Section/division Accident & Incident Investigation

Form Number: CA 12-12b

AIRCRAFT INCIDENT REPORT AND EXECUTIVE SUMMARY

			Reference:	CA18/3/2/0568	
Aircraft Registration	**ZS-RBB**	**Date of Incident**	1 February 2007	**Time of Incident**	1008Z
Type of Aircraft	MBB BO-105-CBS-4 (Helicopter)		**Type of Operation**	Law Enforcement	
Pilot-in-command Licence Type	Commercial	**Age**	42	**Licence Valid**	Yes
Pilot-in-command Flying Experience	Total Flying Hours	6 378.4		Hours on Type	3 598.2
Last point of departure	Nelspruit Aerodrome (FANS)				
Next point of intended landing	Roossenekal Area (Mpumalanga)				
Location of the incident site with reference to easily defined geographical points (GPS readings if possible)					
Open area next to Kulna dam (GPS position: South 25° 22.983’ East 030° 25.235’)					
Meteorological Information	Wind was light and variable, Temperature; 28°C, Visibility; +10km				
Number of people on board	1 + 1	**No. of people injured**	0	**No. of people killed**	0

Synopsis

The pilot, accompanied by a Law Enforcement Officer, departed from Nelspruit Aerodrome (FANS) to the Roossenekal area, to assist South African Police ground forces with a stock theft operation.

Approximately 15 minutes after take-off, while established in cruise flight, the pilot noted a slight increase in the TOT (Turbine Outlet Temperature) on the number one engine. Shortly thereafter, they experienced two consecutive compressor stalls on the number one engine. The pilot then decided to execute a precautionary landing to investigate the engine abnormality.

On landing the number one engine “CHIP” warning light illuminated on the instrument panel and smoke was observed from the cockpit, and the pilot immediately shut down both engines.

Probable Cause

The 3rd stage compressor wheel airfoil fractured in fatigue due to erosion, resulting in high radial loads on the No. 1 bearing.

IARC Date		Release Date	

AIRCRAFT SERIOUS INCIDENT REPORT

Name of Owner	**:** South African Police Services
Name of the Operator	**:** South African Police Services
Manufacturer	**:** Messerschmitt-Bolkow-Blohm
Model	**:** MBB BO105-CBS-4
Nationality	**:** South African
Registration Marks	**:** ZS-RBB
Place	**:** Kulna dam area (Mpumalanga Province)
Date	**:** 1 February 2007
Time	**:** 1008Z

All times given in this report are Co-ordinated Universal Time (UTC) and will be denoted by (Z). South African Standard Time is UTC plus 2 hours.

Purpose of the Investigation:

*In terms of Regulation 12.03.1 of the Civil Aviation Regulations (1997) this report was compiled in the interests of the promotion of aviation safety and the reduction of the risk of aviation accidents or incidents and **not to establish legal liability**.*

Disclaimer:

This report is produced without prejudice to the rights of the CAA, which are reserved.

1. FACTUAL INFORMATION

1.1 History of Flight:

1.1.1 The pilot, accompanied by a Law Enforcement Officer, departed from Nelspruit Aerodrome to the Roossenekal area, to assist the South African Police's ground forces with a stock theft operation.

1.1.2 Approximately 15 minutes after take-off, while established in cruise flight, the pilot noted a slight increase in the Turbine Outlet Temperature (TOT) on the number one engine. Shortly thereafter they experienced two consecutive compressor stalls on the number one engine. The pilot then decided to execute a precautionary landing to investigate the engine abnormality.

1.1.3 On landing, the number one engine's "CHIP" warning light illuminated on the instrument panel and smoke was observed from the cockpit. The pilot then immediately shut down both engines.

1.1.4 On further investigation it was found that the No. 1 engine oil reservoir was empty, and that the engine was covered in oil. It was also noted that the No. 1 bearing (located in the front of the engine) was substantially disrupted, which explained the oil leakage.

1.1.5 Nobody was injured in the incident.

1.2 Injuries to Persons:

Injuries	Pilot	Crew	Pass.	Other
Fatal	-	-	-	-
Serious	-	-	-	-
Minor	-	-	-	-
None	1	-	1	-

1.3 Damage to Aircraft:

1.3.1 Damage was limited to the engine air intake and compressor rotor assembly.

1.4 Other Damage:

1.4.1 There was no other damage caused.

1.5 Personnel Information

1.5.1 Pilot-in-command:

Nationality	South African	Gender	Male	Age	42
Licence Type	Commercial				
Licence valid	Yes	Type Endorsed	Yes		
Ratings	Instrument Rating, Undersling / winch Rating, Cull Rating				
Medical Expiry Date	31 August 2007				
Restrictions	None				
Previous Incidents	None				

Flying Experience:

Total Hours	6 378.4
Total Past 90 Days	153.1
Total on Type Past 90 Days	51.1
Total on Type	3 589.2

1.6 Aircraft Information:

Airframe:

Type	MBB BO-105-CBS-4	
Serial No.	S-821	
Manufacturer	Messerschmitt-Bolkow-Blohm	
Year of Manufacture	1989	
Total Airframe Hours (At time of Incident)	4 795.8	
Last MPI (Hours & Date)	4 700.0	13 September 2006
Hours since Last MPI	95.8	
C of A (Issue Date)	21 August 1991	
C of R (Issue Date) (Present owner)	12 July 1991	
Operating Categories	Standard	

Engine No. 1:

Type	Rolls Royce 250-C20B
Serial No.	CAE 836360
Hours since New	4 796.7
Hours since Overhaul	Not applicable, module engine

Engine No. 2:

Type	Rolls Royce 250-C20B
Serial No.	CAE 836361
Hours since New	4 796.7
Hours since Overhaul	Not applicable, module engine

1.7 Meteorological Information:

1.7.1 Weather information was obtained from the pilot's questionnaire:

Wind direction	Light	Wind speed	Variable	Visibility	+ 10km
Temperature	28°C	Cloud cover	No	Cloud base	No
Dew point	8.9°C				

1.8 Aids to Navigation:

1.8.1 The helicopter was equipped with the following navigational aids:

Magnetic Compass

Transponder

Automatic Direction Finder (ADF)

Variable Omni Range Finder (VOR)

Global Positioning System (GPS; Garmin 295)

1.9 Communications:

1.9.1 The helicopter was equipped with two VHF radios as well as a police band radio for communication with ground forces.

1.10 Aerodrome Information:

1.10.1 The pilot executed an uneventful landing in an open area next to the Kulna dam.

1.11 Flight Recorders:

1.11.1 The helicopter was not fitted with a Cockpit Voice Recorder (CVR) or a Flight Data Recorder (FDR) and neither was required by regulations to be fitted to this type of helicopter.

1.12 Wreckage and Impact Information:

1.12.1 An uneventful forced landing was executed in an open area.

1.13 Medical and Pathological Information:

1.13.1 Nobody was injured in the incident.

1.14 Fire:

1.14.1 Although smoke was observed coming from the number one engine following the landing, no evidence of fire was observed. The origin of the smoke was attributed to seizure of the bearing.

1.15 Survival Aspects:

1.15.1 The pilot executed an uneventful single engine landing, with no damage to the helicopter, therefore nobody was injured in the accident, rendering it survivable.

1.16 Tests and Research:

1.16.1 The engine in question, model Rolls-Royce 250-C20B, Serial No. CAE 836360 was removed from the helicopter ZS-RBB and was made available for a teardown inspection at a Rolls-Royce approved engine facility at Rand Aerodrome, South Africa. The teardown inspection was performed in the presence of a SACAA Accident

Investigator and a Rolls-Royce Safety Investigator.

Evaluation of the No. 1 bearing revealed significant damage to the ball bearings and oil separator. A cross-section of the inner raceway of the bearing revealed localized thermal damage consistent with high radial loads.

It was, however, found that the bearing failure was secondary to the failure of the 3rd stage compressor wheel airfoil that had fractured in fatigue, with the evidence of corrosion present on the leading edge before the airfoil separated in overload.

Following these observations it was decided to forward the complete Compressor Assembly as well as the Bearing Housing and Components for metallurgical investigation to the Rolls-Royce Corporation Materials Laboratory in Indianapolis, Indiana in the United States of America.

A detailed metallurgical investigation report is attached to this report as Annexure A.

1.17 Organisational and Management Information:

1.17.1 The helicopter was being operated under the auspices of the South African Police Services, which was in possession of the required operational approvals.

1.17.2 The helicopter was maintained by Aircraft Maintenance Organisation (AMO) No. 1037, which was in possession of a valid AMO Approval Certificate at the time when the last maintenance was certified on the helicopter.

1.18 Additional Information:

1.18.1 Compressor Rinsing:

During operation in an industrial atmosphere, deposits build up on the compressor blades, resulting in a loss of engine efficiency. During flights in a salt-laden atmosphere, corroded residues are trapped in the engine.

The compressor-rinsing procedure enables such contamination to be removed easily, quickly and effectively.

The compressor may be rinsed with distilled water or for washing the compressor, a cleaning fluid should be used in accordance with the Rolls-Royce (Allison) 250-C20 engine Operating and Maintenance Manual.

1.18.2 Following the incident, the investigator contacted the chief maintenance engineer at AMO No. 1037, to discuss the compressor rinsing method. According to the feedback received, these engines were subjected to a compressor rinsing procedure every 50 hours while in service, irrespective of where (area) the helicopter was deployed in the country. In areas with a high air pollution rate (i.e. Gauteng and Cape Town) this in-house arrangement could have been beneficial, but the helicopter in question was operating from Nelspruit and was serving the Mpumalanga area. It should be noted that helicopters that were being operated at coastal stations would have been subjected to a water rinse procedure on a daily basis due to the corrosive environment. It was further noted that normal tap water was being used to perform these tasks, which was contrary to what the Rolls Royce 250-C20 Operation and Maintenance Manual stipulates, by recommending that distilled water be used. The use of normal tap water with all the chemicals it contains, accelerated the corrosion that was detected on the leading edge of the compressor wheel airfoil, which subsequently fractured in fatigue.

1.19 Useful or Effective Investigation Techniques

1.19.1 None.

2. ANALYSIS

2.1 The compressor blade was found to have fractured in fatigue. It was noted that the fracture originated from an area of intergranular corrosion and the leading edge, which propagated 0.31 inches (7.8 mm) before the blade separated in overload. It was further found that one additional blade on the same stage (3^{rd} stage) exhibited cracking near the leading edge. Examination showed that the fracture was consistent with fatigue progression from corrosion damage.

2.2 From the available laboratory examination, it was evident that the third stage compressor wheel reflected substantial erosion as well as corrosion pitting damage along the leading edge of all the blades, with cracks being identified on some of the blades. The erosion and corrosion evidence was not limited to the 3^{rd} stage compressor wheel alone, but was detected in nearly all of the six stages of the compressor assembly. Once the blade (airfoil) had failed, a substantial amount of radial load was placed on the No. 1 bearing, which was unable to sustain these loads.

2.3 The use of normal tap water with all the chemicals it contains over the time frame that the engine was in operation, accelerated the corrosion process that ultimately resulted in fatigue failure of the blade with other blades also displaying evidence of cracking.

Failure by the maintenance organisation to follow the laid-down procedure as called for in the engine maintenance manual, aggravated and ultimately caused this assembly to fail. As a result the compressor wheel assembly was unable to complete its designed service life.

3. CONCLUSION

a) Findings

(i) The pilot was the holder of a valid commercial helicopter pilot's licence and had the helicopter type endorsed in his logbook.

(ii) The engine compressor rinsing procedure was performed every 50 hours of operation.

(iii) Normal tap water was used for the compressor-rinse procedure according to the Chief AME, which was contrary to the maintenance manual guidance.

(iv) The pilot performed an uneventful landing.

(v) The metallurgical examination revealed a substantial amount of erosion and corrosion being present within some of the compressor airfoils in all six stages of the assembly.

b) Probable Cause/s

(i) The 3rd stage compressor wheel airfoil fractured in fatigue, due to erosion resulting in high radial loads on the No. 1 bearing.

c) Contributory Factor/s:

(i) The maintenance personnel failed to comply with the stipulated maintenance requirements as called for in the Rolls-Royce 250-C20 Operation and Maintenance Manual regarding compressor-rinsing methods, by making use of normal tap water instead of distilled water.

4. SAFETY RECOMMENDATIONS

4.1 It is recommended that the SACAA review the maintenance requirements as defined in the relevant SAPS Operations Manuals to ensure that with the rotation of their helicopters through the country, that when operated in a coastal environment, the engines are subjected to daily compressor washes.

4.2 That the SACAA ensure that the correct procedures were followed during these compressor washes.

5. APPENDICES

5.1 Annexure A (Rolls-Royce Metallurgical Investigation Report)

-END-

Report reviewed and amended by the Advisory Safety Panel
5 May 2009

ANNEXURE A

METALLURGICAL INVESTIGATION REPORT

DEPARTMENT OF TECHNOLOGY
MATERIALS, PROCESSES, AND REPAIR ENGINEERING

Rolls-Royce

Rolls-Royce Corporation
P.O. Box 420
Indianapolis, Indiana 46206-0420 USA

PAGE	PAGES	REPORT NO.
1	OF 27	07FA8-042

TITLE

EVALUATION OF A THIRD STAGE COMPRESSOR WHEEL P/N 23057112 FROM A MODEL 250-C20B ENGINE S/N CAE 836360 OPERATED BY THE SOUTH AFRICAN POLICE.

PREPARED

Amy L. Morrissey *(Signatures on File)*

APPROVED	DATE
Jacque S. Bader	6/8/07

Reference: QN 800080337

Identification

Part Name:	2nd - 3rd Stage Compressor Wheel
Part Number:	23057112
Part S/N:	C30663
Material:	AMS 5355 (17-4PH)
Total Part Time:	4796.7 Hours (5706.0 Cycles)
Engine Model:	250-C20B
Engine S/N:	CAE836360
Removal Station:	NAC, South Africa
User:	South African Police

Foreword

Selected components from a Compressor Assembly were submitted to the Rolls-Royce Corporation Materials Laboratory for metallurgical investigation. The compressor components were reportedly from a Model 250-C20B engine S/N CAE 836360 operated by the South African Police. Preliminary examinations revealed damage of the Third Stage Compressor Wheel and the No. 1 Bearing.

Findings

1. One (1) Third Stage Compressor Wheel airfoil fractured in fatigue approximately 0.063 inch outboard of the wheel rim. The fracture initiated from an area of intergranular corrosion at the leading edge and propagated 0.31 inch before the airfoil separated in overload.
2. One (1) additional Third Stage airfoil exhibited cracking near the leading edge root area. The crack was lab-fractured revealing fracture features consistent with fatigue progression from corrosion damage.
3. The material composition, microstructure, and hardness of the Third Stage Compressor Wheel met the requirements of the engineering drawing.
4. Evaluation of the No. 1 Bearing revealed significant damage to the ball bearings and separator. A cross-section of the inner raceway of the No. 1 Bearing revealed localized thermal damage consistent with high radial loads. Hardness measured on the inner race was consistent with the observed heat distress.

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Results

Figure 1 shows the as-received condition of the Compressor Front Support, No. 1 Bearing Housing and adjacent components, Compressor Rotor Assembly, and Upper and Lower Compressor Case Assemblies. Table I lists the components submitted to Rolls-Royce Corporation Materials Laboratory.

Table I. Components Submitted to the Laboratory

Component	Part Number	Serial Number
Front Support	6890530-A	20792
No. 1 Bearing Housing	6893617-A	Date Code 8-77-16
No. 1 Bearing	Illegible	Illegible
Carbon Oil Seal	23004513-B	Non-serialized
Compressor Case Assembly	23057142-A	42433
1st Stage Compressor Wheel	Illegible	E8965OR
2nd-3rd Stage Compressor Wheel	23057112	C30663
4th Stage Compressor Wheel	23060414	C28676
5th Stage Compressor Wheel	23057115	KR52108
6th Stage Compressor Wheel	23057116	KR57723
Impeller	23058147-C	KR100150
Splined Adapter	23039791-E	67377
Tiebolt	6871259-B	KU61792

Compressor Rotor Assembly

Stage 1 Wheel P/N Illegible, S/N E8965OR
Stage 2 & 3 Wheel P/N 23057112, S/N C30663
Stage 4 Wheel P/N 23060414, S/NC28676
Stage 5 Wheel P/N 23057115, S/N KR52108
Stage 6 Wheel P/N 23057116, S/N KR57723
Impeller P/N 23058147-C, S/N KR100150

Visual Examination

Figure 2 shows the general condition of the rotor assembly. An airfoil was separated from the third stage compressor wheel. The third stage compressor wheel airfoils were labeled sequentially clockwise (forward looking aft) for the purposes of this report and the separated airfoil was identified as position #1. The general condition of the second and third stage compressor wheel is shown in *Figure 3* after the rotor was disassembled. Impact damage was observed on the second and third stage airfoil leading edges. The tips of the airfoils were bent opposite the direction of rotation and evidence of coating cracks were observed on many of the airfoils. The coating cracks were considered secondary damage.

The second stage wheel was cut from the third stage wheel to facilitate visual examination of the third stage wheel forward face, shown in *Figure 4*. *Figure 5* shows a photograph detailing erosion of the coating observed along the leading edge of a representative third stage airfoil. Further inspection identified corrosion pits on the leading edges of multiple third stage airfoils. Severe examples of corrosion pitting included airfoils #7 and #17. Fluorescent penetrant inspection (FPI) of the third stage wheel revealed background fluorescence due to imperfections and cracks present in the coating.

However, leading and trailing edge cracks were identified on the pressure side of airfoil #2. Photographic references and detailed evaluation for airfoils #7, #17, and #2 are included in the fractographic examination section.

Visual examination of the first, second, fourth, fifth, and sixth stage wheels revealed erosion of the coating on the airfoil leading edges. Several corrosion pits were also observed on the second stage wheel near the root or along the leading edge of the airfoil. The first, fourth, fifth and sixth stage wheels did not exhibit pitting equivalent in frequency or severity to observations of the second-third stage wheel under binocular examination. Detailed metallurgical and chemical analyses were not conducted.

Fractographic and Metallographic Examination

Figure 6 shows the fracture surface of airfoil #1 had features consistent with fatigue propagation. The crack grew approximately 0.31 inch before the blade ultimately separated in overload. The fracture originated approximately 0.063 inch outboard from the rim and corrosion damage was also generally observed along the leading edge inboard of the fracture surface, near the root, shown in *Figure 7*. Scanning electron microscope (SEM) images detailing the intergranular features of the corrosion damage are shown in *Figure 8*.

Corrosion damage was also observed at other two other locations along the fracture surface pressure and suction sides. An SEM montage of the transition region shown in *Figure 9* identifies the location of the two regions of corrosion damage that are detailed in *Figures 10 and 11*. Fatigue propagation was observed originating from one region of corrosion damage located on the pressure side of the airfoil shown in *Figure 11*. *Figure 12* shows a detailed SEM image of the transition from fatigue propagation to overload. Damage to the fracture surface precluded detailed analysis of the stria spacing, but the general fracture morphology was consistent with high cycle fatigue (HCF) progression.

Figure 13 shows a metallographic plane through the corrosion damage at the leading edge of airfoil #1. The observed cracking was consistent with intergranular corrosion and spanned approximately 0.038 inch along the fracture surface and down the leading edge inboard to the root.

The general microstructure not associated with the corrosion damage is shown *Figure 14*. The microstructure was typical for solution and precipitation heat-treated AM 5355 (17-4 PH).

Severe examples of corrosion pitting visually observed on the leading edges of airfoil #7 and #16 are shown in *Figure 15*. Airfoil #17 was lab-fractured through the corrosion pit located approximately 0.093 inch outboard from the rim (reference lower photograph in *Figure 15*). Corrosion damage was observed up to 0.075 inch deep but no evidence of fatigue propagation was observed. *Figure 16* details the fracture surface which had features consistent with overload resulting from lab-fracture.

Leading and trailing edge cracking visually observed on airfoil #2 is shown in *Figure 17*. Airfoil #2 was lab-fractured approximately 0.125 inch outboard from the rim. Fatigue propagation emanating from regions of corrosion damage (dark areas) along the fracture surface was observed, shown in *Figure 18*. An SEM image, shown in *Figure 19*, details the intergranular features of the corrosion damage near the leading edge.

Hardness

The hardness of the Third Stage Compressor Wheel was 37.8 HRC (averaged value of 69.4, 69.2, 68.3 HRA and interpolated). The engineering drawing requires a hardness of 30 to 38 HRC per EPS 401-5.

Chemistry

Semi-quantitative x-ray energy dispersive analysis (XEDA) determined that third stage wheel was an AMS 5355 (17-4 PH) type material as required by the engineering drawing.

Compressor Front Support
P/N 6890530-A, S/N 20792

Visual Examination

Figure 24 shows the general condition of the compressor front support. Seven (7) radial struts fractured from the inner hub. The oil supply and oil scavenge tubes supplying lubrication to the No. 1 bearing running through the radial struts were considered to have fractured when the bullet nose (inner hub) of the front support separated. Photographs showing the fractured tubes are shown in *Figure 25*. All seven radial struts also visually exhibited cracking at the attachments to the outer wall on the forward end of the support. Damage to the compressor front support precluded identification of a specific failure mode and detailed fractographic examination of the radial struts was not conducted. The damage was indicative of secondary damage generated during the event sequence. The oil inlet tube, although fractured, had no indications of blockage. No metallurgical or chemical analyses were performed on the compressor front support.

Compressor Case Assembly
P/N 23057142-A, S/N Set 42433

Visual Examination

Figures 26 and 27 show the general condition of the upper and lower compressor case halves. The upper and lower compressor cases exhibited impact damage to the leading edges of multiple vanes. Several vanes also exhibited rub wear on the outboard tips or were observed bent in the direction of rotation of the compressor rotor.

The abradable plastic coating inside the cases also exhibited impact damage. The sheet metal of the vane assembly was exposed between the second and third stage vane rows (this is also the third stage blade path for the third stage compressor wheel) on the lower case. The location of the missing plastic was consistent with secondary damage resulting from the separation of the third stage airfoil from the compressor wheel. A detailed view of the damage to the abradable plastic coating is shown in *Figure 28*.

Damage to the upper and lower compressor cases was consistent with secondary damage generated during the event sequence. No metallurgical or chemical analyses were performed on components of the compressor case assembly.

Compressor Splined Adapter and Compressor Tiebolt
P/N 23039791-E, S/N 67377 and P/N 6871259-B, S/N KU61792

Visual Examination

Photographs showing the general conditions of the compressor splined adapter and compressor tiebolt are shown in *Figure 29*. The compressor splined adapter exhibited no visual indications of fretting wear or cracking on the splines. Debris consistent in appearance to coked oil was observed. The compressor tiebolt exhibited rub wear on the mating surfaces to the fourth stage compressor wheel and the impeller. No metallurgical or chemical analyses were performed on the compressor splined adapter or compressor tiebolt.

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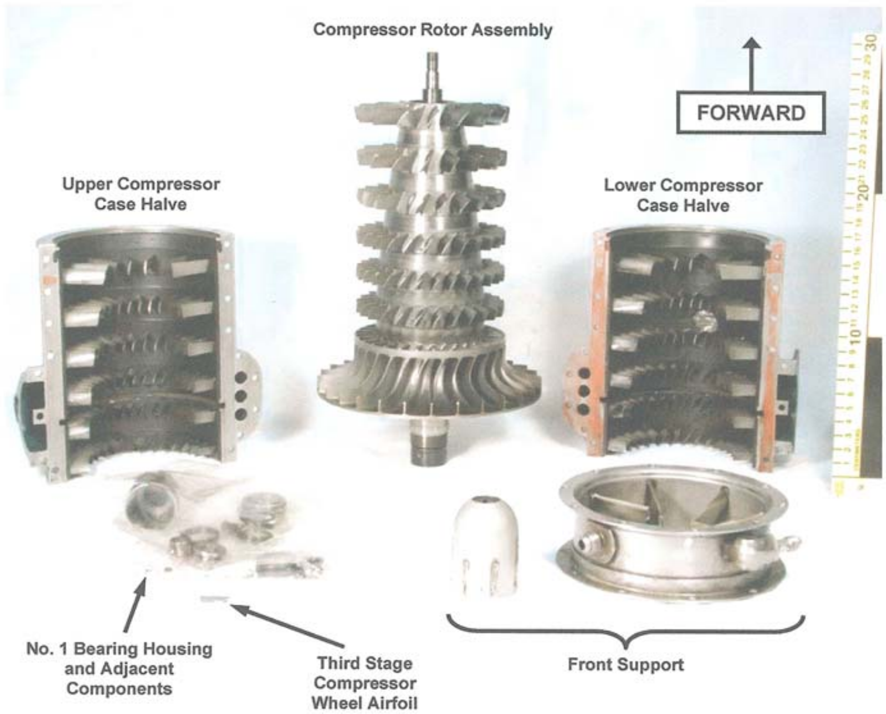

Figure 1. **As-received conditions of the Front Support, No. 1 Bearing housing and components, Rotor Assembly (with separated third stage wheel airfoil), and the Upper and Lower Case halves. Scale = cm.**

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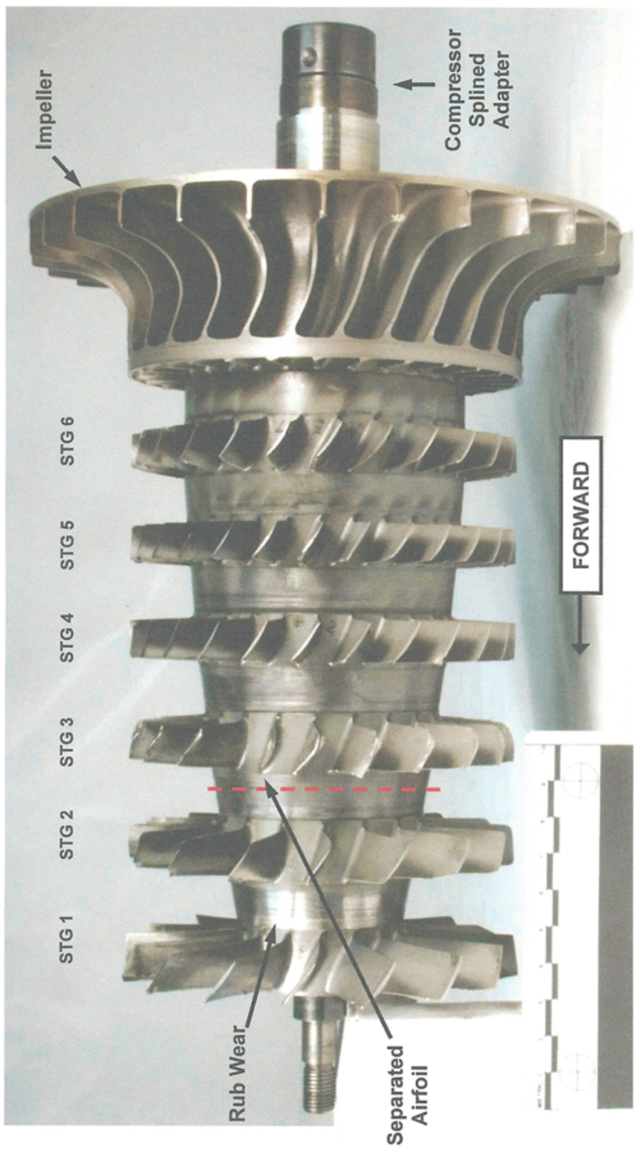
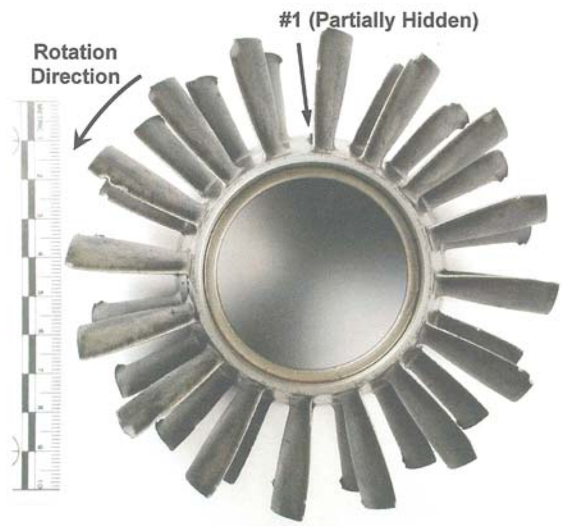


Figure 2. As-received condition of the rotor. Scale = cm.

Rolls-Royce



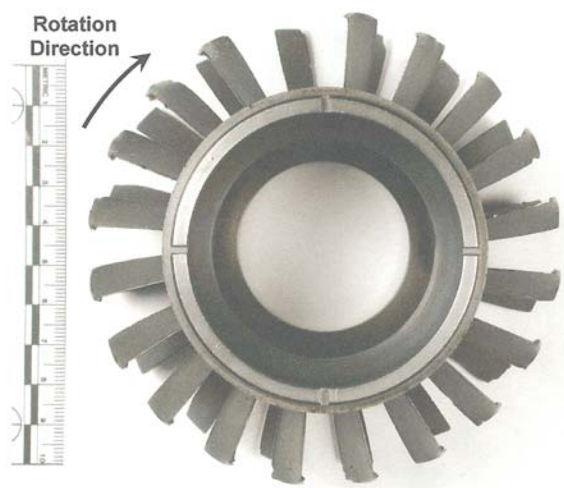


Figure 3. Photographs showing the as-received condition of the second and third stage compressor wheels. Scale = cm.

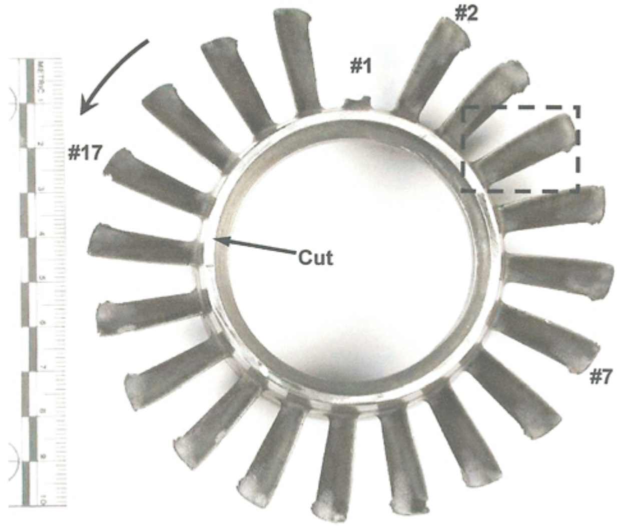


Figure 4. Photograph showing the third stage compressor wheel (forward view, second stage removed). Arrow shows the direction of rotation during engine operation. Cracks in the coating give a whitish appearance to the airfoils. Dashed box shows region of further examination. Scale = cm.

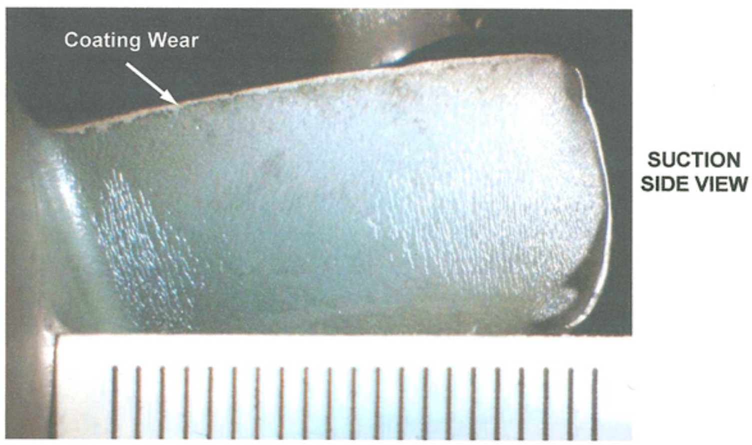


Figure 5. General view showing representative erosion of the coating at the leading edge of airfoil #4 (suction side). Cracks in the coating were considered secondary damage. Scale = mm.

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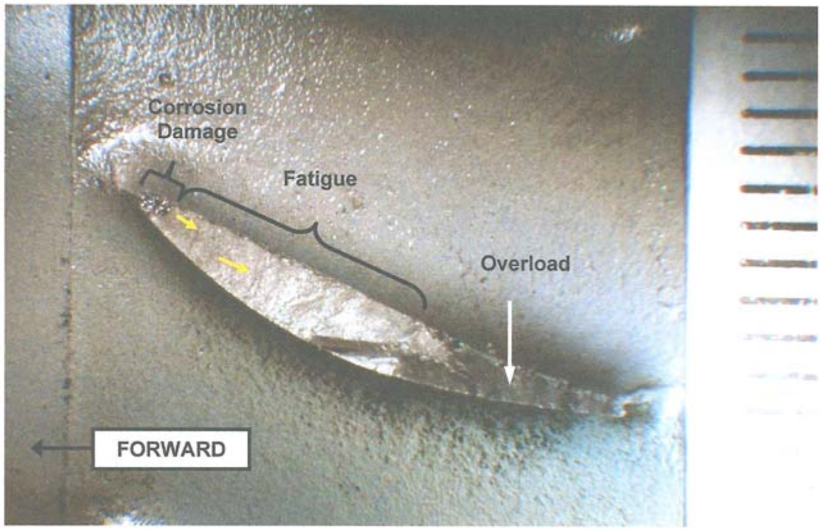


Figure 6. **Photograph showing the fracture surface of the separated third stage airfoil. Yellow arrows show the general direction of fatigue propagation. Scale = mm.**

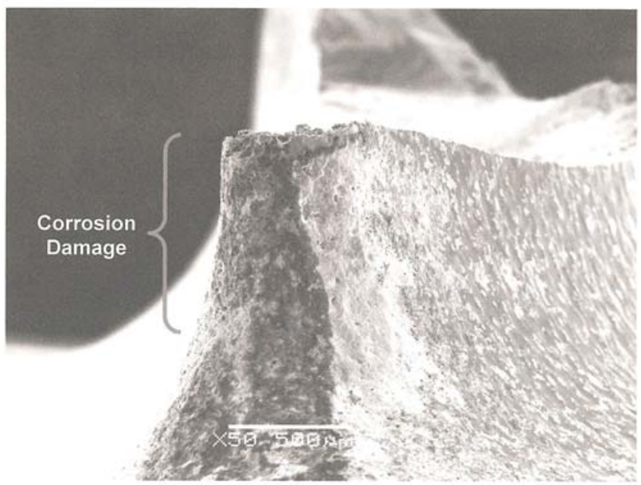
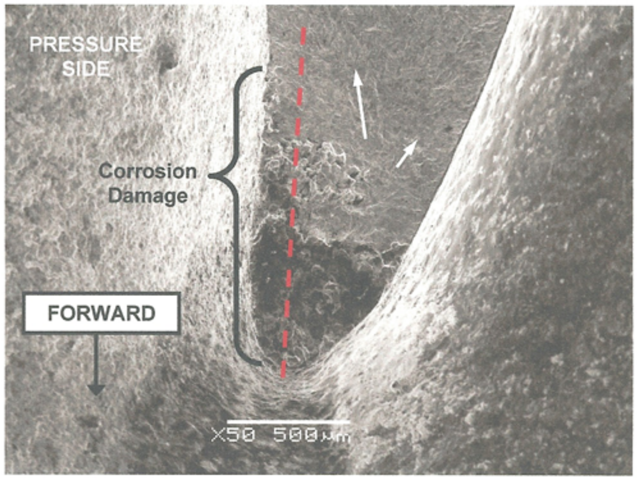


Figure 7. **SEM image showing corrosion pitting along the leading edge of the fractured airfoil.**



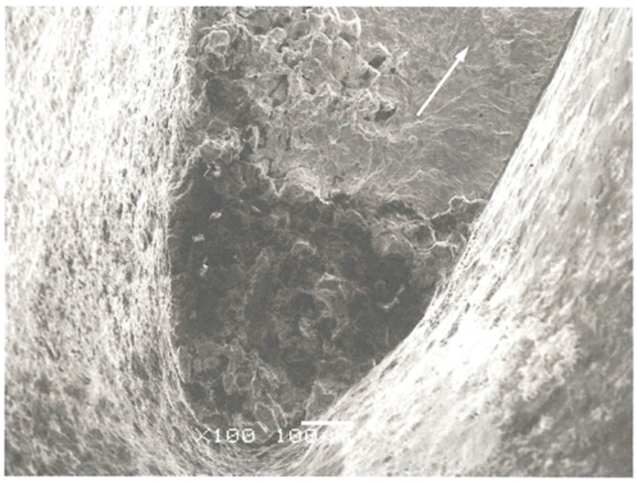


Figure 8. **Photographs showing corrosion damage at the leading edge near the fracture origin. White arrows indicate the general direction of fatigue propagation. A dashed line shows the plane of metallographic examination.**

Rolls-Royce

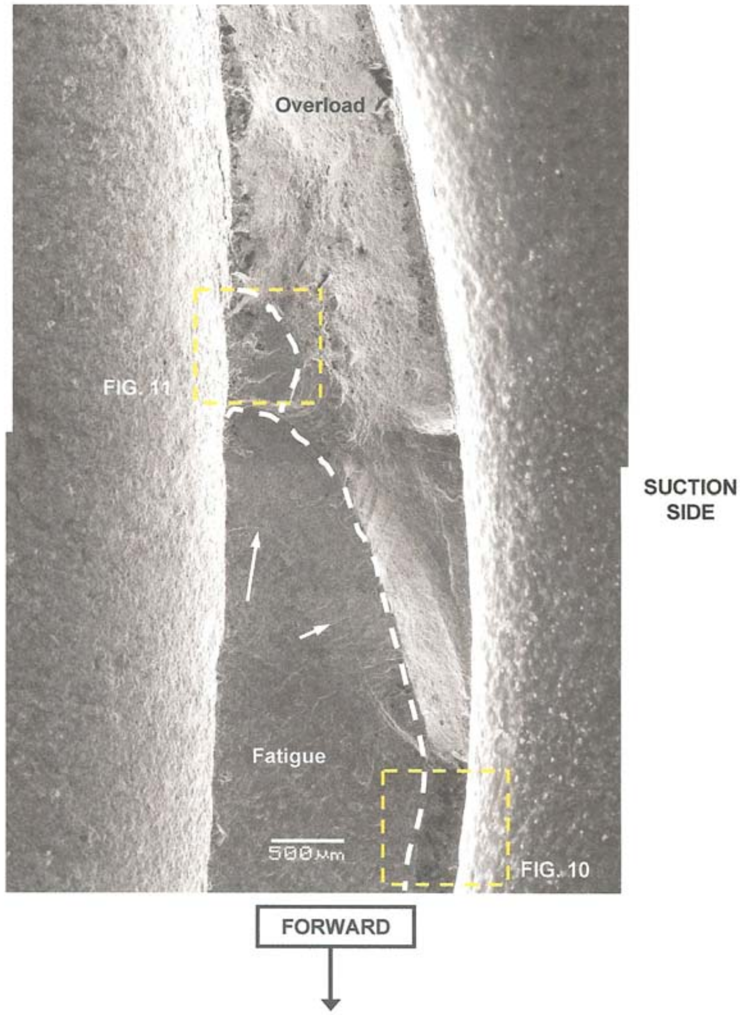


Figure 9. **SEM montage showing the fracture surface near the airfoil trailing edge. Arrows show the general direction of propagation. Dashed boxes show regions of further examination. Mag ~30x.**

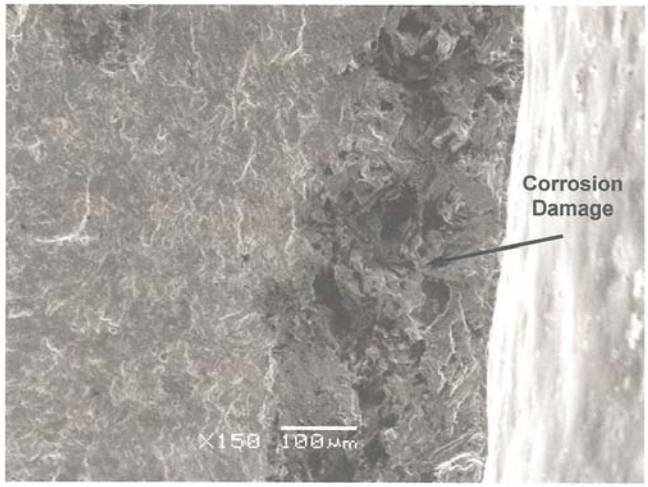


Figure 10. SEM image showing detailed view of corrosion damage observed on the suction side of the airfoil.

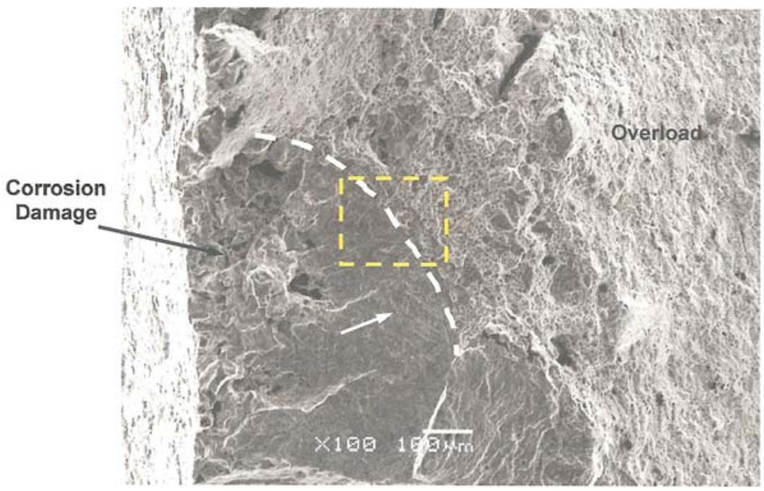


Figure 11. SEM image showing detailed view of fatigue propagation from a region of corrosion damage observed on the pressure side of the airfoil. Dashed box shows region of further examination.

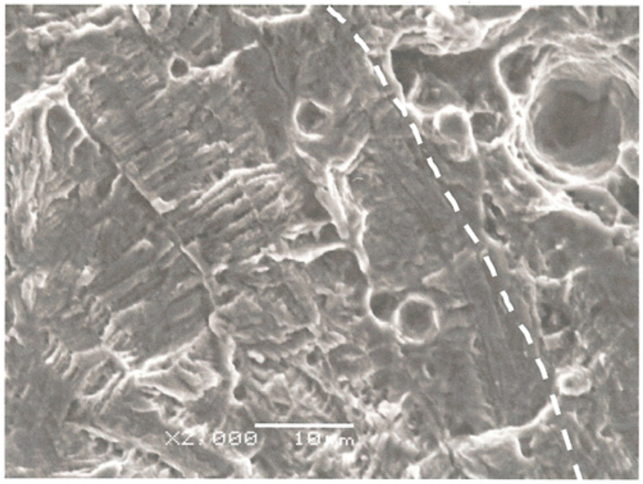


Figure 12. SEM image showing transition region (reference Figure 11) from fatigue (lower left) to overload (upper right).

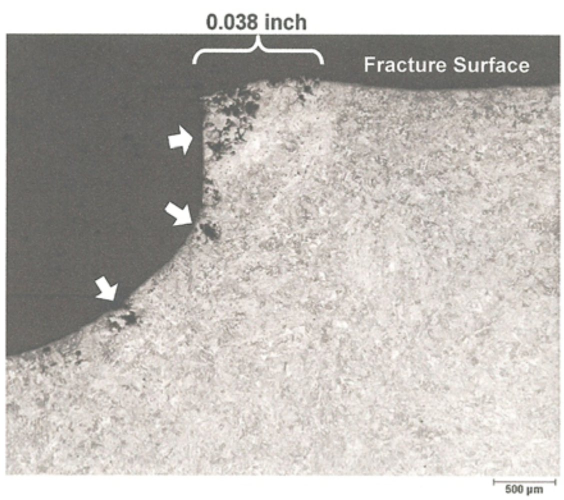


Figure 13. Micrograph of airfoil #1 showing cross section through corrosion damage along plane indicated in Figure 8. Bracket and arrows show corrosion damage. Etchant: Stainless Steel #2, 25x.

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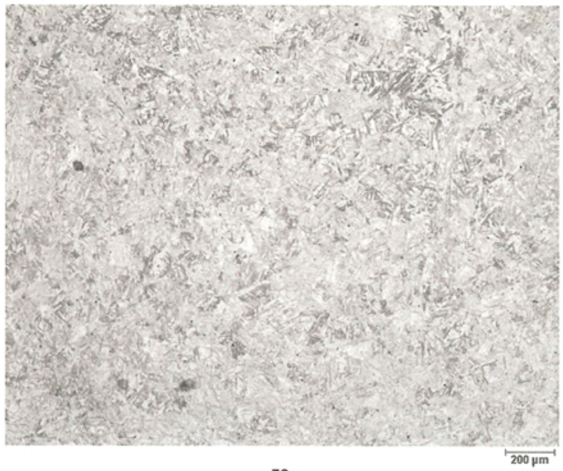
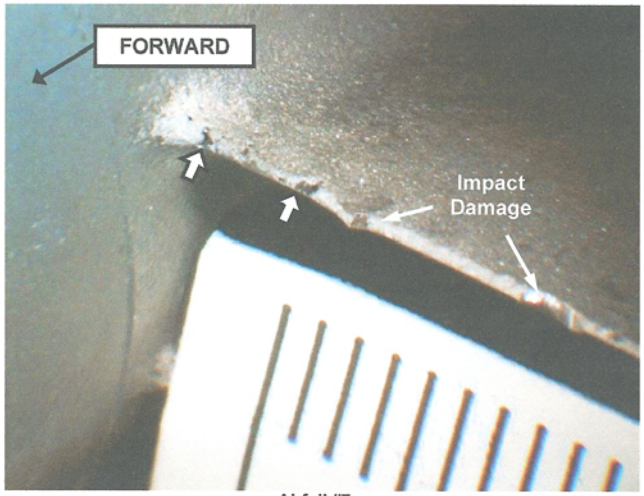


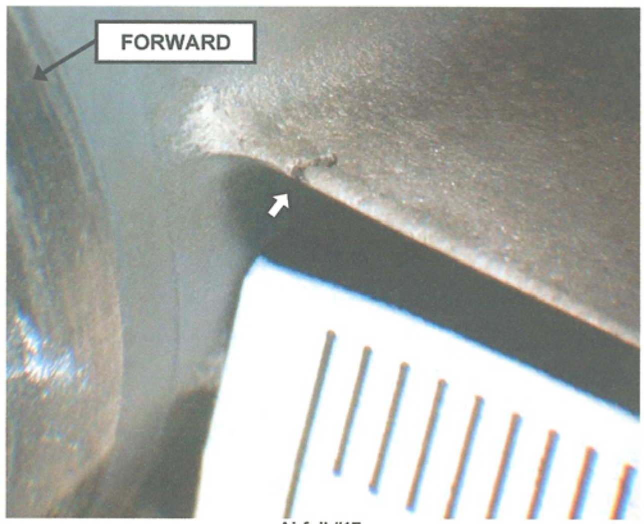
50x

500x

Figure 14. Micrograph showing representative microstructure of the wheel (away from region of corrosion damage) was typical for 17-4PH. Etchant: Stainless Steel #2.



Airfoil #7



Airfoil #17

Figure 15. Detailed views showing most severe examples of pitting observed on the airfoil leading edges and identified by block arrows. Scale = mm.

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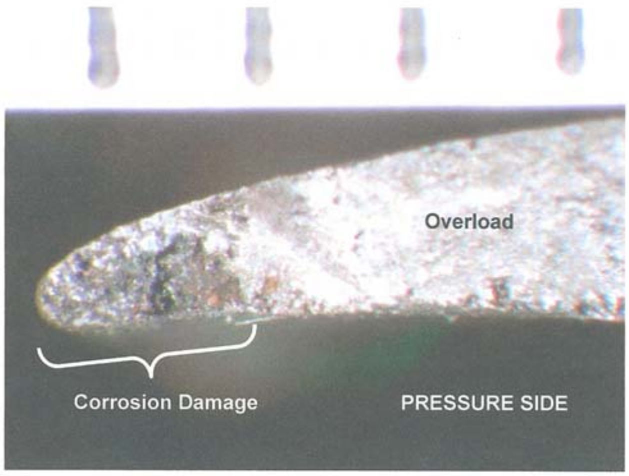

Figure 16. Photograph showing lab-fractured surface of airfoil #17 (view looking inboard). Corrosion damage was observed at the lead edge. Scale = mm.

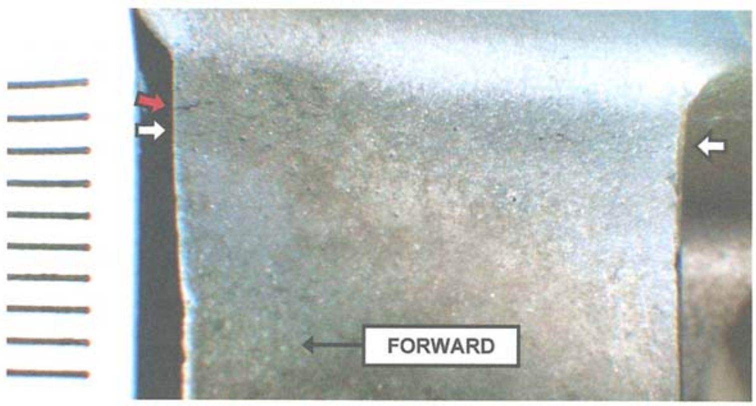

Figure 17. Detailed view showing leading and trailing edge cracks observed near the root of airfoil #2 (pressure side). Block arrows identify location of observed cracks and the red block arrow indicates the lab-fractured crack. Scale = mm.

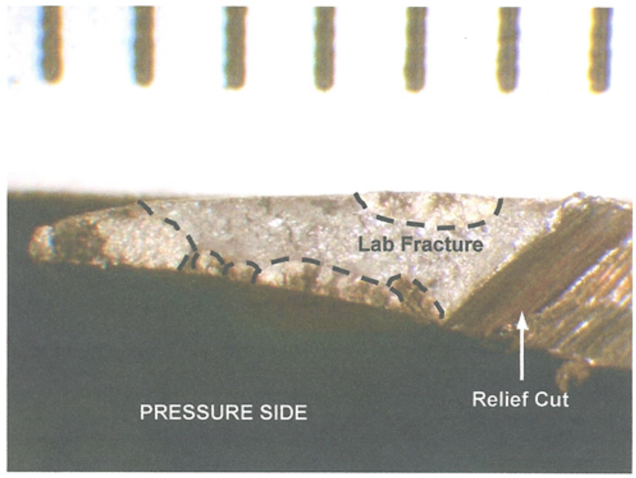

Figure 18. Photograph showing the lab-fractured surface of airfoil #2 (view looking outboard). Corrosion damage (dark regions) was observed along the pressure and suction sides and at the leading edge. Dashed lines show multiple regions exhibiting fatigue propagation. Scale = mm.

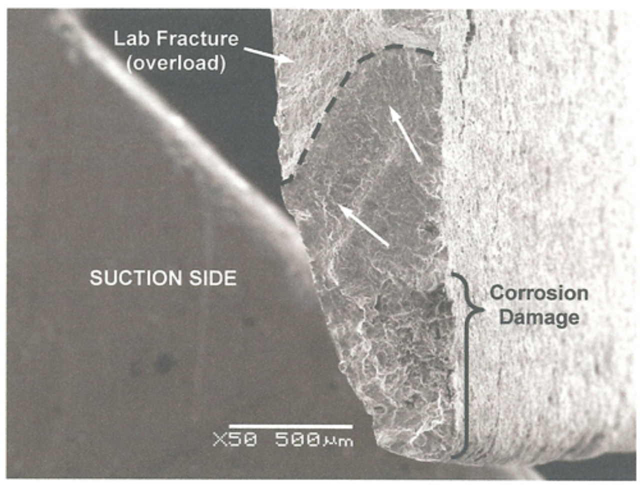

Figure 19. SEM image showing fatigue propagation from a region of corrosion damage at the leading edge of airfoil #2 (view looking outboard). Arrows show the general direction of fatigue propagation.

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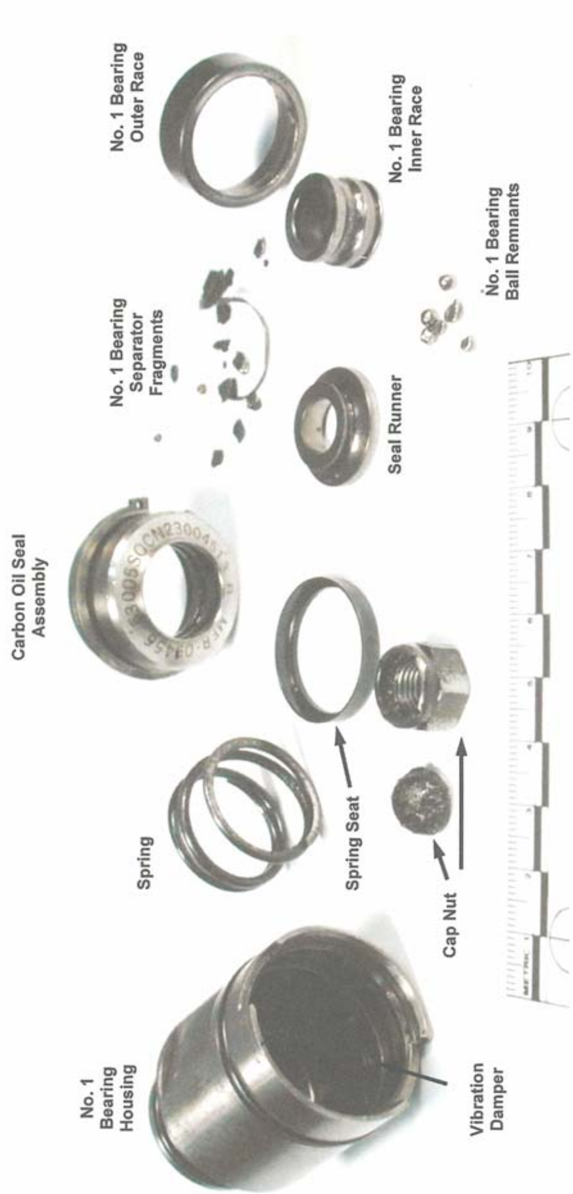


Figure 20. As-received condition of the No. 1 Bearing housing and components. Scale = cm.

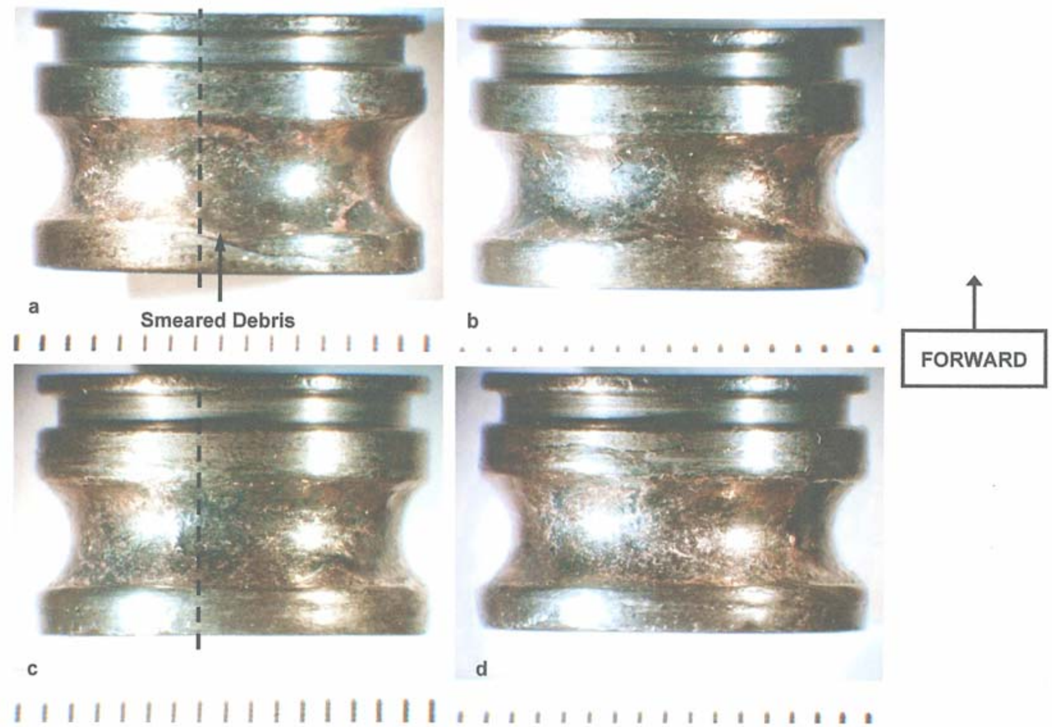
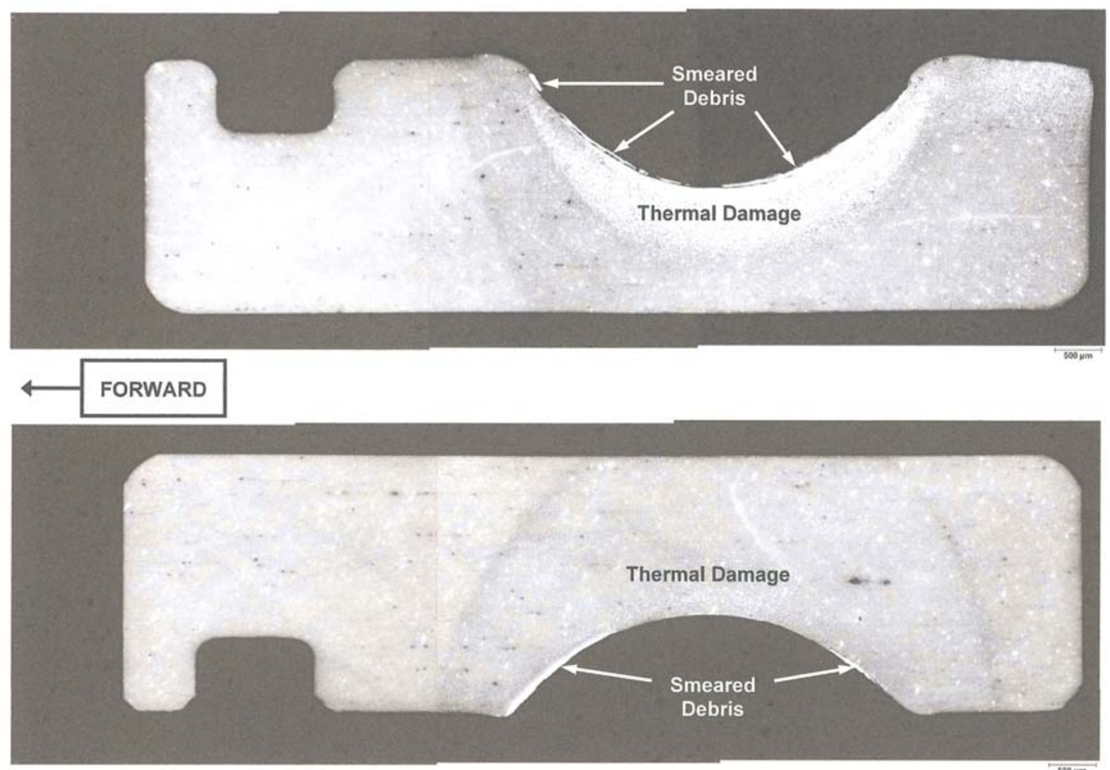
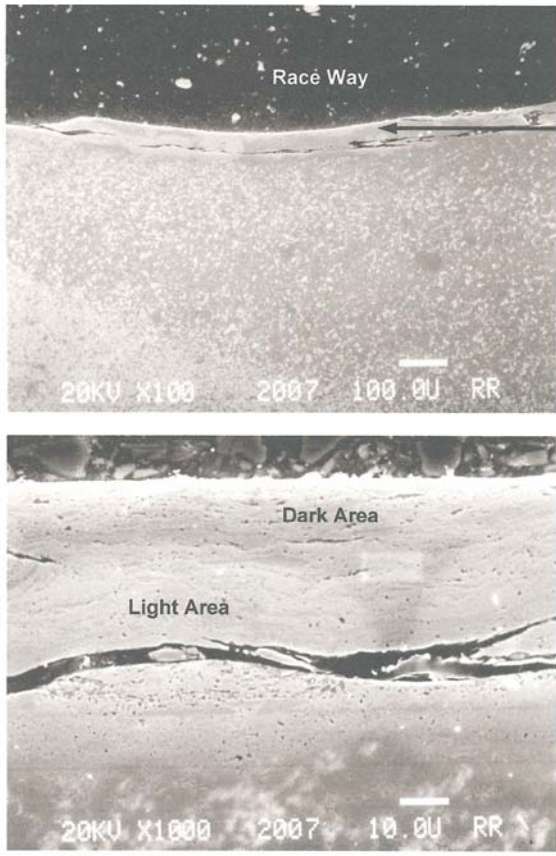


Figure 21. Detailed views showing the inner race of the No. 1 bearing rotated increments of 90 degrees (clockwise, aft looking forward. Debris from the separator was observed smeared onto the race. Dashed lines show approximate plane of metallurgical examination. Scale = mm.



(approximately 180 degrees away)

Figure 22. **Photographic montages showing the cross section through the No. 1 bearing inner raceway. Evidence of thermal damage was observed. Etchant: 5% Nital, 18x.**



	Si	Sn	Cr	Mn	Ni	Cu	Fe
Dark Area	0.5	3.1	0.4	0.2	0.2	74.2	21.5
Light Area	0.6	2.6	0.7	0.3	0.0	59.1	36.8

	Si	Mo	Cr	Mn	Ni	Cu	Fe
Inner Race	0.5	0.0	1.7	0.4	0.1	0.3	97.0
Ball	0.5	0.0	1.5	0.5	0.1	0.1	97.4

Figure 23. SEM images showing metal debris smeared onto the inner raceway. XEDA results indicating composition for light and dark regions and the inner race and ball bearing material included.

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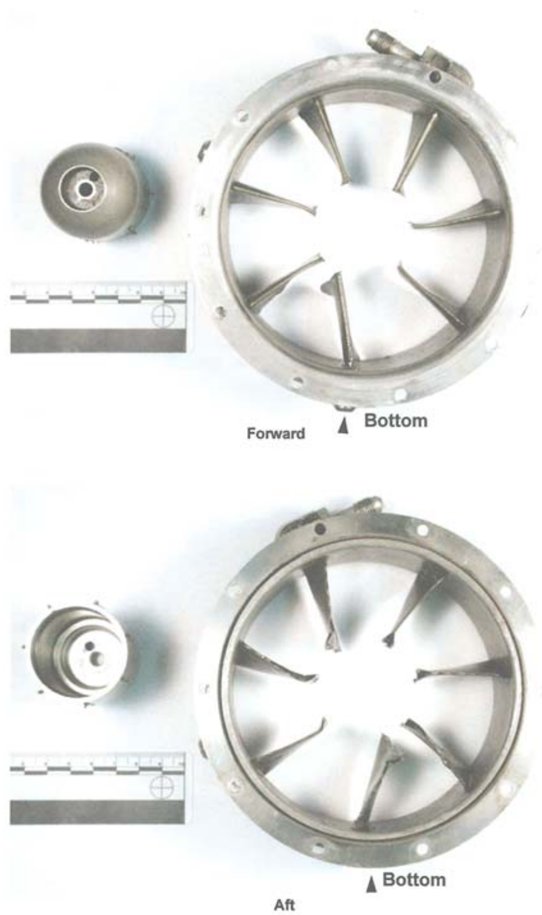
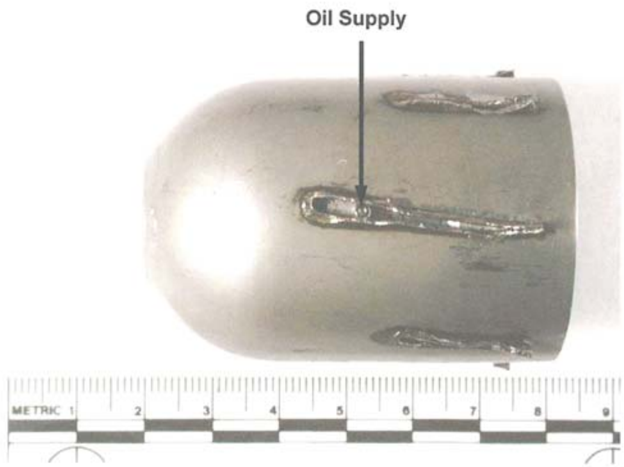


Figure 24. As-received photographs of the front support. Scale = cm.



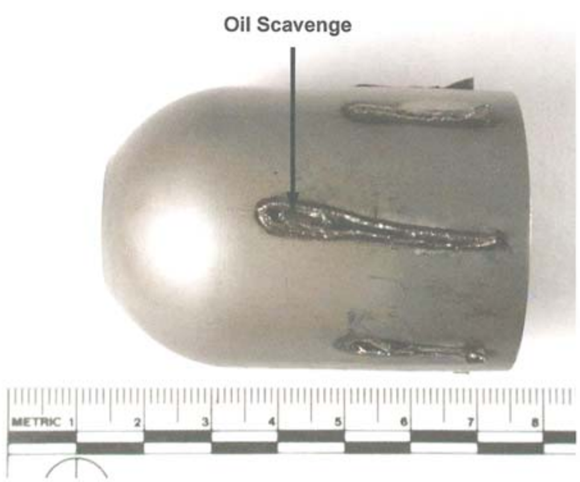


Figure 25. Photograph showing the fractured bullet nose (inner hub) of compressor front support. The oil supply and oil scavenge tubes were fractured. Scale = cm.

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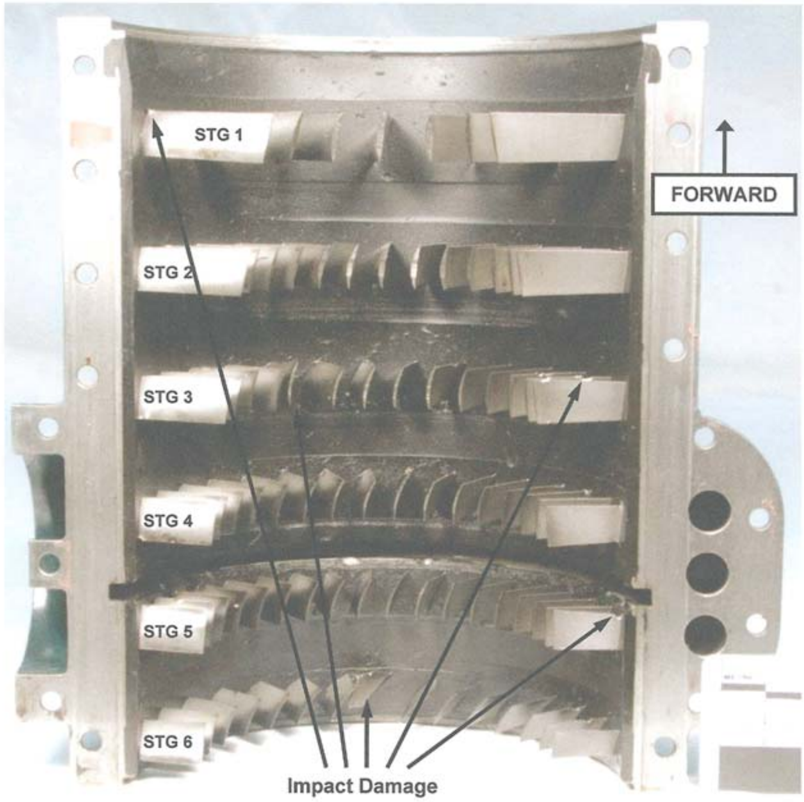

Figure 26. As-received condition of the Upper Compressor Case and Vanes. Scale = cm.

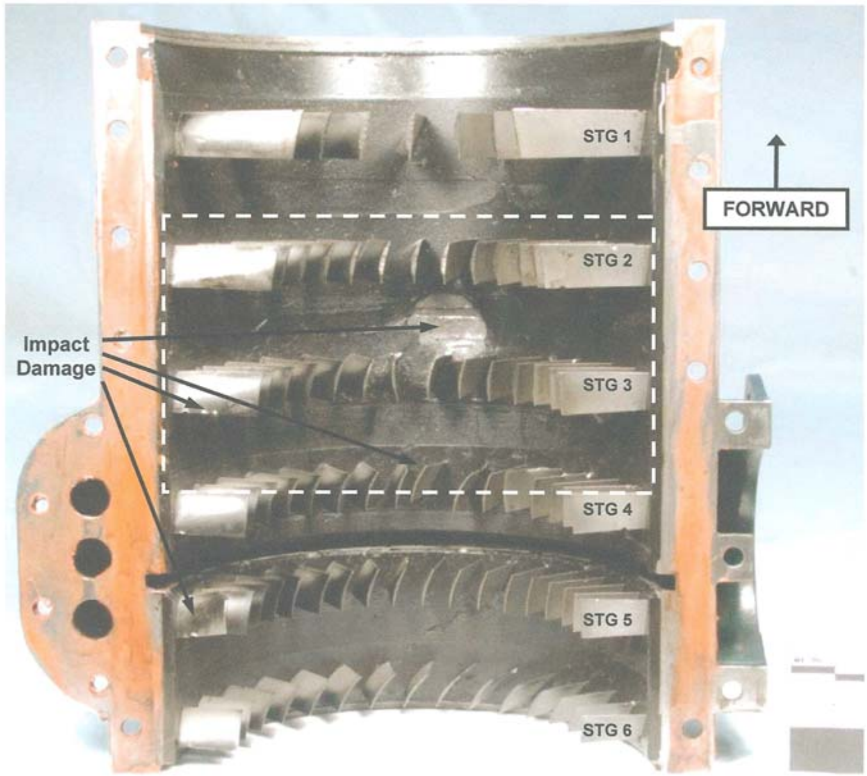

Figure 27. As received condition of the Lower Compressor Case and Vanes. Dash-boxed region is detailed in Figure 28. Scale = cm.

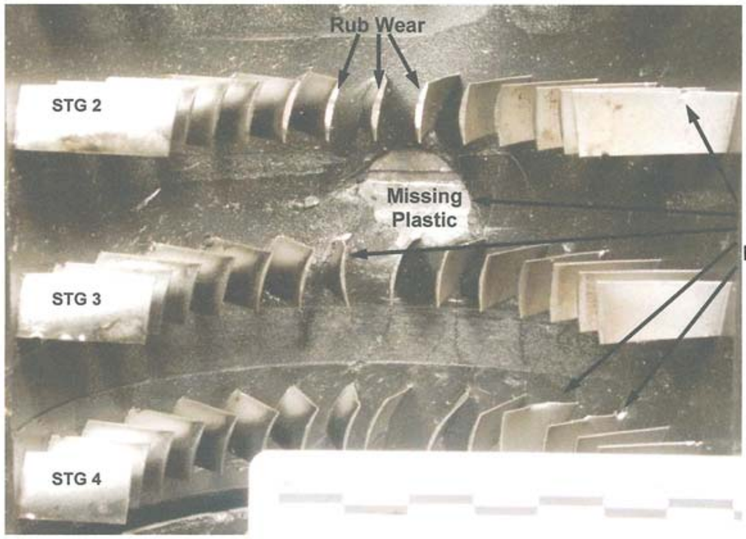

Figure 28. Detailed view of the lower compressor case showing rub wear on the inboard vane tips. Impact damage to the vanes, abradable plastic, and cracking of the abradable plastic was observed. Scale = cm.

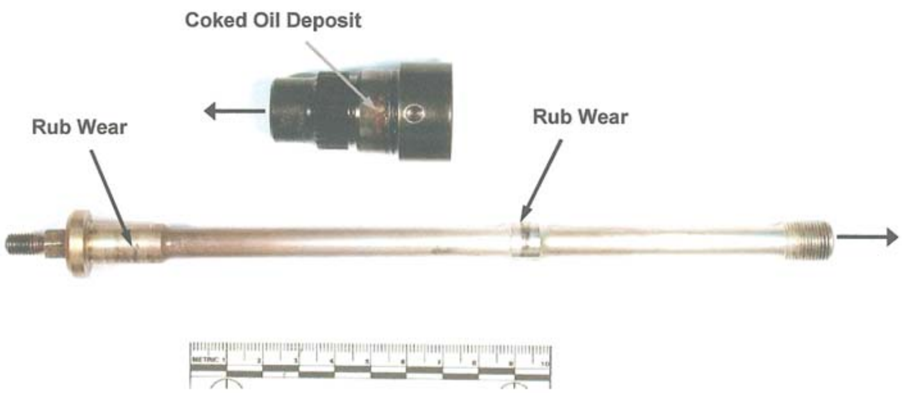

Figure 29. General condition of the compressor splined adapter and tiebolt. Arrows at center-line indicate forward direction for each component. Scale = cm.