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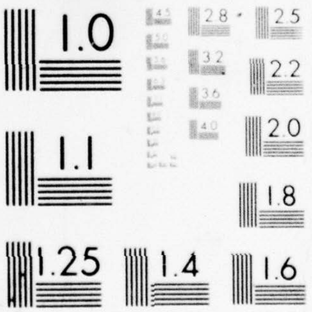

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Softbody Impact Resistance of Beryllium/Titanium Composite Blades

Detroit Diesel Allison
Division of General Motors Corporation
Indianapolis, Ind. 46241

May 1976

TECHNICAL REPORT AFAPL-TR-76-69
Final Report for Period July 1975 - March 1976

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Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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FOR THE COMMANDER

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Propulsion Mechanical Design

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Seven prototype Be/Ti aircraft engine fan blades had been fabricated during a previous program. From all indications the blades were dimensionally and structurally sound except for indication of poor attachment bonding. Two of the fan blades were selected, based on strength considerations, for demonstration of structural capability by overspeed and softbody impact testing. The testing demonstrated that the Be/Ti metal matrix system can have good tensile strength and softbody impact capability, however good root attachment bonding is essential.

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Preface

This report describes the work accomplished by Detroit Diesel Allison (DDA), Division of General Motors Corporation during the period 1 July 1975 through 31 March 1976 on "Softbody Impact Testing of Beryllium/Titanium Composite Blades". The work was conducted under Department of the Navy, Naval Air Systems Command Contract N00019-75-C-0503 with Mr. W.T. Highberger (NASC/AIR-52031D) and Mr. M.P. Wannemacher (AFAPL/TBP) acting as the Navy and Air Force project engineers. R.L. Fannin, Mechanics Research, was program manager and D.E. Guthrie, Test Department, was the test project engineer.

Summary

Seven prototype Be/Ti aircraft engine fan blades had been fabricated during a previous program. From all indications the blades were dimensionally and structurally sound except for indication of poor attachment bonding. Two of the fan blades were selected, based on strength considerations, for demonstration of structural capability by overspeed and softbody impact testing. The testing demonstrated that the Be/Ti metal matrix system can have good tensile strength and softbody impact capability, however, good root attachment bonding is essential.

1.0 INTRODUCTION

1.1 Background

A total of seven prototype beryllium/titanium composite fan blades have been fabricated using the TF41 fan blade configuration.[1] These blades were selected for machining from thirteen isothermal forgings. The forgings were made using two types of Be/Ti composite extrusion preforms. One type consisted of beryllium and titanium alloy powders coextruded in a titanium alloy sheath, while the other type was beryllium rods coextruded with wrought titanium sheaths for both rod and final composite package. Typical cross sections of both type composite extrusions are shown in Figure 1. Titanium (6AL-4V) root block split halves were contour machined to fit the elliptical composite preforms and were subsequently diffusion bonded by hot isostatic pressing.

Three Be/Ti powder and four Be/Ti rod type composite forgings were finish machined using existing tooling from an all titanium prototype fan blade program.

Two of the finished machined Be/Ti blades are shown in Figure 2. All seven of the blades were satisfactory in respect to visual, dimensional, and radiographic quality. Some localized disbond was observed in the root block-composite airfoil interface of the blades as shown by fluorescent penetrant inspection. First torsional resonant frequency was increased 11% and blade weight reduced 9%, compared to the all titanium (6AL-4V) blade of the same basic design. Tensile properties and metallographic structures were determined from one blade forging of each type composite material. Tensile strengths of the Be/Ti rod composite airfoil ranged from 90-91 ksi and the Be/Ti powder composite airfoil produced strengths of 46-67 ksi.

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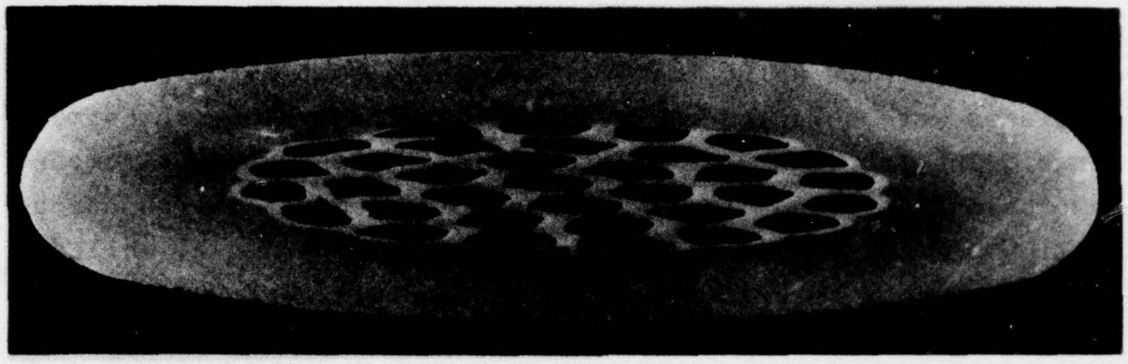
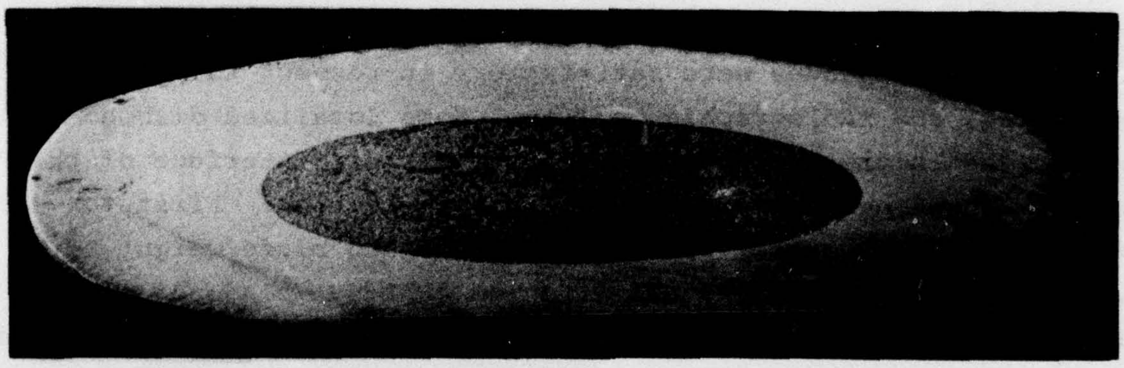
[1] G. R. Sippel, et al, "Beryllium Reinforced Titanium Matrix Composite Blade for Turbine Fans and Compressors", EDR 8057, Final Report, NASC Contract N00019-72-C-0247, February 1974.



(a) Be Rod/Ti Extrusion



(b) Be/Ti Powder Extrusion

Figure 1. Macrostructures of Be/Ti composite extrusions fabricated from (a) continuous Be rods with wrought Ti and (b) Be and Ti powders (Mag. 2 1/2 X) (Keller's Etch)

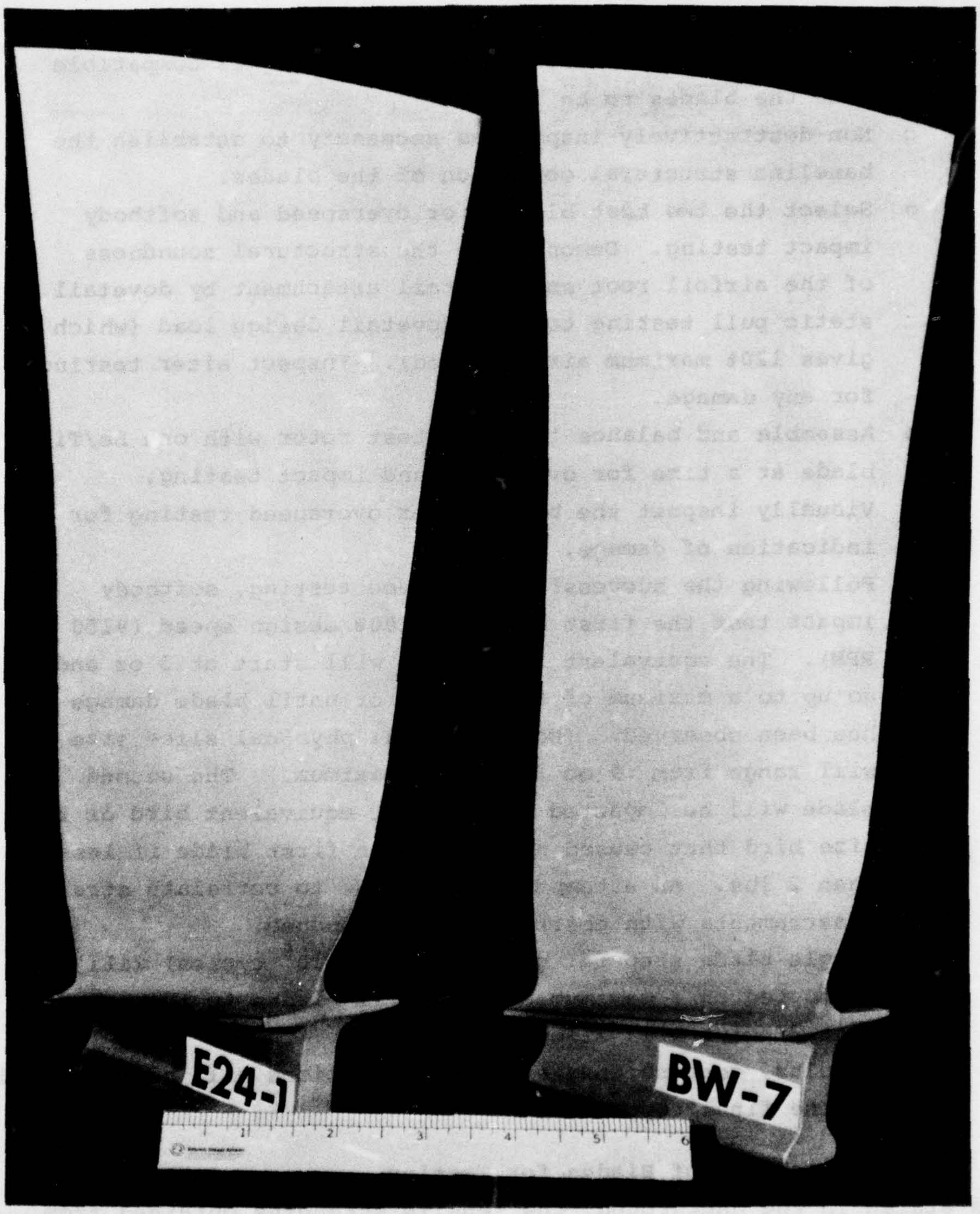


Figure 2. Finish machined TF41 Be/Ti Composite LP-1 Fan Blades S/N E24-1 (Be Rod/Ti) and BW-7 (Powder Be/Ti).

1.2 Program Objectives

The key items in the program plan were as follows:

- Assure that the DDA single-blade spin rig is compatible with the blades to be tested
- Non-destructively inspect as necessary to establish the baseline structural condition of the blades.
- Select the two best blades for overspeed and softbody impact testing. Demonstrate the structural soundness of the airfoil root and dovetail attachment by dovetail static pull testing to 100% dovetail design load (which gives 120% maximum airfoil load). Inspect after testing for any damage.
- Assemble and balance the spin-test rotor with one Be/Ti blade at a time for overspeed and impact testing. Visually inspect the blade after overspeed testing for indication of damage.
- Following the successful overspeed testing, softbody impact test the first blade at 100% design speed (9150 RPM). The equivalent bird sizes will start at 3 oz and go up to a maximum of two pounds or until blade damage has been observed. (Note: Actual physical slice size will range from .9 oz to 3.5 oz maximum.) The second blade will be impacted with a 2 lb equivalent bird or the size bird that caused damage to the first blade if less than 2 lbs. An attempt will be made to correlate strain measurements with observed blade response.
- Single blade step fatigue tests (5×10^6 cycles) will be conducted on a maximum of two Be/Ti blades to the extent that funding will allow.
- Results, conclusions, and recommendations will be presented in the final report.

1.3 Selection of Blades for Testing

As stated in the background, the tensile strengths obtained from airfoil sample tensile tests during the blade fabrication program were 90-91 ksi for the Be/Ti rod composite blade compared to 46-67 ksi for the Be/Ti powder composite blade. The average centrifugal stress at the hub of the airfoil for 100% design speed is approximately 40 ksi. At the overspeed condition of 110% design speed, the average hub centrifugal stress would approach 48.5 ksi which could exceed the ultimate tensile strength of the Be/Ti powder composite airfoil. Therefore, the Be/Ti powder composite blades were eliminated for use in this test program, and the two highest quality Be/Ti rod composite blades were selected. Based on the fluorescent penetrant inspections, the two best blades were S/N E23C-3 and S/N E24-1 with S/N E24-1 being the better of the two (see Figure 3).

2.0 OVERSPEED AND IMPACT TESTING

2.1 Test Conditions

Existing DDA single-blade spin-test equipment was used for the softbody impact testing of the Be/Ti composite blades. A schematic of this facility is shown in Figure 4. Details of the bird injection gun are shown in Figure 5. The bird holding assembly includes a removable bird holder which contains the molded-into-place RTV bird.

A brief description of the softbody impact procedure using the DDA single-blade spin facilities is as follows:

1. The selected size of RTV 560 formula bird is loaded into the bird holding piston and the piston is latched in the gun in an up position.
2. All systems are checked, the spin tank is evacuated and the single-blade rotor is brought up to speed by the steam turbine.
3. The camera lights are turned on and the high-speed cameras and the bird injector timing device are simultaneously triggered or activated. At the proper blade angular position, the solenoid opens the latching mechanism which releases the bird holding piston.
4. The RTV bird and holding piston is driven into position to place the bird in the path of the blade during the time interval between blade passage and is held in position against a stop by the differential pressure.

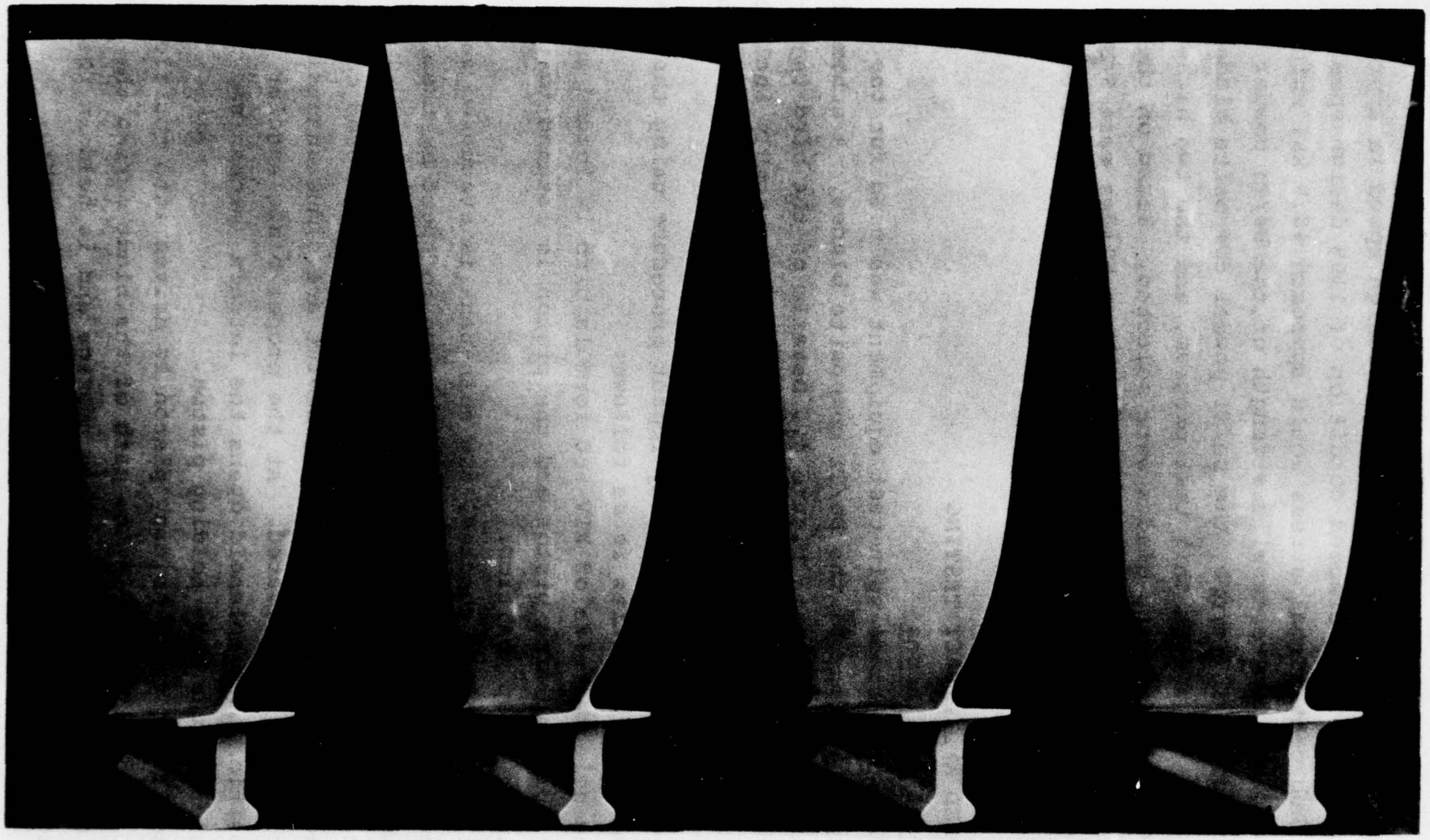


Figure 3. Pressure surface of finish machined Be rod/Ti composite fan blades. (Magn. .4X)

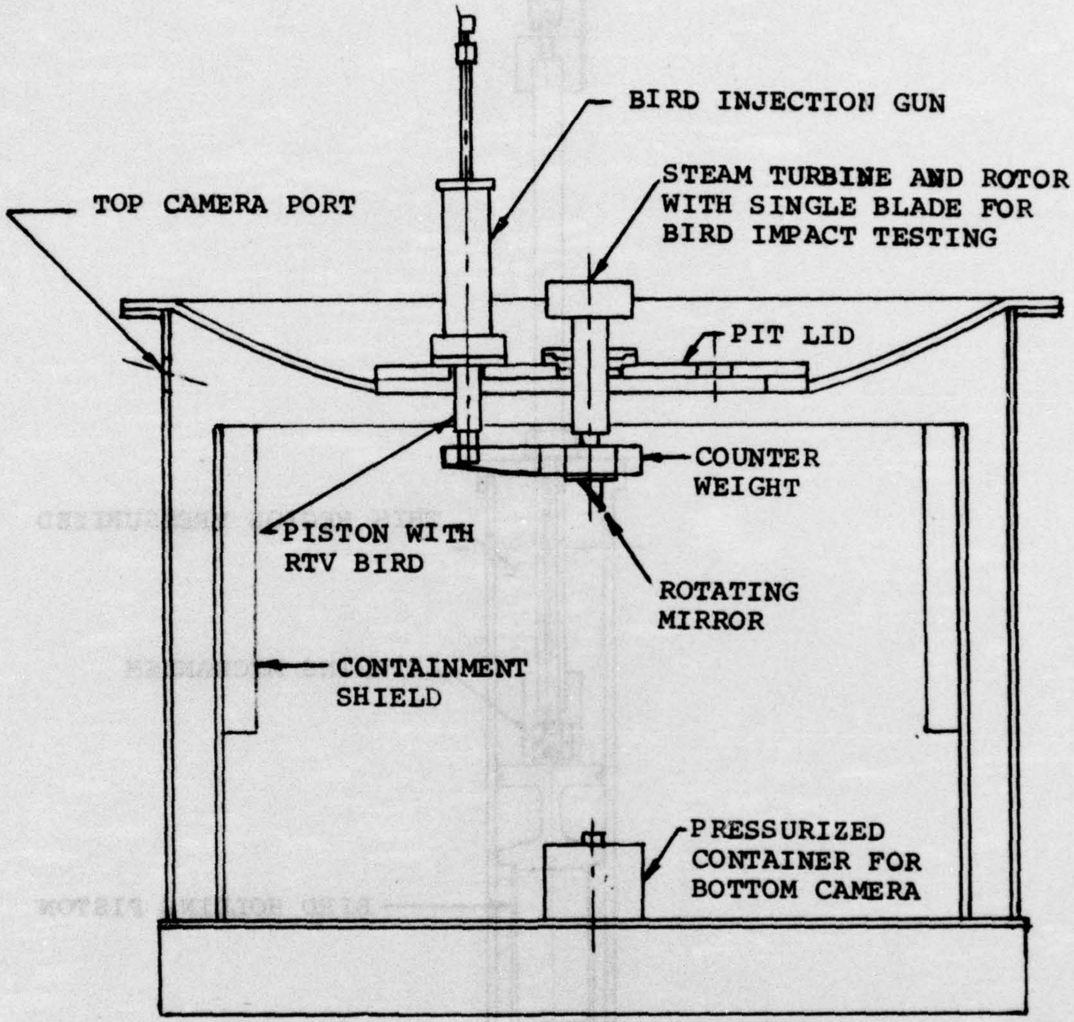


FIGURE 4. SPIN-PIT SCHEMATIC

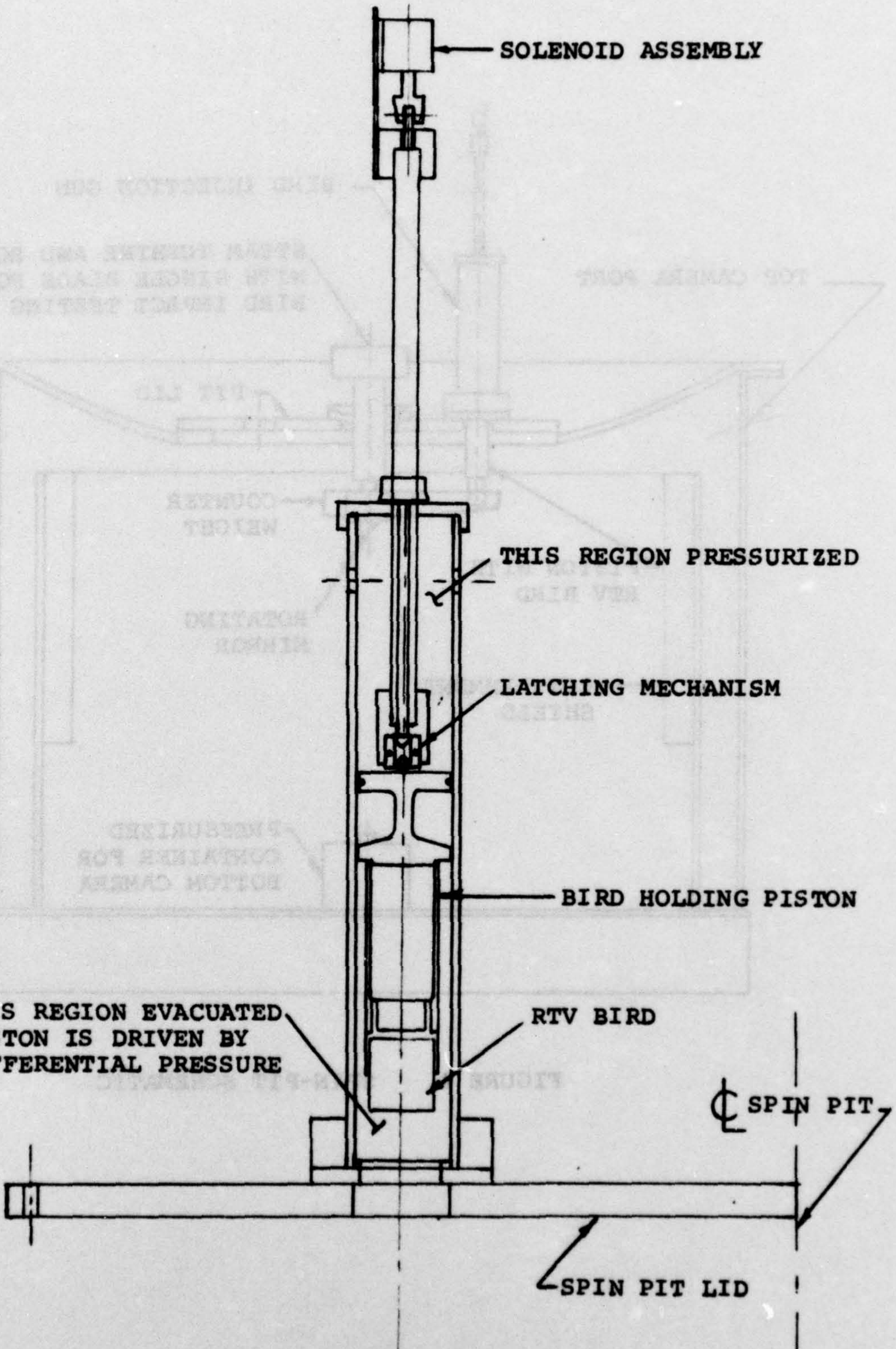


FIGURE 5. BIRD INJECTION GUN

5. With the RTV bird held in position for the desired length and mass of slice, the blade impacts the bird.

A photograph of a blade after a 3 oz equivalent RTV bird impact is shown in Figure 6. The dovetail slot in the test wheel had been machined at the proper angle to give the correct bird incidence angle at 3/4 blade span in order to simulate a calculated worst full-power take-off condition.

The calculations are based on the assumption that the bird enters the engine intake axially and is cut into equal length pieces on impact with the first stage blades. These pieces are accelerated through the blade row and on back through the engine. The length of bird chopped off by each blade is a function of the blade pitch at the impact radius, rotor speed, and the bird velocity relative to the aircraft. The bird velocity vector (magnitude and angle) relative to the airfoil is obtained from the vector addition of the blade tangential velocity and the bird velocity relative to the aircraft. The impact energy transferred to the blade by the slice of bird is approximated by:

$$E_T = 1/2\ M\ V_N^2$$

where:

E_T = transferred impact energy (ft-lb)
M = mass of bird slice (slugs)
V_N = normal component of bird velocity relative to the airfoil (ft/sec)

The calculated values of transferred impact energy for the Be/Ti composite blades at 1/2 and 3/4 blade span are shown in Figure 7. Note that the maximum transferred impact energy for a mid-span strike is approximately 30% higher than for a 3/4 span strike. However, the 3/4 span strike was selected as the more critical due to the reduced thickness of the airfoil for local impact strength and due to the larger airfoil root-bending loads that would be induced by the impact at the 3/4 span radius. In addition, softbody impacts are more likely to occur at 3/4 span than at mid-span.

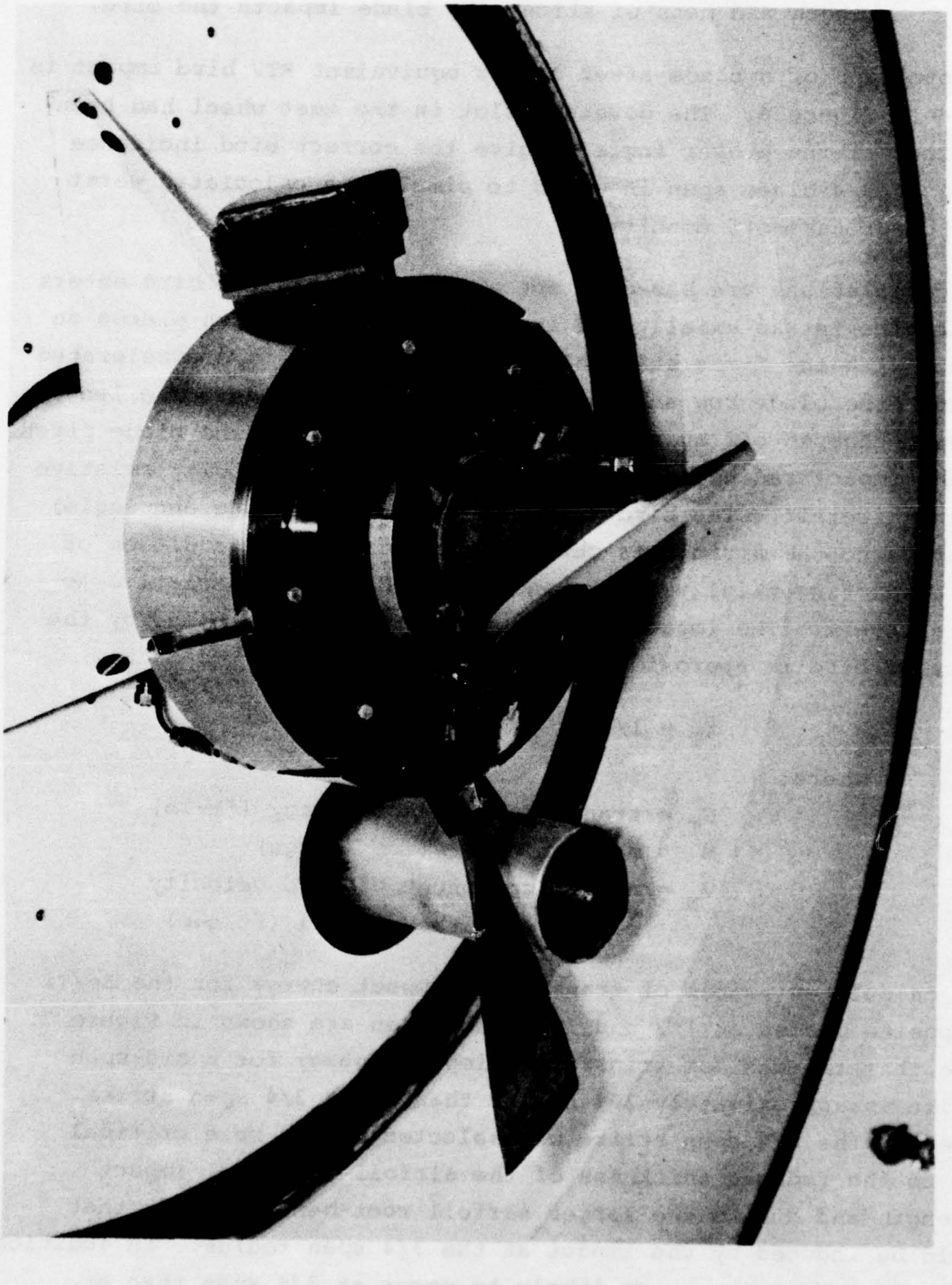


Figure 6. All Titanium Baseline Blade After 3 Oz. Impact.

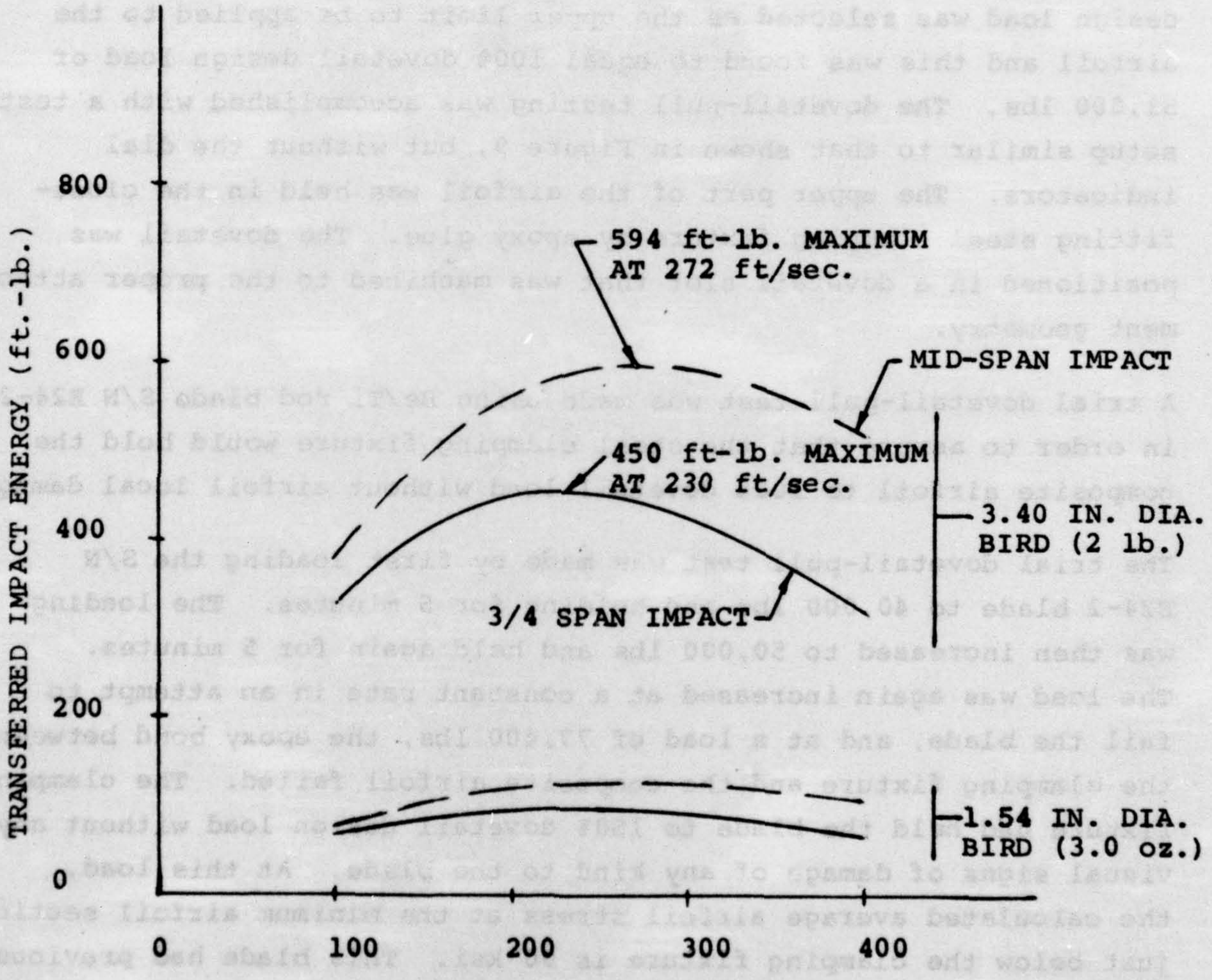


FIGURE 7. TRANSFERRED IMPACT ENERGY vs AIRCRAFT SPEED FOR MID-SPAN AND 3/4 SPAN IMPACTS

2.2 Dovetail Pull Testing

Fluorescent penetrant inspection indicated localized disbonding of the root blocks at the composite airfoil interface (see Figure 8). In fact, the overall quality of the diffusion bonding in this region was unknown and had been judged questionable. In order to partially demonstrate the structural soundness of the root block attachment, the decision was made to dovetail-pull test the two selected Be/Ti rod blades. A load equal to 120% of maximum airfoil design load was selected as the upper limit to be applied to the airfoil and this was found to equal 100% dovetail design load or 51,000 lbs. The dovetail-pull testing was accomplished with a test setup similar to that shown in Figure 9, but without the dial indicators. The upper part of the airfoil was held in the close-fitting steel clamping fixture by epoxy glue. The dovetail was positioned in a dovetail slot that was machined to the proper attachment geometry.

A trial dovetail-pull test was made using Be/Ti rod blade S/N E24-2 in order to assure that the steel clamping fixture would hold the composite airfoil to 100% dovetail load without airfoil local damage.

The trial dovetail-pull test was made by first loading the S/N E24-2 blade to 40,000 lbs and holding for 5 minutes. The loading was then increased to 50,000 lbs and held again for 5 minutes. The load was again increased at a constant rate in an attempt to fail the blade, and at a load of 77,400 lbs, the epoxy bond between the clamping fixture and the composite airfoil failed. The clamping fixture had held the blade to 150% dovetail design load without any visual signs of damage of any kind to the blade. At this load, the calculated average airfoil stress at the minimum airfoil section just below the clamping fixture is 90 ksi. This blade had previously been impact tested with RTV 560 rubber birds at the Air Force Material Laboratory's bench-test facilities in Dayton, Ohio. One of the shots consisted of an approximate slice or bite of 2.4 oz at 3/4 span and 1320 ft/sec. The calculated transferred impact energy for this shot is 408 ft-lb which is estimated to be equivalent to a 1.8 lb bird impact.

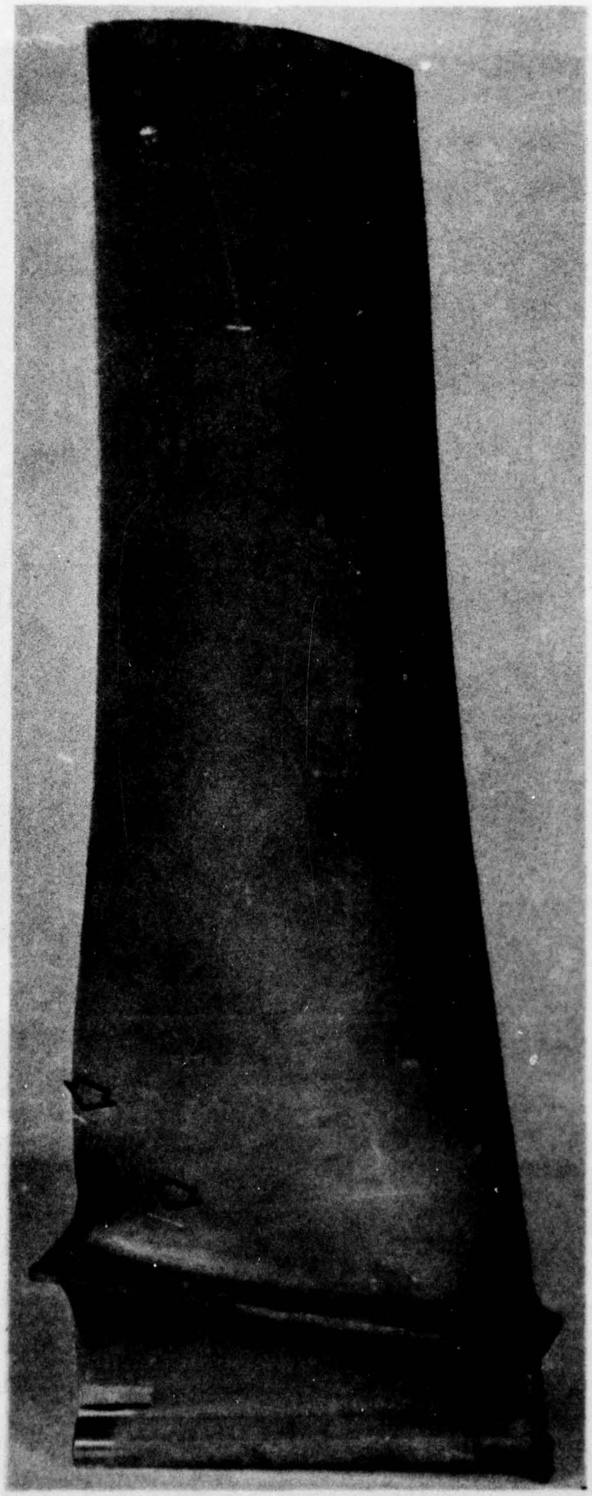


Figure 8. Fluorescent penetrant indications of localized root block-airfoil disbonds (Magn: 2/3X)

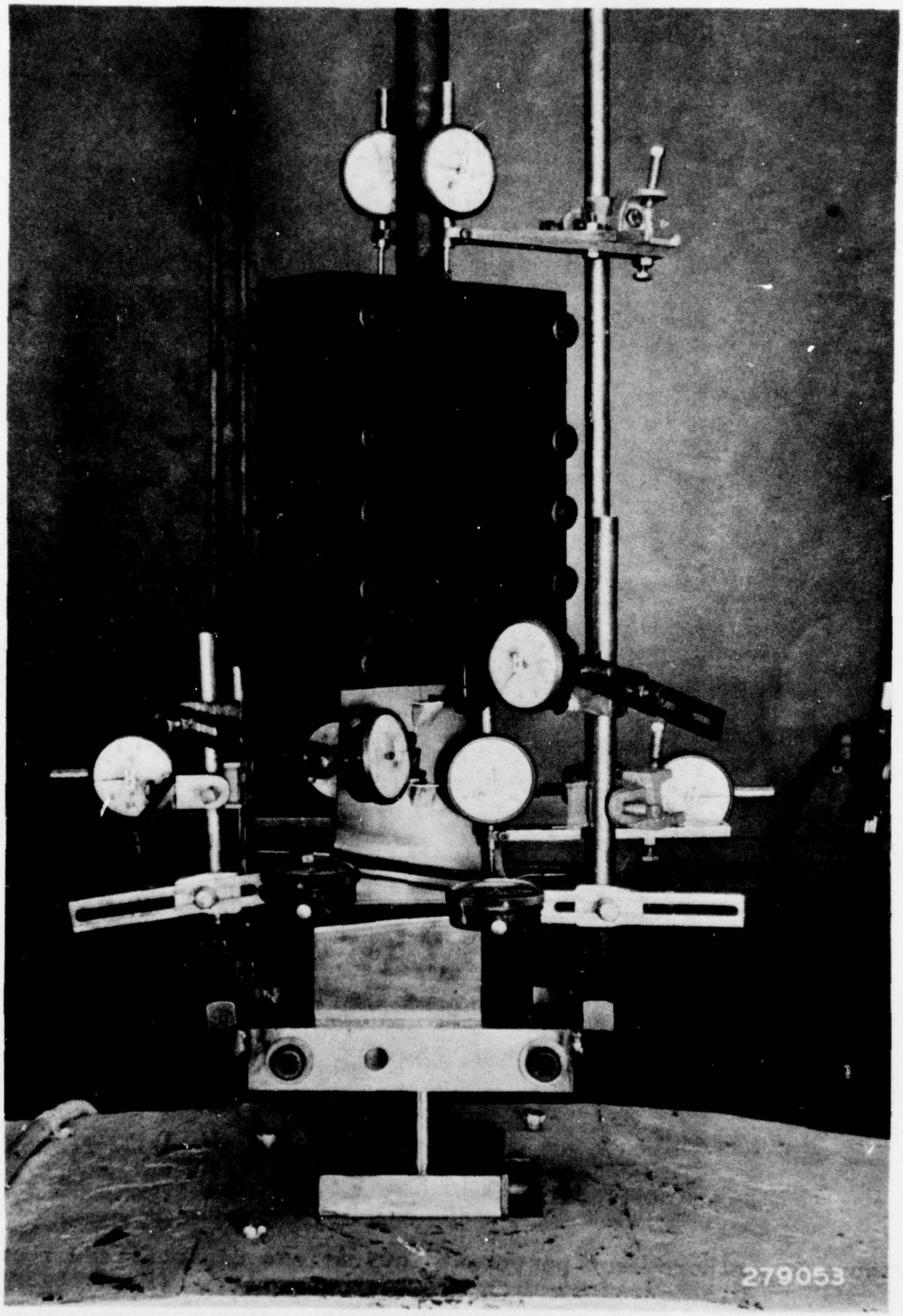


Figure 9. Dovetail-Pull Test Set-Up.

The first Be/Ti rod blade (S/N E24-1) to be spin tested, was mounted in the static pull-test equipment and loaded to 40,000 lbs and held for 3 minutes. The application of load was continued to 51,000 lbs, held for 5 minutes, and then the load was removed. Pinging noises were heard during the application of load; however, an acoustic pick-up mounted directly to the airfoil did not generate any unusual noise such as might occur due to fiber or rod breakage. The pinging noises are thought to have come from the epoxy in the clamping fixture.

A third Be/Ti rod blade (S/N E23C-3) was also pull tested in the same manner as blade S/N E24-1. Both S/N E23C-3 and S/N E24-1 blades were inspected following the dovetail pull-testing by fluorescent penetrant inspection and x-ray. These inspection results were compared to the previous inspection records (see Figures 8 and 10) with the result that no change in the condition of the two blades was detected.

2.3 Overspeed Testing

The two Be/Ti rod blades were placed one at a time into the DDA single-blade spin-test equipment for overspeed and softbody impact testing. The overspeed testing was accomplished on each blade by spinning the rotor to 110% design speed and holding for approximately two minutes, followed by rig shut-down. In light of the successful dovetail pull-testing at 100% dovetail design load and due to the high cost of disassembly and reassembly required for a detailed blade inspection, the decision was made to make a visual inspection only, of the blade in the spin rotor, prior to continuing with the softbody impact testing. This visual inspection produced no indication of damage to either blade.

2.4 Softbody Impact Testing

2.4.1 Test History

The test equipment for softbody impacting a single blade in the DDA spin rig is relatively new and had only been used in two other tests prior to the Be/Ti composite testing.

In order to minimize timing problems, and provide for accurate

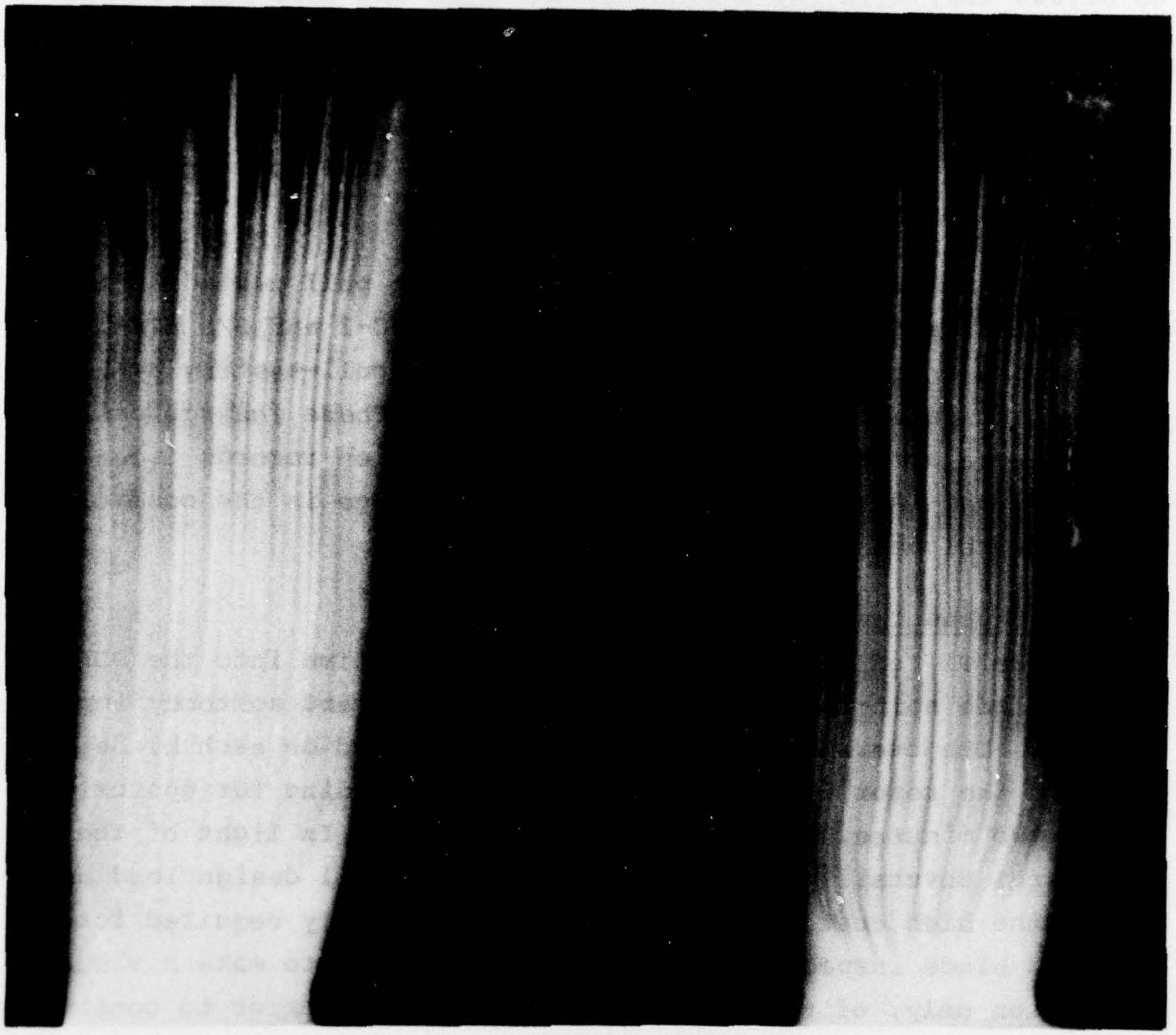


Figure 10. Radiographs of Be Rod/Ti Composite blade E24-1 after finish machining.

(Magn: 1/2X)

calculation of the bird slice mass, the bird injection gun was designed to insert the RTV bird into the path of the blade and hold it in position at impact. The correct velocity and incidence angle relative to the airfoil is obtained by resetting the dovetail angle in the test wheel. By weighing the amount of RTV bird remaining in the holder after impact, the weight of the bird sliced off by the blade impact can be calculated.

Bird gun bench tests were conducted to establish the timing and velocity requirements for injection into the blade path with good repeatability. The trigger setting was found to be critical and redesign was considered, however, due to the cost and time involved and in view of the repeatability achieved during the bench tests, it was decided to proceed.

Five test firings of the bird gun were conducted in the spin facility for a variety of conditions; with dummy birds, rotor stationary, and at speed. No problems were identified except the need for some trimming of the timing delay and this was accomplished. The first test blade (P/N EX 106651, S/N 30) was installed in the spin-test rotor and four successful gun firings were made, consisting of three test firings (without birds) and one 3 oz softbody impact at 100% rotor design speed.

The second blade (P/N 6867374) selected for testing was a TF41 baseline all-titanium clapperless blade. This blade was selected because of previous bird impact test history. A full set of these LP1 blades had previously been installed in an engine and with the engine running at full rated thrust, a four pound duck was shot into the inlet and impacted the blades. (Note: this aerodynamic configuration or design is not the same as the Be/Ti composite blade configuration).

The baseline TF41 blade was installed in the spin-test rotor and two successful softbody impacts were made, one utilizing a 3 oz equivalent bird and the other a 2 lb equivalent bird. During this series, two additional test firings of the gun were made, bringing the total number of successful gun firings to thirteen.

The blade damage due to the 3 oz and 2 lb equivalent baseline impacts are shown in Figures 11 and 12. Impact damage due to the 4 lb duck shot into the running engine is shown in Figure 13. Blade local damage due to the single-blade 2 lb equivalent RTV bird impact is more severe than that obtained from the 4 lb duck impact in the engine. The maximum blade tip deflection that occurred during the engine test is estimated from the high speed photos to be 3.50 inches. Detailed study of the single-blade 2 lb RTV bird impact high speed movies gave a maximum tip deflection of approximately 2.0 inches. Based on these observed deflections, the DDA 4 lb duck full rotor engine test should be about 1.8 times more severe than the 2 lb equivalent RTV bird impact test. The difference in local damage between the engine test and single blade test is thought not to be due to a poor simulation of bird material but rather due to the very positive way in which the RTV 560 bird is held in position by the piston bird holder in the single blade test.

2.4.2 Be/Ti Composite Impact Testing

The best quality Be/Ti rod composite LP1 blade (S/N E24-1) was installed in the spin-test rotor for proof spin and softbody impact testing. The rotor was brought up to 110% design speed and stabilized. After about one minute of proof spin at 10,050 RPM, the bird gun accidentally fired. The bird holder was empty so that there was no impact of any kind and the overspeed test was completed successfully. A review was conducted and poor trigger engagement was cited as the probable cause of the misfire since 13 successful firings had preceded the one misfire.

The blade was visually inspected for any signs of damage due to the overspeed testing and the test equipment was set up for the 3 oz equivalent RTV 560 bird impact.

A simple check sheet was reviewed as the rotor was brought up to 100% speed followed by triggering the release for the 3 oz bird impact. All components performed well and the condition of the blade after the 3 oz equivalent shot is shown in Figures 14 and 15. Note the slight bend in the airfoil leading edge. The high speed

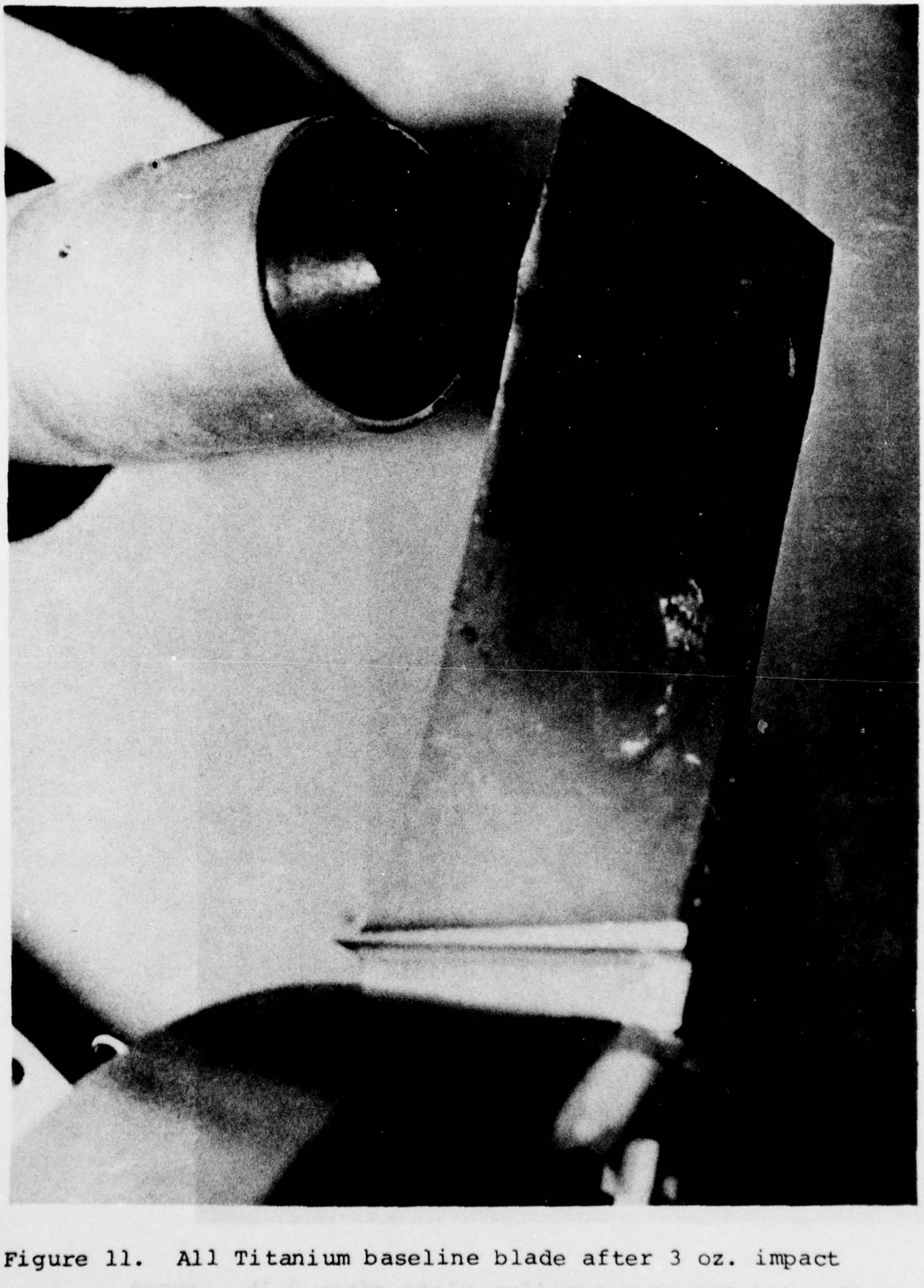


Figure 11. All Titanium baseline blade after 3 oz. impact

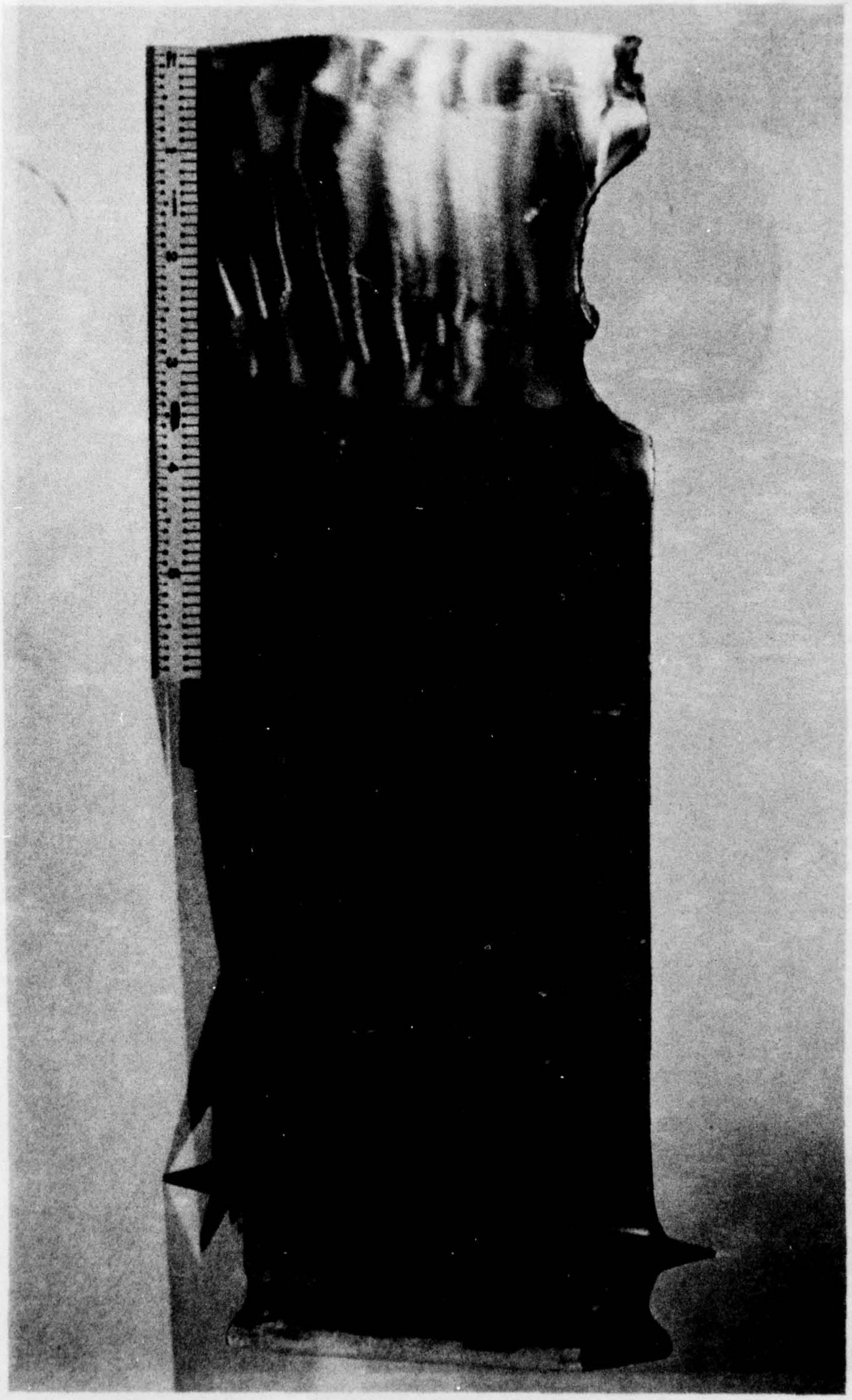


Figure 12. All Titanium baseline blade after 2 lb. impact

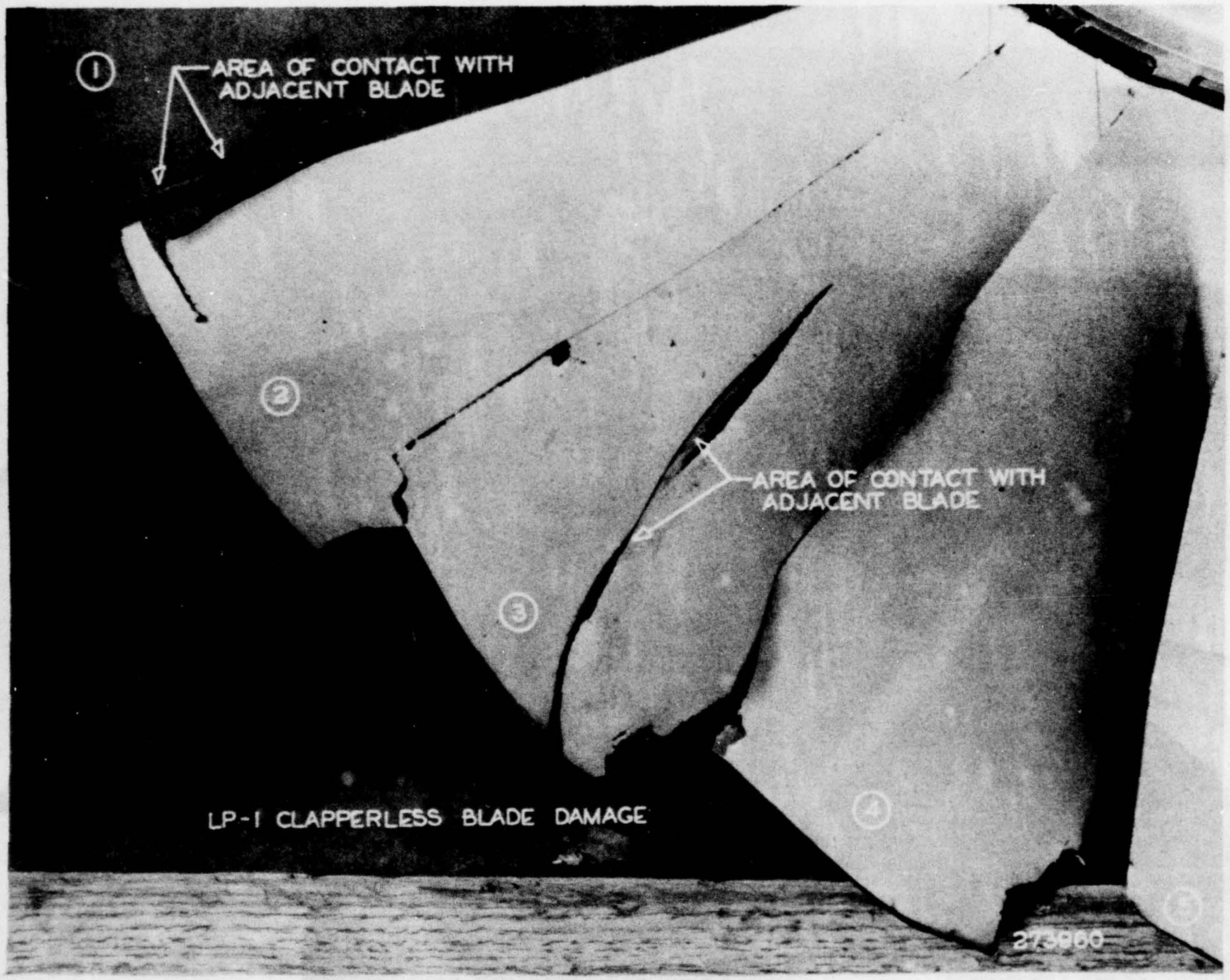


Figure 13. Blade Damage After 4 lb. Bird Impact In An Engine

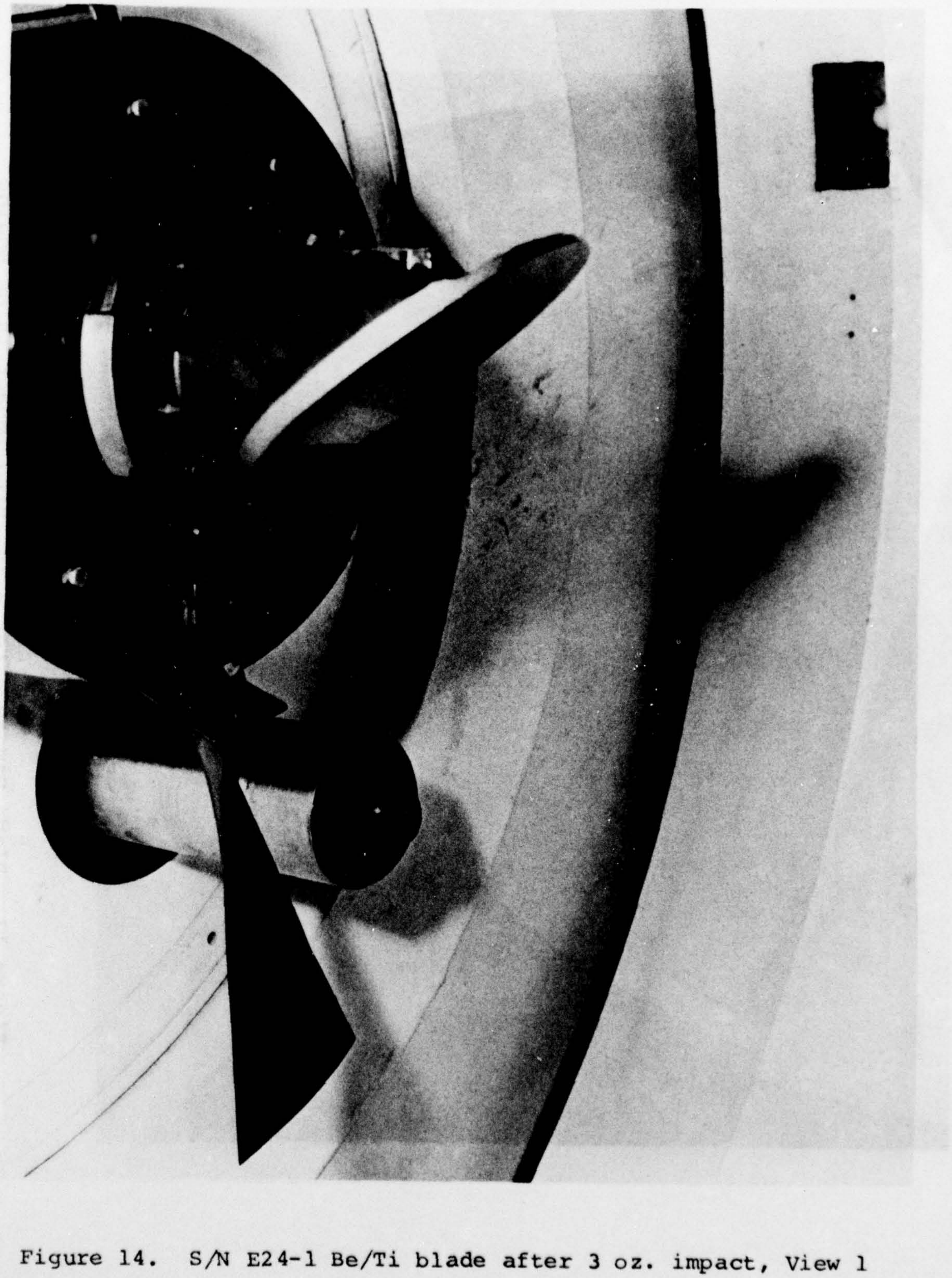


Figure 14. S/N E24-1 Be/Ti blade after 3 oz. impact, View 1

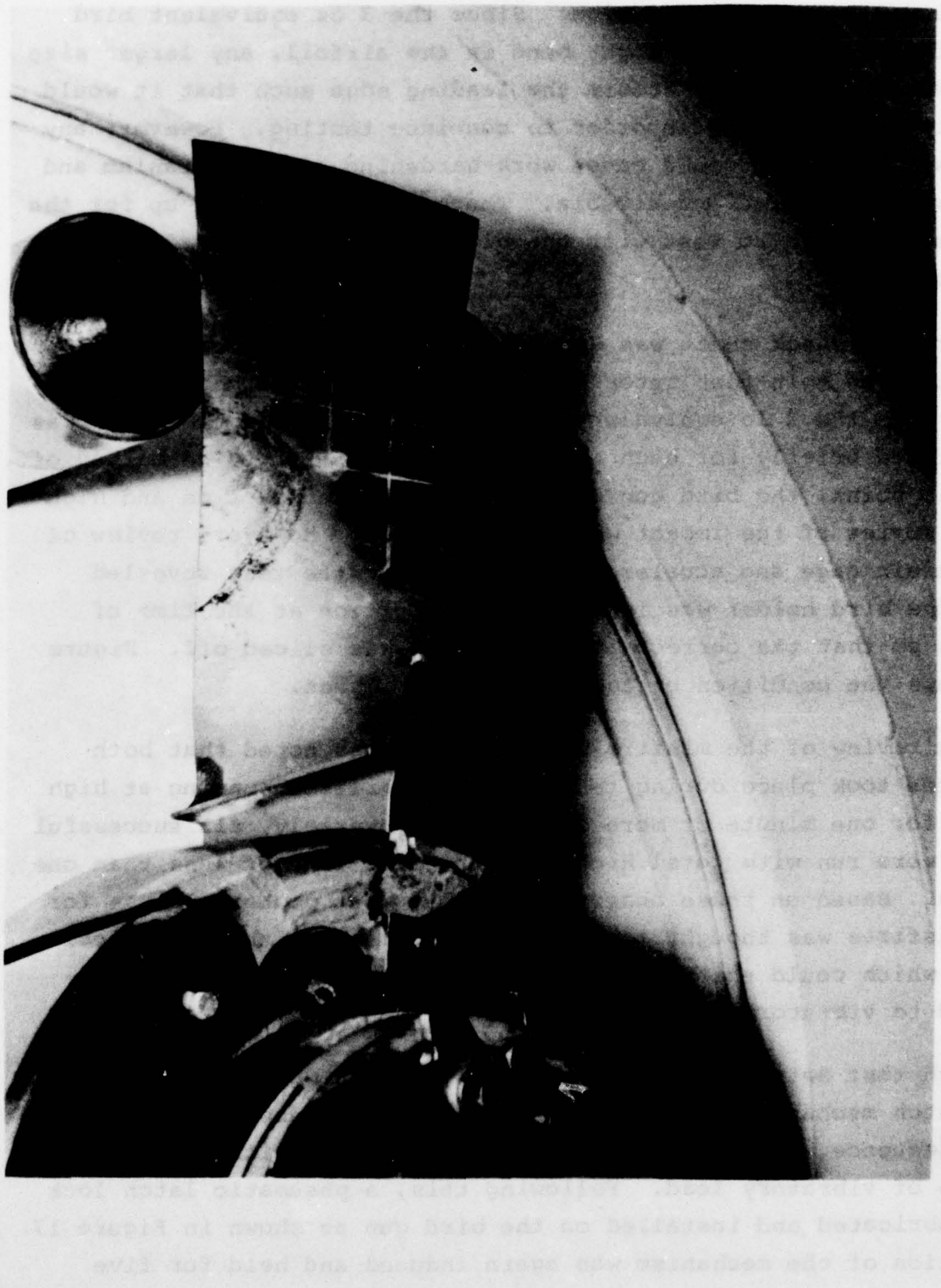


Figure 15. S/N E24-1 Be/Ti Blade After 3 Oz. Impact, View 2

movies were reviewed and it was determined that the simulated bird was in the correct position at the time of impact with approximately the desired length of bird being sliced off. The blade was visually in good condition. Since the 3 oz equivalent bird size impact produced a slight bend in the airfoil, any larger size bird would most likely deform the leading edge such that it would require straightening in order to continue testing. However, any cold straightening would cause work-hardening of the titanium and this was considered undesirable. Therefore, it was set up for the simulated 2 lb bird test with the blade in its slightly deformed condition.

The written check sheet was expanded to cover all functions in more detail. The spin-test rotor was brought up to just below 100% speed with the 2 lb equivalent RTV bird loaded and the speed was stabilized briefly for each item on the check list to be marked off. At this point, the bird gun misfired for the second time and high speed movies of the impact were not obtained. However, review of the strain gage and accelerometer data after the test revealed that the bird holder was in the proper position at the time of impact so that the correct amount of bird was sliced off. Figure 16 shows the condition of the blade after impact.

During review of the misfire situation, it was noted that both misfires took place during tests where stabilized running at high speed for one minute or more occurred. Conversely, all successful tests were run with total high speed running time of less than one minute. Based on these observations, the most probable cause for the misfires was thought to be a disengagement of the mechanical latch which could shift up out of the locking position when subjected to vibratory loads.

A bench test setup of the bird gun was made in which vibration of the latch mechanism was induced in an effort to duplicate the misfire sequence. Latch disengagement was obtained with about one minute of vibratory load. Following this, a pheumatic latch lock was fabricated and installed on the bird gun as shown in Figure 17. Vibration of the mechanism was again induced and held for five

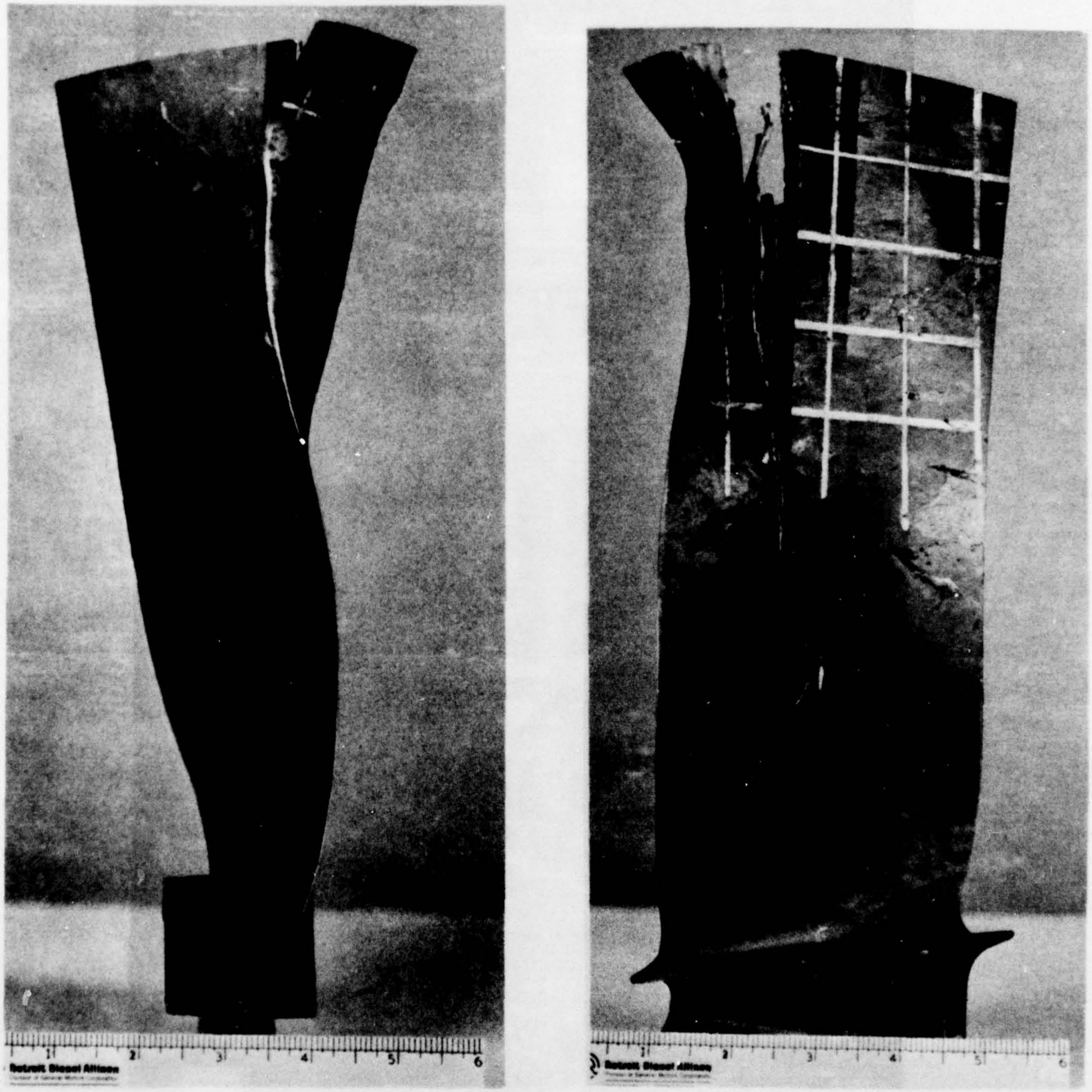


Figure 16. S/N E24-1 Be/Ti blade after impact with 2 lb bird

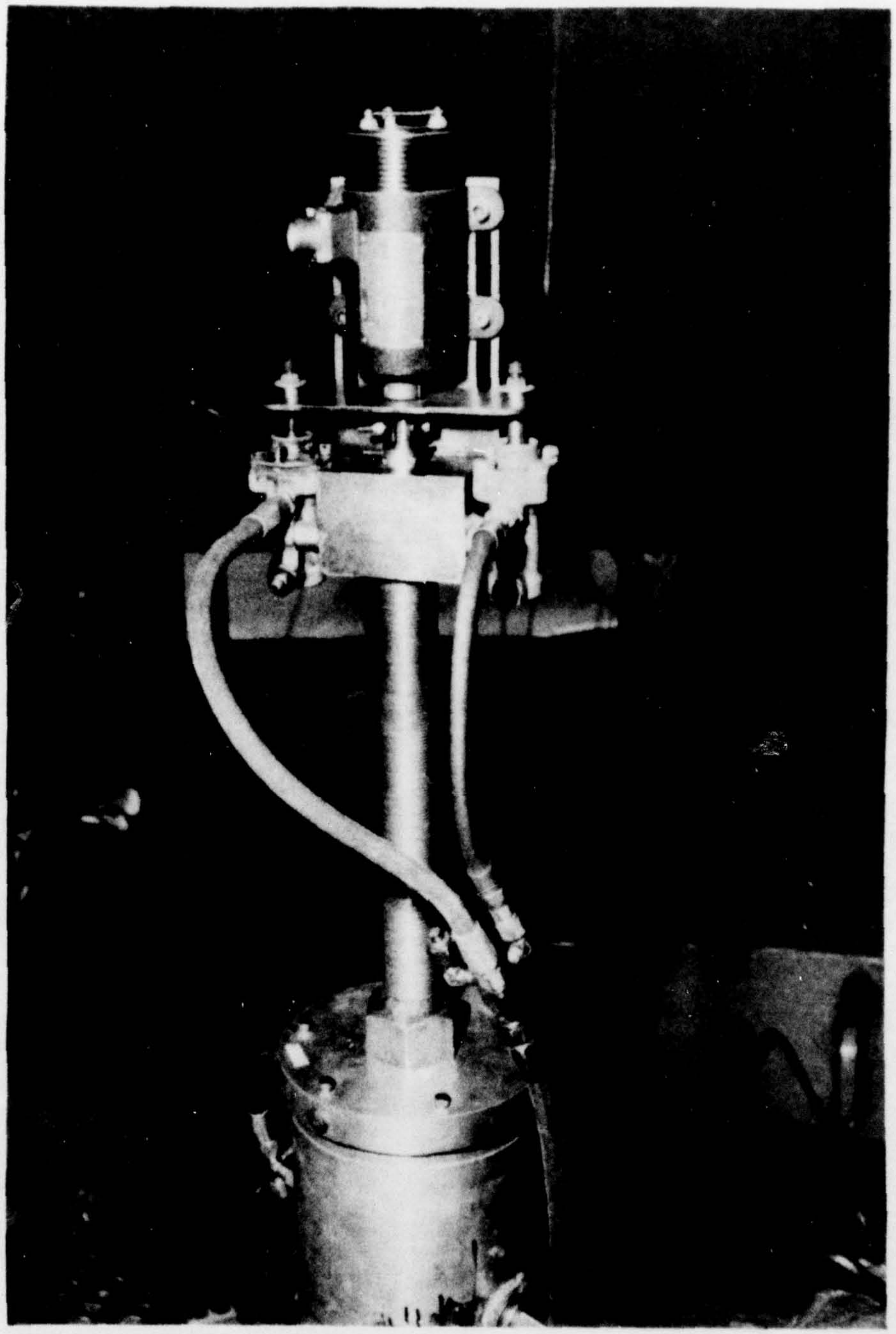


Figure 17. Modified Bird Injection Gun

minutes without a misfire. The latch lock was then released and the gun was triggered successfully to simulate an actual test shot. this bench test sequence was repeated three times. A new check sheet procedure was formulated to fire the bird gun with no more than a six second delay after the latch lock was released.

The second Be/Ti rod composite blade (S/N E23C-3) was installed in the spin facility and the 110% proof spin test was made. In order to obtain a final check of the bird gun system and test sequence, a dummy impact test was made in all respects the same as an actual test except the RTV 560 bird was not loaded in the holder. The dummy test was successful with the latch lock system working correctly.

A two pound RTV bird was placed in the holder and the test sequence was started. At just below 100% test speed, the check list items were marked off and then the latch lock released in anticipation of triggering the bird shot. However, a misfire immediately occurred when the latch lock released and the bird impact took place again without the high speed photography.

Review of the recorded test data again showed that the bird holder was in the correct position at impact. This time, the entire composite airfoil pulled out of the dovetail halves with the resulting blade damage as shown in Figure 18. The failure is thought to have initiated with a radial split similar to that obtained with the first blade (see Figure 16), followed by the pulling out of the entire leading edge portion down to the bottom of the dovetail and then pull out and disintegration of the remainder of the airfoil. Close examination of the dovetail halves where the airfoil pull-out occurred revealed that the quality of the diffusion bond was very poor (see Figure 18).

Figure 18. S/N E23C-3 Be/Ti Blade after 2 lb. impact

3.0 RESULTS AND CONCLUSIONS

- Dovetail-pull testing to 150% of dovetail design load (equivalent to 122% design speed) was accomplished without any visual evidence of airfoil local damage. The average tensile stress at the airfoil minimum section approached the expected ultimate strength of the composite material without visual indication of damage. This testing was accomplished on blade S/N E24-2 following previous softbody bench impact testing which included an equivalent 1.8 lb size bird impact. The demonstrated structural soundness and capability of blade S/N E24-2 was beyond expectations.

- Be/Ti rod blades S/N E24-1 and S/N E23C-3 were dovetail-pull tested to 100% dovetail design load. X-ray and fluorescent penetrant inspections produced the same results as previously obtained prior to the testing. The successful pull tests correlated with the two successful overspeed tests, but did not demonstrate the soundness of the S/N E23C-3 dovetail bonding for softbody impact.

- The structural integrity of blades S/N E24-1 and S/N E23C-3 was demonstrated by overspeed testing to 110% design speed.

- Blade S/N E24-1 withstood a calculated 3 oz equivalent size bird impact with only slight leading edge damage. This was followed by a calculated 2 lbs equivalent size bird impact where the blade essentially remained in one piece with the leading edge portion bending away from the main airfoil along a radial split or fracture. The bird injection gun misfired and prevented the high-speed movies from being taken, however the bird holder was down in the correct position at impact to give the correct amount of bird slice. The radial splitting type failure of the blade leading edge should have been expected due to the lower strength of the composite in the direction normal to the radially-configured Be rods. The use of an orientation other than uniaxial could increase the transverse strength. Previous single blade impact testing on monolithic titanium blades indicates that the DDA 2 lbs size equivalent bird impact as currently done is more severe than real birds shot into an engine in the actual 4 lbs size category. The amount of damage sustained by blade S/N E24-1 demonstrates that the Be/Ti rod system can have a high level of softbody impact capability.

- The blade S/N E23C-3 airfoil completely pulled out of the blade attachment during the 2 lbs equivalent size impact. A gun latch-locking mechanism had been incorporated to prevent misfire, but misfire accidentally occurred again and as a result high-speed photography was not obtained. The bird holder again injected into proper position for impact. Examination of the attachment halves after failure revealed a very poor quality of root bonding and this is considered to be the significant factor contributing to the total failure of S/N E23C-3. Good attachment bonding is essential to the satisfactory performance of the Be/Ti rod blades.

- Overall, the Be/Ti rod blades demonstrated good tensile strength and reasonable softbody impact capability and, with improved attachment bonding, would most likely be structurally satisfactory for application to aircraft engine fan blades. One aspect not addressed in this program is the environmental/toxicity hazards which could exist with the use of beryllium as a fabrication material. This aspect would require careful consideration and treatment in any potential applications.

4.0 RECOMMENDATIONS

- Further development of the DDA softbody single-blade impact procedure is required, particularly for the bird injector triggering mechanism and the bird holding system. An alternate bird material should be considered.

- Blade fabrication processes could be developed that provide for a positive attachment of the root to the airfoil.

- Life-cycle cost studies, design pay-off evaluations and environmental toxicity impact studies could be made to establish the most advantageous applications for the Be/Ti metal-matrix composite material.