areas of the ring in a hydrostatic manner than would a symmetric burst.

In order to minimize the weight of ring used for containment, whether it is made of steel or Kevlar, the ring should be allowed to deform and displace freely during the fragment interactions so as to take maximum advantage of the energy that can be absorbed in the distortion process. Where weight is to be minimized, this concept dictates that the ring installations on an engine should approach that which was used for test; namely, freely supported. Under these conditions the Kevlar ring did admirably well in containing the fragments at minimum weight.

P. Gardner, Norton Co.

Why did you limit your studies of Kevlar to Kevlar 29 and not 49?

G.J. Mangano, NAPTC

We did only exploratory testing of Kevlar: Boeing has provided us with the rings. We have conducted only four or five tests to date. Kevlar 29 was supplied and used.

J.H. Gerstle, Boeing

I might just add a comment to that. Boeing has tested both Kevlar 29 and 49. We did not see substantial differences.

A. Weaver, P&W

Concerning the weight effectiveness, with the increased axial widths of your rings, above the ratio of 1:1 that you cited, although the long rings are heavier, did the actual thickness for threshold containment decrease when compared with the 1:1 ratio case?

G.J. Mangano, NAPTC

Thickness required for containment at an axial length ratio of 2 was greater than for a ratio of 1. This is a surprising result.

Sol Weiss, NASA-Lewis

As you presented the containment data on the small wheel, I got the impression (I think you said this) that apparently the threshold containment weight did not depend upon the number of equal-size fragments. I think yesterday we heard some people intuitively say (and I think we all believe this) that if you decrease the size of the fragments and increase the number of fragments, you may have a better opportunity for containment at lower containment ring weight. Now, when you went to a large wheel, it seems that the number of fragments did have an effect upon containment capability. Now, with what we've done so far, can we conclusively say, that the number of fragments did not affect containment in the small wheel tests, but did in the large wheel tests?

G.J. Mangano, NAPTC

For the small-rotor containment tests, the results definitely indicate an independence between the weight of ring required for containment (or SCFE) and the number of fragments generated at burst. The large rotor test results tend to indicate the opposite.

A.K. Forney, FAA

Guy, if I may, I'd like to go back to the motivation portion of your presentation because I'd hate to have these experts leave here with an incorrect impression about the FAA sitting on all of this beautiful data. First, I'd like if you could, to put your slide back up that shows the causes of the uncontained rotor bursts. Could you, I'm going to ask you to show two things: one that SDR, and second: your causes.

Now, since he's found the SDR I'll go ahead with it first. I wanted you to see that you get very little information on an SDR; here you see just about all that you really ever get. Now, a few things about it that maybe you wanted to know. This one is "open"; it does mean that there will be a subsequent report. It says "under investigation" so that there will be another one that will close it. All three of these happen to be open and so we do get a subsequent report; it's interesting what some of these subsequent ones say. This one could very well say "engine torn down and inspected, insufficient stall margin". We have a little difficulty determining how the airline's overhaul shop determines by inspection that the hardware had an insufficient stall margin (that it obviously did have insufficient stall margin under the conditions that caused it to stall). We in FAA engineering have found that we cannot use the SDR's to provide us with any engineering information. All the SDR's can do is tell us that something happened, and if we want to get details, we really do not depend on the SDR. Now there are several reasons. One is they don't have very much more detail than you see here. Secondly, all of this is fed into a computer and the computer is not programmed, for example, to let us pull out "uncontained failures". So if it does not specifically happen to mention it (and frequently you can't tell from the SDR whether the rotor failure was contained or not) the SDR really is of no value there. Then (and maybe I should have started out here) these things are submitted by an air carrier (that's the FAA term for airlines). They are required by the regulations to report certain things that occur, and one of the things they are required to report is all of the in-flight shutdowns of engines. Now, it's interesting, what is in-flight; there's a fuzzy area. If something requires them to shut an engine down before rotation, then some of the airlines don't record it; it wasn't in-flight so it wasn't an in-flight shutdown. But you know, we're interested in what happens to the engines just the same but we don't often get the reports. So having made my comment, I would like to ask you how you determined the causes. Did you attempt to determine the causes from SDR's, or did you do it like we do, use the SDR to alert yourself to an incident and then go back not even to the airline but to the engine company? Experience has shown us that we get the best information on what really happened and what the causes were by going back to the engine manufacturer whose engine was involved. I do not know enough of your work to know how you're doing that.

G.J. Mangano, NAPTC

Let me explain our procedures to you. I agree with you, there isn't very much information in the SDR, but there is enough to give us some measure of what's happening. When there's any controversy as to whether or not a fragment was contained or if fragments were generated, we just don't include it in our analysis. We operate to the limits of what the SDR has to offer, nothing more. If the SDR doesn't have the cause (and this is FAA data), if it doesn't stipulate what the cause is, then we do not use it. This is evidenced by the preponderance of "unknowns" that we nave here; the "unknown" category is far and away the largest category. We compile data to the level of what the SDR provides. However, this compilation gives a reasonably good indication of what's going on. I do not think that our compilation is nearly as extensive as that of the SAE committee; theirs is a very fine effort, and a very welcome one. Our tabulation is intended to keep our finger on the pulse of the situation; the data are no better than the information provided by the FAA. Now, Bob DeLucia is in charge of reducing this information, I would like to ask if he has any comments to make.

R. DeLucia, NAPTC

I'd just like to address one point. As of June of last year we got together with the FAA in Washington and explained the problem that we're having identifying uncontained rotor bursts. They are sympathetic and as of last year, they have included a code letter T, which means "engine case punctured". So any subsequent SDR, say from about last June to the present will have a code letter "T" in the computer runoff sheet if a fragment penetrated the engine casing and came out.

A.K. Forney, FAA

I would like to express publicly my appreciation to the Navy for that. First of all, I didn't know that; I'd be interested in knowing who in FAA headquarters you talked to. But our maintenance people, not engineering, looked after this program. When the SAE Committee's activities started, we asked them to pull out of the computer all of the uncontained failures, and they couldn't. We tried officially from engineering and maintenace to get the program changed to identify uncontained failures, and we were unsuccessful. So the fact that you now have done it, I want to express my appreciation publicly, but I'd like to know who you did it with so I can find out the details of it.

G. Gunstone, CAA-FAA

I would just like to say that the last question reinforces yesterday's plea that the constructors should get together to supply a consistent set of data which could be used by all. We are all fumbling around with insufficient, incomplete, inaccurate data. It is quite silly that we should be in that position, and I hope that a strong recommendation for a consistent data input will come from this meeting.

H. Garten, GE-Lynn

I would just like to reinforce some of the other technical comments about the tests. It seems to me that the first series of tests with the small turbine wheel were really hydrostatic tests. If you had bothered to measure the length of the shield after testing, you might have found that it was quite long, (circumferentially long) as compared to the original circumference, because most of the strain energy went into tension. Now, when you got to the larger rotor, you had to build your ring shield very deep, and the shield failed before it ever could support the hydrostatic load in tension, and it failed in bending. So I just wonder if you had considered comparing a metal shield with a Keval shield, building a metal shield in layers so that you would get more strain energy into tension and less strain energy into bending?

G.J. Mangano, NAPTC

Herb, in fact, we did run layered rings. The results were not presented here because those tests were exploratory and not part of a systematic testing effort. As an abstract idea they worked well but appear not to be a practical configuration.

J.H. Gerstle, Boeing

I'd like to make a comment about the separate-rings tests -- I happen to have seen those three concentric rings which the Navy tested, and which worked. I believe that the three rings responded similarly to a Hopkinson bar apparatus with the outer ring doing the momentum trapping. That is, the stress waves will first propagate in the thickness direction of the three rings and will be trapped in the outer ring after it separates, causing it to break while leaving the second ring intact. However, this is not a practical method.

G.J. Mangano, NAPTC

There was a question about the relative ductility of the ring material for the small rotor vs. the large rotor containment tests.

As a matter of fact, I think the materials used for the large rotor tests were less ductile. We have some curves and they're contained in the paper. The material was centrifugal cast 4130 steel. Random samples of the material were taken and subjected to standard ASTM X-ray tests for defects -- none were found. We were concerned about porosity problems. We ran some containment tests on wrought steel rings, and found large rotor threshold containment at a weight of about 135 pounds vs. about 168 pounds for the cast 4130 steel. We did not use titanium for containment tests. As someone mentioned, containment testing under high temperature conditions would be useful.

What we'd like to do to close the loop is, perhaps, run a few more baseline tests using a better steel, perhaps such as a wrought alloy that isn't subject to defects and has better ductility. Then we plan to go on to composites, which Art Holms is going to cover, in a paper later on. We shall explore Kevlar. We are not looking at a particular design but want to provide generally applicable guideline information that will be useful. We would welcome your comments on how we can make the tests more realistic without incurring excessive costs, and without focussing on a particular application or problem. We are looking for rules that will be generally applicable and useful to the aircraft community.

H. Garten, GE-Lynn

I don't know why you're not looking at titanium because titanium is incorporated in some of the fan engines.

G.J. Mangano, NAPTC

We agree with you and Denis McCarthy that titanium does appear to merit attention for containment applications. Some selected testing would be useful.

A. Holms, NASA-Lewis

I have a comment. One question dealt with unsymmetrical bursts. It seems to me that the symmetrical burst is the more severe test of the ring. Mainly with an unsymmetrical burst, you probably have one piece flying out with a lot of translational energy and velocity, but the big piece has a lot of stored rotational energy which it can give up over a longer period of time, dissipating its energy with rubbing friction. So it seems to me that an unsymmetrical burst would be a less severe test than a symmetrical burst.

On the question of the X-rays of the castings, the pieces that were X-rayed were about one and a quarter inch thick with the X-ray beam going through the one and a quarter inch direction. I think that was a reasonable nondestructive test of the material. It is true that the larger castings were more difficult castings than the small castings. The elongation in the tensile specimens from the small casting was quite a bit larger than the elongation from the large casting specimens. That may explain our size effect. But, on the other hand, workers in fracture mechanics often do find size effects in the work they do.

The body armor data that's been gathered by the Dept. of Defense shows that titanium is much superior to most steels for high velocity impact in the range of 2,000 or 3,000 feet per second. Put if you get down around 500 feet per second, titanium is no longer superior.