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ROTOR BURST PROTECTION PROGRAM

PHASE V - FINAL REPORT
PROBLEM ASSIGNMENT NASA DPR R-105

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- 120

TABLE OF CONTENTS

TITLE PAGE NO.

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

INTRODUCTION

1. The purpose of this report is to present the Phase V activities of the Rotor Burst Protection Program (RBPP) as it moves towards its ultimate goal of making design data available to all turbomachine manufacturers so that they can provide rotor burst protection within flight weight limitations.

2. Phase V of the NASA-sponsored RBPP was conducted by the Naval Air Propulsion Test Center (AE), as contracted for in reference a, during the period 1 August 1967 to 31 July 1968.

3. The testing reported herein more closely approximates realistic turbomachine operating conditions than did the previous 21 tests that were concerned primarily with basic fragment kinematics and fragment/ring interactions (reference b).

4. The high speed photographs present a good record of the complex action of both the rotor fragments and impacted containment devices. A qualitative analysis of these photographs provides insight into the effects of various parameters associated with the containment/control phenomena.

5. The comments included in this report concerning certain test observations, and how they may affect the design of containment/control systems, should be of general use to the containment design engineer.

6. The magnitude of the very real uncontained failure problem associated with US commercial airline operators and US Naval aviation is examined. Details concerning the 93 uncontained failures in commercial experience and the 46 uncontained failures reported in Navy air experience, for the respective investigatory periods, are looked at in more detail in Appendix 1.

7. Since the development effort regarding containment/control systems is largely dependent upon the qualification specifications that organizations must meet, an understanding of what some of these turbomachine spacifications have to say about containment is necessary to appreciate the overall containment problem. In Appendix 2, a majority of the applicable specifications are reviewed with regard to their containment requirements for equipment qualification.

8. Recommendations are made as to what avenue should be traveled by the RBPP to arrive at the most beneficial technical level in the immediate future.

CONCLUSIONS

9. The RBPP has continued to generate unique data that is continuing to be of benefit to those concerned specifically with the design of rotor burst fragment containment/control systems, and in general with the protection of personnel and equipment from failed turbine-powered machinery.

10. The uncontained failure problem still plagues the commercial and military air services. FAA and NTSB records indicate that a minimum of 139 such incidences have occurred. Each one should serve as a warning that renewed efforts must be exerted by all safety conscious agencies to greatly minimize the catastrophic potential of an uncontained failure.

11. The rotor fragment control process is very complex and involves the interactions of many time dependent variables. The very rapid initial loading phase, with its generation of stress wave patterns and reflections, could influence the structural characteristics of the system before the gross deformation phase, (i.e., the plastic working of the material(s)) begins. Much work will be required before this phenomenon is understood.

12. A number of containment rings have failed in the weld area prior to undergoing any gross deformation. This indicates that particular attention must be given to the manufacturing process and the elimination of sensitive stress areas so as to enhance the maximum utilization of the containment material.

13. The energy absorbed by blade deformation during rotor burst fragment-control system interaction is significant and should be accounted for in any analysis for the design of flight-weight fragment control systems.

14. The radial clearance between the rotor tip and inside diameter of the containment ring influences the fragment orientation at impact. The orientation, in turn, affects the deformation and kinetics of both the fragments and control device during the fragment control process.

15. The hardness of the control device material has a significant effect on the type of deformation that the blades of a rotor fragment will sustain during their interaction with the control device. Indications are that relatively soft materials induce more rotor blade fragmentation than do relatively hard materials.

16. Rotor blades on fragments were easily deformed by all types of containment devices under the NAPTC(AE) test conditions. This indicates that the fragment passing through the containment ring, and attacking other aircraft areas, will have a smaller contact area and consequently be capable of producing a smaller hole. This consideration is important in the design of the overall aircraft protection system.

17. The single blade impacts experienced during these containment tests indicate that failed single blades can cause large ring excursions. If the rings (or portions of the containment shield) are restrained so as to prevent these excursions, stresses may be created that could cause shield failure. Once a fracture occurs and the integrity of the ring is destroyed, not only is the release of fragments greatly increased, but the escape of hot gases adds to the dangers of engine fire.

18. As a result of the single blade failure tests, it was observed that the blades remaining on the rotor experienced very little damage.

19. The shorter, more rigid, steel starter blades experienced much less bending and buckling than did the "small" engine turbine blades when the starter fragments attacked the steel containment ring. The blades of a titanium starter rotor fragment did not bend or buckle when they interacted with a steel containment ring. The titanium blades experienced a grinding action that gradiently reduced the blade lengths from the center of the fragment to its heel.

RECOMMENDATIONS

20. NASA should continue its active support of the Rotor Burst Protection Program's efforts directed toward the undertanding of the complex phenomena associated with the control of fragments from failed, high-speed, turbomachines, and the generation of data to assist in the design of flight-weight fragment containment/control systems.

21. The material evaluation portion of the RBPP should be intensified. This will serve not only to investigate new designs and materials but also enlarge our material behavior experience that can be applied to the development of analytical models.

22. The efforts to develop a computerized mathematical model capable of providing dynamic response data of containment/control systems under attack by various types of fragments generated by failed turbomachines should continue to receive NASA support. The model should handle many types of materials, designs, and constraints associated with various systems.

23. Rotor fragment control design analyses should definitely consider the energy absorption potential and fragment orientation effects associated with the blades attached to a failed rotor fragment.

24. Particular attention should be directed toward the manufacturing process of a fragment control system since this may be as critical to the system's performance as the material itself (welds are particularly critical).

METHOD OF TEST

25. The test results presented in this report were obtained using basically the same equipment and techniques described in references b and c. Basically, the test procedure is as follows:

The test rotor, modified to fail at a specified speed and produce certain shaped fragments, is connected to the air-driven drive turbine by an arbor. This assembly is positioned on the center cover assembly of the chamber's dished head. The test containment ring is freely suspended from the underside of the center cover. The axial center of the ring is in the plane of the rotor. Electrical connections are made from the photo-triggering strip, fixed to the inner diameter of the containment ring, to the flash circuitry. The photographic mirror (front surface) is accurately positioned at a 45-degree angle directly beneath the plane of action. The two photo-lights are positioned to provide the required illumination. The light from the flash units is reflected off the mirror to the rotor and ring. The high speed continuous-framing camera is positioned so that the optical axis of the camera's taking lens forms an angle of 45 degrees with the plane of the mirror and the lens is adjusted to insure maximum object sharpness. A vacuum is drawn in the spin chamber to reduce the aerodynamic drag on the rotor and thus the power required to accelerate the rotor to burst speed. The test cell is completely darkened and the camera capping shutter is opened. The camera speed is brought to the desired framing rate (it can maintain this constant framing rate for an extended period of time). Air pressure is applied to the drive turbine and it accelerates the rotor to bursting speed. When the rotor fails, the fragments fly outward and contact the photo-triggering strip as they bang into the containment ring. The contact of the fragments with the strip triggers the photo-lighting system, illuminating the interaction of the fragments and the ring. Pictures are taken of the subject image formed by the same mirror used to transmit the light. The duration of the lights is such that film rewrite on the continuous film strip does not occur. The camera capping shutter is then closed and the film is removed for processing.

26. The conditions for each test are listed in Table I of this report.

DISCUSSION

The Problem

27. The complexities of today's and tomorrow's air travel operations are many and varied, and the problems affecting the well-being of the traveler must be recognized, receive top priority, and be solved by the various organizations that constitute the "air industry."

28. One such problem is that of containing or controlling the fragments generated when a high speed turbomachine (main engine, starter, auxiliary power units, environment control systems, etc.) fails. Unless controlled, these fragments may cut through fuel lines or control cables, penetrate fuel tanks, or depressurize the aircraft cabin. Any of these secondary effects may be more critical than the original loss of the turbomachine powerplant.

29. A review of US commercial airline and US Naval aviation experience definitely indicates the presence of an uncontained failure problem. A minimum of 93 fragments have penetrated the casings of commercial engines during the survey period (1962-1968). The Navy reports 46 uncontained engine failures from fiscal year 1960 to fiscal year 1967.

30. These numbers may not be considered large by some, but the catastrophic potential of just one such failure should definitely place this problem high on the priority list of safety measures requiring increased attention.

31. A detailed presentation of the uncontained failure problem for both commercial airline operators and US Navy aviation is presented in Appendix 1.

32. The "fixes" that once satisfied certain uncontained failure problems cannot be applied to today's much larger engines. Economics and safety demand lighter weight and more positive solutions. These solutions will be delayed unless all members of the air industry actively contribute their talents to a general effort. Individual company efforts under a cloak of propriety have only very limited value since the air transport community cannot afford "safe" engines and "unsafe" engines. The dark shadow of an accident caused by an uncontained failure falls equally heavy on all airline operations.

The Aircraft Design Review

33. Design data produced by the RBPP is required not only by the turbomachine manufacturers but also by the airframe manufacturers. In Appendix 2 to this report this requirement is discussed. Basically, the airframe manufacturer must be able to evaluate the containment/control characteristics of each turbomachine being considered for use in his aircraft. The proposed system's soundness must be examined, the weight penalties determined, and comparisons made against other methods of providing equivalent protection from bursting turbine-powered equipment for both passengers and aircraft.

34. The safety design reviews conducted for each new aircraft can certainly utilize a greater quantity and quality of data concerning the uncontained failure phenomena. It is at this early stage of aircraft development that answers should be obtained for this problem. Early efforts will prevent the poor situation of having to provide containment/control systems as afterthoughts that will be completely parasitic weight problems instead of possibly incorporating protective systems that could serve as structural members, noise and/or heat insulators, etc., as well as fragment controllers.

General Test Objectives

35. The experiments presented in this report were conducted to study the processes that are involved when high-energy fragments from a

burst rotor interact with a simulated rotor casing or a fragment control device - a device, usually cylindrical, that is designed to withstand the penetration and gross deformation failures induced by fragment impact. More specifically, these experiments were conducted to:

a. Study and measure the variables and factors associated with rotor burst fragment control.

b. Evaluate the effectiveness of light weight ballistic protection materials when used in rotor burst fragment control applications.

c. Determine what effect fragment and control device material properties have on the fragment control process.

36. Generally speaking, the variables that affect fragment and control device reaction during the fragment control process are:

a. The control device

    (1) material properties

    (2) shape

    (3) size

    (4) constraint

b. The fragment

    (1) material properties

    (2) geometry

    (3) size

    (4) weight

    (5) velocity

These basic variables combine to form what we term factors. The fragment energy factor, for example, is a combination of the fragment variables: shape, size, weight and velocity. The fragment control variables and factors are time dependent; that is, they change value with time during the control process: A cylindrical control device may, under fragment attack, continuously deform to an ellipse. The material used may be strain rate sensitive; the fragment weight may diminish and as a result change in size and shape; and so on. Even these elementary observations indicate that the fragment control process is complex and will involve the interaction and combination of a myriad of time dependent variables. An awareness of these complexities has, to a large extent, influenced our experimental philosophy. Because we knew the phenomenon to be studied was complex, our approach was to design experiments that would isolate the effects of certain variables. This was done by parametrizing the variables and factors whose effects were to be studied, while holding the others constant from one experiment to another. For example, in experiments 28 and 34 of this report the fragment control device material was the parameter (using steel and aluminum); other variables such as fragment mass, velocity, control device constraint and dimensions were held constant. Using this procedure, the effect of the various material properties on fragment deformation and behavior was studied.

ANALYSIS OF RESULTS

37. The results and discussion of our experiments will be presented according to their primary experimental objectives. It should be understood, however, that the common objective of all the experiments conducted was to observe and measure fragment control variables and factors.

Series I Investigation - Ring Material Hardness

38. Experiments 25, 27, 28, 29 and 34 were conducted to study the deformations and kinetics experienced by rotor burst fragments when they interact with cylindrical fragment control devices made from metals of different hardness.

a. Fragment Generator:

The fragments were three equal annular sectors from a T58 engine power turbine rotor. The general configuration and details regarding the fragment dimensions, weight, and material properties can be found in Table I, and a photograph of the turbine rotor modified to fail in the tri-hub mode is shown in Figure 1.

b. Control Devices:

The devices used for these experiments were continuous right circular cylinders made from different metals. The details concerning the dimensions, weight, and material properties of the cylinders can be found in Table I. The thickness of the control rings was determined by equating the kinetic energy of the fragments at burst to the product of the control device material toughness and its dimensions. This expression was then solved for the control device thickness. This type of design analysis is usually referred to as the "Strain Energy Method".

c. Results - Test 25:

The setup for test 25 is shown in Figure 2. The 4130 steel cylindrical control device (hardness 30 R_c) was only slightly deformed and experienced only slight gouging along portions of the ring's inner surface (Figures 3 and 4). The rotor burst produced a tri-hub failure at 14750 rpm. As can be seen in Figure 5, the fragment deformation was limited to the blades; the disk fragments were not damaged. There is a blade deformation gradient that progressed from the "heel" of the sector (the initial impact point), where it is most severe, to the forward edge where the deformation was considered slight. The severely deformed blades curled onto themselves from tip to root in a direction opposite that of rotor rotation. High speed photographs which capture the fragment-control device interactions are shown in Figure 6.

d. Results - Test 27:

Figure 7 depicts the modified rotor and three-inch thick 2024-T4 aluminum cylindrical control device mounted beneath the inner cover of Spin Chamber No. 1 prior to test 27.

High-speed photographs of test 27 are shown in Figure 8. The "fog" developed in the latter pictures is attributed to the generation of fine aluminum particles. Note also that the massive ring has apparently not been moved or rotated from its original position.

The control ring suffered no gross deformation; however, severe gouging and some ballistic penetration were evident on its inner surface where the fragments impacted (refer to Figures 9 and 10). The rotor sector blades experienced a similar gradient deformation as that mentioned in test 25. Unlike the extensive curling type of blade failures noted in test 25 against the hard steel ring, the blades of test rotor 27 experienced much more fragmentation. Note the many small pieces of blades in the post-test photograph of the test 27 rotor (Figure 11).

e. Results - Test 28:

A ribbed aluminum cylindrical control device (Figure 12) was evaluated under attack by a tri-hub rotor burst at 22100 rpm. This 6063 ribbed aluminum material is normally used for lightweight deck and bulkhead ship structures. A typical cross section of this structure is shown in Figure 13. High-speed photographs of the impact phenomena are shown in Figure 14.

The control device experienced both severe ballistic type penetration and gross deformation (refer to Figure 15). A secondary shield of steel that surrounded the control device was struck by the fragments; was severely deformed; and fractured (refer to Figure 16). Although the containment ring did not substantially resist the movement of the fragments, it is interesting to note (Figure 14) the large amount of damage done to the blades before the fragments passed through the ring.

f. Results - Test 29:

Test 29 was a tri-hub burst of a power turbine rotor into a 4130 steel, rectangular cross section, cylindrical control device. By error, this test was made with the rotor turning in a direction opposite to that of normal rotation (blade installed upside down).

High-speed photographs of test 29 are shown in Figure 17. Note that two of the three fragments are still contained within the containment ring after six milliseconds (last picture of Figure 17) while the third fragment has flipped out of the original plane of rotation. This "flipping" is one of the things a good containment device design will prevent. Effective containment is usually associated with maintaining the fragments in contact with the device so as to maximize the interaction time.

The control device experienced: minor gross deformation; some ballistic type penetration; and mild gouging (refer to Figures 18 and 19). The blades of the rotor annular section were gradiently deformed; some characteristically curled back on themselves; others sheared at the root; and still others were torn from the disk with the fir-tree fastener intact (Figure 20). The blade curling is similar to that experienced by the rotors of tests 25 and 27 even though one may intuitively expect it to be more difficult to bend and curl a blade backwards as was the case with this test.

g. Results - Test 34:

The high-speed photographs of test 34, a tri-hub burst of a power turbine rotor into a flanged, cylindrical control device made from heat-treated 4130 steel, are shown in Figure 21.

The control device failed at its two weldments during fragment impact and was severely deformed, each half being bent almost flat (Figure 22). The impacted surfaces were slightly scored. The blades of the annular rotor sectors were gradiently deformed. Most of the blades had sheared at their roots after curling onto themselves.

The results of test 34 serve to emphasize just how critical is the presence and quality of the ring weld. A number of rings have failed in the weld before the ring has had an opportunity to be plastically deformed. The method with which containment/control devices are fabricated was shown to be critical to the performance of these devices and it is expected that the fabrication method will be a very sensitive and important parameter for these systems.

Series I - Ring Material Hardness Observations

39. The hardness of the control device material has a significant effect on the type of deformation that the blades of a rotor fragment will sustain during their interaction with the control device. Indications are that relatively soft materials induce more rotor blade fragmentation than do relatively hard materials. This observation is based on a comparative analysis of the results from similar rotor burst experiments where 2024-T4 aluminum (test 27) and a relatively hard heat-treated 4130 steel (test 34) were used as fragment control device materials. One explanation for this could be as follows: The harder materials, being less penetrable than the soft, provide a relatively smooth surface along which the blades can slide or skid. As a result, a more uniform kinetic interaction occurs between the blades and the control device ; thus the integrity of the blade is preserved even though it is grossly deformed. It is difficult at this time to predict which of the blade actions --the fragmented or integrally deformed --would be preferable for fragment control.

Series I - Radial Clearance Observations

40. An examination of this series of tests also provides information concerning another important consideration regarding the design of containment/control systems, radial clearance. A study of the high-speed photographs indicates that the general action associated with a rotor sector fragment can be described as follows:

a. When the fragment breaks away from the hub section it moves along a tangential path through its center of mass and rotates about its center of mass with approximately the same angular velocity as the rotor at its burst speed. It is this combined motion that causes the fragment to strike on its trailing edge (heel) while the leading edge, rotating away from the ring, does not strike the ring immediately. From this it is seen that the percentage of rotor outer edge area that makes initial contact with the inner surface of the ring, and the fragment's orientation relative to that surface, is dependent upon the type of rotor fragment, the burst speed, and the distance between the rotor and the ring, i.e., the radial clearance.

41. The aforementioned experiments indicate how radial clearance influences fragment orientation at impact. They also demonstrate how the orientation, in turn, affects the deformation and kinetics of both the fragments and control device during the fragment control process. The gradient deformation sustained by the fragment blades during their interactions with the different control devices is an example of the influence of orientation (or radial clearance - one depends on the other) on fragment deformation. This is an important observation because it follows that preferential orientation of the fragment at impact can serve to promote more effective fragment control.

Series I - Energy Absorbed by Deforming Blades

42. This series of tests also points out a fallacy with the majority of containment design procedures used today. No consideration is given to the energy absorption capacity of the blades on the rotor. The energy absorbed by blade deformation during rotor burst fragment / control device interaction is significant and should be accounted for in any analysis for the design of flight-weight fragment control devices. Future RBPP efforts will study this phenomenum further.

Series II - Critical Fragment Size

43. Experiments 30 and 31 were the first of a series of experiments to determine what size rotor fragment has the most devastating effect on a cylindrical fragment control device.

44. For this series of experiments several identical rotors were modified to fail at the same speed producing 2, 3 and 4 equal rotor sector fragments. These rotors were to be surrounded by identical cylindrical fragment control devices. Only the tri-hub bursts were performed to date. Test 31 was a repeat of the previous test since high-speed photographs were not obtained for test 30.

a. Fragment Generator:

The fragments were three equal sectors from an axial flow, air turbine starter rotor (refer to Figure 23). Details concerning their fragment weight, dimensions and material properties are contained in Table I.

b. Control Device:

The control devices were the flanged 1020 steel cylinders shown in Figure 24. Details on the dimensions, weight and material properties of the control device can be found in Table I.

c. Results - Tests 30 and 31:

High-speed photographs of experiment 31 are shown in Figure 25. Tests 30 and 31 were tri-hub bursts of an air turbine starter rotor into a 1020 steel, flanged, cylindrical control device. The control devices experienced no noticeable gross deformation. The impacted inner surfaces of the rings were severely gouged and suffered some shallow ballistic type penetration (refer to Figures 26 and 27 for test 30 and Figures 28 and 29 for test 31). Rotor sector deformation was limited to the blades which appeared to have buckled and bent (refer to Figures 26 and 28).

Series III - Momentum Transform Fragment Control Device

45. Experiment 26 was conducted to evaluate a design concept for containing rotor burst fragments. This particular concept is not suggested as a directly applicable design for a containment/control device, but it does emphasize the fact that protective systems should not be restricted to a cylindrical shape, as has been the case in almost all devices to date. It is the combination of material and design that will eventually solve the fragment protection problem, rather than just the use of a material or a design without consideration of the other factor.

a. Fragment Generator:

The fragments generated in this experiment were three equal annular sectors of titanium (Ti 6A14V), shown in Figure 30, from an air turbine starter rotor. Details concerning fragment dimensions, weight, and material properties may be found in Table I.

b. Control Device:

The control device was the 1020 steel lobed configuration shown in Figure 30. This device was termed a momentum transform fragment control device because it was designed to transform a considerable portion of the fragment's angular momentum into linear radial momentum of the control device. This would greatly reduce the torsional loading that generally accompanies containment with cylindrical fragment control devices, especially those associated with smaller turbomachines.

c. Results - Test 26:

Test 26 was a tri-hub burst of an air turbine starter rotor into a three-lobed 1020 steel control device. High-speed photographs of the event are shown in Figure 31. Note that in picture 4 of Figure 31 (three milliseconds after impact) the once daisy-shaped containment ring has become circular. Deformation of the device was extensive. Two failures occurred at section weldments. The impact surface of the ring was slightly abraded. No ballistic penetration was apparent. The titanium blades of annular rotor sectors were ground during the impact process. Here again a gradient of deformation or "wear" was evident, being worse at the impact point and lessening toward front edge of the fragment (refer to Figure 32).

Series IV - Large Rotor Tri-hub Burst

46. Experiment 22 was conducted so that we could study the interaction between fragments from a relatively large rotor and a cylindrical fragment control device and also gain some experience with the testing of moderately large rotors.

a. Fragment Generator:

The fragments were three equal annular sectors from the J65 engine, 2nd stage turbine rotor. Refer to Table I for details concerning the fragment dimensions, weight, and material properties.

b. Control Device:

The control device was a 4130 steel cylinder heat-treated to a strength of 220,000 psi. Details concerning the control device dimensions, weight and material properties can be found in Table I.

c. Results - Test 22:

Test 22 was an intentional tri-hub burst of a J65 engine second stage turbine rotor into a 4130 steel cylindrical control device. Unfortunately, no high-speed photographs were obtained of this test. The control device was severely deformed and, from the fracture surface appearance, had failed in tension at three locations (refer to Figure 33). The impact surface had experienced light to moderate gouging; no ballistic type penetration of this surface was noted.

The rotor blades on each annular sector or fragment were sheared from the rotor and severely deformed. In some cases the blade root section appeared to have been torn from the rotor (refer to Figure 34).

Series V - Blade Burst in a Fully-bladed Rotor

47. Experiments 23, 32, and 33 were conducted to study the behavior of a blade as it bursts from a rotor, impacts a surrounding steel cylindrical casing, and interacts with the blades remaining fixed to the rotor.

a. Fragment Generator:

The fragments for all three tests were three blades from a T58 engine power turbine rotor. These blades were notched as shown in Figure 35 and placed in equally spaced locations on the rotor. Details concerning the fragment dimensions, weight, and material properties can be found in Table I.

b. Control Device:

The control device was a continuous circular 1020 steel cylinder whose thickness approximated the composite thickness of the layered power turbine casing of the T58 engine. Details concerning the size and material properties of the control device are contained in Table I.

c. Results - Test 23:

High-speed photographs of experiment No. 23 are shown in Figure 36. The power turbine rotor three-blade burst into a mild steel cylindrical control device produced slight deformation of the control ring. However, there was evidence of penetration and back bulging of the control device material at the areas of initial blade impact (refer to Figure 37). The ring did remain intact; there were no plugging failures or circumferential failure surfaces. The released blades (3) underwent severe deformation and fracture during the impact process (refer to Figure 38). A tendency of the blade tips to curl in a direction opposite that of rotor rotation was noted. No blades other than those modified to fail were released from the rotor. The blades remaining on the rotor were only mildly deformed at their tips. It should be noted that the containment ring was freely supported; i.e., no external structures restricted the comparatively large ring excursions shown in Figure 36.

d. Experiments 32 and 33 were conducted to study and evaluate the effectiveness of HY140 steel in rotor blade burst control applications. HY140 steel is produced by the United States Steel Corporation.

e. Fragment Generator:

Same as that specified for experiment 23.

f. Control Device:

The control devices were continuous, circular cylinders of HY140 steel (refer to Figure 39). In this photograph one of the four strain gages that are equally spaced on each containment ring evaluated at the NAPTC(AE) can be seen. The white mass of epoxy and the plastic installation strip help prevent the strain gage leads from being damaged during installation.

g. Results - Tests 32 and 33:

High-speed photographs of experiment 33 are shown in Figure 40. No photographs were obtained of test 32. Both rings experienced similar damage; deformation of both the control devices was slight and only a limited amount of abrasion on the impacted surfaces was noted (refer to Figures 41 and 42). The failed blades were badly deformed and had fragmented during impact. Those blades remaining on the rotors had only their tips deformed; they were bent perpendicularly backwards in a direction opposite to that of rotor rotation (Figure 43).

Series V - Blade Burst Observations

48. The single blade impacts experienced during these tests indicate that failed single blades can cause large ring excursions. If the rings (or portions of the containment shield) are restrained so as to prevent these excursions, stresses may be created that could cause shield failure. Once a fracture occurs and the integrity of the ring is destroyed, not only is the release of fragments greatly increased, but the escape of hot gases adds to the dangers of engine fire. For the particular rotor used in these tests the damage to the follow-up blades was slight. Although the radial clearance for these tests was greater than for normal operating conditions, it is expected that this difference would not have substantially changed the results observed in these tests.

49. Test 24 was a burst test of an air turbine starter rotor to evaluate a disk crack sensing device. This test was terminated prematurely by a drive spindle failure. No conclusive results can be stated other than the fact that the sensing system triggered the photographic system, as expected under the conditions imposed.

Industrial-Federal Coordination

50. The RBPP encourages industrial and Federal organizations to participate in the program. It is believed that the additional inputs from the various disciplines will enlarge our experience background, increase our technical awareness, and shorten the time required to provide satisfactory design data. The interest in the RBPP is increasing and more organizations are contributing to the overall effectiveness of the program.

The MIT Analytical Program

51. In June 1968 the NASA provided funds (Grant No. NGR 22-009-339) to the Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Aeroelastic and Structures Research Laboratory, to investigate the concepts, methods of analysis, and evaluation thereof for the containment/control of fragments from bursting turbomachines. The MIT goal is to generate the mathematical model(s) described in reference b. Basically, this theoretical effort encompasses such areas as the development of methods of analysis which may be used to predict the transient responses of fragments and control devices, including impact, penetration, and deflection response of the containment/control device. The NAPTC(AE) will continue to coordinate with the MIT personnel to provide experimental data required to establish various fragment-control system interactions and verify the computer model(s) to be developed. Although once this computerized mathematical model is developed, it will not be the final answer to the uncontained failure problem. Computers are here to help the designer by grinding out calculations and investigating various parametric relationships. The computer should amplify the effectiveness of the program by mathematically assisting in the selection of the most promising systems that will be translated into hardware and evaluated and thus avoiding the usual costly and time-consuming guideless cut-and-try testing. The use of the computer as an analytical tool will enlarge upon our ability to explore new things, but is should be remembered that the computer is just a tool and the designer is the innovator.

TABLE I

PHASE V TEST DATA COMPILATION

1. A detailed compilation of the twelve tests that were performed during Phase V of NASA DRP R-105 is presented in this table. This compilation is divided into four sections:

a. Test objectives, photographic coverage, and burst speeds.

b. Fragment generator details.

c. Containment system details.

d. Photographic system details.

2. The following is a list of symbols used in this compilation:

a. N = No or none

b. Y = Yes or available

c. C = Contained, i.e., no fragment perforated the containment device.

d. Error = Actual speed minum design speed

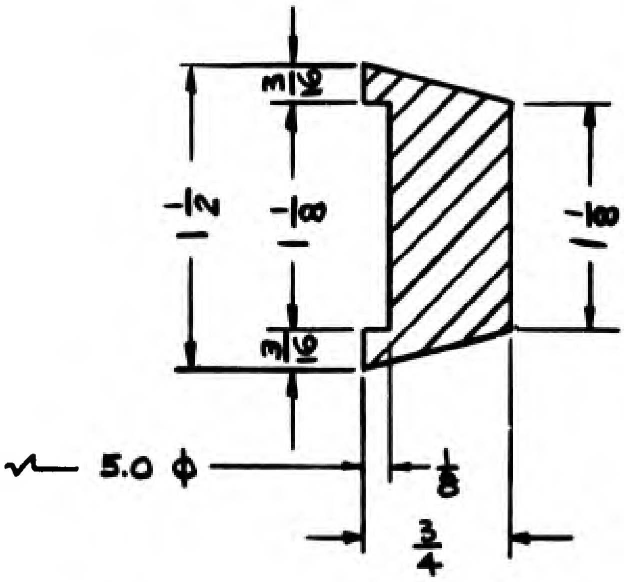
e. Percent Error = $\frac{\text{Error x 100}}{\text{Design}}$

f. Computational error in rotor design calculation.

g. Detailed photograph of containment device shown in main body of report (Figure 13).

h. Lamination of masking tape (1 inch wide) and aluminum tape (1/2 inch wide).

i. Ring cross section as per following sketch:



j. Ring cross section as per following sketch:

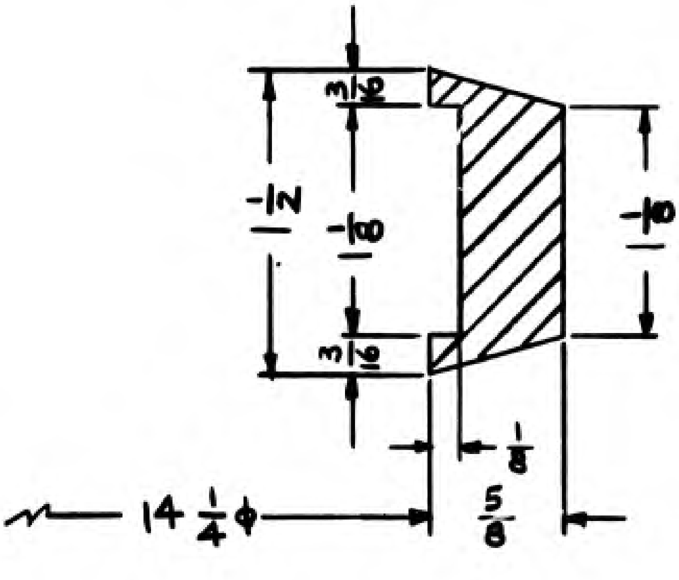


TABLE I (Continued) - PHASE V TEST DATA COMPILATION

					STILL PHOTOS			BURST SPEED			
Test No.	Test Objective	High Speed Photographs	Enlarged Prints	Animation	Polaroids	Pre-test	Post-test	Design (rpm)	Actual (rpm)	Error (d)	Percent Error (e)
22	"Medium" Rotor Tri-hub Burst Dynamics	(a) N	N	N	Y	Y	Y	9,300	9,200	100	-1.08
23	Single Turbine Blade Dynamics within a Fully-bladed "Small" Turbine Rotor	(b) Y	Y	N	N	Y	Y	22,000	21,500	-500	-2.27
25	Ring Material Hardness - "Small" Turbine Rotor	Y	Y	Y	Y	Y	Y	13,500	14,750	1250	9.26
26	Momentum Transfer Control Device - Starter Rotor (Ti) Tri-hub Burst	Y	Y	N	N	Y	Y	40,000	38,700	-1300	-3.25
27	Ring Material Hardness - "Small" Turbine Rotor	Y	Y	N	Y	Y	Y	22,000	20,000	-2000	-9.09
28	Ring Material Hardness - "Small" Turbine Rotor	Y	Y	N	Y	Y	Y	22,000	22,100	100	0.45

TABLE I (Continued) - PHASE V TEST DATA COMPILATION

Test No.	Test Objective	High Speed Photographs	Enlarged Prints	Animation	STILL PHOTOS Polaroids	STILL PHOTOS Pre-test	STILL PHOTOS Post-test	BURST SPEED Design (rpm)	BURST SPEED Actual (rpm)	BURST SPEED Error (d)	BURST SPEED Percent Error (e)
29	Ring Material Hardness - "Small" Turbine Rotor	Y	Y	N	Y	Y	Y	22,000	14,750	(f) -7,250	-39.9
30	Critical Fragment Size Determination - Tri-hub Starter (Steel) Rotor Burst	N	N	N	Y	Y	Y	60,000	37,650	-22,370	-37.3
31	Critical Fragment Size Determination - Tri-hub Starter (Steel) Rotor Burst	Y	Y	N	Y	Y	Y	60,000	43,000	-17,000	-28.3
32	Single Turbine Blade Dynamics within a Fully-bladed "Small" Turbine Rotor	N	N	N	Y	Y	Y	22,000	21,200	-800	- 3.60
33	Single Turbine Blade Dynamics within a Fully-bladed "Small" Turbine Rotor	Y	Y	N	Y	Y	Y	22,000	21,000	-1,000	- 4.5
34	Ring Material Hardness - "Small" Turbine Rotor	Y	Y	N	Y	Y	Y	22,000	21,100	-900	- 4.1

TABLE I (Continued) - PHASE V FRAGMENT GENERATOR

Test No.	Type	No. of Fragments	Rotor Diameter (in.)	Disk Thickness (in.)	Blade Fragment Length (in.)	Disk Weight (lb)	Fragment Weight (lb)	Fragment Centroid (in.)	Radius Ratio	Material	UTS (K psi)	Hardness (R_C)
22	"Medium" Engine Turbine Rotor	3	30.64	Variable	3.18			7.404				
23	"Small" Engine Turbine Rotor	3	14.0	Variable	3.5	12.98	0.08	4.8125		SEL		
25	"Small" Engine Turbine Rotor	3	14.0	Variable		12.98	2.96	3.125		SEL		
26	Starter Rotor	3	7.25	Variable		2.32	0.72	1.8125	4.833	Ti-6Al-4V		60
27	"Small" Engine Turbine Rotor	3	14.0	Variable	3.5	12.98	2.96	3.125		Lapelloy C		
28	"Small" Engine Turbine Rotor	3	14.0	Variable	3.5	12.98	2.96	3.125		Lapelloy C		

TABLE I (Continued) - PHASE V FRAGMENT GENERATOR

Test No.	Type	No. of Fragments	Rotor Diameter (in.)	Disk Thickness (in.)	Blade Fragment Length (in.)	Disk Weight (lb)	Fragment Weight (lb)	Fragment Centroid (in.)	Radius Ratio	Material	UTS (K psi)	Hardness (R_C)
29	"Small" Engine Turbine Rotor	3	14.0	Variable	3.5	12.44	2.96	3.125	0.207	Lapelloy C		
30	Starter Rotor	3	4.75	Variable	0.625	1.625	0.504	1.125		Ti-6Al-4V		
31	Starter Rotor	3	4.75	Variable	0.625	1.64	0.504	1.125		Ti-6Al-4V		
32	"Small" Engine Turbine Rotor	3	14.0	Variable	3.5	12.98	0.08	4.875		SEL		
33	"Small" Engine Turbine Rotor	3	14.0	Variable	3.5	12.98	0.08	4.875		SEL		33.5
34	"Small" Engine Turbine Rotor	3	14.0	Variable	3.5	12.98	2.96	3.125	0.207	SEL		33.5

TABLE I (Continued) - PHASE V CONTAINMENT DEVICE

Test No.	Type	Degree of Containment (C)	Inside Diameter	Radial Thickness (in.)	Axial Width (in.)	Material	UTS (K psi)	% Elongation in 2"	Hardness	Total Weight (lb)
22	Ring, 4130 Steel, Rectangualr X-Section	N	31.313	0.1875	3.0	4130 HT	220	20		15.78
23	Ring, 1020 Steel, Rectangualr X-Section	C	15.375	0.125	3.0	1020 Steel	65	30	$78R_B$	5.175
25	Ring, 4130 Steel, Rectangular X-Section	C	14.5	0.4525	3.0	4130 HT	220	20		19.0
26	Ring, 4130 Steel, Rectangular X-Section	N		0.250	3.0	4130 HT	220	20	$85R_B$	8.42
27	Ring, 2024-T4 Alum, Rectangular X-Section	C	14.5	3.0	3.0	2024-T4 Alum				50.75
28	Note (g), Ring, Ribbed Aluminum	N	14.5	Note (g)	3.875	6063-T6 Alum				3.41

TABLE I (Continued) - PHASE V CONTAINMENT DEVICE

Test No.	Type	Degree of Containment	Inside Diameter (in.)	Radial Thickness (in.)	Axial Width (in.)	Material	UTS (K psi)	% Elongation in 2"	Hardness (R_C)	Total Weight (lb)
29	Ring, 4130 Steel, Rectangular X-Section	C	14.5	0.45	3.0	4130 HT	220	20		18.275
30	Ring, 1020 Steel, Angled Flange X-Section	C	5.25	0.5625	Note (i)	1020 Steel	65		78 R_B	3.641
31	Ring, 1020 Steel, Angled Flange X-Section	C	5.25	0.5625	Note (i)	1020 Steel	65		78 R_B	4.028
32	Ring, HY 140 Steel, Rectangualr X-Section	C	14.5	0.125	3.0	HY 140 Steel	152	14	34.5	5.536
33	Ring, HY 140 Steel, Rectangular X-Section	C	14.5	0.125	3.0	HY 140 Steel	152	14	34.5	5.372
34	Ring, 4130 Steel, Angled Flange X-Section	N	14.5	0.500	Note (j)	4130 HT	220	20	28.7	9.325

TABLE I (Continued) - PHASE V PHOTOGRAPHIC SYSTEM

CAMERA							LIGHTING					FILM	
Test No.	Framing Rate (pps)	Quantity of Pictures	Total Writing Time (msec)	Frame Interval Time (μsec)	Stop Size	Lens Setting (mm)	No. of Lights	Light Duration (msec)	Intensity (10^6 BCP)	Triggering Mode	Type Grid	Type	Developer
22	14432	0	10.8	69.29	3/8	3.5	2	10.8	3.0	Pos. Volt Pulse	Horizontal Wire	2475	DK-50
23	14441	146	10.8	69.25	3/8	2.9	2	10.8	3.0	Pos. Volt Pulse	Horizontal Wire	2475	DK-50
25	14502	156	10.8	68.96	3/8	2.9	1	10.8	3.0	Pos. Volt Pulse	Horizontal Wire	2485	MX-642-1
26	9829	126	10.8	101.74	3/16	3.1	2	10.8	3.0	Closed Contact	(h) Laminate	2475	DK-50
27	15429	156	10.8	64.81	3/8	2.8	2	10.8	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50
28	15498	168	10.8	64.52	3/8	2.8	2	10.8	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50

TABLE I (Continued) - PHASE V PHOTOGRAPHIC SYSTEM

CAMERA							LIGHTING					FILM	
Test No.	Framing Rate (pps)	Quantity of Pictures	Total Writing Time (msec)	Frame Interval Time (µsec)	Stop Size	Lens Setting (mm)	No. of Lights	Light Duration (msec)	Intensity (10^6 BCP)	Triggering Mode	Type Grid	Type	Developer
29	14530	156	10.8	68.82	3/8	2.8	2	10.8	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50
30	14658	0	5.4	68.22	3/16	100	2	5.4	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50
31	14843	80	5.4	67.37	3/16	50	2	5.4	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50
32	14298	0	10.8	69.94	3/8	50	2	10.8	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50
33	14956	160	10.8	66.86	3/8	50	2	10.8	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50
34	14619	172	10.8	68.40	3/8	50	2	10.8	3.0	Pos. Volt Pulse	(h) Laminate	2475	DK-50

MODIFIED TURBINE ROTOR
TYPICAL TRI-HUB FRAGMENT GENERATOR

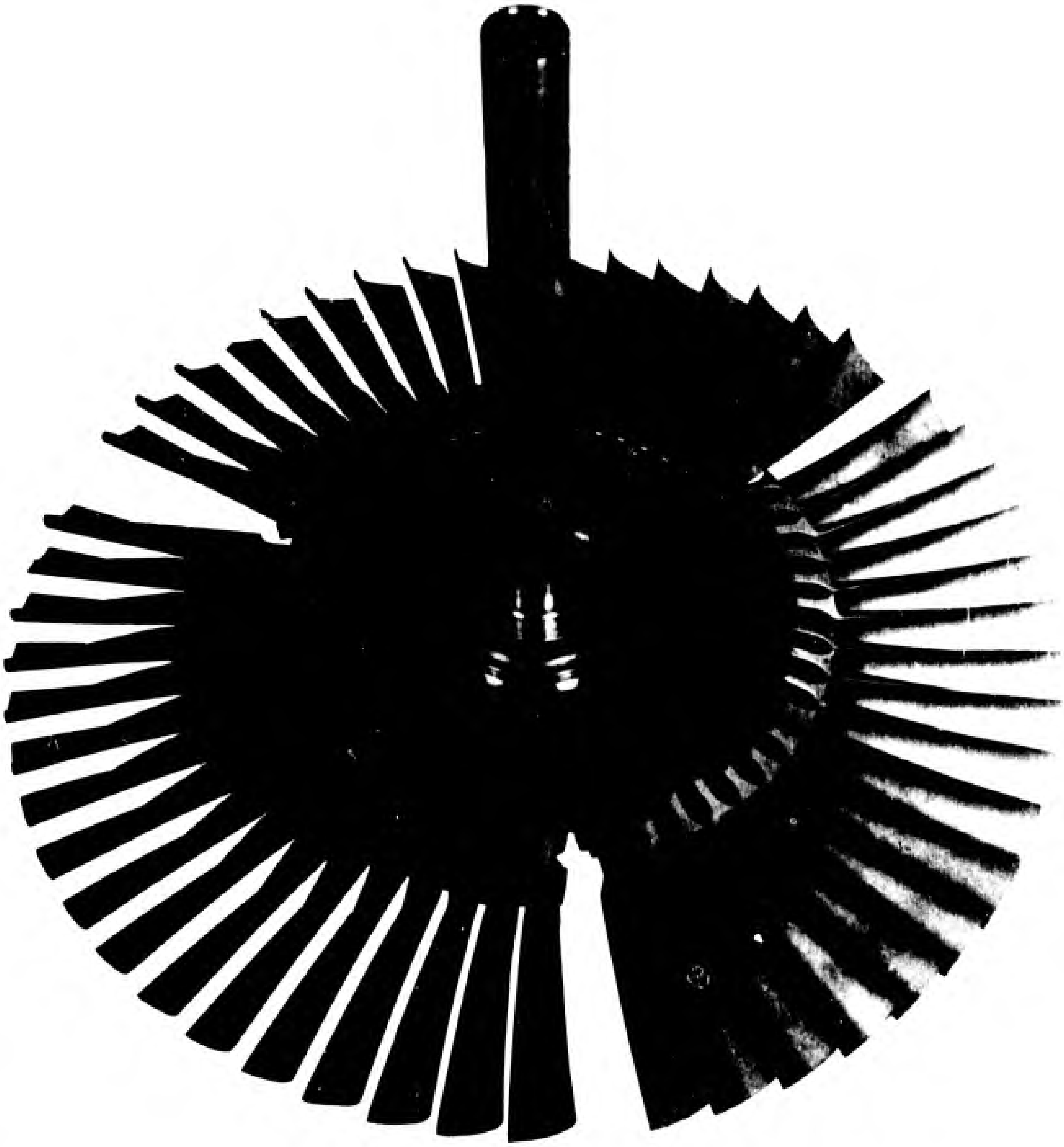
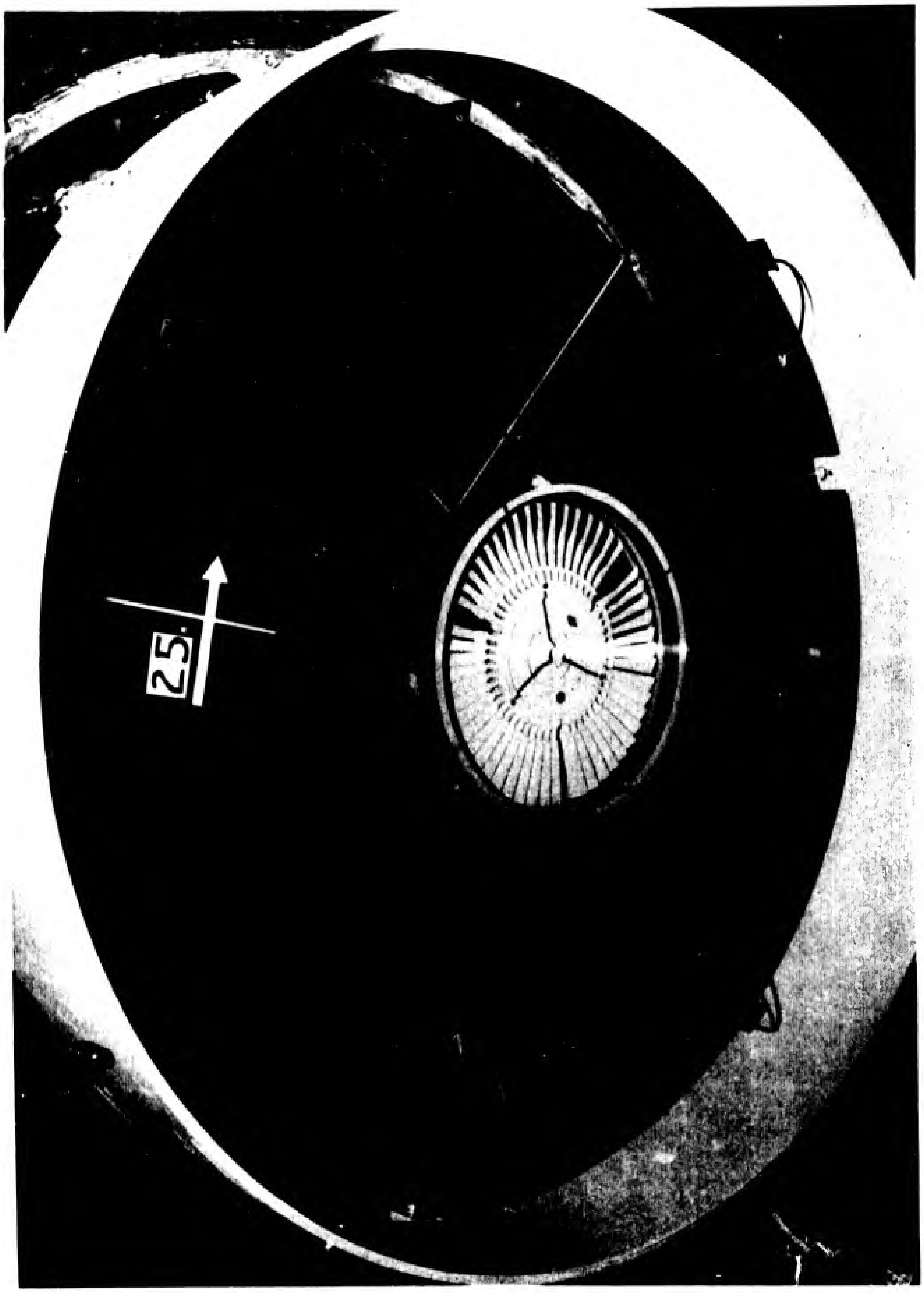


PHOTO NO: CAN-386644(L)-3-68

FIGURE 1



PRE-TEST 25 INSTALLATION

PHOTO NO: CAN-386322(L)-2-68

FIGURE 2

POST-TEST 25
CONTAINMENT RING DEFORMATION

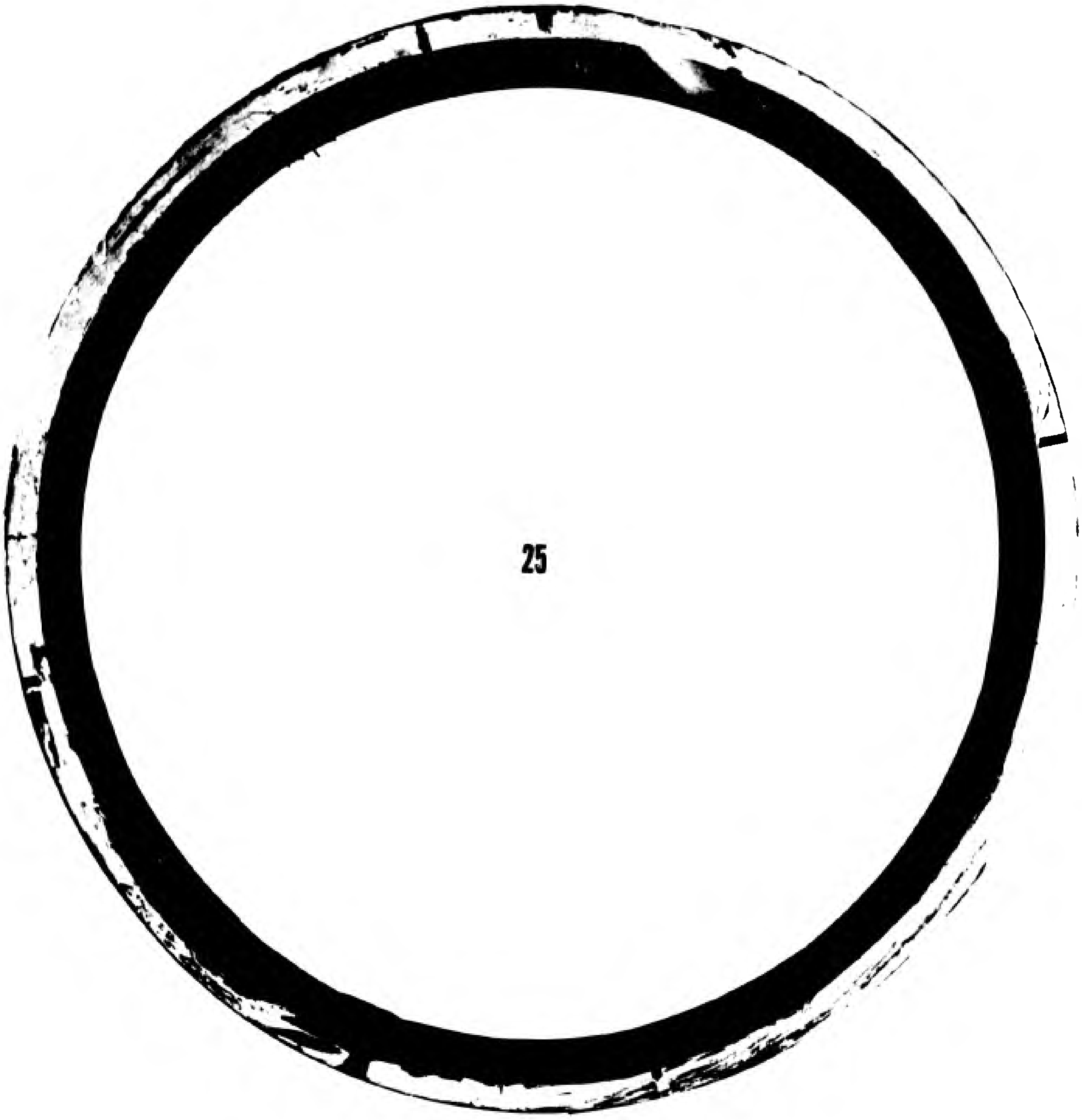


PHOTO NO: CAN-386544(L)-2-68

FIGURE 3

POST-TEST 25
CONTAINMENT RING GOUGING - DETAILS

PHOTO NO: CAN-386542(L)-2-68

FIGURE 4

TRI-HUB FRAGMENTS FROM TEST 25

PHOTO NO: CAN-386503(L)-2-68

FIGURE 5

EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 25 .... FRAMING RATE: 14500 PICTURES/SECOND

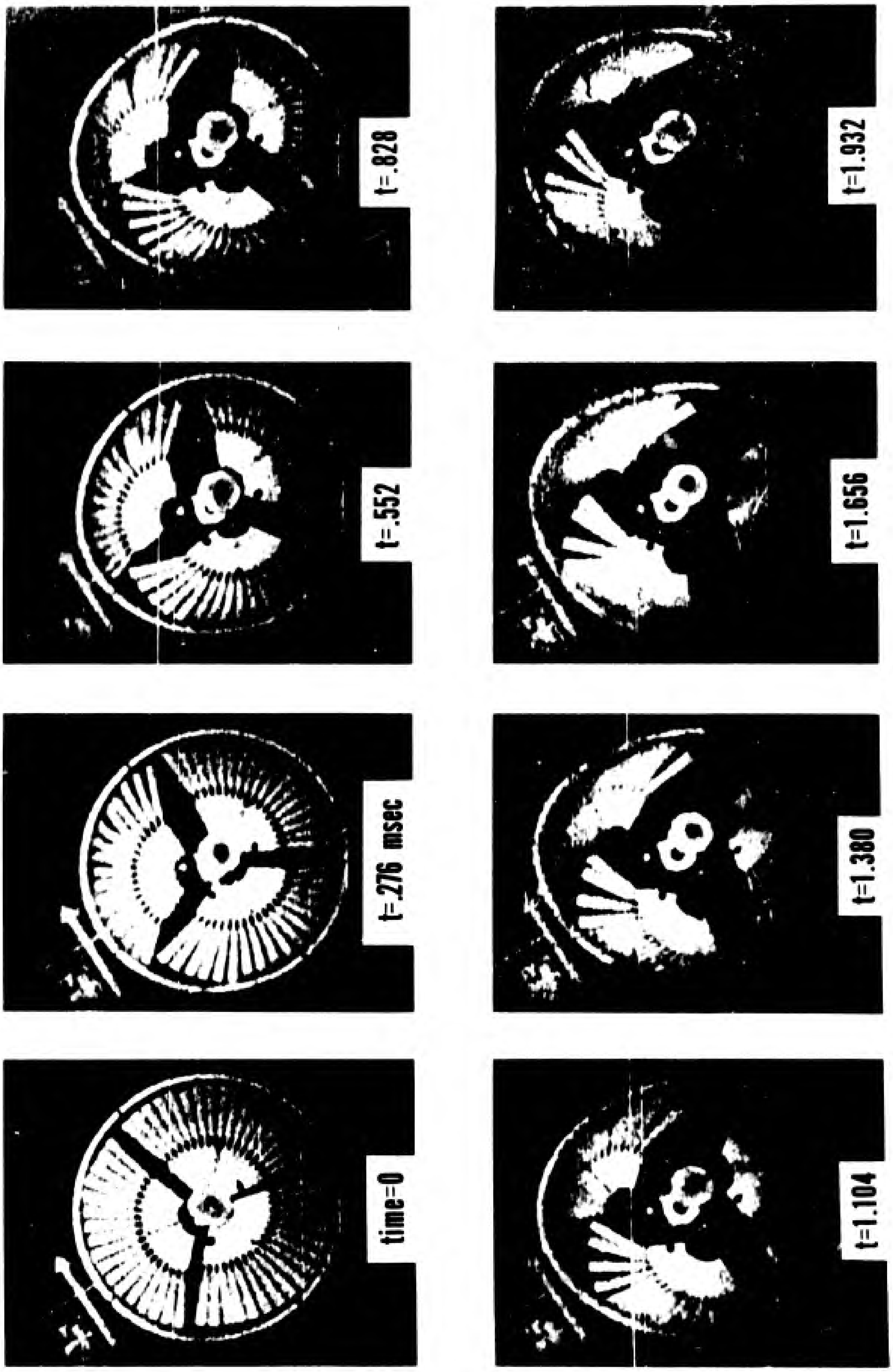


PHOTO NO: CAN-391002(L)-1-69

FIGURE 6

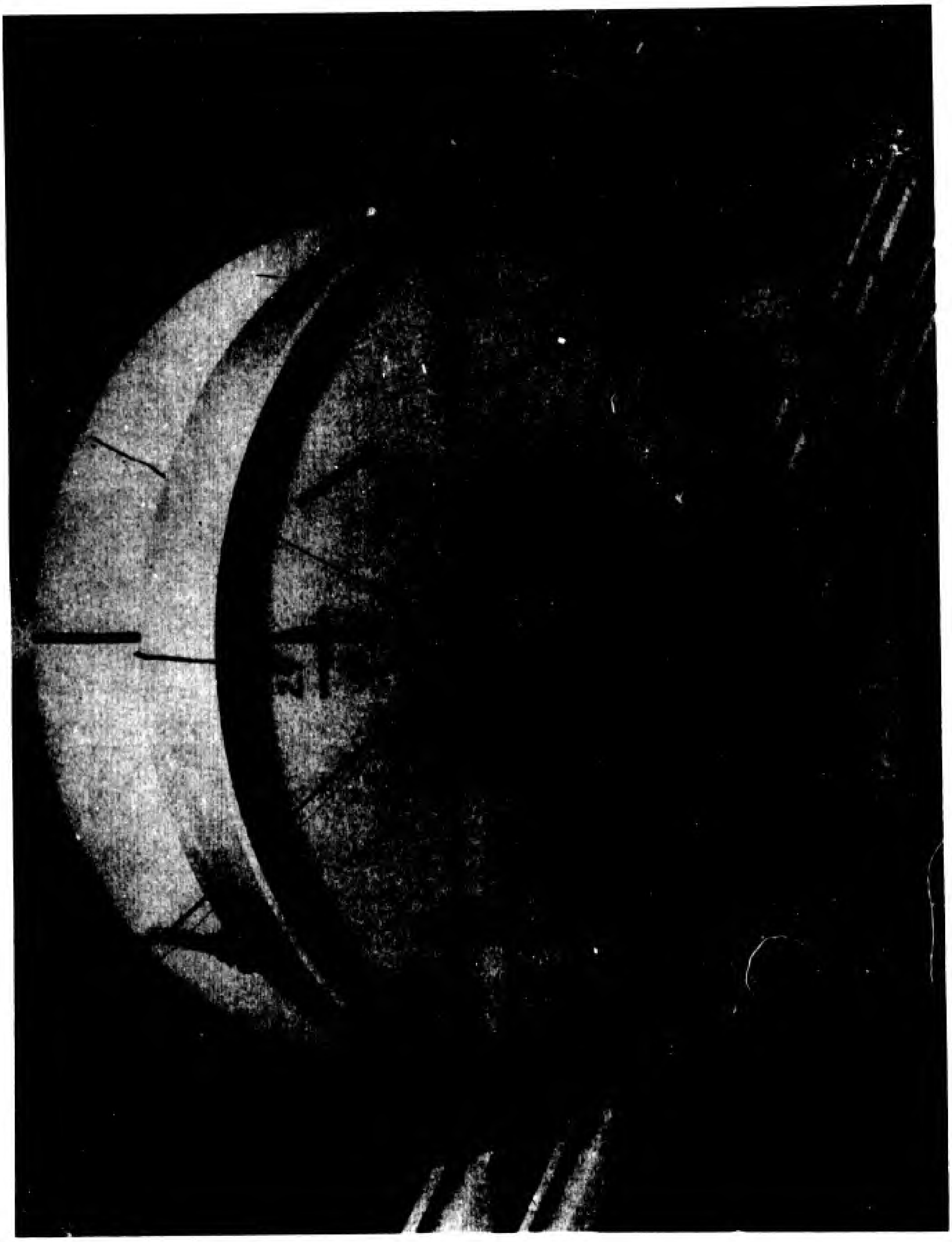
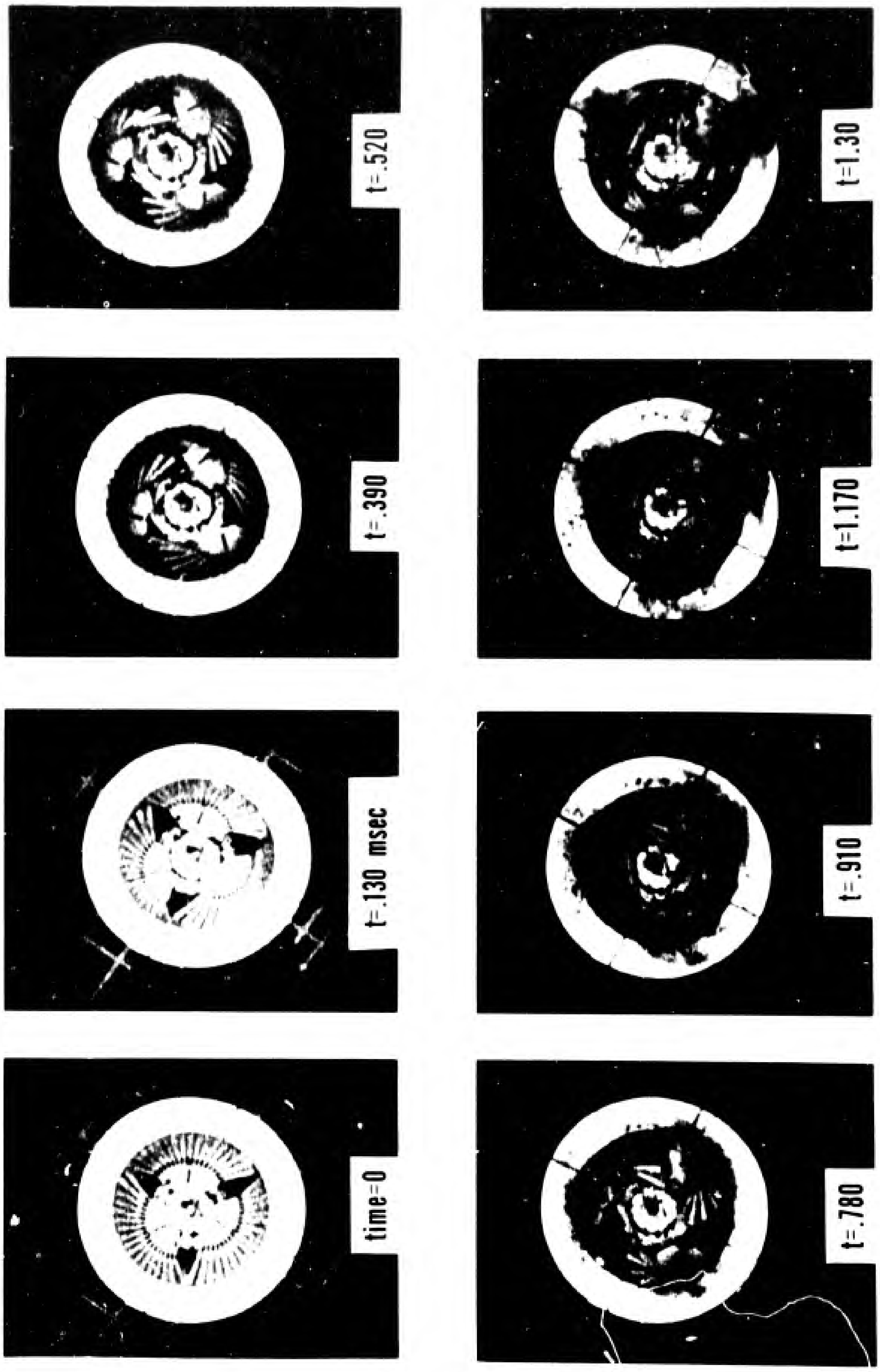


PHOTO NO: CAN-387048(L)-4-68

FIGURE 7



EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 27 .... FRAMING RATE: 15430 PICTURES/SECOND

PHOTO NO: CAN-391004(L)-1-69

FIGURE 8

POST-TEST 27
CONTAINMENT RING DEFORMATION

PHOTO NO: CAN-387198(L)-4-68

FIGURE 9

POST-TEST 27
CONTAINMENT RING DETAILS

PHOTO NO: CAN-387201(L)-4-68

FIGURE 10

POST-TEST 27 FRAGMENT GENERATOR

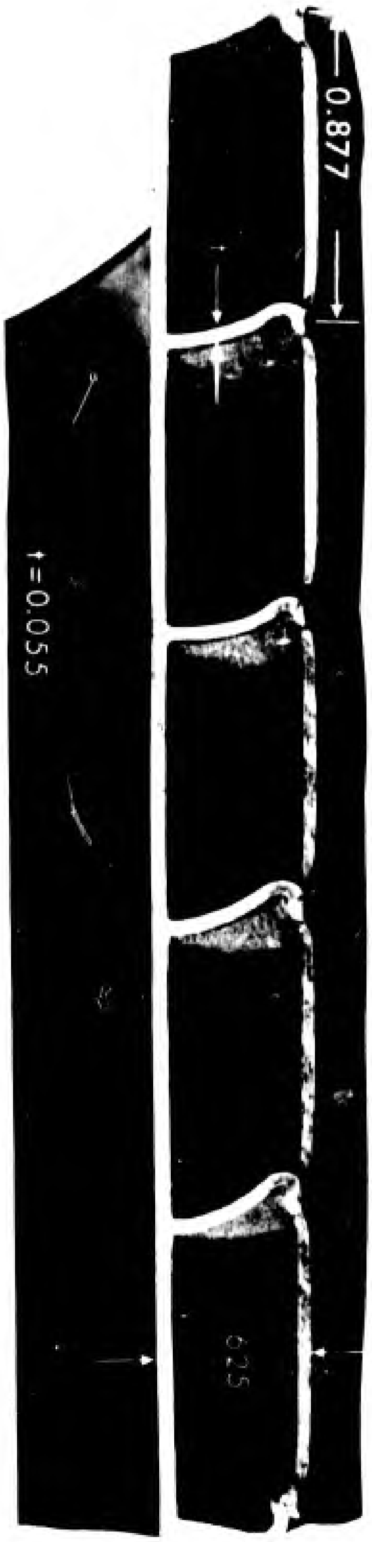
PHOTO NO: CAN-387200(L)-4-68

FIGURE 11

PRE-TEST 28
RIBBED ALUMINUM CONTAINMENT RING

PHOTO NO: CAN-385931(L)-1-68

FIGURE 12



PRE-TEST 28
TYPICAL RIBBED ALUMINUM STRUCTURE

PHOTO NO: CAN-389056(L)-8-68

FIGURE 13

EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 28 .... FRAMING RATE: 15500 PICTURES/SECOND

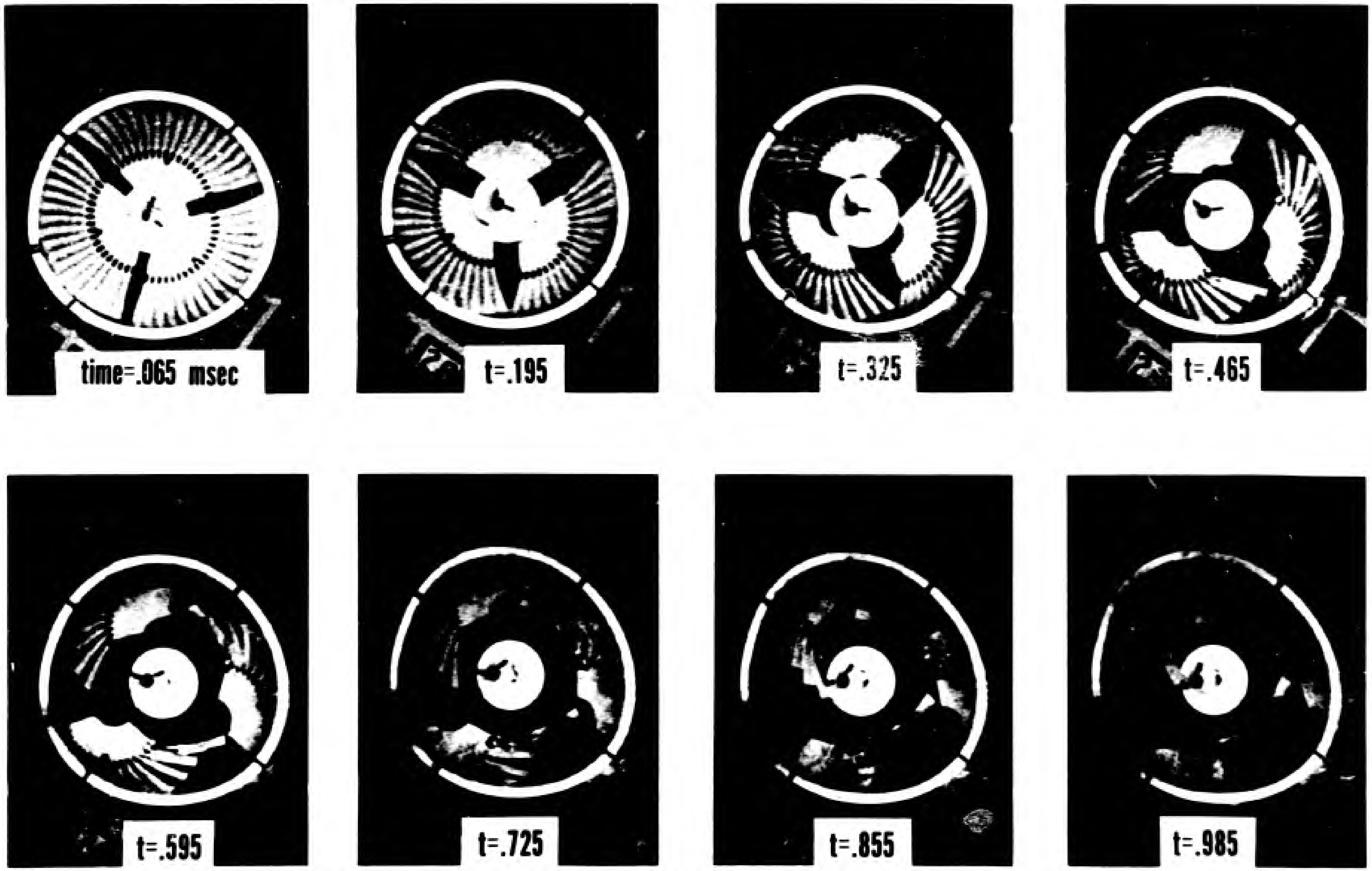


PHOTO NO: CAN-391005(L)-1-69

FIGURE 14

POST-TEST 28
CONTAINMENT RING

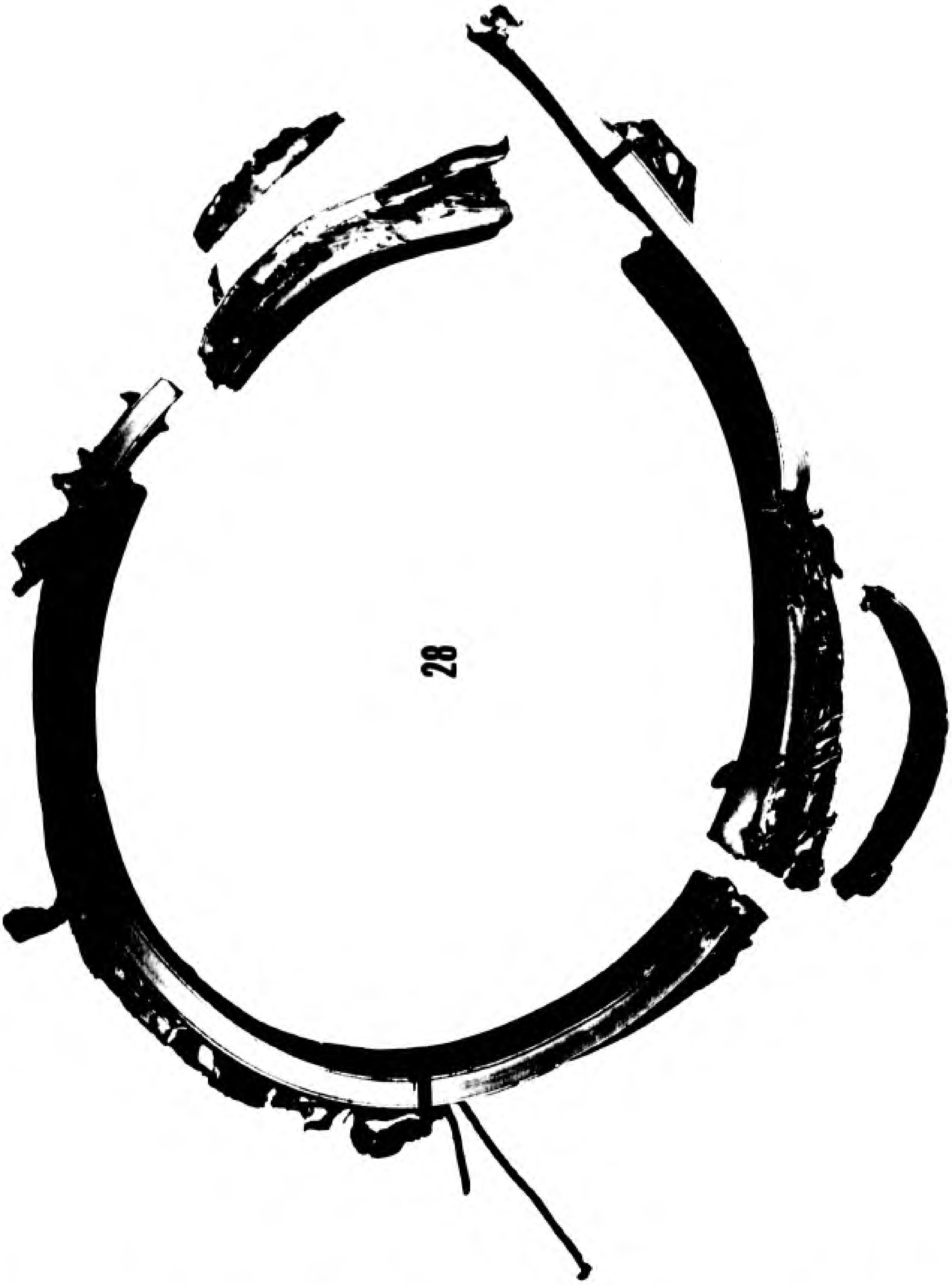


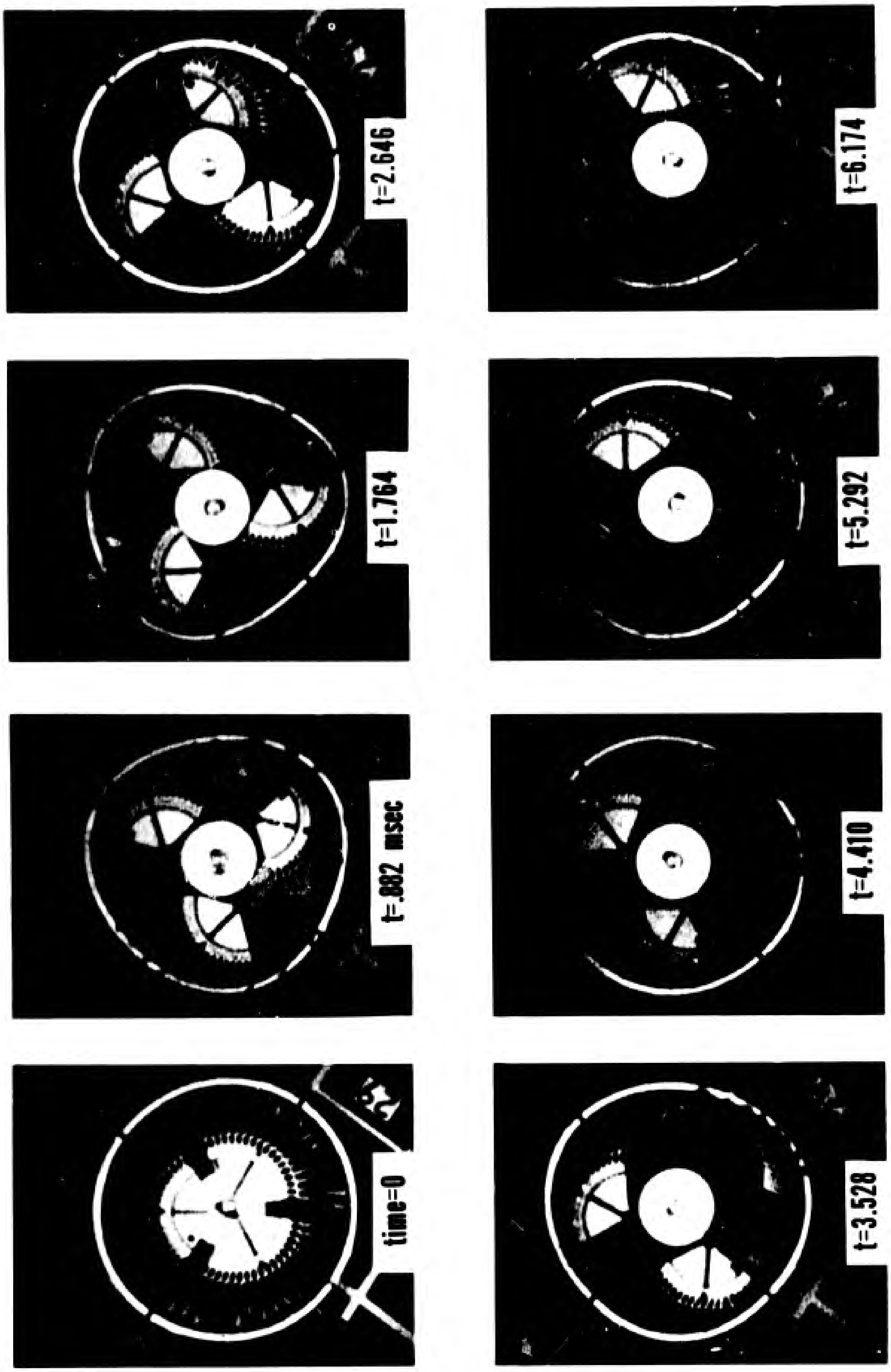
PHOTO NO: CAN-387329(L)-5-68

FIGURE 15

POST-TEST 28
DAMAGED SECONDARY SHIELD

PHOTO NO: CAN-387318(L)-4-68

FIGURE 16



EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 29 .... FRAMING RATE: 15810 PICTURES/SECOND

PHOTO NO: CAN-391006(L)-1-69

FIGURE 17

POST-TEST 29
CONTAINMENT RING DEFORMATION

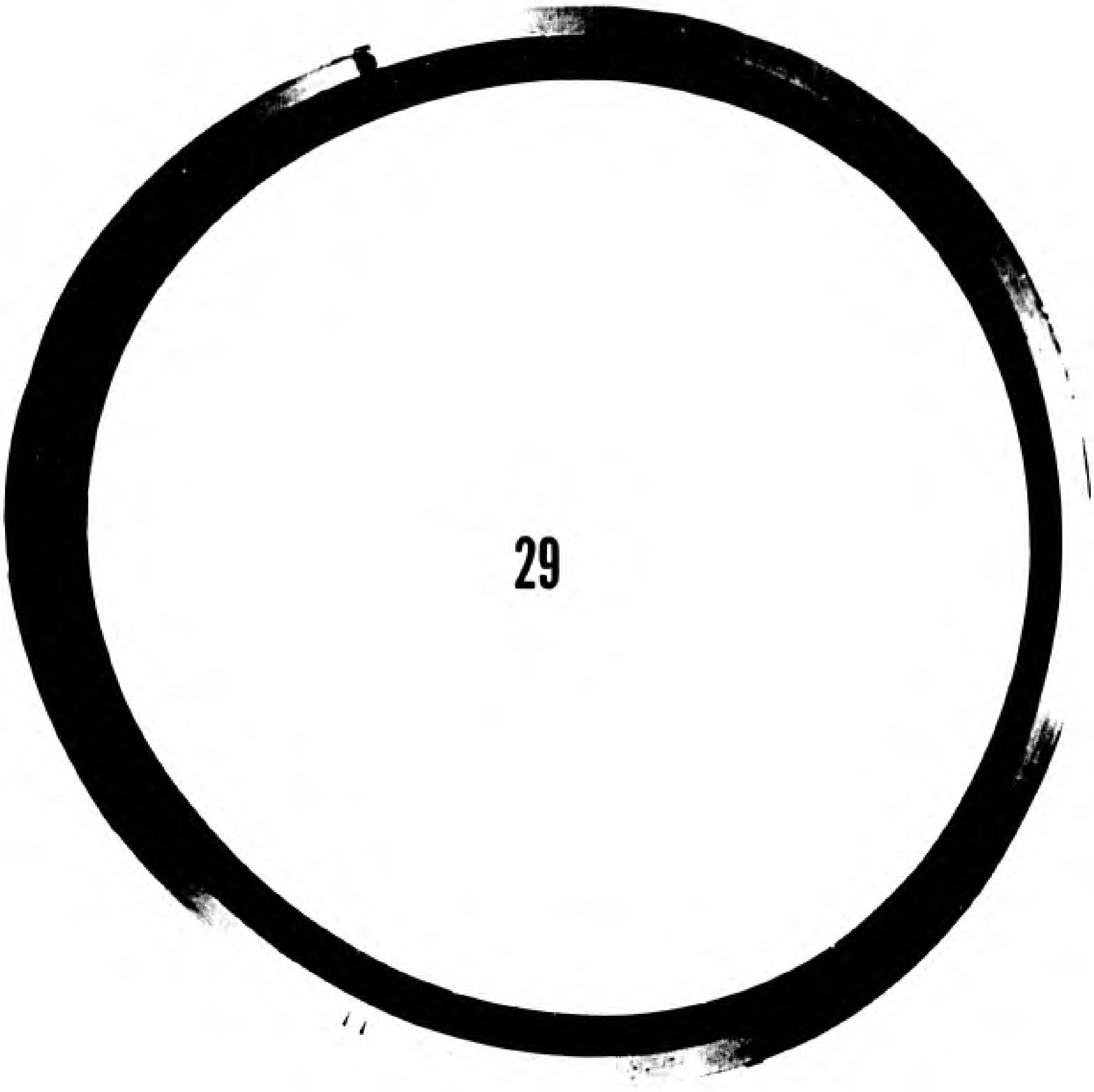


PHOTO NO: CAN-387474(L)-5-68

FIGURE 18

POST-TEST 29
CONTAINMENT RING DETAILS

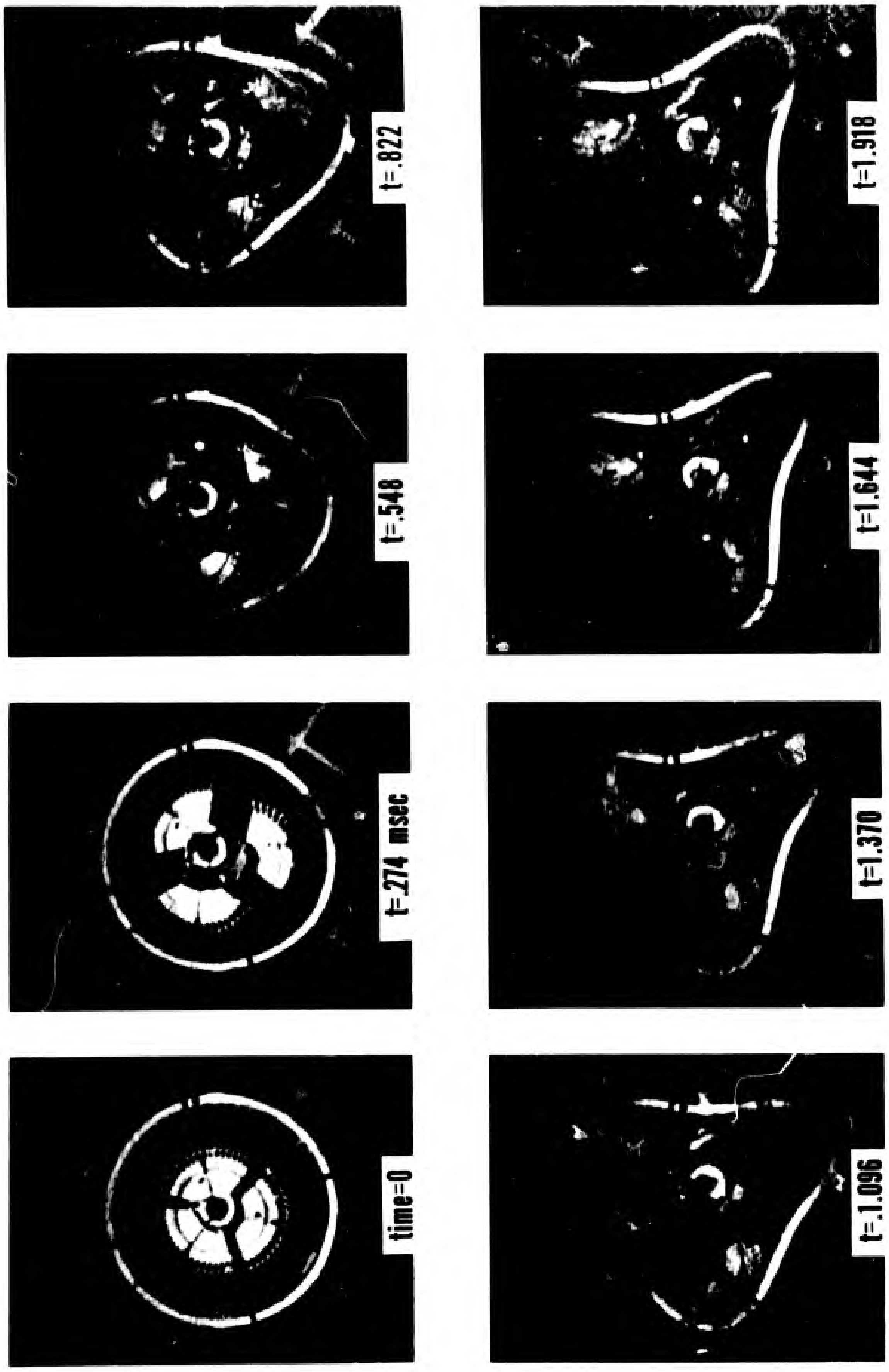
PHOTO NO: CAN-387473(L)-5-68

FIGURE 19

POST-TEST 29
POWER TURBINE ROTOR

PHOTO NO: CAN-387475(L)-5-68

FIGURE 20



EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 34 .... FRAMING RATE: 14620 PICTURES/SECOND

PHOTO NO: CAN-391009(L)-1-69

FIGURE 21

POST-TEST 34
ROTOR AND CONTAINMENT RING FRAGMENTS

PHOTO NO: CAN-388263(L)-7-68

FIGURE 22

PRE-TEST 30 AND 31
MODIFIED STARTER ROTOR-TRI-HUB FAILURE

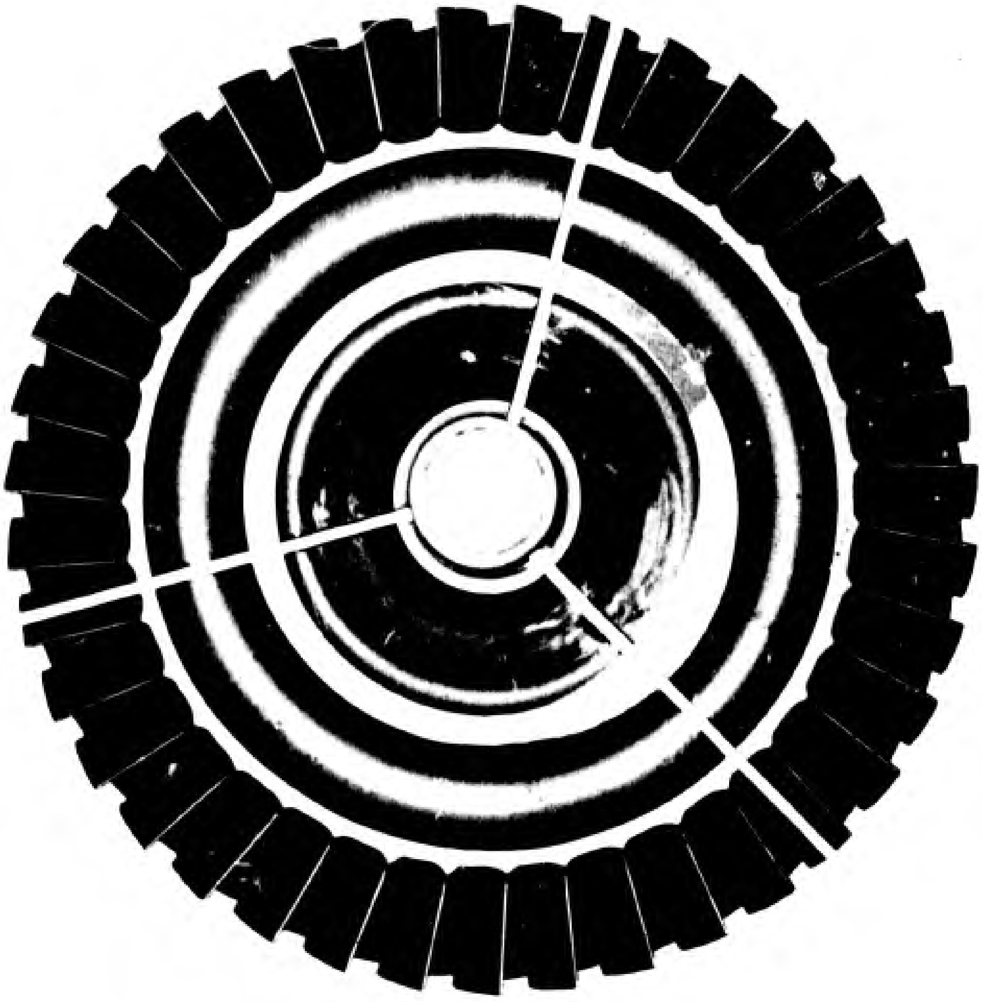
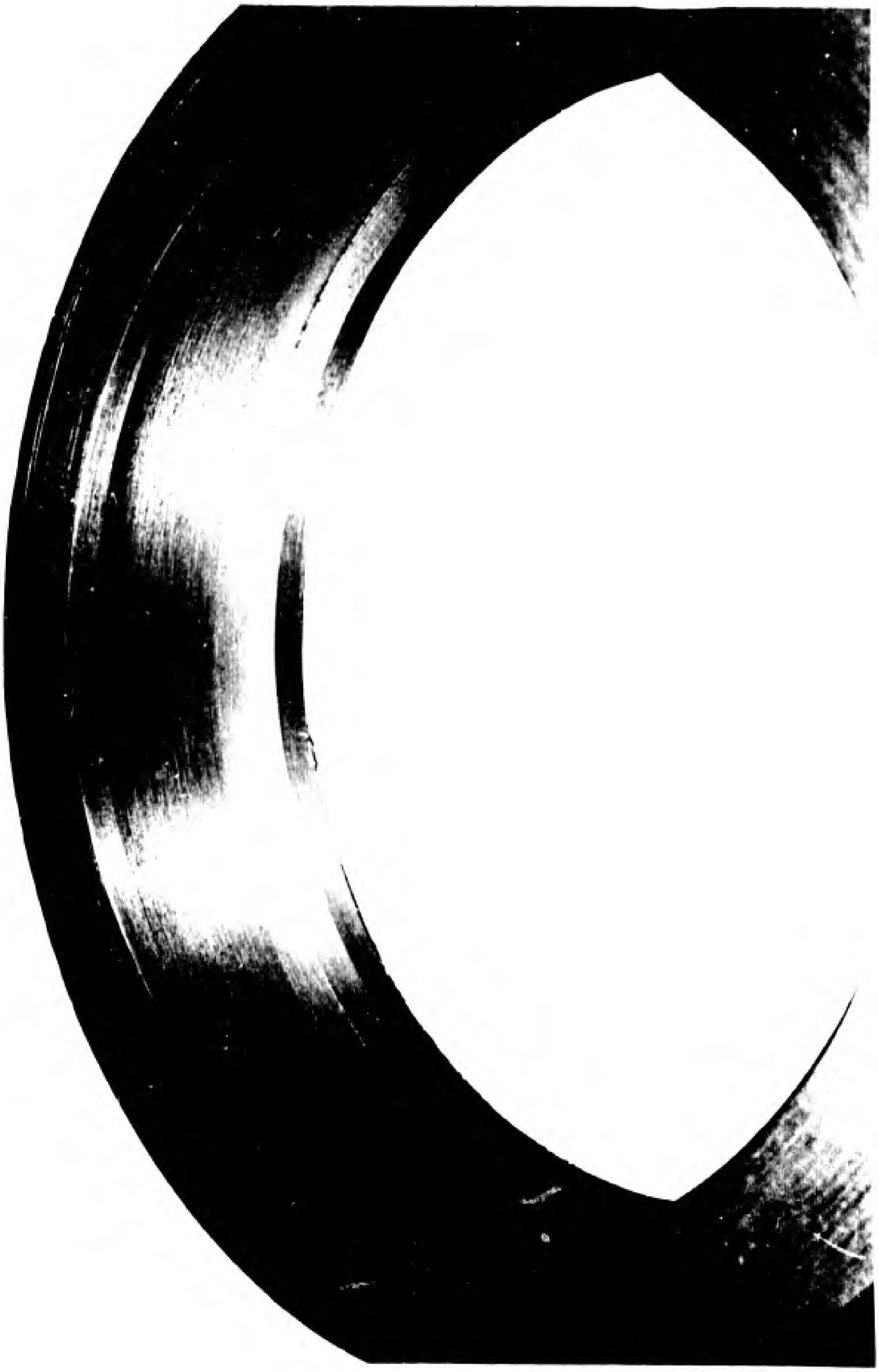


PHOTO NO: CAN-387537(L)-5-68

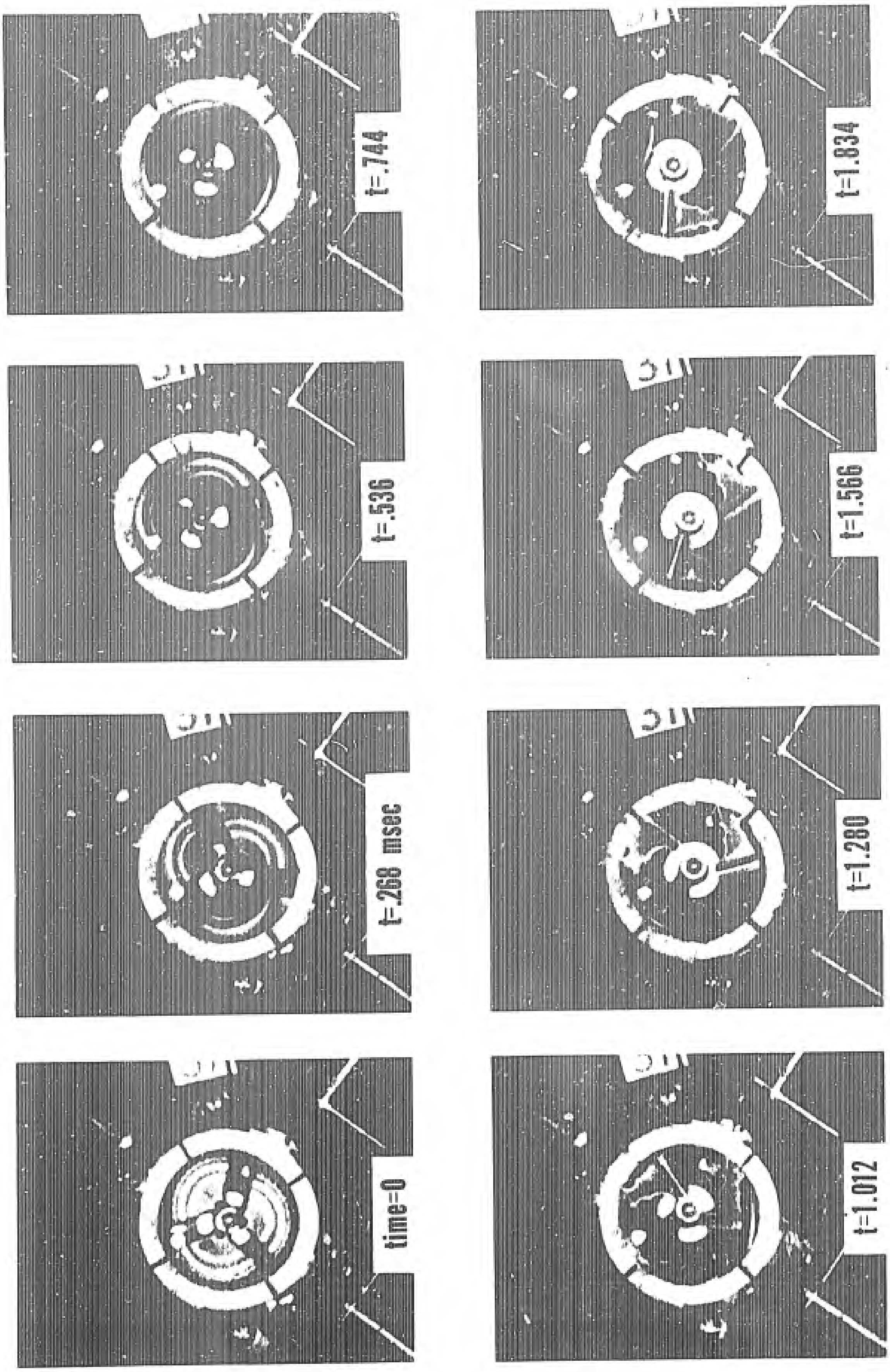
FIGURE 23



PRE-TEST 30 AND 31
FLANGED CONTAINMENT RING

PHOTO NO: CAN-387536(L)-5-68

FIGURE 24



EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 31 .... FRAMING RATE: 14840 PICTURE/SECOND

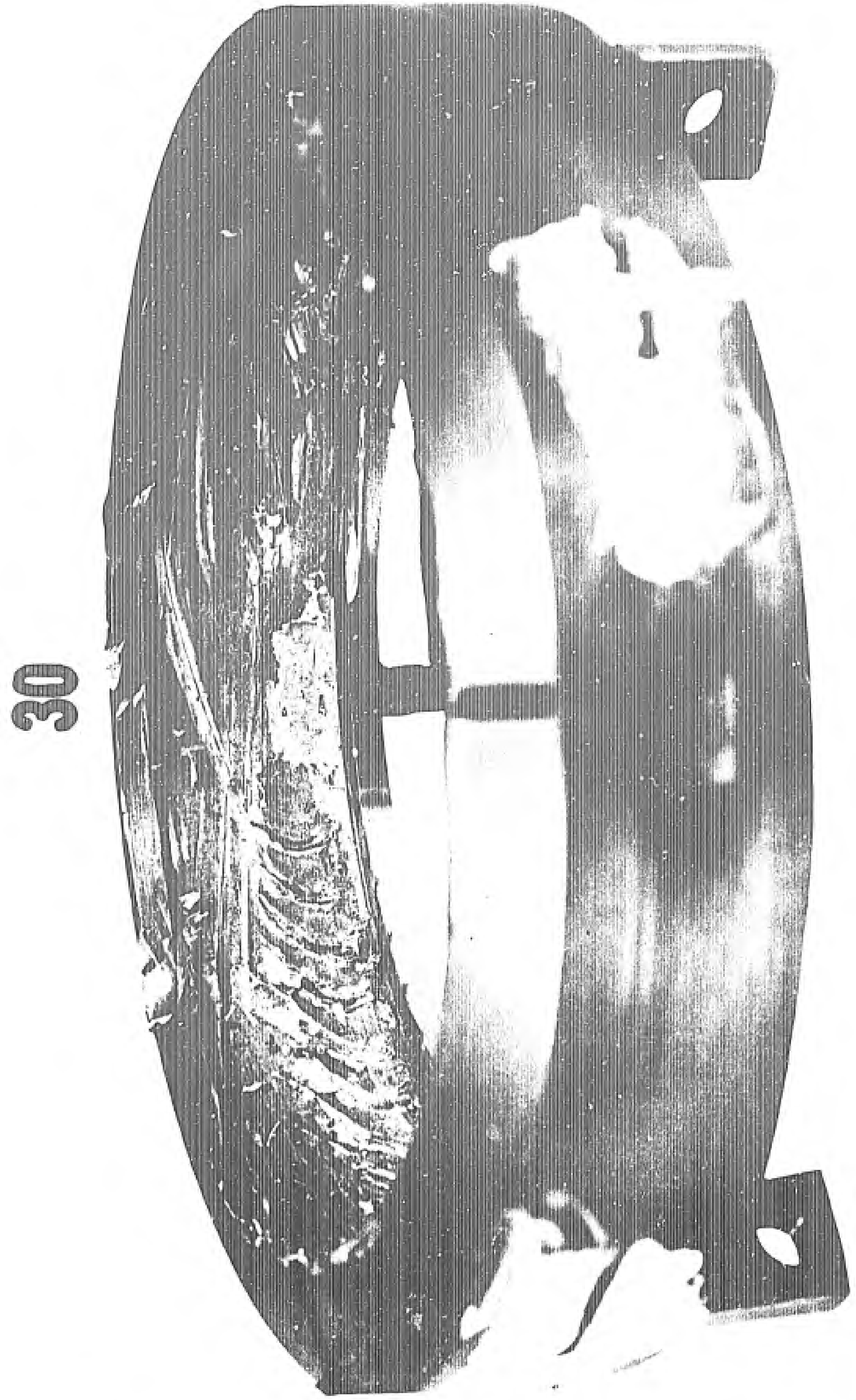
PHOTO NO: CAN-391007(L)-1-69

FIGURE 25

POST-TEST 30
ROTOR FRAGMENTS AND CONTAINMENT RING

PHOTO NO: CAN-387757(L)-6-68

FIGURE 26



POST-TEST 30
CONTAINMENT RING DETAILS

PHOTO NO: CAN-387754(L)-6-68

FIGURE 27

POST-TEST 31
ROTOR FRAGMENTS AND CONTAINMENT RING

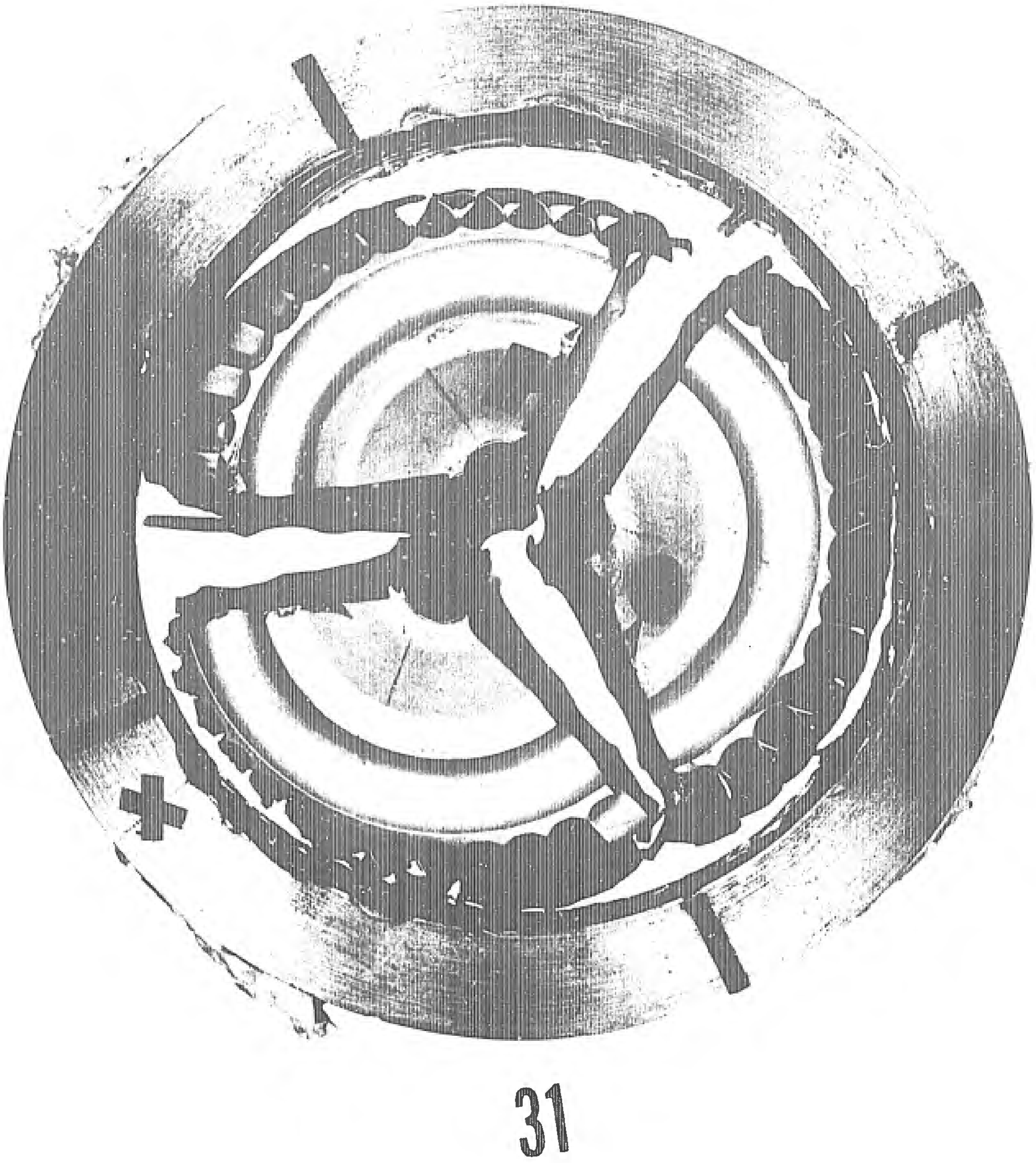
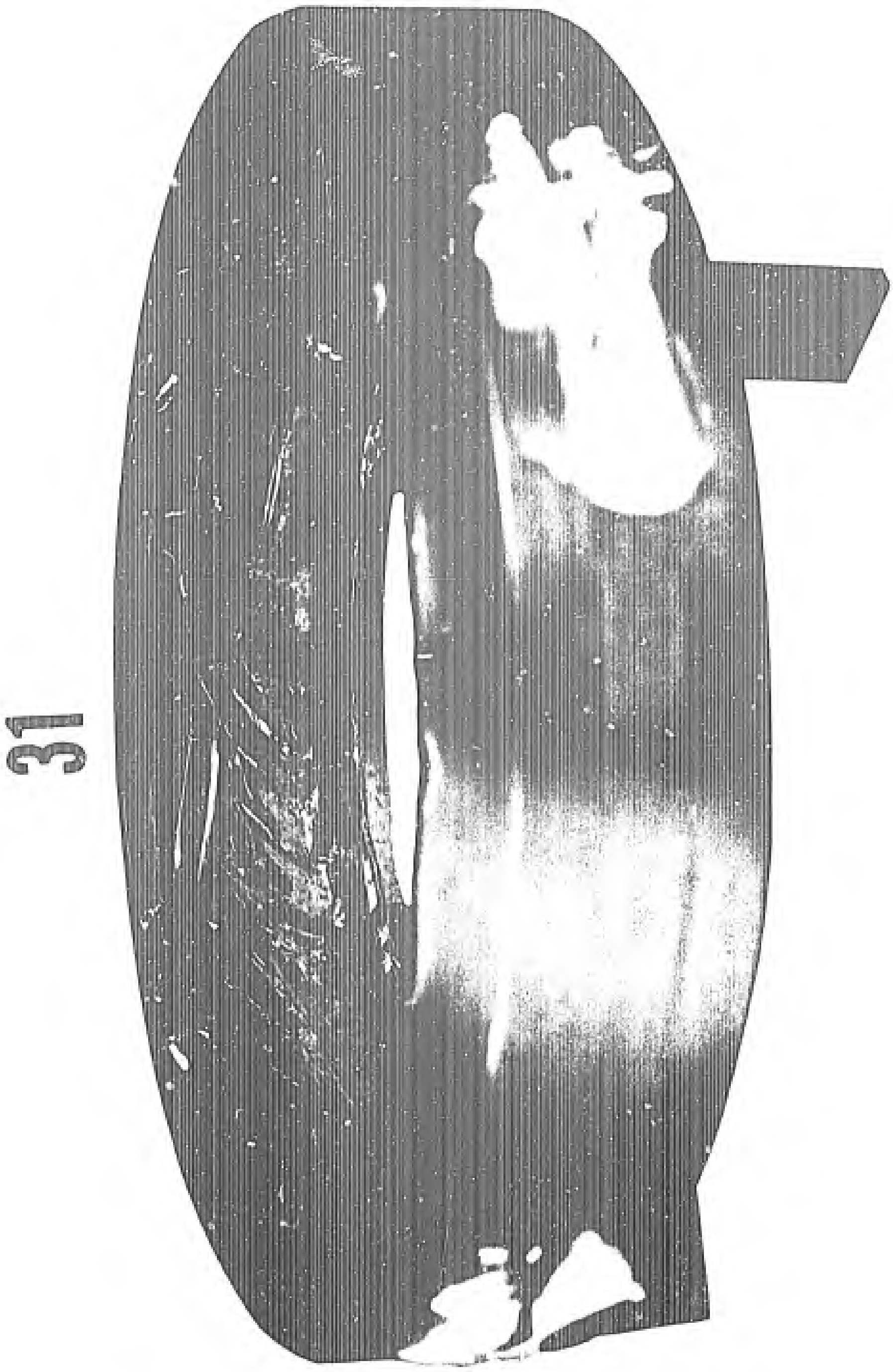


PHOTO NO: CAN-387832(L)-6-68

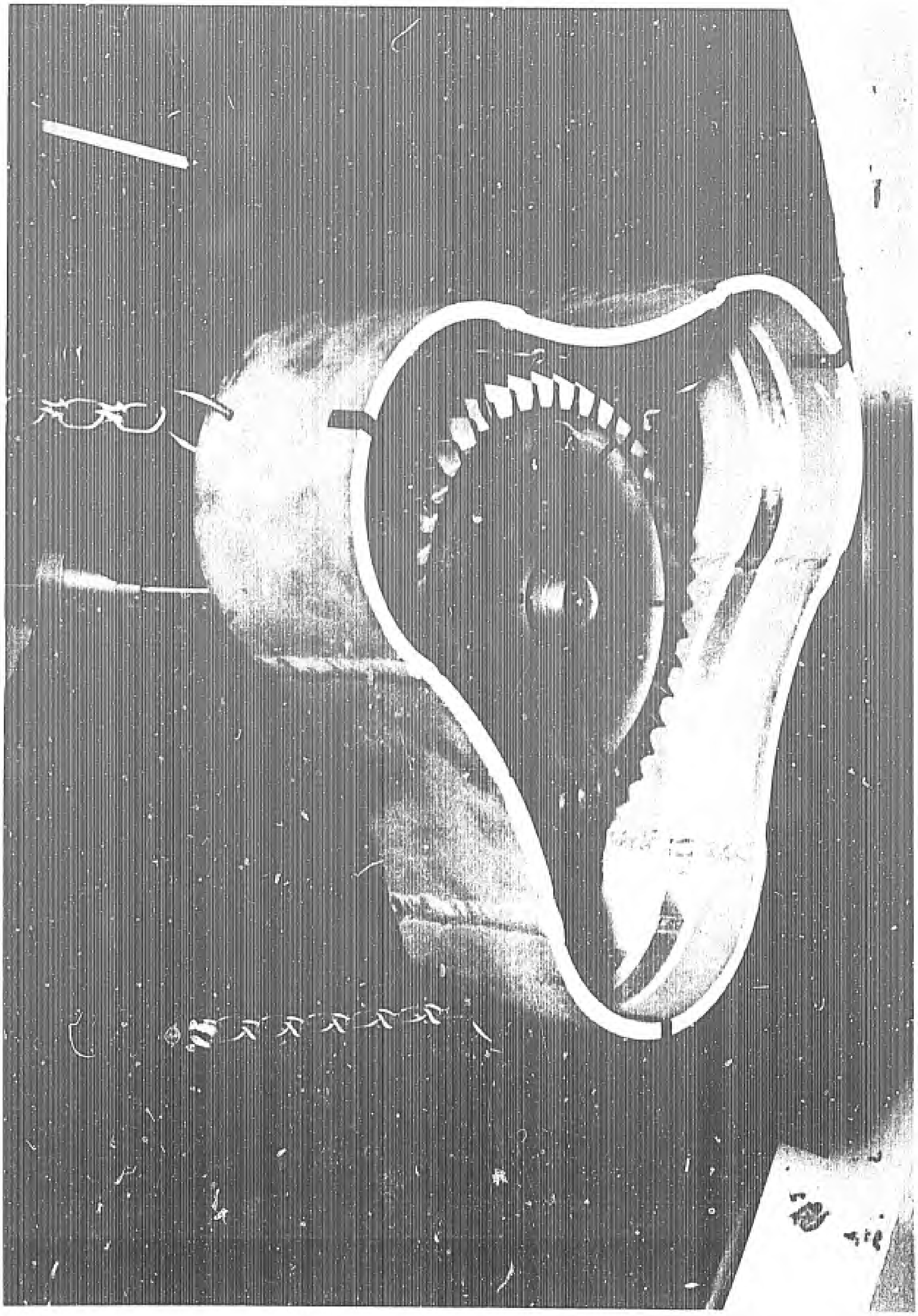
FIGURE 28



POST-TEST 31
CONTAINMENT RING DETAIL

PHOTO NO: CAN-387830(L)-6-68

FIGURE 29



PRE-TEST 26
MOMENTUM TRANSFER FRAGMENT
CONTROL DEVICE INSTALLATION

PHOTO NO: CAN-386805(L)-3-68

FIGURE 30

EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 26 .... FRAMING RATE: 9830 PICTURES/SECOND

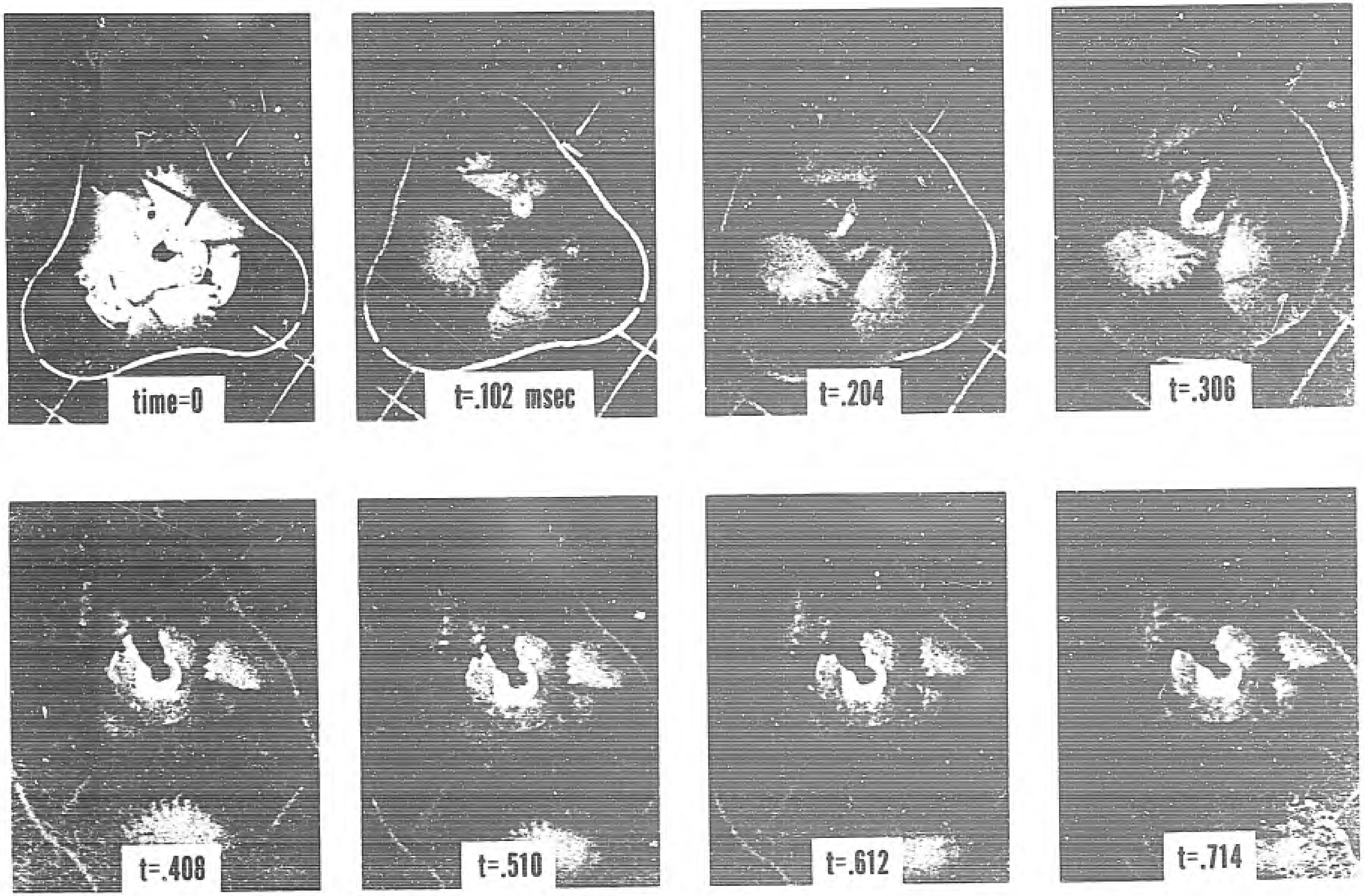


PHOTO NO: CAN-391003(L)-1-69

FIGURE 31

POST-TEST 26
ROTOR AND CONTROL DEVICE FRAGMENTS

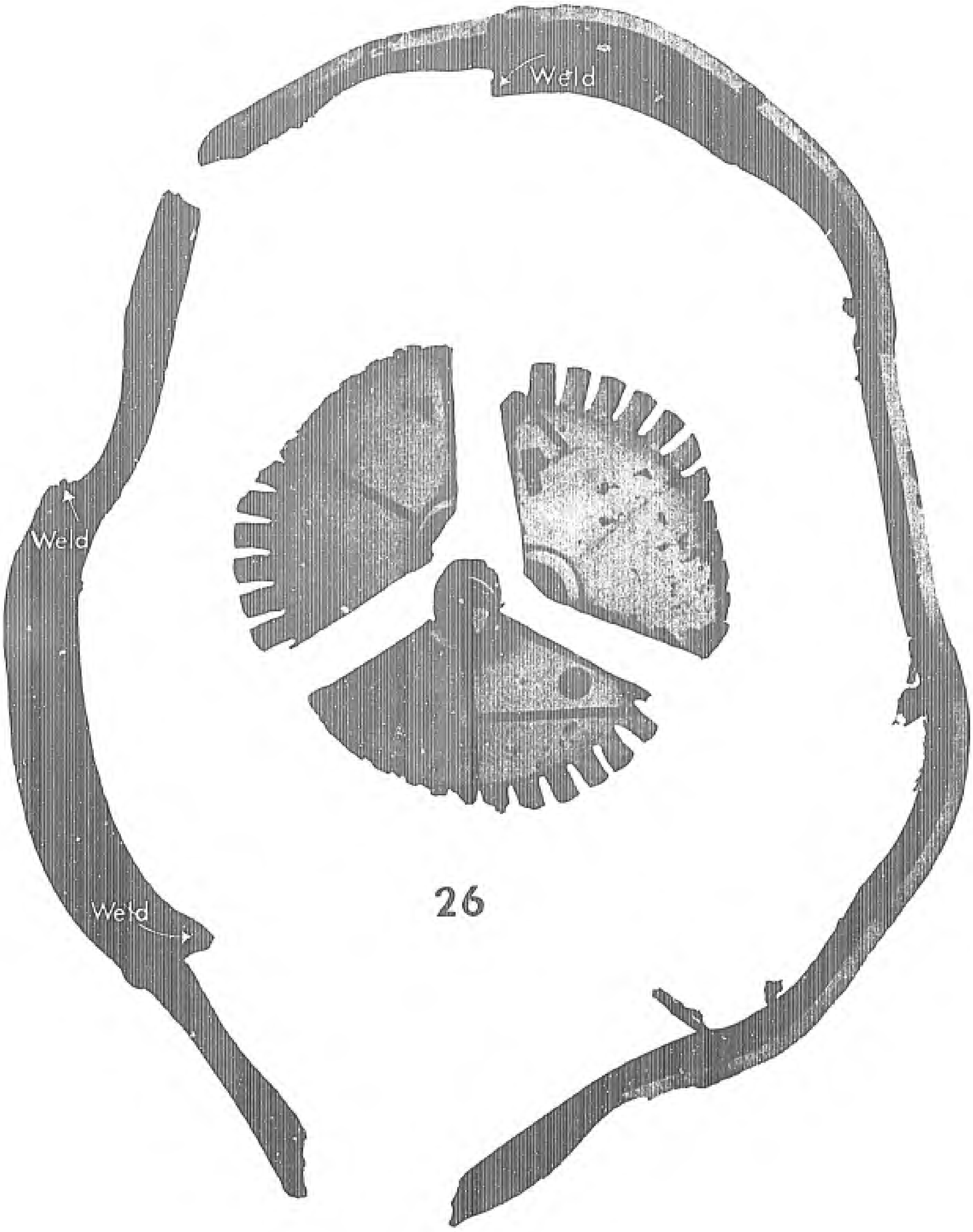


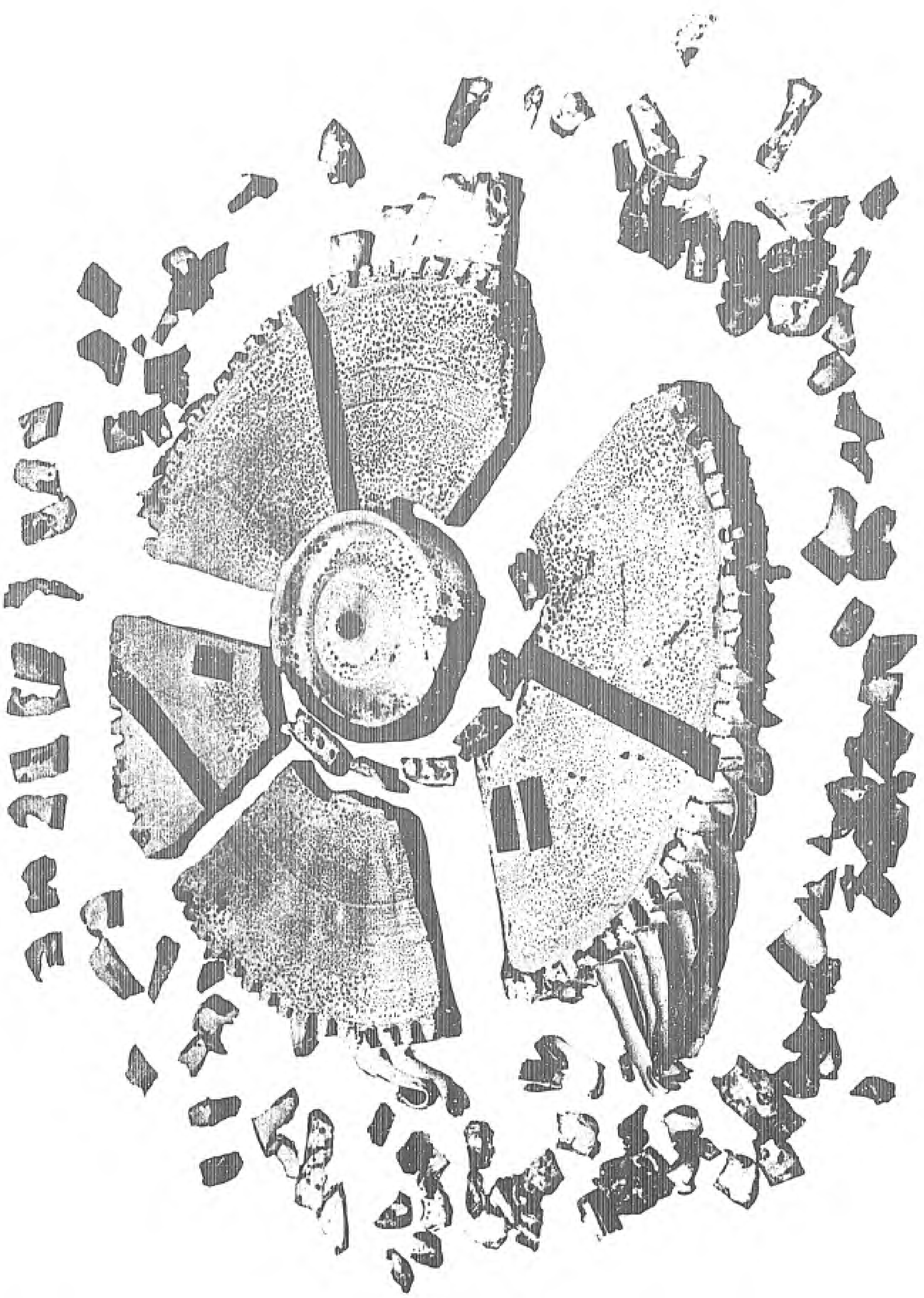
PHOTO NO: CAN-386961(L)-4-68

FIGURE 32

POST-TEST 22
CONTAINMENT RING FRAGMENTS

PHOTO NO: CAN-385218(L)-11-67

FIGURE 33



POST-TEST 22
ROTOR FRAGMENTS

PHOTO NO: CAN-385219(L)-11-67

FIGURE 34

MODIFIED TURBINE BLADE

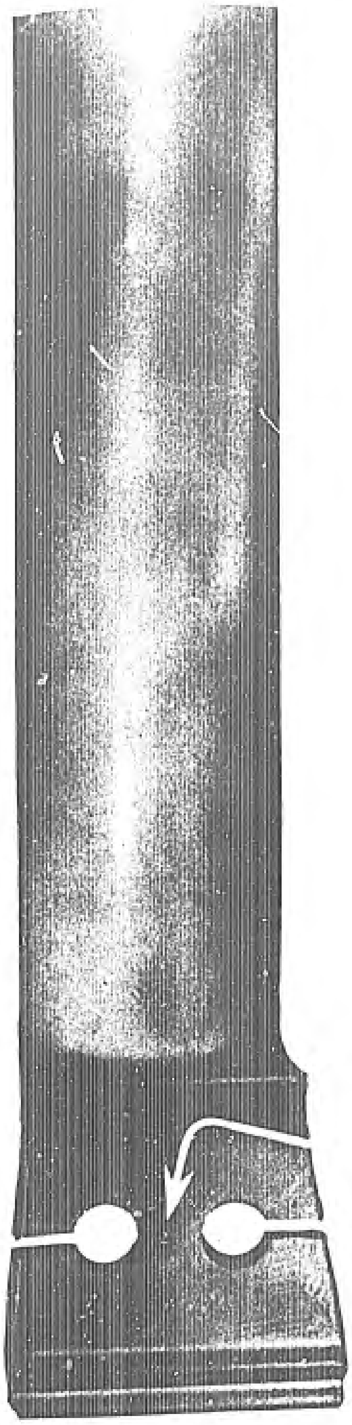


PHOTO NO: CAN-385991(L)-1-68

FIGURE 35

EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 23 .... FRAMING RATE: 14440 PICTURES/SECOND

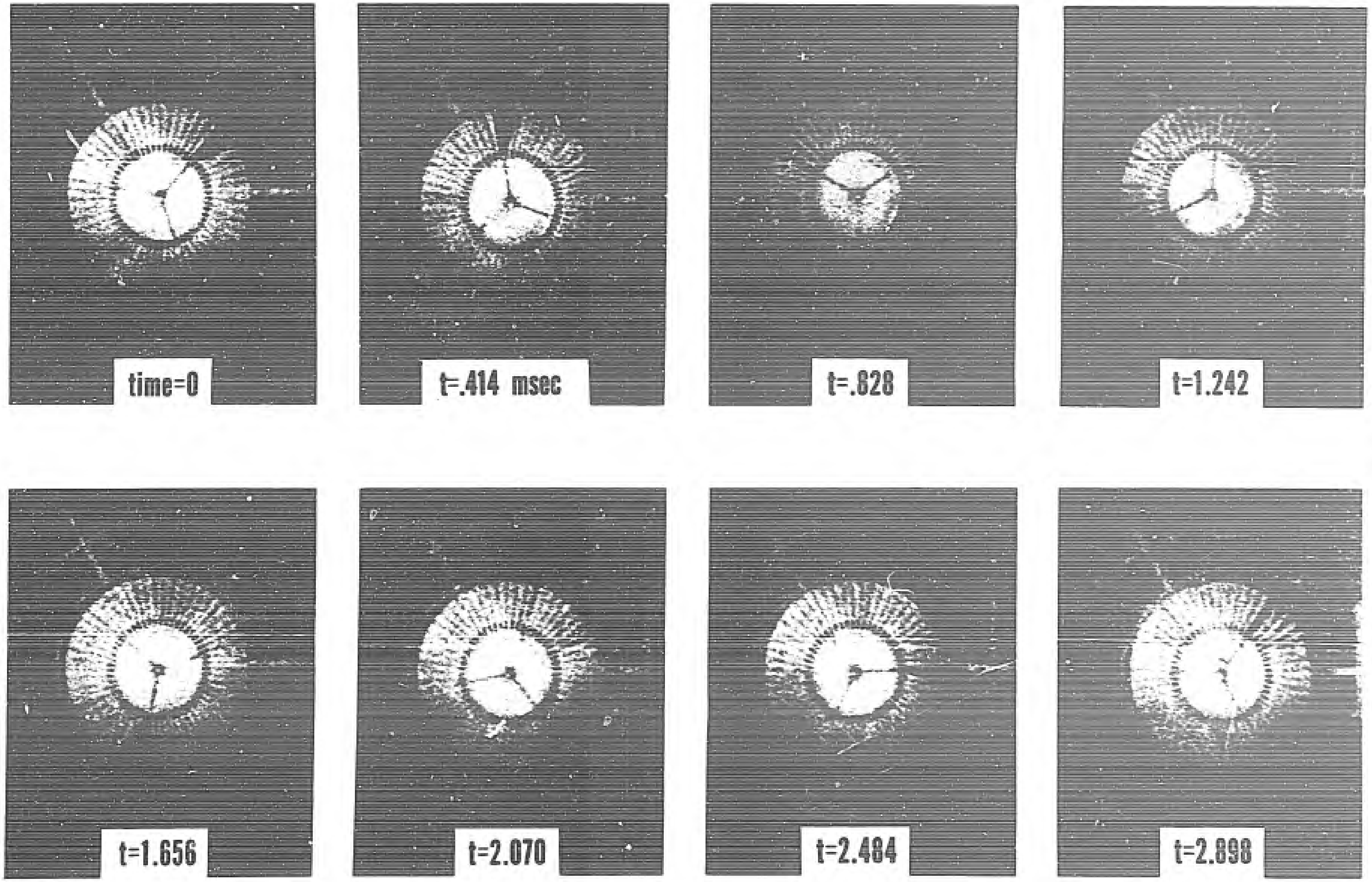
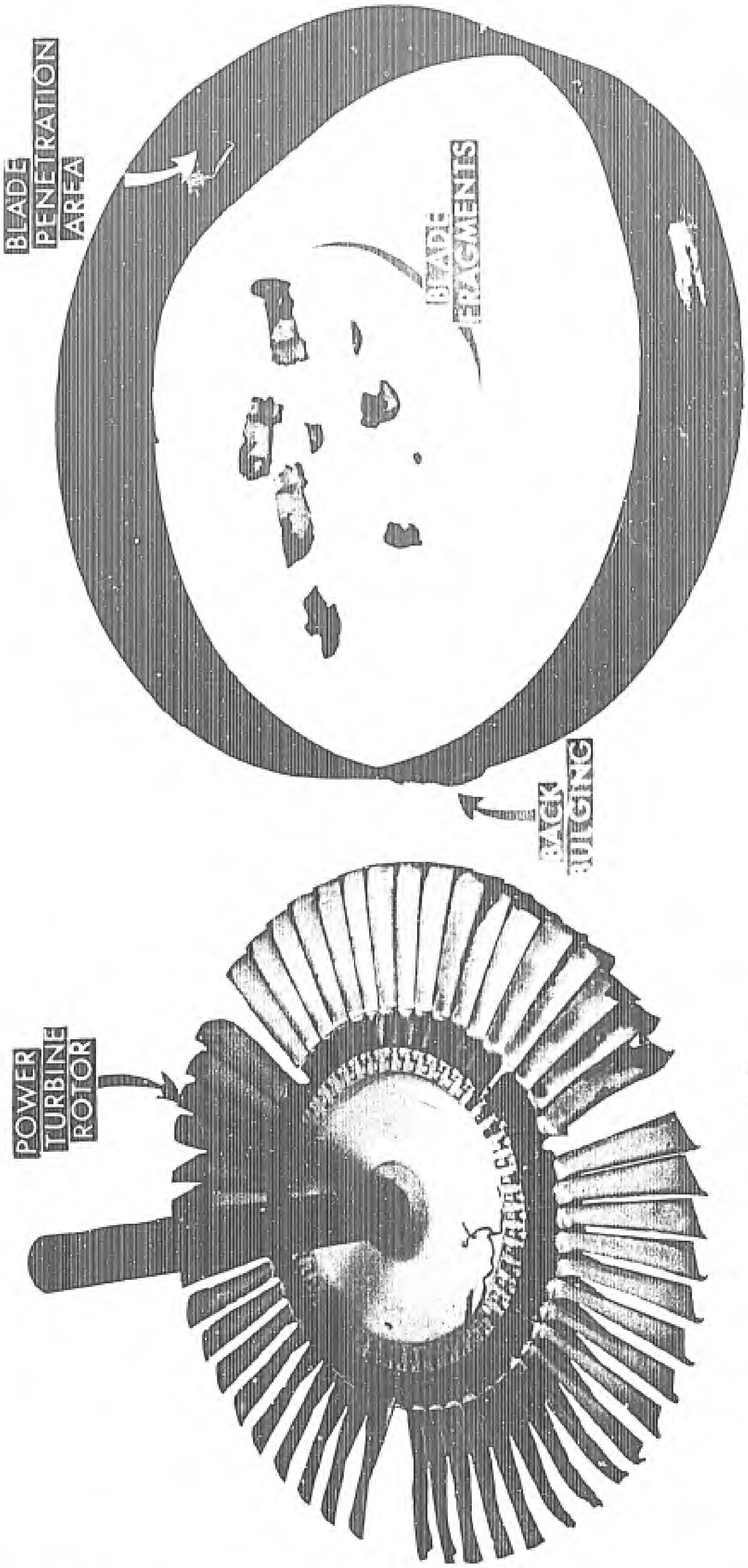


PHOTO NO: CAN-391001(L)-1-69

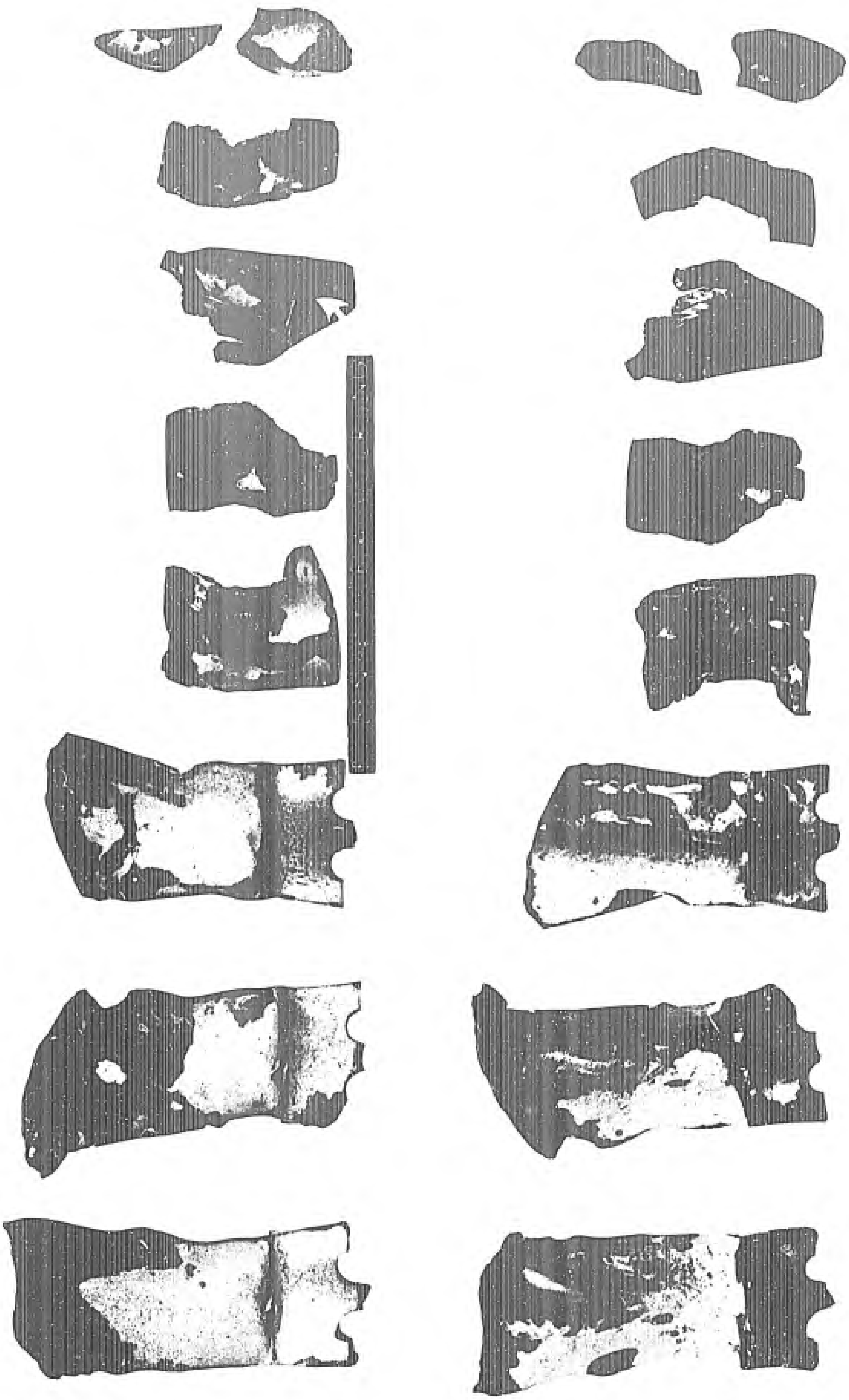
FIGURE 36



POST-TEST 23
ROTOR, ROTOR FRAGMENTS, AND CONTAINMENT RING

PHOTO NO: CAN-385367(L)-12-67

FIGURE 37



POST-TEST 23
BLADE FRAGMENTS

PHOTO NO: CAN-385848(L)-1-68

FIGURE 38

PRE-TEST 33
CONTAINMENT RING WITH INSTRUMENTATION

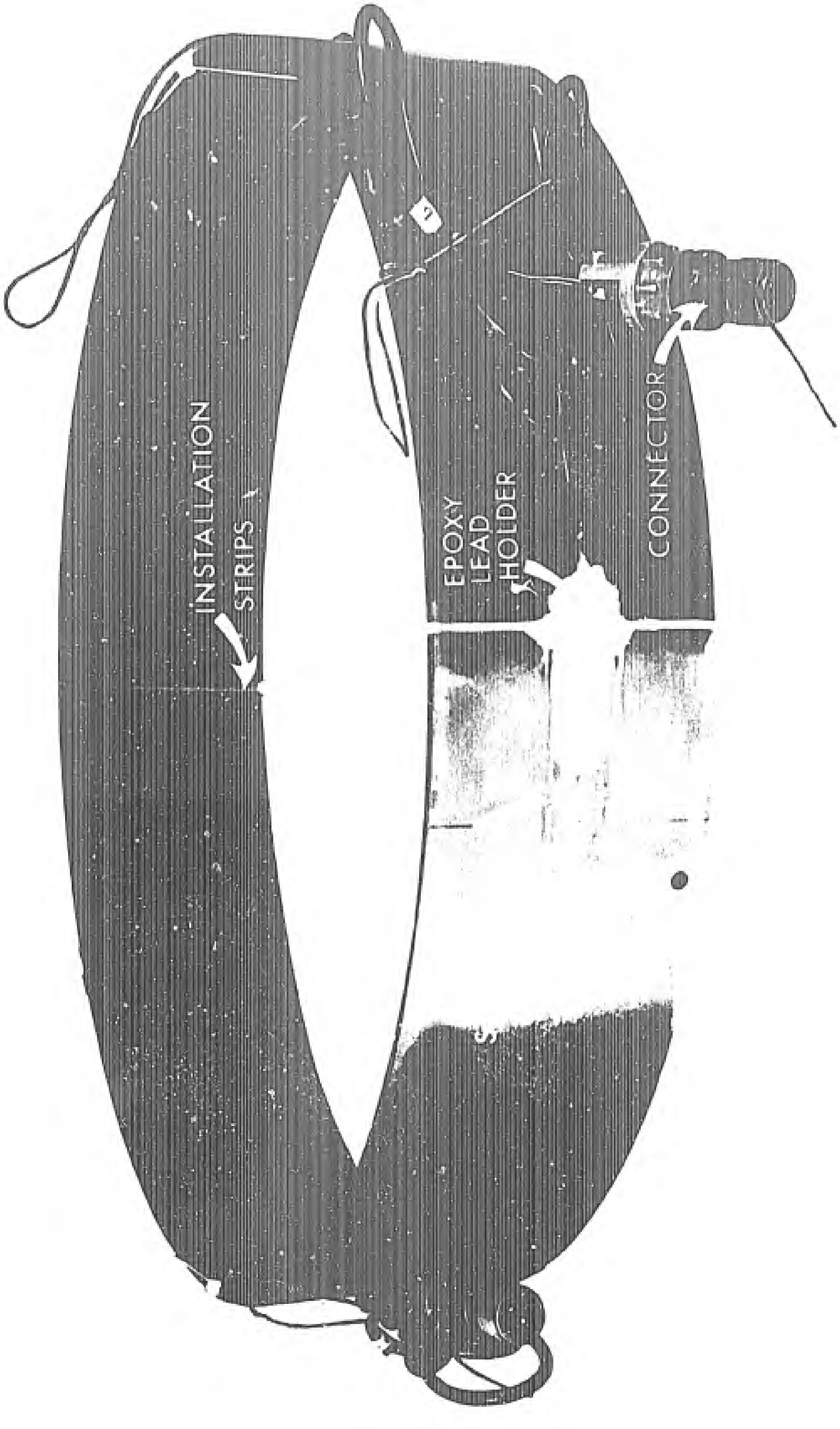
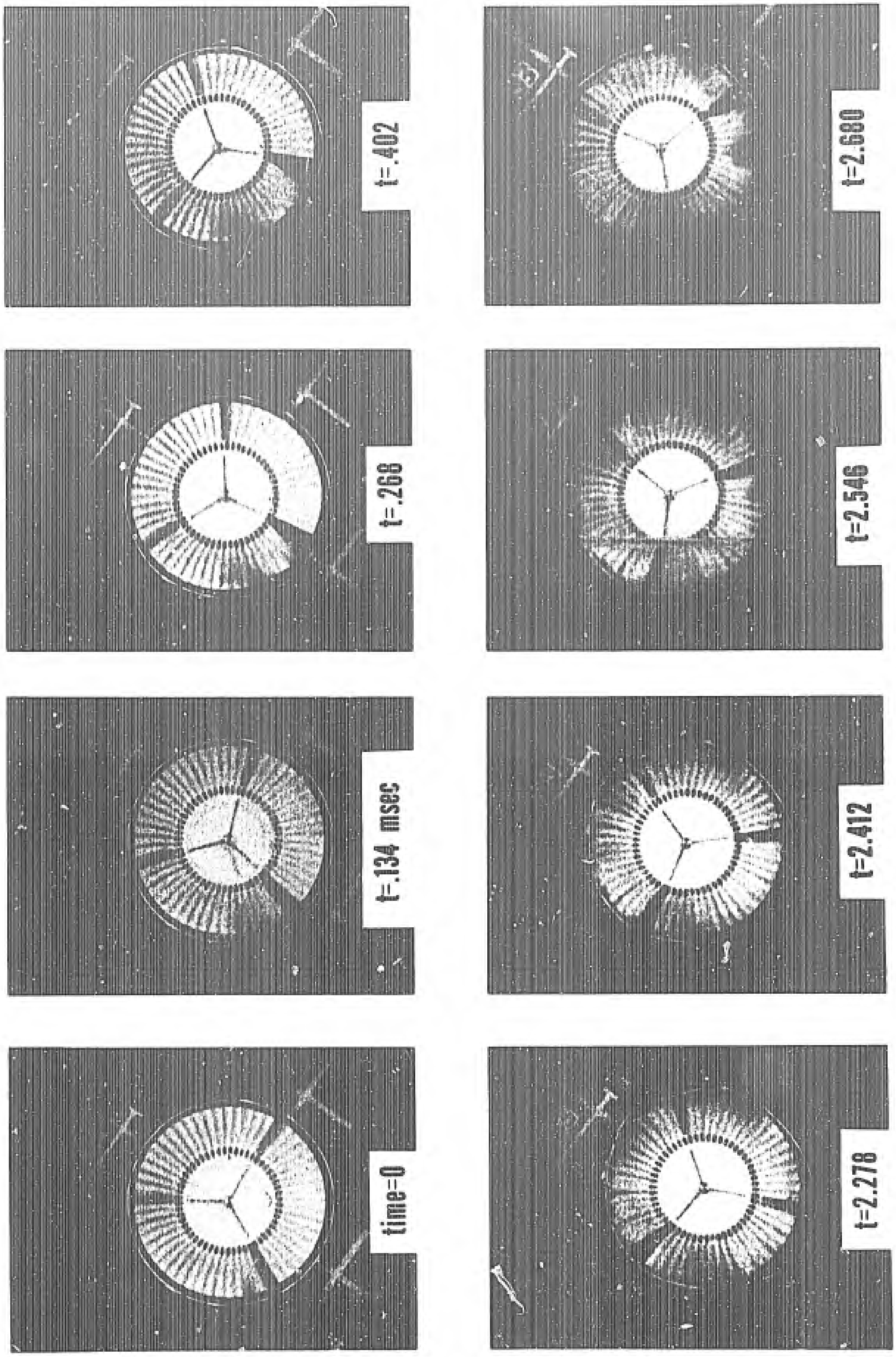


PHOTO NO: CAN-387900(L)-6-68

FIGURE 39



EXCERPTS FROM HIGH-SPEED MOTION PICTURES OF EXPERIMENT 33 .... FRAMING RATE: 14955 PICTURES/SECOND

PHOTO NO: CAN-391008(L)-1-69

FIGURE 40

POST-TEST 33
CONTAINMENT RING

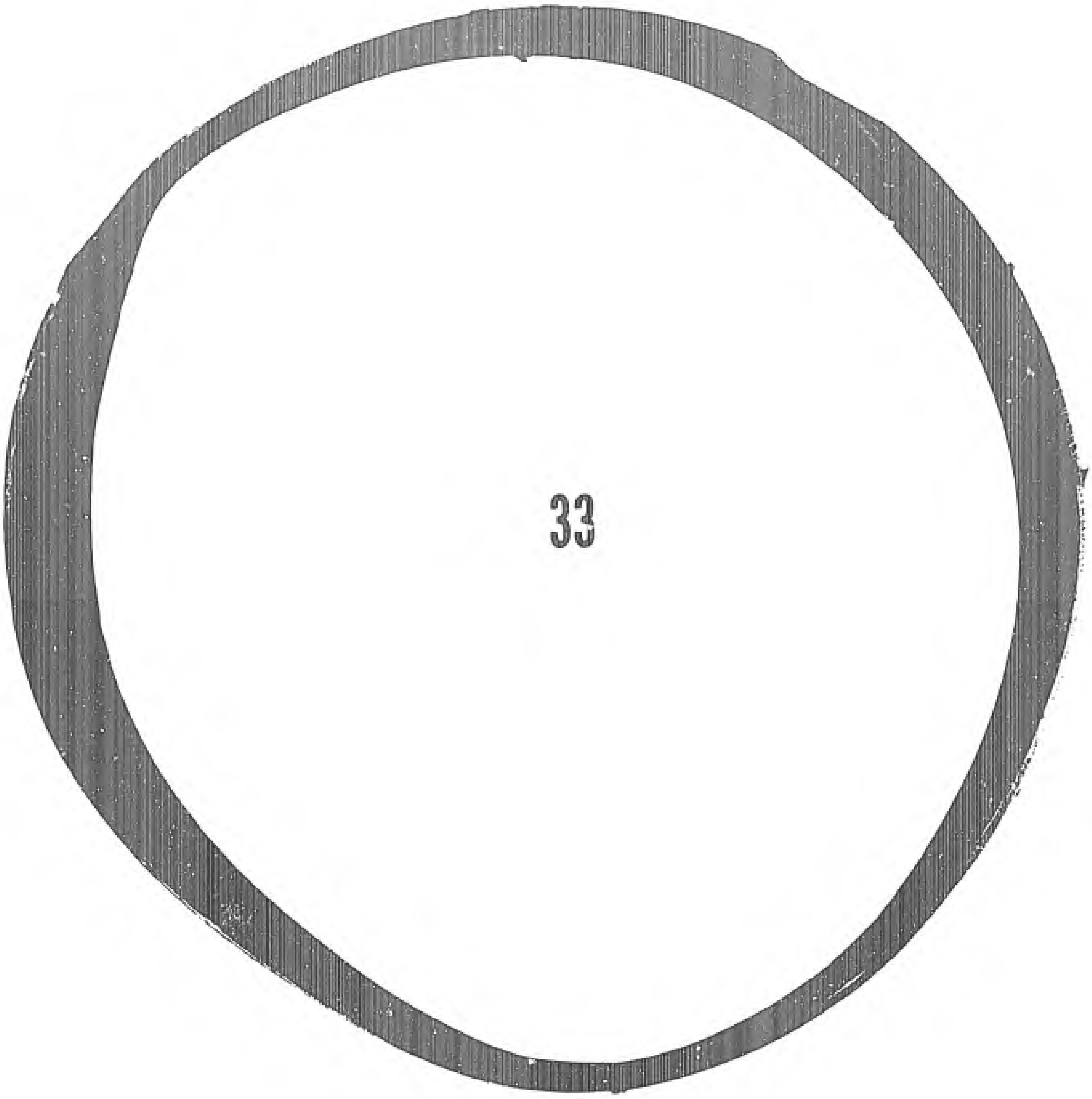
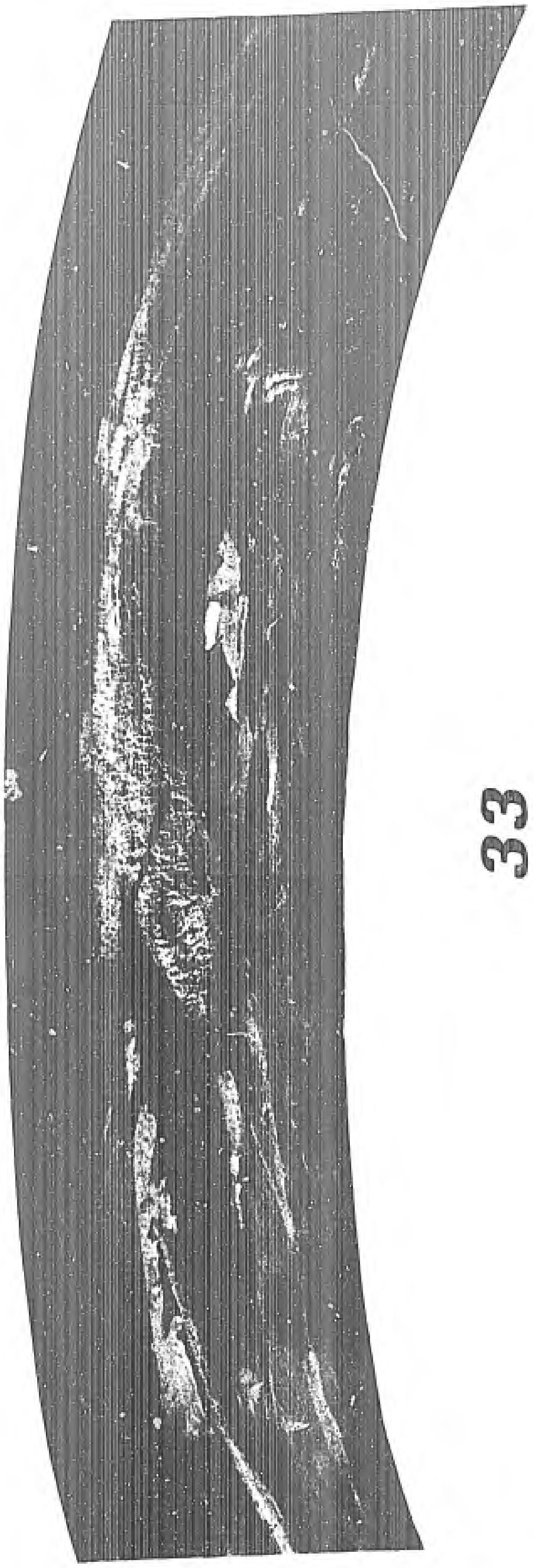


PHOTO NO: CAN-388209(L)-6-68

FIGURE 41



POST-TEST 33
CONTAINMENT RING DETAIL

PHOTO NO: CAN-388213(L)-6-68

FIGURE 42

POST-TEST 33
ROTOR FRAGMENTS

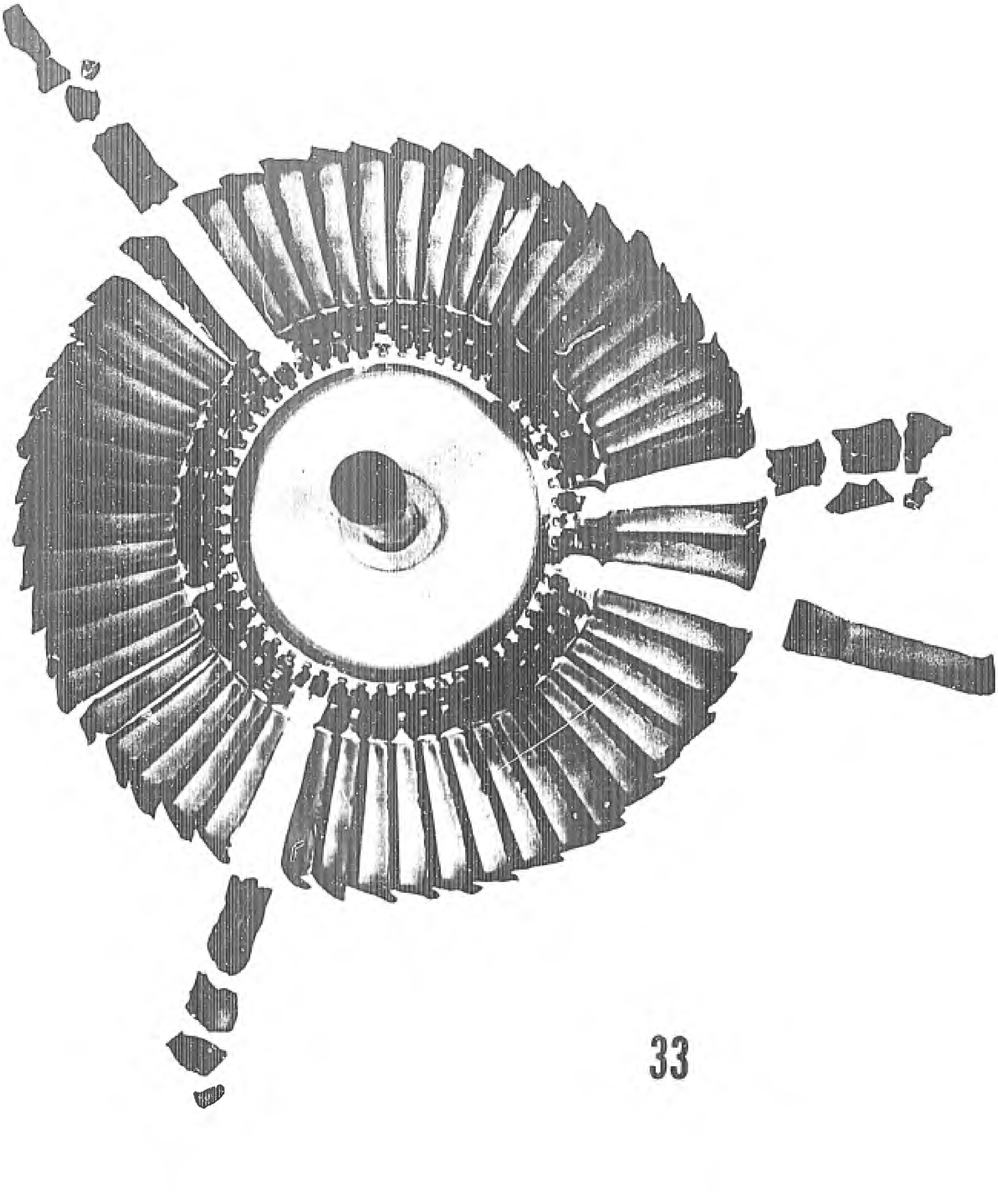


PHOTO NO: CAN-388214(L)-6-68

FIGURE 43

REFERENCES

Reference material noted in this report is as follows:

a. NASA Defense Purchase Request R-105, Amendment No. 4, dated 22 August 1967

b. Martino, A. A. and Mangano, G. J., "Rotor Burst Protection Program - Initial Test Results - Final Phase IV Report on Problem Assignment NASA DPR R-105," NAPTC-AED-1869, 5 April 1968

c. Martino, A. A. and Mangano, G. J., "Turbine Disk Burst Protection Study - Final Phase II-III Report on Problem Assignment NASA DPR R-105," NAEC-AEL Report No. 1848, 28 February 1967

ACKNOWLEDGEMENT

The authors with to express their appreciation to the many industrial and government organizations who have actively participated in the Rotor Burst Protection Program. The continuation of these interchanges is essential to the attainment of the program's goals.

APPENDIX 1

THE UNCONTAINED FAILURE PROBLEM

1. There is definitely an uncontained failure problem associated with the main engine powerplants used by the US commercial airline operators and by the US Navy. This fact is borne out by the 139 uncontained failures reported by the Federal Aviation Agency (FAA), National Transportation Safety Board (NTSB), and US Navy Aviation Safety Center during the period of NAPTC(AE)'s compilation.

2. For every turbomachine in use on commercial air transports, military aircraft, ground support equipment, etc., an acceptable "system safety factor" must be determined by someone. That "someone" varies throughout the industry and is dependent upon many established policies, both federal and civilian.

3. An exact definition of a satisfactory system safety factor is difficult to state. The ideal factor would be equivalent to a perfectly safe condition (100% safe). Such a system would have absolutely no chance of failure; i.e., a permissible failure rate, based on any failure criteria of 0.00. An interesting discussion on this point is presented in reference a where it is remarked that an absolutely safe aircraft would not fly; and an absolutely safe airways system would not permit a single aircraft to take off, because of the measurable, even if remote, probability that it might crash.

4. The question now becomes: what is an acceptable system safety factor? This is, what is an acceptable casualty rate with respect to a desired performance level. The RBPP has not discovered one, and the development of one is outside the scope of this program. Some values are called out in various publications, but it is understood that they are based upon mathematical manipulation of data concerning electronic component production and a direct correlation between this type of data and the turbomachine problem is not appreciated.

5. Terminology plays an important part in any discussion of safety factors. In most instances people think and talk of a system's "reliability" rather than using the word "safety". The permissible failure rate is rarely translated into fatality rates. It is our opinion that a safety criteria concerning the uncontained failure problem should not be misleading by its expression in terms of engine operating hours or possibly aircraft flights. It should be based on the potential loss of life that can be caused by an uncontained failure. The RBPP's view of the turbine-powered equipment system safety picture can be understood with the assistance of Figure A1-1. A proper system safety factor can be obtained by increasing the

reliability of the hardware to a satisfactory level and/or providing protection against failures.

6. Hardware reliability is basically dependent upon four subfactors: design, manufacture, use, and maintenance.

7. Engineers have advanced in design techniques and their growing backlog of operational experience increases their ability to provide high performance equipment within more definite safety limits. No one designs a part to fail in the operational range of the equipment.

8. Manufacturers state that they use the highest quality materials, the latest processes, and many of the most recently developed inspection techniques to provide a high quality item.

9. Equipment operators are better trained all along the line from the pilot to the test bench operator. Increased experience has led to the establishment of more realistic operating limitations.

10. Equipment maintenance has been improved by the awareness, during the initial equipment design phase, of certain maintenance requirements and thus provisions are made for necessary servicing and inspection.

11. Modern equipment is used by larger work forces in better facilities to keep the equipment working properly.

12. From the general efforts listed above, it is reasonable to believe that a general improvement in the safety picture should be observed. This is the case when one reviews the experience of US commercial airline operators with main turbine-powered, propulsive powerplants. Figure A1-2 indicates a steady increase in the use of gas turbine engine operating hours. Along with this increase, there is a decrease in the number of powerplant shutdowns (for any reason) per engine operating hour. This favorable safety trend is indicative of improved hardware reliability and failure-sensing instrumentation (reducing the number of false shutdowns).

13. Unfortunately, this favorable safety trend is not seen when looking at the number of uncontained failures experienced by the US commercial airline operators. A minimum total of 93 occurrences of fragments from failed engines penetrating the engine casing has been reported--22 of these occurring as recently as 1967. Note that the 1968 record is not complete since the NTSB data has not been reviewed and incorporated into this yearly total. The total is considered a "minimum", since for various reasons, certain airlines were not required to participate

in the MRR Program from time-to-time, and therefore, their failure experience is not made available although their usage rate is.

14. This total of 93 failures is not just the product of one particular engine section. A breakdown of the uncontained failures by compressor and turbine sections is shown on Figure A1-4. Evidently, the problem is not isolated to one section or type of fragment.

15. For those who consider system reliability factors in terms of component or failure rates, Figure A1-5 presents the number of uncontained failures per million engine operating hours. The 1.27 uncontained failures per million engine operating hours in 1967 is equivalent to 1.75 uncontained failures per month, which should be alarming considering the potential danger associated with such a failure.

16. From these data it is apparent that hardware reliability alone is not adequate to provide the type of "system safety" required by turbine-powered engines. Therefore, to increase this factor, additional protection must be provided for this system. As indicated in Figure A1-1, this protection could possibly be provided by two means. The first is to sense the impending rotor failure and rapidly shut down the engine before failure occurs. This does not seem to be practical at this time considering the rapidity of such a failure and the inadequate instrumentation systems capable of the proper sensing and rapid response necessary to obtain the action required. The second approach to increasing the "system safety factor" is to provide special protection that will either contain the fragments completely in a predetermined envelope or control the trajectory of the fragment away from sensitive areas, such as fuel lines and cabins, into less sensitive areas. It is this approach that the RBPP is following. The protection systems considered here should be structurally functional and impose the minimum weight penalty on the overall system.

17. Figures A1-6, A1-7, A1-8, and A1-9 present the Navy picture, which is similar to that of the US commercial airline operation. The type of operation and maintenance procedures available under certain operating conditions has to be considered when comparing commercial with military data. An item of prime importance of Navy data is the large number of uncontained failures during the fiscal years 1966, 1967, and apparently carrying on into fiscal year 1968.

18. Although the previous discussion has dealt exclusively with the turbine-powered engines, used in the aircraft's main propulsive system, it should be noted that the uncontained failure problem is not isolated to this category of turbomachinery. Detailed data has not been compiled concerning the number of uncontained failures associated with "smaller" turbine-powered equipment, but a number of such incidents have come to the attention of the RBPP.

19. With the increased size of the newer aircraft, the requirement for larger and more powerful auxiliary systems to provide more engine starting power, higher hydraulic pressures, and greater conditioned-air flow also increases. Even though considered small in size compared to the main powerplant, these units can not be considered less dangerous with respect to an uncontrolled failure when one realizes the extremely high operating speeds and the critical locations in which these units are sometimes placed.

20. Another point to consider concerning turbine-powered starters, auxiliary power units, and environmental control systems is that they are not only used for airborne applications. Many units are operated in crowded air terminal boarding areas, on aircraft carrier decks surrounded by aircraft, weapons, and personnel and at tactical Army power-generator and/or communication centers.

REFERENCE

a. "Air Safety - How Safe is Air Travel?", Frank Leary, Space/Aeronautics, May 1968

COMMERCIAL AIR CARRIERS'
TURBINE-POWERED AIRCRAFT EXPERIENCE
1962 - 1968
ENGINE OPERATING RATE AND POWERPLANT SHUTDOWN RATE

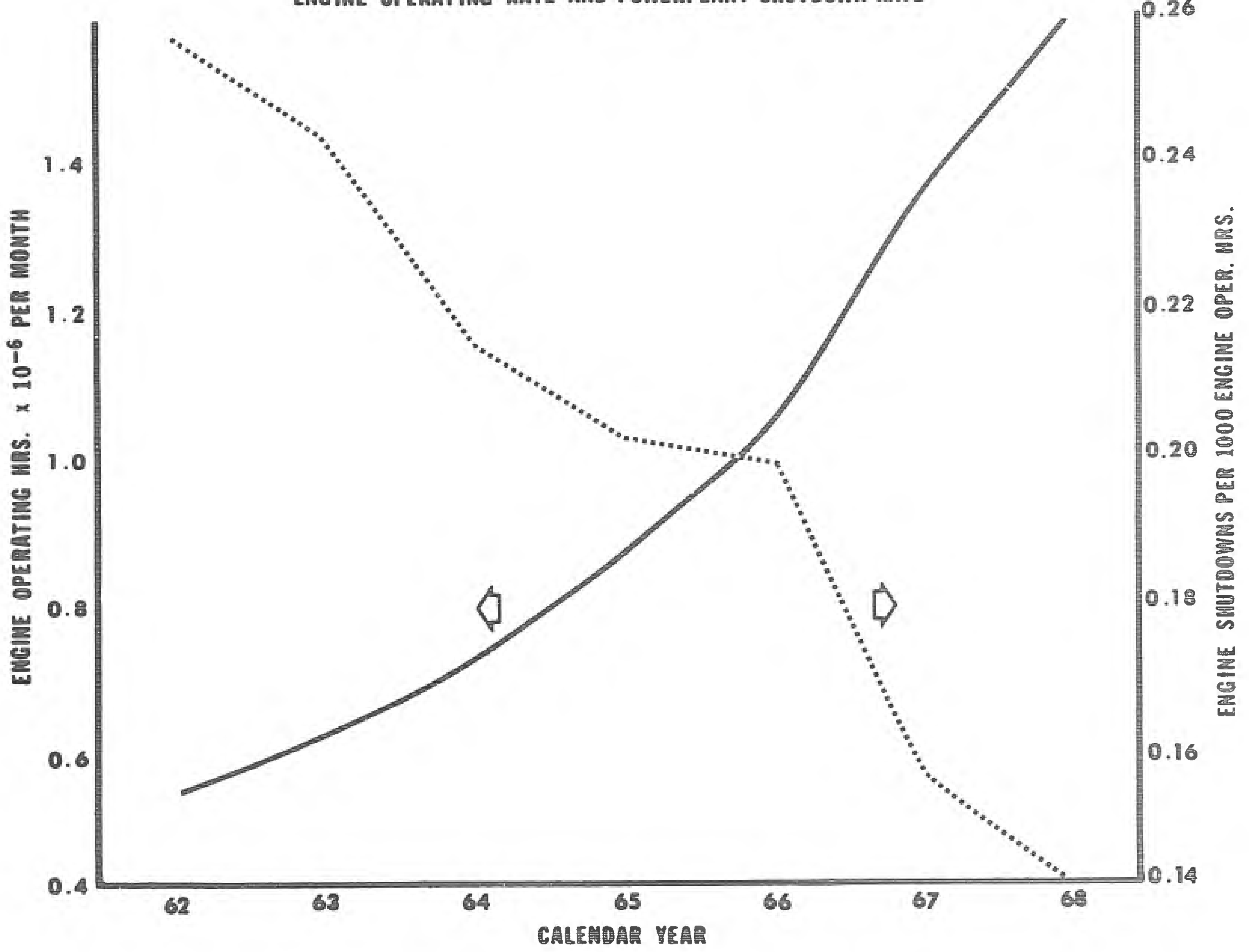


FIGURE A1-1

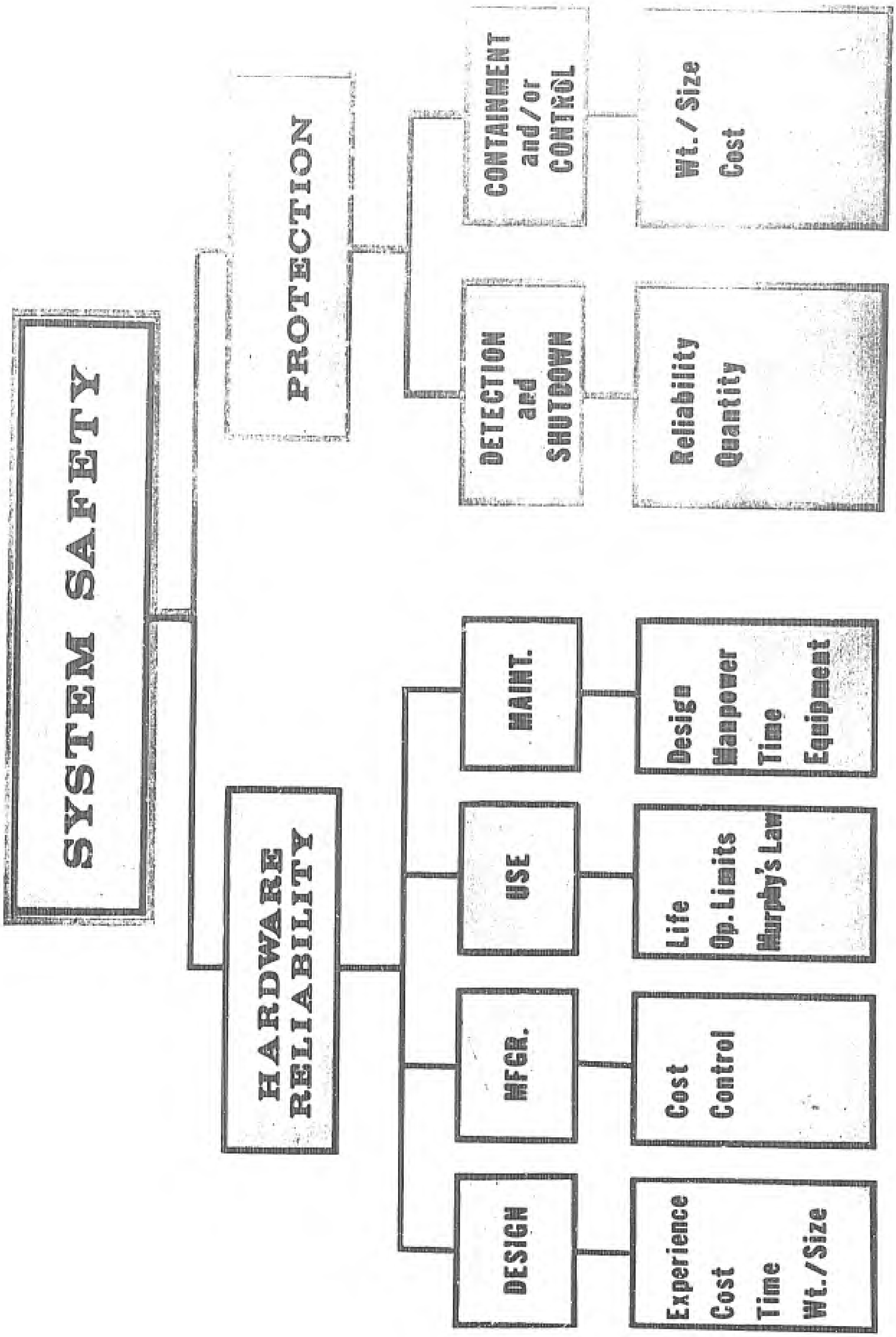

SYSTEM SAFETY
HARDWARE RELIABILITY
PROTECTION
DESIGN
MFGR.
USE
MAINT.
DETECTION and SHUTDOWN
CONTAINMENT and/or CONTROL
Experience
Cost
Time
Wt./Size
Cost
Control
Life
Op. Limits
Murphy's Law
Design
Manpower
Time
Equipment
Reliability
Quantity
Wt./Size
Cost

FIGURE A1-2

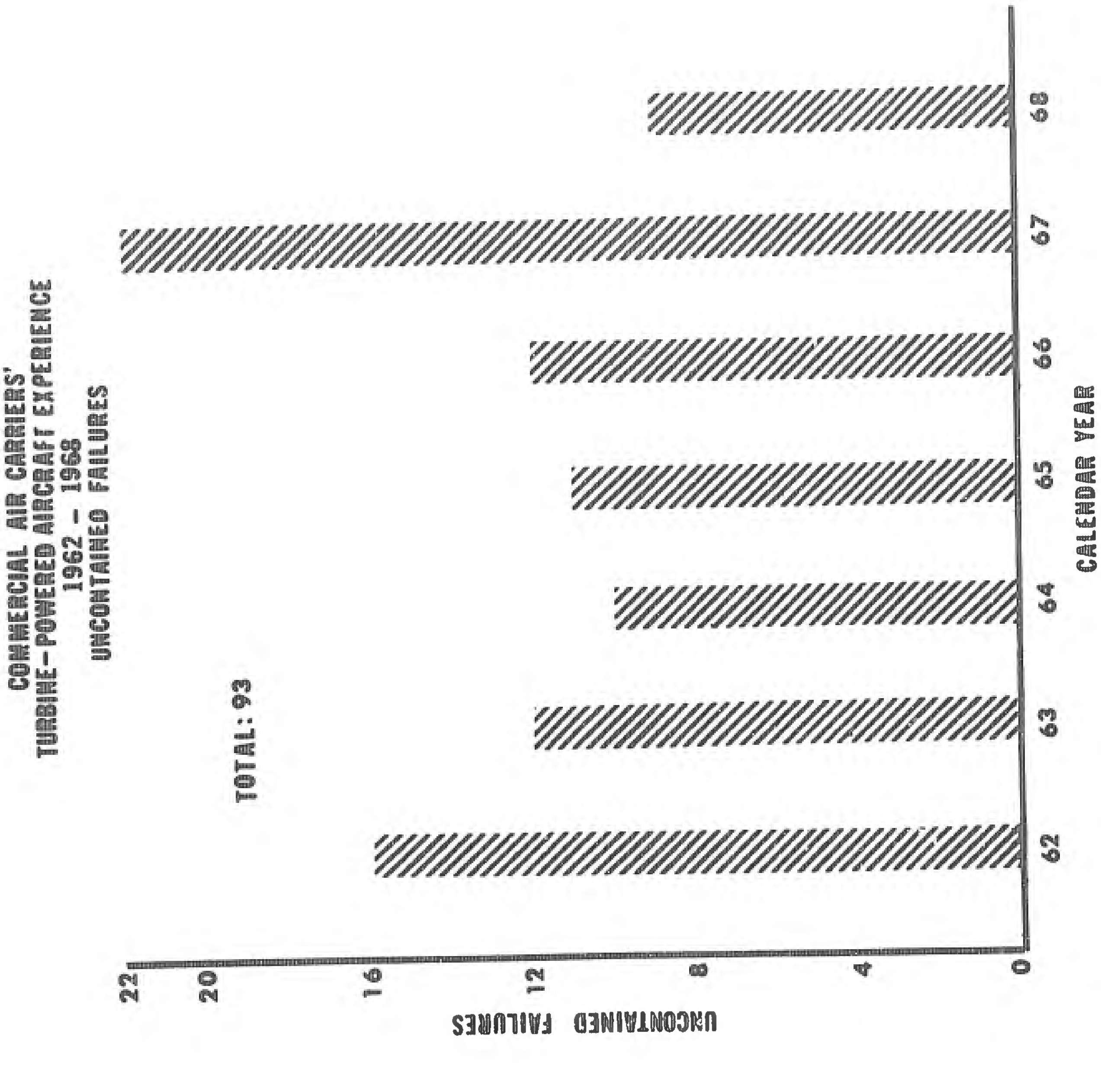

COMMERCIAL AIR CARRIERS'
TURBINE-POWERED AIRCRAFT EXPERIENCE
1962 - 1968
UNCONTAINED FAILURES
TOTAL: 93
UNCONTAINED FAILURES
0
4
8
12
16
20
22
62
63
64
65
66
67
68
CALENDAR YEAR

FIGURE A1-3

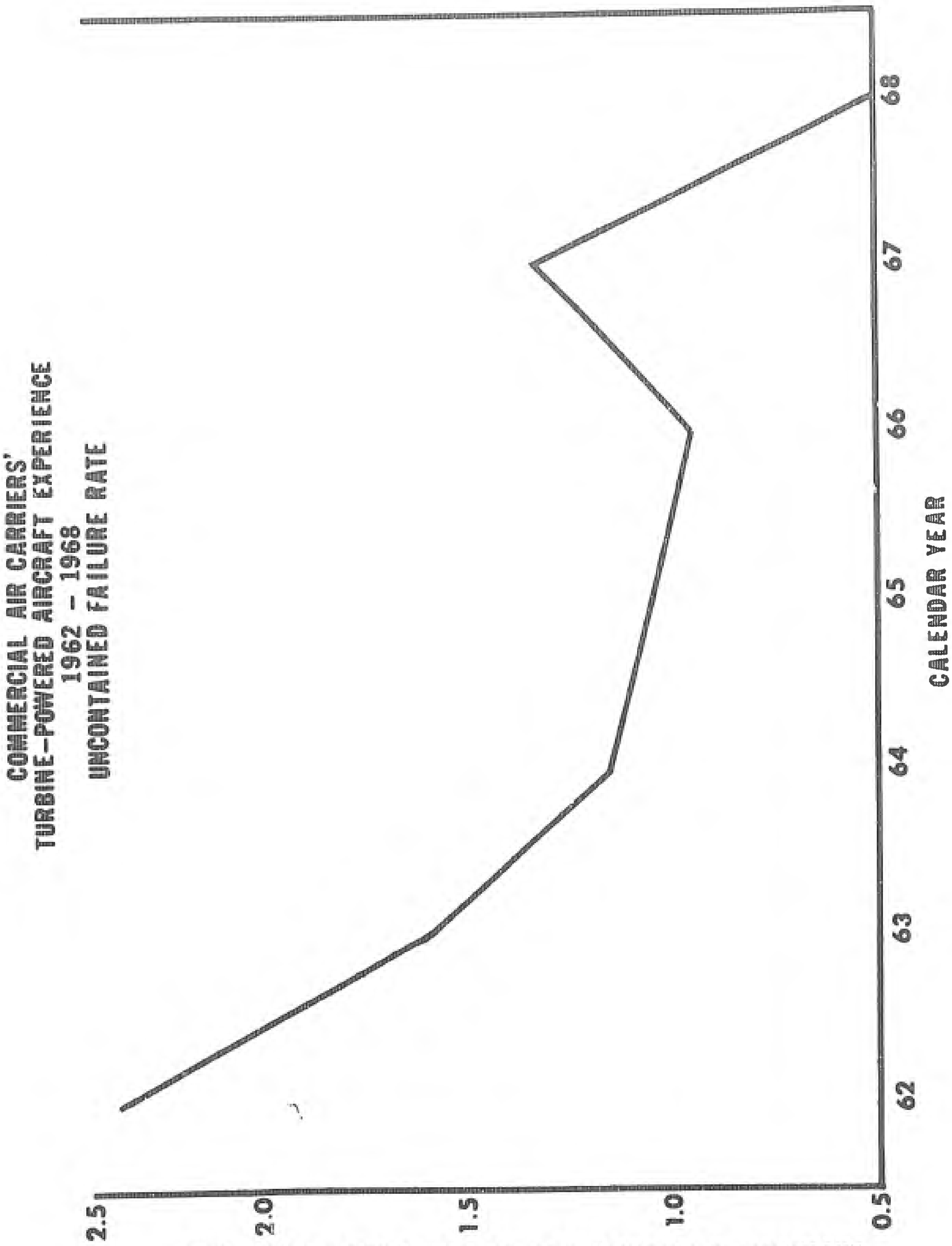
COMMERCIAL AIR CARRIERS' TURBINE-POWERED AIRCRAFT EXPERIENCE

UNCONTAINED FAILURES by ENGINE SECTIONS

1962 - 1968

BLADES	Compressor	17
	Turbine	18
SPACERS	Compressor	5
	Turbine	8
DISKS	Compressor	29
	Turbine	16
	TOTAL	93

FIGURE A1-4



COMMERCIAL AIR CARRIERS'
TURBINE-POWERED AIRCRAFT EXPERIENCE
1962 – 1968
UNCONTAINED FAILURE RATE

FIGURE A1-5

USN AVIATION
TURBINE-POWERED AIRCRAFT EXPERIENCE
ENGINE OPERATING HOURS AND AIRCRAFT FLIGHTS
FY60 - FY67

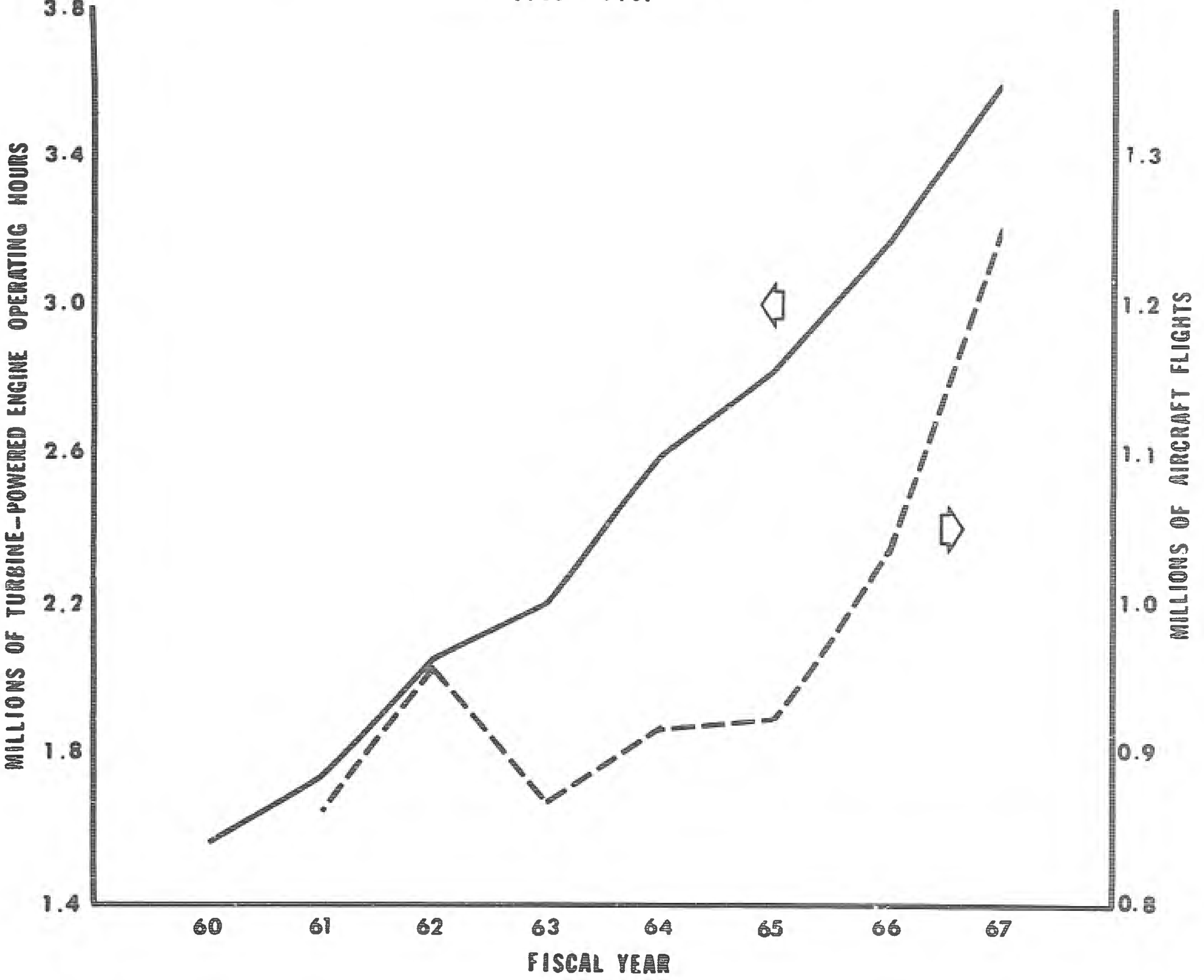


FIGURE A1-6

USN AVIATION
TURBINE-POWERED AIRCRAFT EXPERIENCE
UNCONTAINED FAILURES

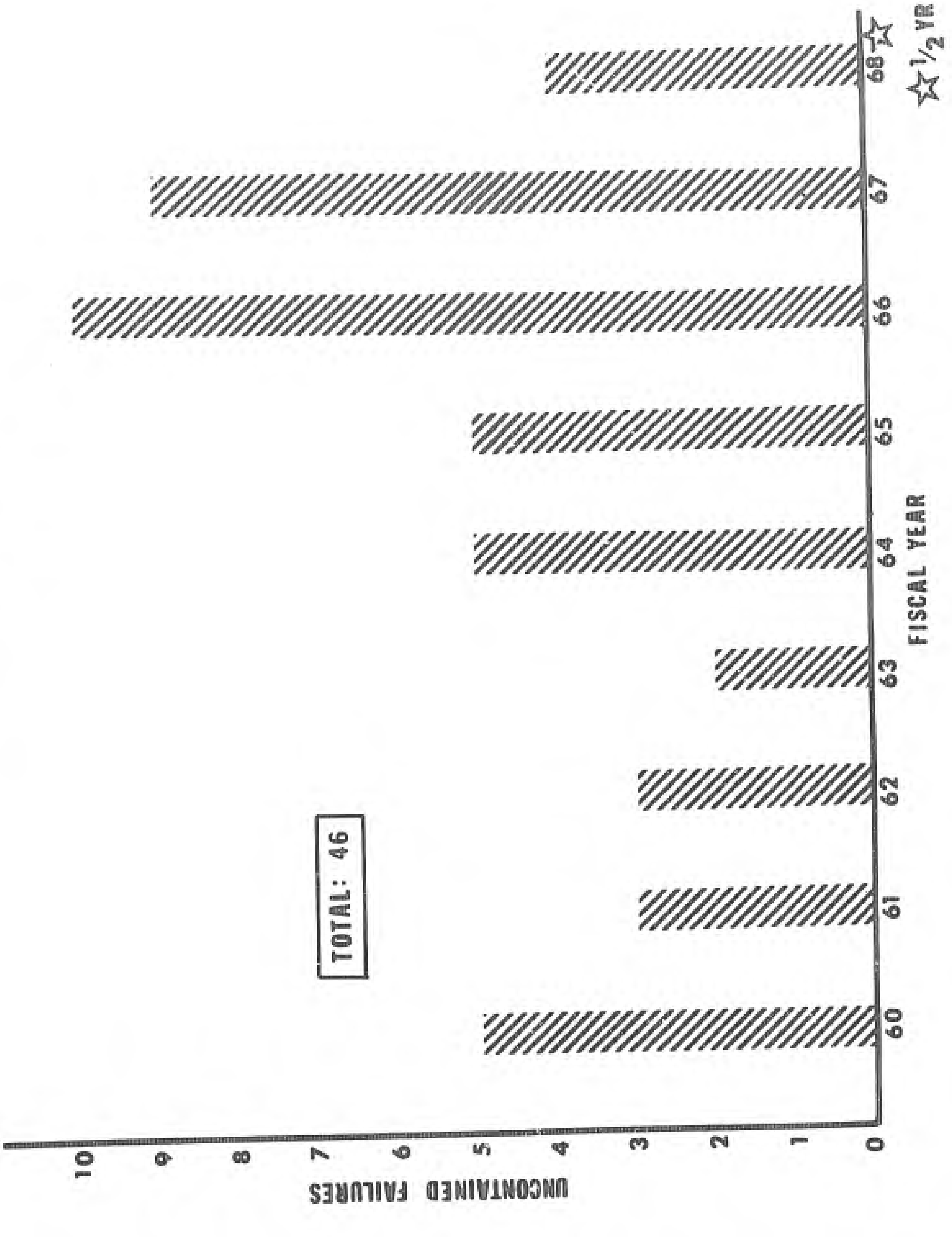


FIGURE A1-7

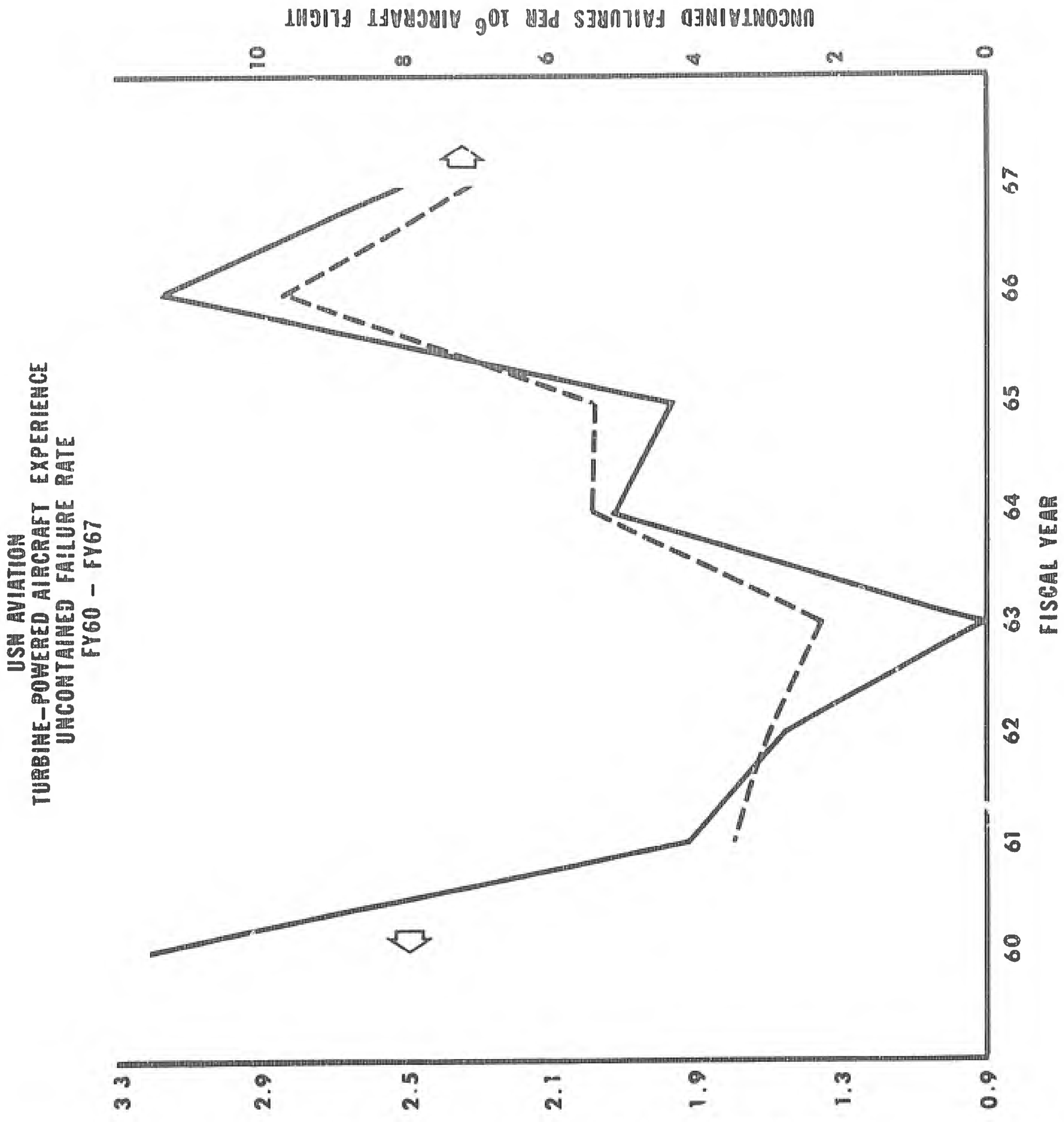
USN AVIATION
TURBINE-POWERED AIRCRAFT EXPERIENCE

UNCONTAINED FAILURES by ENGINE SECTIONS

FY60 - FY68 * (1/2 of 1968)

BLADES	Compressor	1
	Turbine	22
SPACERS	Compressor	4
	Turbine	2
DISKS	Compressor	7
	Turbine	10
	TOTAL	46

FIGURE A1-8



USN AVIATION
TURBINE-POWERED AIRCRAFT EXPERIENCE
UNCONTAINED FAILURE RATE
FY60 - FY67

FIGURE A1-9

APPENDIX 2

THE AIRCRAFT DESIGN REVIEW

1. The objective of this appendix is to emphasize the definite need that can be partially satisfied by the application of the results of the RBPP. Information about the types of fragments that exit the casings of failed turbomachines, the energy level of these fragments and some knowledge about the associated containment/control phenomena is essential to those concerned with insuring adequate vehicle and passenger protection against rotor bursts.

2. As a result of the initial design phase of an air transport vehicle, the powerplants and other major components are positioned to provide optimum aircraft operational characteristics. Following this, a safety design review is conducted. Its objective is to discover and correct all hazardous conditions. A hazardous condition is one that could result in a loss of life. A portion of this design review procedure is the analyses of the damage potential, to both vehicle and passengers, in the event of an uncontained failure of a turbine-powered component such as an engine, starter, auxiliary power unit, or environmental control system unit. All possible failure paths are investigated and the damage associated with each one is estimated. If a potential failure can inflict critical damage, the fragments must either be contained, controlled, or the turbomachine must be relocated so that the uncontained fragments will not damage a sensitive area. Before the engineer can make such determinations, he must have many facts based upon reliable data.

3. During the RBPP's investigations, it became apparent that decisions were apparently being made based on assumptions or statements not supported by sound engineering facts. This lack of good data could be quite critical to the final aircraft design. An example of the type of problem that can be precipitated by an "unsound" value is illustrated by this hypothetical situation. As a result of the aircraft's preliminary design, an engine was positioned such that an extension of the plane of rotation of the large fan rotor cut across a stabilizer section. Damage to this section could critically affect the aircraft's controllability and therefore is not permitted. Obviously, all fan fragments must be contained or controlled so as to be incapable of striking the panel, or the engine relocated so as to have all passengers and crew seats and other sensitive areas outside the fan's plane of rotation.

4. Which of these three alternatives (contain, control, or relocate) to select is the problem. Various criteria are established to evaluate the alternatives, but for the purpose of this brief discussion let it be assumed that aircraft weight is the prime consideration. The weight penalty incurred by relocating the engine is probably the most accurately determined value, since all input values are accurately known to the aircraft designer. The most questionable value to be considered is the estimated weight penalty to provide containment or control of the engine fragments. This is questionable for a number of reasons. Mainly, the newly designed engine is usually much different (size, blade shape, etc.), than any other engine with extensive operating experience. Therefore, an extrapolation of either the same protective system design used on previous engines, or the design data and procedures used in establishing this previous system, have very little basis. Extrapolation of all impact data is questionable because of the sensitivity of such data to the type of impactor (projectile) and target conditions. In addition, the weight of this previous containment device, assuming it truly does contain all fragments it was designed to contain, may not necessarily be of minimum weight. Usually containment ring development dealt with material evaluations only and very seldom were they the combination of system design and material investigations. Previous protection systems considered only the complete containment of fragments and no thought was given to the possible schemes to control the trajectory of the fragments away from the sensitive areas rather than to completely capture the fragments. So this potential has no real data to offer for the decision-making process. The engineer could be faced with making a decision based on a protective system weight that may be 100% in excess of what is actually necessary. Since sound decisions are based on sound facts, it is obvious that today's aircraft designers do definitely have a requirement for the type of information being produced by the RBPP.

APPENDIX 3

TABLE OF CONTENTS

ROTOR INTEGRITY SUBSTANTIATION AND CONTAINMENT CRITERIA

A. GENERAL

1. All turbine-powered equipment is designed in compliance with a specification that establishes the requirements for minimum performance and quality control standards. In this part of the report we will discuss those sections of certain turbomachine specifications dealing with rotor integrity substantiation and containment criteria. These sections are, of course, of greatest interest to the Rotor Burst Protection Program. During our investigations a number of specifications have been reviewed. These specifications were discussed with authors and users.

2. The purpose of our discussion is to provide the reader with sufficient information so that he may generate a feeling for the type of requirements that in many cases determine the level of effort devoted to rotor fragment control.

3. The comments made in this section of the report concerning these specifications are those of the authors, based on the specifications herein listed, and should not be interpreted as official statements of the policies of any agency. There may be other regulations that apply to this discussion but time limitations did not allow for a more exacting examination than that made.

4. The basic document for U. S. commercial aircraft operations is the Code of Federal Regulations. Of major interest to the RBPP is the book that contains the rules and regulations which constitute Parts 1 to 59 of Title 14, Aeronautics and Space, revised as of 1 January 1967. It is one of three volumes that replaced the 1966 revision and became an integral part of the Code of Federal Regulations.

5. In addition to the Federal Aviation Regulations (FAR), the Department of Transportation, FAA, publishes Advisory Circulars that provide guidance and acceptable means, although not sole means, by which compliance may be shown with the requirements of certain portions of the FAR. The FAA also publishes other documents that contain minimum performance standards and specifications for materials, parts, and appliances used in the aircraft. A Technical Standard Order (TSO) is an example of this type.

6. For turbine-powered equipment to be qualified for use in the military service, it must meet military specifications that cover the standard requirements set forth by the using service.

7. Part 25 of reference (a) presents the Airworthiness Standards for Transport Category Airplanes. Subpart E - Powerplants, General, considers the general regulations for powerplant installations, engines, and propellers.

a. Paragraph 25.901, Installation states:

"(1) For the purpose of this part, the airplane powerplant installation includes each component that:

(a) Is necessary for propulsion;

(b) Affects the control of the major propulsive units; or

(c) Affects the safety of the major propulsive units between normal inspections or overhauls.

(2) For each powerplant:

(a) The engine installation must meet the applicable provisions of this subpart;

(b) The components of the installation must be constructed, arranged, and installed so as to ensure their continued safe operation between normal inspections or overhauls;

(c) The installation must be accessible for necessary inspections and maintenance; and

(d) The major components of the installation must be electrically bonded to the other parts of the airplane."

b. Portions of paragraph 25.903 discuss engine type certification, isolation, and turbine engine installation.

"(1) Engine type certification. Each engine must be type certificated under Part 33 (New).

(2) Engine isolation. The powerplants must be arranged and isolated from each other to allow operation, in at least one configuration, so that the failure or malfunction of any engine, or of any system that can affect the engine, will not:

(a) Prevent the continued safe operation of the remaining engines; or

(b) Require immediate action by any crewmember for continued safe operation.

(3) Turbine engine installations. Unless the engine type certificate specified that the engine rotor cases can contain damage resulting from rotor blade failure, turbine engine powerplant installations must have a protection means so that rotor blade failure in any engine will not affect the operation of remaining engines or jeopardize continued safety. In addition, design precautions must be taken to minimize the probability of jeopardizing safety if an engine turbine rotor fails, unless:

(a) The engine type certificate specified that the turbine rotors can withstand damage-inducing factors (such as those that might result from abnormal rotor speed, temperature, or vibration); and

(b) The powerplant systems associated with engine control devices, systems, and instrumentation give reasonable assurance that those engine operating limitations that adversely affect turbine rotor structural integrity will not be exceeded in service."

c. Paragraph 25.905 pertains to propellers:

"(1) Each propeller must be type certificated under Part 35 (New).

(2) Engine power and propeller shaft rotational speed may not exceed the limits for which the propeller is certificated."

8. Similar regulations are called out in Subpart E - Powerplants, of Part 23 - Airworthiness Standards: Normal, Utility, and Acrobatic Category Airplanes.

9. Part 33 - Airworthiness Standards, Aircraft Engines (reference (a)) is of special interest to the RBPP. This part describes airworthiness requirements for issuing type certificates, supplemental type certificates, and changes to those certificates, for aircraft engines. Each applicant must show that the aircraft engine concerned meets the applicable requirements of this part.

a. Paragraph 33.13 stated that: "the engine may not have design features that experience has shown to be hazardous or unreliable. The suitability of each questionable design detail or part must be established by test."

10. FAA Advisory Circular No. 33-2, Aircraft Engines Type Certification Handbook, dated 30 March 1966, reference (b), contains guidance relating to type certification of aircraft engines.

11. "Official engine certification tests are conducted in accordance with the authorization directed to the applicant. The tests required for engine certification are as prescribed by pertinent sections of FAR, Part 33."

12. "Witnessing of tests by FAA representatives as prescribed in FAR, Section 21.33, is accomplished at least for the engine calibration, endurance, and operation tests, and the teardown inspection following these tests. Federal Aviation Agency representatives may also witness such specialized tests as vibration measurement, detonation, rotor integrity, rotor blade containment, icing and ingestion tests. The engine manufacturer's designated engineering representative should witness all certification testing and subsequent parts improvement tests, conducted by the manufacturer, for the purpose of authenticating the tests and the results."

13. Since all containment testing must be authenticated, it would contribute to the general knowledge of the RBPP if the results of these tests, both the successful and unsuccessful occurrences, are made available to the RBPP.

B. ROTOR INTEGRITY SUBSTANTIATION

14. Now we will direct our attention to those sections of the Federal Aviation Regulations and military specifications that are concerned with rotor integrity substantiation.

a. Engines

(1) Paragraph 33.27 of reference (a) relates to the substantiation of engine rotor integrity. The regulation states:

"(a) To minimize the probability of failure of rotors:

1 Rotors must be demonstrated to be of enough strength to withstand damage inducing factors such as those that might result from abnormal rotor speeds, temperatures, or vibration and other stress inducing factors, and

2 The design and functioning of engine control devices, systems, and instrumentation must give reasonable assurance that affect rotor structural integrity will not be exceeded in service."

15. Advisory Circular 33-3 (reference (b)) (which cancelled AC 20-26) sets forth guidance and acceptable means, not the sole means, by which compliance may be shown with the turbine and compressor rotor substantiation requirements in Federal Aviation Regulations, Part 33.

16. "To provide reliability and safety of turbine and compressor rotors of turbine engines, turbosuperchargers, and power recovery turbines used with reciprocating type engines, their design and construction must provide structural integrity of sufficient strength to withstand specified overspeeds and overtemperatures without failure unless rotor bursts are demonstrated to be contained within their respective housings. To cope with the possibility of critical deterioration of rotor assemblies from service use, inspection and life limit criteria are established and are set forth in the engine instruction manual. The substantiation procedures stated in this Advisory Circular are those which have been used and found to be acceptable."

17. Paragraph 6a of reference (b) requires that the "engine manufacturer should design turbine and compressor rotors to have sufficient strength margin to allow safe operation with likely variations in materials and operating environment. The effects of damage-inducing factors, which may effectively reduce the strength of rotor discs, should be minimized by design features, taking into account the reduction of strength that may be caused by surface damage and corrosion, occasional overheating, material flaws or other substandard metallurgical properties difficult to detect, likely dimensional and quality variations, vibration, and fatigue. Vibratory stresses should be determined and allowable stress limits established. Consideration should be given to the loads and stresses, occasioned from airplane inlet distortion, bleed air, and exhaust system effects, start-stop cyclic stresses (low-cycle fatigue), and vibratory stresses (high-cycle fatigue)."

18. Test techniques to demonstrate the overstrength margin of rotors are listed in paragraph 6(d) of reference (b):

a. "Representative design turbine and compressor rotors should be subjected to operation for a stabilized period of at least five minutes' duration, at the maximum rated temperature conditions and accompanied by an overspeed r.p.m. as determined in the following paragraphs. In demonstrating adequate overstrength margins, evaluation of the effects of actual overload stresses at the specified maximum test conditions is desired. Knowledge of the stresses in all rotor components is needed, but the most critically stressed discs and the most critical stresses in these discs are of paramount interest. For multistage compressors and turbines, demonstration of only the most critical stages is acceptable. The condition of critical rotor components following this demonstration should be such that there is no evidence of incipient failure or critical distortions which could cause hazards to an aircraft. A five-minute stabilized test period is acceptable for the purpose of this test, which is made to evaluate short-term creep and elongation that could lead to rupture.

(1) Testing at Overspeed Stresses. Overstrength margins relative to overspeeds may be demonstrated by any of the following test techniques:

(a) Rig testing a rotor disc, equipped with dummy blade weights, at maximum overspeed while heated to its usual maximum operating temperature conditions.

(b) Testing rotor assemblies in a complete engine to maximum overspeed while developing the maximum permissible gas temperature for the highest rated speed.

(c) Testing a rotor in a complete engine, but with the disc(s) having appropriately thinned sections at critical areas to produce maximum rated gas temperatures and maximum operating r.p.m.

(d) Turbosupercharger units tested as complete units and driven by a hot gas supply from a special burner rig.

(e) Testing rotors or units separately (complete with blades or dummy weights) by cold spinning, plus acceptable calculated data to ascertain the effects of temperature on critical stresses. For this method to be successful, accurate and extensive data are required including disc temperature survey data from operating engines and data on hot strength properties of the disc material.

(2) Determination of overspeed r.p.m. for test. The overspeed r.p.m. of all turbine engines, turbosuperchargers and power recovery turbines to which rotor discs are to be tested should be established through failure analyses criteria in determining the effects of reasonably probable and likely remote failures causing engine overspeeds. The failure of structural elements of the engine and its installation need not be considered if the probability of such failure is considered to be extremely remote. The highest r.p.m. of the following should be established as the overspeed r.p.m.

(a) One hundred and fifteen percent of the maximum rated r.p.m. if the demonstration is made on a complete engine incorporating standard compressor and turbine assemblies.

(b) One hundred and twenty percent of the maximum rated r.p.m. if the demonstration is made under simulated conditions acceptable to the Administrator, such as in rotor component test rigs.

(c) An r.p.m. equal to 105 percent of the highest speed that would result from failure of the most critical component or system in a representative installation of the engine

(d) An r.p.m. equal to the highest speed, which would result from the combination of two failures of components and/or systems in a representative installation of the engine. For each combination considered, one of the failures causing overspeeding should include a component or system whose failure would not normally be detected during a routine preflight check nor during normal flight operations.

(3) Testing at Overtemperatures. Turbine engine rotor assemblies should be operated at least five minutes at the maximum rated r.p.m., with the measured turbine gas temperature (as normally measured in the engine) at least 75°F in excess of the highest maximum permissible rated temperature value. This test should be accomplished by operating sufficiently long to heat-soak the turbine elements. The strength margin is sufficient only when the condition of the turbine assembly following this test is satisfactory and still within serviceable limits. The purpose of this test is to insure that excess strength is provided to preclude rapid deterioration or failure of turbine rotors in the event of 75°F overtemperatures, which may result from sudden control or other system failures in a time interval in which a flight crew can be expected to be alerted and take corrective action."

19. The general military specification for turbojet and turbofan aircraft engines, MIL-E-5007C (reference (c)), spells out the rotor overstrength margin requirements for military aircraft engines. Paragraph 3.16.32 of reference (c) states:

a. "To provide necessary margin for rotor structural integrity, the compressor, fan and turbine rotor(s) shall be of sufficient strength to withstand the following abnormal conditions:

(1) Rotor speed(s) of 115 percent of maximum allowable speed and at maximum allowable measured gas temperatures as specified in the model specification for 5 minutes.

(2) Measured gas temperature at least 75°F (14.7°C) in excess of the maximum allowable measured gas temperature and at maximum allowable speed as specified in the model specification for 5 minutes.

Substantiation of conformance with this requirement shall be submitted to the using service prior to initiation of the 150-hour endurance test."

20. The model specification mentioned above refers to the specification that applies to one particular engine only, whereas the general specification applies to all engines of a general type. That is, the J65 and J71 turbojet engines each have a different model specification but each have to comply with the requirements of MIL-E-5007C, the general military specification for turbojet aircraft engines.

21. Paragraph 3.16.3.1 of reference (c) calls out the action required by the engine manufacturer to avoid the possibility of a catastrophic failure. "The contractor shall conduct a study of all possible failure modes of all high rotational speed portions of the engine with the objective of eliminating the possibility of catastrophic failure where failed parts penetrate the engine cases. Fail-safe designs shall be incorporated with the objective of eliminating the possibility of catastrophic failure. Particular attention shall be given to the following:

a. The integrity of turbine and compressor discs with the objective of having blades fail first under overspeed or overtemperature malfunctions.

b. The integrity of shafts connecting compressors to turbines such that bearing or lubrication failure shall not cause parting or decoupling of the shaft.

The results of the study and the fail-safe designs shall be submitted to the using service prior to initiation of the Preliminary Flight Rating Test (PFRT)."

22. Manufacturers comply with the aforementioned rotor structural integrity specifications by analytically showing sufficient safety factors and speed and overtemperature control systems. Main powerplant engine rotors are never designed to intentionally fail in the rotor rim section at some slight overspeed condition. A "rim failure" would release a small section from the outer edge of the disk. This disk segment would probably have a few blades attached to it. The proposed advantage of a rim failure over a hub failure is that less massive fragments (rather than disc chunks) are released and the loss of the blades will retard the rotor speed. Intentional rim failures will be discussed later in the "Starter" section of this appendix.

b. Auxiliary Power Units

(1) Gas turbine auxiliary power units are intended to be used as power sources for driving generators, hydraulic pumps, and other accessories and equipment, and to provide compressed air for pneumatic systems. APU's are found in a variety of locations both airborne and on the ground. The advent of the larger aircraft has made it necessary to utilize a number of units throughout rather than the customary single unit servicing the entire aircraft.

23. The FAA Technical Standard Order TSO-C77 "Gas Turbine Auxiliary Power Unit", reference (d), contains minimum performance requirements for gas turbine auxiliary power units for use in civil aircraft. Paragraphs 7.2.1 and 7.2.1.1 specify the overspeed and overtemperature capabilities of rotor assemblies that must be substantiated for the critical stages. A determination of what is a critical stage is usually more of a problem when discussing containment criteria than when discussing rotor integrity. Additional comments will be made concerning the determination of a critical stage when containment specifications are reviewed.

24. Paragraph 7.2.1 requires that: "the overstress margin for compressor and turbine rotors shall be substantiated to be adequate to withstand operation for five minutes at the critical rotational speed which is the highest of the speeds specified by subparagraphs a, b, and c below while at the turbine inlet or exhaust gas temperature which would prevail during actual operation under the fault conditions of b or c.

a. A speed equal to 115% of the maximum rated speed.

b. If safety devices are incorporated a speed equal to 115% of the highest speed which would result from failure of any one of the normal engine control systems.

c. If no safety devices are incorporated a speed equal to the highest speed which would result from the failure of any one of the normal engine control systems.

25. The overstress margin for compressor and turbine rotor is also required to be substantiated as adequate to withstand operation for five minutes at a turbine inlet or exhaust gas temperature of 75°F more than the maximum rated turbine inlet or exhaust gas temperature while not less than the maximum rated speed. Acceptable methods for substantiating the overstress margin of turbine and compressor rotors are:

a. Testing a full scale rotor at speed and temperature in a complete unit.

b. Testing a full scale rotor at speed and temperature in a spin pit.

c. Testing a modified rotor in a complete unit at a speed and temperature which will induce stresses equal to or greater than those required.

d. Calculation of the overstress margin of the rotor at speed and temperature from basic data obtained by cold spinning."

26. The general military specification, MIL-P-8686(ASG), reference (e), approved by the Department of the Air Force and by the Navy, covers the general requirements for gas turbine type aircraft auxiliary power units. Rotor integrity substantiation is attempted by having the APU manufacturer perform material quality inspections. Paragraphs 4.3.1, 4.3.2, 4.3.3, and 4.3.5 of reference (e) (listed below) describe the required tests and test methods:

"4.3.1 Material tests.- Samples of all materials used in the APU and components shall be selected in the manner and quantity specified in the material specification, and subjected to the required tests.

4.3.2 Magnetic inspection.- The following parts shall be subject to magnetic particle inspection in accordance with Specification MIL-I-6868 or AMS2640 if made of magnetic materials:

(a) All magnetic parts constituting the compressor-turbine rotor assembly, including threaded fastenings.

(b) Other highly stressed magnetic parts.

(c) All accessory drive and vibration or friction dampener springs.

4.3.3 Fluorescent penetrant inspection.- The following nonmagnetic parts shall be subject to fluorescent penetrant inspection in accordance with Specification MIL-I-6866 or AMS2645:

(a) Turbine disk.

(b) Turbine blades.

(c) Turbine nozzle vanes and assemblies.

(d) All other highly stressed parts.

4.3.5 Radiographic or ultrasonic inspection.- The following parts shall be subject to radiographic or ultrasonic inspection for defects or soundness to a degree of inspection on each article as agreed between the contractor and the procuring activity:

(a) The compressor impeller or rotor(s), if it is nonmagnetic.

(b) The turbine rotor(s), if it is nonmagnetic.

(c) Highly stressed magnesium and aluminum castings."

27. When performing the fluorescent penetrant inspection, some manufacturers apply the penetrant to the rotor while it is being rotated at military speed in a spin chamber. Supposedly, if there is a small crack, the dye will have a better chance to penetrate while in the stressed condition.

28. Reference (f) is a model specification covering the requirements of a particular gas turbine power unit used by the Navy. Paragraph 3.36.2 of reference (f) states that: Design integrity of high-energy rotors shall be provided to the extent that each rotor shall be capable of withstanding the stabilized speed required to produce 1.50 times the kinetic energy of the rotor as determined at the maximum speed that the unit would experience under transient conditions and which is limited by the unit's safety devices and at maximum operating temperature. The integrity test requires that each turbine, exducer, and compressor rotor be subjected to an overspeed whirlpit spin test conducted at the conditions required to produce the kinetic energy specified in paragraph 3.36.2 as a means of checking for material flaws that are undetectable by other established inspection procedures. All tests shall be conducted at speeds which have been corrected to compensate for maximum operating temperature."

c. Starters

29. Recent philosophies regarding aircraft engine starter rotor integrity substantiation can be gathered by reviewing certain portions of the general aircraft engine starter exhibit (reference (g)) proposed by the USAF. This exhibit establishes the general requirements for jet fuel starters (designed to operate on jet fuel as a self-contained unit) for aeronautical gas turbine engines.

30. Paragraph 3.9.1 of reference (g) states: "The starter shall be designed and developed to achieve the highest operational reliability commensurate with the design requirements. The starter covered by this specification shall have a minimum reliability of 0.99 for a 1 cycle mission at a confidence factor of 90 percent. Satisfactory completion of all tests set forth under paragraph 4 of this specification will demonstrate compliance with the quantitative reliability requirements of this specification." An explanation of confidence factor is included in reference (h).

31. Prior to conducting any operational starter tests, paragraph 4.4.3.9 of reference (g) requires that the following be accomplished on all high speed components:

"a. Subject each part to X-Ray inspection in accordance with MIL-STD-453. Any cracks or occlusions that will adversely affect starter performance or life shall be cause for rejection.

"b. Subject each part to fluorescent penetrant inspection in accordance with MIL-I-6866. Any cracks or occlusions that will adversely affect starter performance or life shall be cause for rejection.

"c. Proof spin each turbine wheel for one minute at room temperature at the proof speed." (Proof speed is less than the minimum yield speed and greater than the maximum free running speed. Its exact value is specified in the model specification.)

"d. Upon completion of a, b, and c above, subject each turbine wheel to X-Ray inspection to determine the extent of deformity, structural damage, and growth of cracks or occlusions. Any deformity, structural damage, growth of cracks or occlusions, or any new cracks shall be cause for rejection."

32. Establishment of a minimum overhaul life for the starter is verified when the unit performs as required by paragraph 3.7.18 of reference (g): "The unit shall perform in accordance with the requirements of this specification throughout (1) 3000 hours of overrunning (normal aircraft operating time) and 2000 start cycles or (2) 3000 hours of overrunning, 1200 start cycles, and ten hours of motoring time. The duration of the motoring cycles shall be from two to ten minutes."

33. To provide overspeed protection, the starter must be able to contain all starter fragments and, "incorporate a speed limiting feature which will safely limit the starter speed, either loaded or unloaded. The speed limiting feature(s) shall limit rotation of all high speed components to 75 percent of the minimum burst speed(s). The limiting

feature shall not require manual resetting and shall function, as necessary, throughout the overhaul life of the starter without maintenance or adjustment. In addition, the speed limiting feature shall be totally contained within the starter and shall not require external power of any kind. The speed limiting feature(s) shall be described in detail in the model specification. Demonstration of the speed limiting feature(s) during the most severe operating condition shall be required. Operation of the speed limiting feature(s) shall not result in damage to the starter."

34. MIL-S-38399 (USAF) (reference (i)) is a specification that covers the general requirements for pneumatic starters for aeronautical gas turbine engines. Its content concerning rotor integrity is basically the same as stated in reference (g).

C. CONTAINMENT CRITERIA

a. General

35. Basically it can be said that fragment containment is required when experience has dictated that a satisfactory level of passenger and equipment protection can not be attained despite all efforts directed toward good design and quality control. The degree of protection depends largely on the type of equipment, its location, its use, and the economic and weight penalty associated with the protective system available.

36. The following section of this appendix reviews some of the specifications dealing with commercial and military containment requirements for engines, auxiliary power units, and starters.

b. Engines

37. For a commercial aircraft engine to be certificated by the FAA it must comply with Part 33 of reference (a). The durability of the engine casings is specifically mentioned in paragraph 33.19: "Engine design and construction must minimize the development of an unsafe condition of the engine between overhaul periods. The design of the compressor and turbine rotor cases must provide for the containment of damage from rotor blade failure." Note that there is no mention of containment of disk fragments and there is no differentiation made between the compressor section and the fan section.

38. A large portion of Advisory Circular 33-1A (reference (k)) provides guidance and acceptable means, not the sole means, by which compliance may be shown with the design and construction requirements of Part 33 of the FAR dealing with rotor blade containment.

39. The FAA considers that a compressor and/or turbine rotor blade failure is likely to be encountered only as a single occurrence affecting just one engine of any multiengine aircraft in any one flight.

40. "The most critical single blade(s), usually of the largest size, with failure assumed in the retention member or in adjacent base sections is considered more likely to fail in service. While the majority of failures are expected to occur in the blade airfoil section, failures in or near the retention sections of the blade are also anticipated and are more difficult to contain in the engine. For integrally bladed rotors, failure of a significant portion of a blade should be assumed."

41. In complying with the regulations relative to demonstrating containment of damage from broken rotor blades, it is acceptable to conduct tests of the nature indicated in paragraph 10 of reference (k) (below) to meet the substantiation criteria in paragraph 11 (reference (k)). "In lieu of planned official tests, pertinent related development experience, service experience, and analyses are usually acceptable means of compliance for engine substantiation. Any special operating precautions or techniques determined from these tests, which will aid in quickly restoring engine power for preventing further adverse effects to the engine after ingestion typical of those expected to occur in service, are suggested to be incorporated in the engine manual.

42. "When demonstrating blade containment, substantiation should cover the effects on containment with rotor cases at the maximum temperatures reached in service. The objective is to demonstrate both single blade containment and that the possibility of secondary internal failures penetrating the engine cases is minimized. Lack of containment has occurred from the secondary balling-up action of internal engine debris. It is desired that demonstration of blade containment be accomplished with a complete engine but, when component testing is chosen, complete compressor and turbine rotor section assemblies should be used."

43. The rotor blade substantiation test of reference (k) states: "Rotor blades are to be evaluated for both ingestion effects and containment, and should be released from a rotor at maximum operating r.p.m. The rotor blades evaluated normally include all those which in combination with the adjacent rotor case wall section are likely to be the most difficult to contain. A representative delay in initiating engine shutdown is recommended after the first indication of a fault from engine instruments, following blade ingestion, to simulate crew reaction time."

44. Relative to rotor blade containment, "the engine is acceptable if, during the ingestion tests, the damage from rotor blade failures is contained by the engine, e.g., without causing (1) extreme hazards, and (2) significant case rupture or hazardous distortion of the engine casing and the expulsion of blades through and beyond the engine case in a manner which could cause hazard to the aircraft."

45. The military engine specification (reference (d)) makes only a brief statement relative to rotor blade containment. Paragraph 3.16.3.1 states: "The design of the compressor and turbine cases shall provide containment of damage from rotor blade failures."

46. It is of interest to note the following concerning the FAA and military requirements for rotor blade containment:

a. Only blade fragments are required to be contained. No mention is made of disk (any size fragment) containment.

b. There is no specific criteria available to judge what stage of rotor-casing constitutes the most difficult containment problem. The RBPP is not aware of data indicating the fragment mass or fragment translational kinetic energy is the most critical containment parameter, and engine experience with similar previous models does not help the newly designed engines of differing physical characteristics.

c. The large fan blades are considered in the same category as all other compressor and/or turbine blades. It has been suggested that these large fan blades be exempt from the blade containment regulations and be considered as propellers which would mean these blades would be subjected to paragraph 35.35, "Centrifugal load test" and paragraph 35.37, "Vibration test" of reference (a). A discussion of this situation is considered not in the scope of this immediate discussion.

d. The deflection of blade fragments, i.e., the control of their trajectories away from sensitive aircraft areas, is not mentioned.

47. Paragraph 25.361 - Engine torque (reference (a)) requires that each engine mount and its supporting structures must be designed for engine torque effects and for turbine engine installations, "the limit engine torque load imposed by sudden engine stoppage due to malfunction or structural failure (such as compressor jamming) must be considered in the design of the engine mounts and supporting structure."

48. This particular paragraph is mentioned here since there were some questions as to whether a major rotor failure would be of such magnitude to rip an engine from its mount. Engine manufacturers have

replied that the requirements of the above paragraph are more severe than those predicted as a result of an uncontained rotor failure and so they do not consider the possibility of an uncontained rotor failure causing an engine to be wrenched from its mount.

c. Auxiliary Power Units

49. TSO-C77 (reference (e)) divides APU's into two categories:

> "Category I: Essential Power. Power which is used to drive accessories necessary for maintaining safe operation of the aircraft either on the ground or in flight.
>
> "Category II: Nonessential Power. Power which may be discontinued without jeopardizing safe operation of the aircraft either on the ground or in flight."

The containment requirements of TSO-C77 vary according to the category of the APU.

50. All units are required (paragraph 5.13) to have their compressor and turbine rotor cases designed to provide for containment of damage from rotor blade failures. For rotors incorporating more than one stage, containment need be demonstrated for the critical stage only. The manufacturer is required to substantiate which stage is the critical one (in paragraph 3.23 a critical stage is designated as the stage whose casing is most susceptible to penetration). Again it should be noted, as it was during the discussion of blade protection for engines, what a large problem is the determination of the most dangerous section of casing.

51. The compressor and turbine rotor cases of nonessential units shall be designed to contain maximum energy failed rotor fragments unless compliance with certain rotor integrity substantiations are established. (A maximum energy rotor is a rotating component or assembly which, if it ruptures, will generate particles with sufficient energy as to cause secondary damage to the rotor housing.) Essential units are required to show compliance with all rotor integrity and service life criteria and are not required to demonstrate rotor burst containment.

52. Rotor and rotor blade containment is to be demonstrated under the conditions in the following paragraphs:

"7.3.1 Speed. Containment shall be demonstrated at the maximum obtainable speed defined by subparagraphs a and b.

"a. If safety devices (to prevent hazardous overspeed or overtemperature conditions) are incorporated, a speed equal to the highest speed which would result from failure of any one of the normal engine control systems.

"b. If no safety devices are incorporated, a speed equal to the highest speed which would result from the failure of any one of the normal engine control systems.

"7.3.2 Temperature. Containment shall be demonstrated with the containing components at the temperature prevalent during operation at maximum rated power."

53. The military (Air Force and Navy) general specification for gas turbine type aircraft auxiliary power units is MIL-P-8686(ASG) (reference (f)). This specification categorizes APU's into four type groups dependent upon their primary use. Paragraph 3.5.15 (reference (f)) specifies that the design of the APU shall be such that failure of a major section will not result in damage to either of the other sections. More detailed requirements are spelled out in the model specifications. An example of this can be shown with reference (g) which covers the requirements of a Service Type IV APU. Paragraphs 3.36.1 and 3.36.1.1 relate to rotor blade and turbine rotor hub containment respectively.

"3.36.1 Rotor Blade Containment. For the event of rotor blade failure, full containment of the failed rotor blade(s) most likely to occur shall be provided.

3.36.1.1 Turbine Rotor Hub Containment. For the event of the rotor hub failure, full containment of a maximum-energy turbine rotor segment shall be provided. Containment is to be shown at any combination of speeds up to the maximum speed (speed that would result from the most adverse, single control-system failure) and at any temperature up to the maximum operating turbine temperature."

54. In this specification a maximum energy rotor segment is considered to be a fragment from a three-piece (tri-hub) burst, i.e., each fragment has an included angle of 120°. Actually, as it was shown in reference (e), a flat rotor fragment having an included angle of 133.56° possesses the maximum translational kinetic energy per fragment, not maximum total fragment energy per fragment. The usage of "maximum energy burst" as equivalent to a tri-hub burst has unfortunately found some acceptance with containment people. The RBPP has found no proof that a tri-hub

burst produces the most critically-shaped, potentially dangerous fragments. Future RBPP efforts will be directed toward the determination of what is the most critical fragment for each type of control system. It is interesting to note that a tri-hub burst does promote a "uniform" impacting condition in a containment ring which may be easier to control than a "single" impact caused by the release of just one fragment. The RBPP strongly suggests that a tri-hub burst not be classified as a "maximum energy burst".

55. Military specification MIL-E-38453 (USAF) (reference (m)) outlines the performance, design, data submittal, and testing requirements for environmental control, environmental protection and engine bleed air subsystems.

56. Equipment that performs the following functions is included in specification:

"a. Pressurization, cooling, heating, ventilation, contamination control and moisture control in personnel and equipment compartments.

"b. Pressurization of inflatable pressure seals, fuel tanks and miscellaneous equipment.

"c. Air supply for air-driven power conversion devices and boundary layer control.

"d. Removal of rain, snow, insects, salt, frost, fog and ice from transparent surfaces.

"e. Anti-icing or deicing of flight surfaces, radomes, antenna, and ram air scoops.

"f. Pressurization and temperature control of electronic equipment, anti-G suits, pressure suits and ventilation garments.

"g. Distribution of engine compressor bleed air between the engines and those components and subsystems which require bleed air."

57. Paragraph 3.2.1.11 presents the containment criteria that these units must meet: "The housing and scrolls of all rotating machinery shall completely contain the fragments from rotating blades and wheel bursts (tri-hub failure) at the maximum speed that can result from any failure inducing condition or 135 percent of the maximum normal speed, whichever is greater at the pressure and temperature associated with these speeds. Containment is meant to mean that fragments may penetrate the containing housing but shall not pass through the housing. Particles or parts resulting from a failure and passing through inlet or outlet ports of the assembly shall be contained by the adjoining ducting."

58. To show compliance with this requirement individual rotors are usually modified to fail in three equally sized fragments at the predetermined maximum speed and temperature. Note here again the acceptance of the tri-hub failure as the most severe test.

59. As previously mentioned in this appendix, not all APU's of importance are airborne, although many such gas turbine engines used by the Army are weight sensitive since they must be capable of being air-dropped into areas of operation. Reference (n) is a U. S. Army purchase description that covers "design, construction, and performance requirements for a gas turbine engine suitable for directly driving high speed equipment, primarily electric generators, without the use of power output speed reduction gears, and also suitable for incorporating power output speed reduction gears for lower speed requirements. The engine is to be sized for operating most economically at three power ratings, and is to be designed to operate both as a simple cycle engine or to incorporate a heat exchanger, while using identical or modified components, in lieu of completely new and different components, to the maximum degree."

60. This description requires that "the turbine assembly shall utilize a single radial turbine wheel, a radial axial wheel combination, or multiple axial wheels with appropriate nozzle rings and shrouding. The required machining and balancing, and the use of cast construction shall be considered for minimum production cost." This suggestion that cast rotors be used is becoming more prevalent throughout the industry. It is noteworthy since the RBPP expects that the interactions between the rotor fragments and fragment control system will be very much different than those observed with conventionally forged disks and fastened blades.

61. Paragraph 3.7.3.1 requires that "the turbine assembly shall be designed for wheel containment sufficient to withstand a wheel burst at any speed up to 110 percent of normal rated speed. If a radial turbine wheel is used, the containment shall withstand a maximum energy burst of the entire wheel. If multiple axial wheels are used, the containment shall withstand the simultaneous burst of all rotor blades plus a maximum energy burst of any one turbine disc. The capability of the turbine assembly to provide sufficient wheel containment shall be demonstrated by equipping the test engine with a turbine section containing a turbine wheel which has been prenotched to fail with resulting maximum energy burst at a speed 110 percent of normal rated speed. The engine shall be operated to demonstrate containment of the notched wheel with failure occurring at the 110 percent speed point. For engines containing multiple turbine stages the wheel selection for wheel containment demonstration shall be mutually selected by the contractor and the Government."

62. Here again we see two things: (1) the assumption that a tri-hub burst is the most severe type of rotor failure (ascertained from discussions with ERDL personnel), and (2) the most sensitive (relative to containment) stage must be determined by the contractor and the Government without any specific guidelines being established in the specification.

d. Starters

63. Many specifications have been written covering the requirements for starters for aeronautical gas turbine engines. Pneumatic, cartridge, and jet fuel type starters have all been considered. Rather than discuss all the individual specifications, we have selected some that we believe reflect the most recent thinking relative to containment criteria.

a. MIL-S-27266 (USAF) (reference (o)) is a general specification for cartridge and pneumatic starters. The overspeed failure test requires that "upon satisfactory completion of cycling and endurance testing, the starter shall be subjected to an overspeed condition, using a cartridge conditioned to 160°F, such that a structural failure will occur within the starter. In the event the starter incorporates a containment feature, failure of the starter to remain on its mount or the housing to contain fragments upon structural failure of internal parts shall be cause for rejection." Note that the rotors are not modified to induce any specific type of failure.

b. MIL-S-19557B (WEP) (reference (p)) is a model specification for an air turbine starter. The starter shall provide containment of all rotating components and the starter housing shall remain on the mounting pad of the engine accessory drive. Paragraph 4.5.15.1 concerns the hub containment test. It states that after the starter has completed the endurance testing, "it shall be reassembled with the turbine wheel slotted to induce a three equal segment hub burst at a speed not less than the maximum cutout speed. All rotating components shall be contained within the starter housing and the starter housing shall remain attached to the mounting pad of the engine accessory drive." Paragraph 4.5.15.2 states the no-load failure requirements as: "the starter shall be operated from rest at no-load with the cutout speed switch inoperative at an inlet air pressure and temperature of 110 psia and 680°F until failure occurs and rotation ceases. All rotating components shall be contained within the starter housing and the starter shall remain attached to the mounting pad of the engine accessory drive."

64. The starter covered by exhibit SEJIA-67-1 (reference (q)) was designed to operate on jet fuel as a self-contained unit. This unit is basically divided into three modules; gas generator, accessory, and power turbine. The starter was to be designed to incorporate the

following feature: "The starter shall provide complete containment of all starter fragments (including three section hub burst) and remain on its mount should a failure occur under any operating condition (temperature and altitude) from sea level to 8,000 feet. In addition, the starter shall contain any failure that occurs due to uncontrolled acceleration of the gas generator or energy conversion and speed reduction assembly including failure of the disengaging clutch."

65. "Demonstrations which result in fire external of the starter, external surface temperatures in excess of 700°F, or failure of the starter to contain all fragments and remain on its mounting, shall be cause for rejection. Parts may fall from the starters exhaust duct provided they contain no destructive energy. This shall be demonstrated by placing a sheet of soft aluminum (.032 or thinner) within three feet of the starter's exhaust duct such that the exhaust gases will impinge on the aluminum. The aluminum sheet shall be supported such that it will not have a solid backing within one inch of the under side. Any pronounced dent or puncture of the aluminum shall also be cause for rejection. After each containment demonstration, the starter shall be disassembled and inspected for damage resulting from the test. Photographs shall be taken of the starter before disassembly showing any exterior damage and during disassembly showing all internal damage."

66. Other containment demonstrations required are:

"a. After completion of the teardown inspection, the starter shall be reassembled and subjected to two normal starter cycles to assure correct assembly and operation. The starter shall then be subjected to uncontrolled overspeed conditions which will demonstrate the normal modes of failure of both the gas generator and the energy conversion and speed reduction assembly. Each demonstration shall be conducted as follows:

"(1) The energy conversion and speed reduction assembly shall be subjected to an uncontrolled overspeed condition by operating the starter in a no-load condition with all cutout devices in the energy conversion and speed reduction assembly rendered inoperative.

"(2) The starter shall be refurbished as required to provide normal operation of the complete unit. Development hardware may be used as required to refurbish the portion of the starter damaged during the test required in (1) above. Two normal cycles of operation shall then be conducted to assure correct assembly and operation. The gas generator shall then be caused to fail due to an uncontrolled overspeed condition by rendering all fuel controls inoperative to permit maximum fuel flow.

"b. After completion of the teardown inspection, the energy conversion and speed reduction assembly turbine wheel will be weakened such that a hub failure will occur near the upper limit of the cutout speed range. The cutout switch shall be deactivated or reset to a speed above the specified upper limit. The starter shall then be reassembled and subjected to a normal start cycle to demonstrate turbine wheel hub containment capability. After demonstration of the energy conversion and speed reduction assembly turbine wheel hub containment, and inspection of the resulting damage, the starter shall be refurbished and subjected to two normal start cycles to assure correct assembly and operation. Other test or development hardware may be used to replace the damaged parts. The gas generator shall then be disassembled and the compressor wheel shall be weakened such that a hub failure will occur near the upper limit of the speed range associated with operation of a 60 to 100°F day, whichever is greater. The starter shall then be reassembled and subjected to a start cycle that will cause compressor wheel hub failure. Either or both of the above demonstrations may be conducted on sample number one if the starter can be refurbished to operate normally after the containment demonstrations required in "a" above.

"c. After completion of the teardown inspection, the gas generator turbine wheel shall be weakened such that a hub failure will occur near the upper limit of the speed range associated with operation on a 60 to 100°F day, whichever is greater. The starter shall then be reassembled and subjected to a start cycle that will cause turbine wheel hub failure.

67. "Additional containment demonstrations may be required depending upon the particular starter design or inconclusive demonstrations resulting from the tests required in "a", "b", and "c" above. Additional tests may be directed at time of starter design evaluation or at any time prior to preproduction approval."

68. Members of the SAE Committee AE-6, Starting Systems, are working on a proposed general specification for pneumatic starters for aircraft engines (proposed AS 943) (reference (r)). Paragraph 3.7.1 of this reference relates to unit overspeed protection. It states: "Except for particles emitted from the exhaust, the starter shall be capable of containment of all starter fragments within its envelope and remain on its mount should a free-run failure occur with air at the worst combination of pressure and temperature possible in the system from sea level to the maximum aircraft operational altitude. The starter shall be designed to provide containment of maximum energy hub burst (3-piece 120° segments) of the turbine wheel at a speed not less than the maximum cutout speed or the maximum free running speed as specified in the detail specification. Containment demonstration of all high speed rotating components shall be required. The containment features shall

be described in detail in the model specification and it shall be demonstrated that any fragments emitted from the starter exhaust shall not constitute a fire hazard or have sufficient energy to harm equipment or personnel."

69. The last portion of this section is noteworthy since there is some concern that titanium rotors interacting with steel or titanium shroud may produce hot fragments that could constitute a fire hazard.

D. REFERENCES

(a) Code of Federal Regulations Title 14 - Aeronautics and Space, Parts 1 to 59, (revised as of 1 January 1967)

(b) Advisory Circular 33-2, "Aircraft Engine Type Certification Handbook", dated 30 March 1966, Department of Transportation, FAA

(c) Advisory Circular 33-3, "Turbine and Compressor Rotors Type Certification Substantiation Procedures", dated 9 September 1968, Department of Transportation, FAA

(d) Military Specification, Engines, Aircraft, Turbojet and Turbofan, General Specification for, MIL-E-5007C, 30 December 1965

(e) Federal Aviation Agency Technical Standard Order, Regulations of the Administrator, Part 514, "Gas Turbine Auxiliary Power Units, T50-C77", 3 January 1963

(f) Military Specification, Power Units; Aircraft Auxiliary, Gas Turbine Type, General Specification for, MIL-P-8686(ASG), 4 November 1955

(g) Model Specification, Power Unit; Aircraft Auxiliary Gas Turbine Type, Service Type IV, AiResearch Model GTCP95-2, AiResearch Report SC-5695, 18 July 1966

(h) 66-C-17 Exhibit A, Starter Aircraft Engine, Jet Fuel, General Requirement for, revised 18 November 1965, proposed by the USAF

(i) Flight Vehicle Power Systems Reliability Criteria, Technical Report ASD-TR-61-736, March 1962

(j) Military Specification, Starter, Pneumatic, Aircraft Engine, General Specification, MIL-S-38399 (USAF), 16 February 1965

(k) Advisory Circular 33-1, "Turbine-Engine Foreign Object Ingestion and Rotor Blade Containment Type Certification Procedures", dated 19 June 1968, Department of Transportation, FAA

(l) Martino, A. A. and Mangano, G. J., "Rotor Burst Protection Program - Initial Test Results", Final Phase IV Report on Problem Assignment NASA DPR R-105, NAPTC-AED-1869, 5 April 1968

(m) Military Specification, Environmental Control, Environmental Protection, and Engine Bleed Air Systems Aircraft and Aircraft Launched Missiles, General Specification for, MIL-E-38453 (USAF), 9 September 1966

(n) U. S. Army Engineer Research and Development Laboratories, Purchase Description for Engine, Gas Turbine, 60 HP, 90 HP, and 120 HP, dated 28 October 1963

(o) Military Specification, Starter, Engine, Cartridge and Pneumatic, Shaft Drive, General Specification for, MIL-S-27266 (USAF), 27 January 1960

(p) Military Specification, Starter, Aircraft Engine, Air Turbine Detail Model Specification for, MIL-S-19557B(WEP), 17 March 1965

(q) Systems Engineering Group Exhibit, Starter, Engine, Jet Fuel, STU-26/A, SEJIA-67-1, 27 February 1967

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2. P. A. No. NASA DPR R-105, PHASE V

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The NASA-sponsored Rotor Burst Protection Program reports its continuing study into the kinetics of intentionally failed rotors within fragment control systems and the influence of certain important system parameters on the containment/control process. High-speed photographs have recorded the complex action of bladed rotors which more closely approximate realistic turbomachinery operating conditions than did the earlier RBPP testing. The test observations should assist the containment design engineer. A survey of uncontained failures occurring in U. S. Commercial and Naval aviation experience is reported. A detailed study of commercial and military specifications regarding rotor integrity substantiation and containment criteria is presented.

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