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Turbine Engine Fan Disk Crack Detection Test

September 2004

Final Report

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16. Abstract

The damaging effects from an uncontained aircraft turbine engine failure can be catastrophic and result in significant economic costs.. As a result, the Federal Aviation Administration (FAA) has a program that conducts research to mitigate the damaging effects of such an event. The Aircraft Catastrophic Failure Prevention Program works with industry and government to determine possible engineering solutions to provide the means to detect damage to engine components that could lead to an uncontained engine failure or premature engine failure.

The FAA teamed with the National Aeronautics and Space Administration, the U.S. Navy, and the U.S. Air Force to demonstrate a number of different disk crack detection technologies that the team members evaluated on a full-scale turbine engine test funded by the FAA. The Naval Air Warfare Center, Weapons Division was tasked to conduct the turbine engine disk crack detection test. The objective was to grow a crack in a running engine and to evaluate the ability of various technologies to identify a crack and track its growth prior to an uncontained engine failure. This report documents testing that was conducted in the evaluation of seven different technologies during crack propagation testing on a retired military engine, which was intentionally flawed to initiate the failure condition.

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LIST OF ACRONYMS

AADC	Allison Advanced Development Company
CECI	Creative Engineering Concepts Inc.
EDM	Electron discharge machining
FAA	Federal Aviation Administration
GE	General Electric Company
IDINY	Innovative Dynamics Inc.
IRP	Intermediate-Rated Power
MEMS	Micro Electro-Mechanical Systems
N1	low-speed shaft
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Aviation Systems Command
NAWC	Naval Air Warfare Center
P/N	Part number
PHM	Prognostics and health monitoring
PLA	Power level angle
rpm	Revolutions per minute
S/N	Serial number
USAF	U.S. Air Force
WSL	Weapons Survivability Laboratory

EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) Aircraft Catastrophic Failure Prevention Program has been investigating uncontained engine failure mitigation with extensive studies on historical failures, modeling of aircraft vulnerability, and design of mitigating actions. This effort initiates a proactive approach to detecting cracks in engines while they are running on the airplane that can lead to uncontained engine failures. The FAA, through meetings with the Department of Defense and the National Aeronautics and Space Administration (NASA), learned of emerging technologies that had shown promise in the laboratory. A collaborative test effort was conducted to demonstrate the technologies on a full-scale engine test.

The FAA teamed with NASA, the U.S. Navy, and the U.S. Air Force researchers to design, develop, and test a full-scale fan disk crack propagation test. The FAA provided the test, and each of the government organizations funded the participation of their technology developers. This report summarizes the test effort. Additional reports are available from the various technology offices that sponsored the technology.

A man-made electron discharge machined flaw was inserted to ensure a disk failure during the 2-week test. To initiate crack from the man-made flaws, the disk was cycled in the spin pit before the full-scale engine test. Government and industry experts agreed that this was a critical risk reduction step to ensure crack growth during the full-scale engine test.

During the 2-week test, the engine completed 4474 cycles, and the posttest inspection showed the crack grew 0.03 inch on the outer tip and 0.020 inch on the inner tip. Crack growth was an order of magnitude less that predicted for the number of cycles. Therefore, several of the technologies were not effective at detecting the crack. Many of the crack detecting technologies showed a trend during the test, but the growth did not exhibit characteristics that indicated the crack was near failure.

This was the first successful full-scale test that had achieved crack growth. Researchers have learned a great deal about full-scale engine noise levels and how to execute this type of test. Follow-on work will continue to examine limited crack growth so that future testing will be more successful.

1. INTRODUCTION.

A test was conducted at the Naval Air Warfare Center (NAWC), Weapons Survivability Laboratory (WSL), China Lake, CA, from March 24 to April 4, 2003, to assess various strategies for detecting and monitoring crack growth on the rotating engine components of an Allison TF41-A-1B engine. This test was conducted as part of the Aircraft Catastrophic Failure Prevention Program and was sponsored by the Federal Aviation Administration (FAA), the Naval Aviation Systems Command (NAVAIR), the U.S. Air Force (USAF), and the National Aeronautics and Space Administration (NASA). Collaboration and planning are described in references 1 and 2.

This report will provide the results of the testing, but does not discuss the participants' findings. Reports will be generated and submitted to the sponsoring government organization by each of the seven test participants (Allison Advanced Development Company (AADC), Creative Engineering Concepts, Inc. (CECI), ExSell Inc., General Electric Company (GE), Hood Technology Corporation, Innovative Dynamics Inc. (IDINY), and Test Devices Inc.) documenting their observations of crack growth and their results. Posttest eddy-current testing of the fan disk by the USAF of the TF41-A-1B fan indicated a 0.02-0.03-inch growth on each side of the crack during 4474 engine power cycles performed at the WSL.

1.1 BACKGROUND.

The Aircraft Catastrophic Failure Prevention Program was established by the FAA to perform research that will improve safety related to uncontained engine failures. Part of the strategy to reduce uncontained engine failures is to investigate engine disk crack detection. The detection strategies proposed by the seven test participants allow cracks to be detected as they form, before they reach critical size. Early detection of cracks in the engine rotors can prevent a catastrophic uncontained engine event. This detection system may also reduce maintenance costs by increasing the time between inspections and reducing the number of spares required. Currently, the only method to monitor the engine rotor degradation is to periodically remove the engine from service, teardown the engine, and inspect each rotor. Past experience indicates disassembly of the engines for inspections increases the risk of maintenance errors and has resulted in engine failures.

1.2 PROJECT OBJECTIVES.

The objective of this program was to demonstrate promising technologies in engine rotor prognostics and health monitoring (PHM) for rotor disk fatigue. These technologies have the potential to reduce the likelihood of catastrophic engine events by signaling the formation of cracks before they reach critical size. This test provided the seven participants an opportunity to use their detection strategies to monitor the effects of a propagating crack on the first-stage fan of the TF41-A-1B engine.

2. TEST OBJECTIVES.

Although several of the crack detection strategies that were examined in this test were previously tested in laboratories, none had been tested on an engine with a known crack. This test allowed the seven participants to evaluate their detection strategies on a functioning engine with a seeded fault. The results from this test provided insight into how their detection methods are able to accommodate a real engine vibration and thermal environment and other factors not present in the spin pit test. The participant's results from the test will also help to identify what PHM strategies should be explored in future studies. This test plan defined the approach that was taken in demonstrating the crack detection strategies.

3. APPROACH.

The fan disk was targeted for the test because fan disks have been shown to produce the largest threat to the aircraft, and the environment of the fan section of the engine is considered more suitable for installation of the crack detection components. Impact Technologies, LLC was tasked with performing a stress and fracture analysis on the TF41-A-1B fan disk [3]. The results of their analysis were used to determine the location of a seeded fault in the fan disk. An electron discharge-machined (EDM) notch was made on the front face of the first-stage fan. The fan was then cycled in a spin pit to initiate crack growth thus reducing the risk of the crack not growing on the more expensive on-engine test. The fan was installed on the NAWC, WSL's TF41-A-1B engine. Sensors were placed on the engine as specified by the participants. The disk was subjected to 4474 power cycles during the 2-week test.

Seven participants were selected to monitor the propagation of the seeded crack in the TF41-A-1B fan disk.

1. AADC used Micro-Electro-Mechanical Systems (MEMS) Sensors on the rotors in an attempt to measure acoustic emissions, which are indicative of crack growth.

2. ExSell Inc. used capacitive probes to monitor the change in position of fan blades as a result of the rotor imbalance to determine the crack growth [4].

3. GE used vibration sensors in conjunction with its detection algorithms to detect the vibration signature of the cracked disk [5].

4. Hood Technology monitored the spacing of the fan blade tips to determine blade and disk deformation and applied their algorithms to try to identify impending disk bursts [4, 6].

5. IDINY applied a smart sensor coating to the disk to monitor the size of the seeded crack [7].

6. Test Devices Inc. used vibration and position sensors to detect and track the crack growth [8].

7. CECI used an optical sensor to monitor markings on the back of the fan to provide a 60 per revolution signal. This signal was analyzed after the test was completed to detect changes in the crack size [9].

4. PRETEST PREPARATION AND TEST SETUP.

NAWC WSL coordinated the test plan [10] with the government sponsors and industry participants.

4.1 TEST SPECIMEN REQUIREMENTS.

This test was conducted on a TF41-A-1B test article engine, (figure 1) serial number (S/N) 141786. This turbofan engine's performance and trim were tested and found sufficient to meet the objectives of this test. The first-stage fan used for the engine checkout was part number (P/N) 23002949-B, S/N MM15299, and P/N 23002949-B, S/N MM15045, was used for the seeded fault test.

FIGURE 1. TF41-A-1B ENGINE

4.1.1 Engine Description.

The TF41-A-1B engine is an axial flow gas turbine engine with a round fixed-geometry inlet, five-stage, low-pressure compressor, including a three-stage low-bypass-ratio fan, and a variable geometry 11-stage, high-pressure compressor. The compressor rotors are driven by two-stage, low- and high-pressure turbines through a coaxial shaft. The combustion section consists of ten can-annular axial flow combustors. A bypass duct directs fan discharge air to an annular mixing station to be blended with turbine exhaust gasses upstream of the fixed-area convergent exhaust nozzle. The engine has no afterburner [11]. The TF41-A-1B engine first-stage fan is the first stage of the low-pressure compressor. It has dovetailed blades and a slotted disk with a midspan shroud.

As a result of the engine checkout runs, one section of the three-section exhaust nozzle was removed prior to checkout run 15 to reduce the engine backpressure and to allow higher low-speed shaft (N1) revolutions per minute (rpm). This will be explained in greater detail in section 7. The result of removing this section was a 20% increase in the exhaust nozzle area (A8).

4.1.2 Engine Instrumentation.

Test Devices Inc. provided an instrumentation ring to be mounted on the plate seal of the stators, aft of the first-stage fan. The ring was tack welded to the bolt circle on the front static air seal shown in figure 2. The instrumentation ring contains the radial proximity probes and speed sensors. The sensor wires were routed outside the engine case through the hollow stator vanes. A sensor continuity check was performed prior to reinstalling the first-stage fan, spanner nut, and spinner cap. Test Devices Inc. also monitored the proximity of the sensors to the aft face of the fan during the fan installation to prevent damage to the sensors.

FIGURE 2. TF41-A-1B WITH SPINNER CAP, SPANNER NUT, AND FIRST-STAGE FAN REMOVED TO SHOW THE BOLT CIRCLE

Figures 3 and 4 show the sensors installed on the engine as well as their locations. Figure 3 shows the front face of the engine with the fan removed, exposing the first-stage stator section. The IDINY and AADC sensors are not shown since they were mounted on the fan.

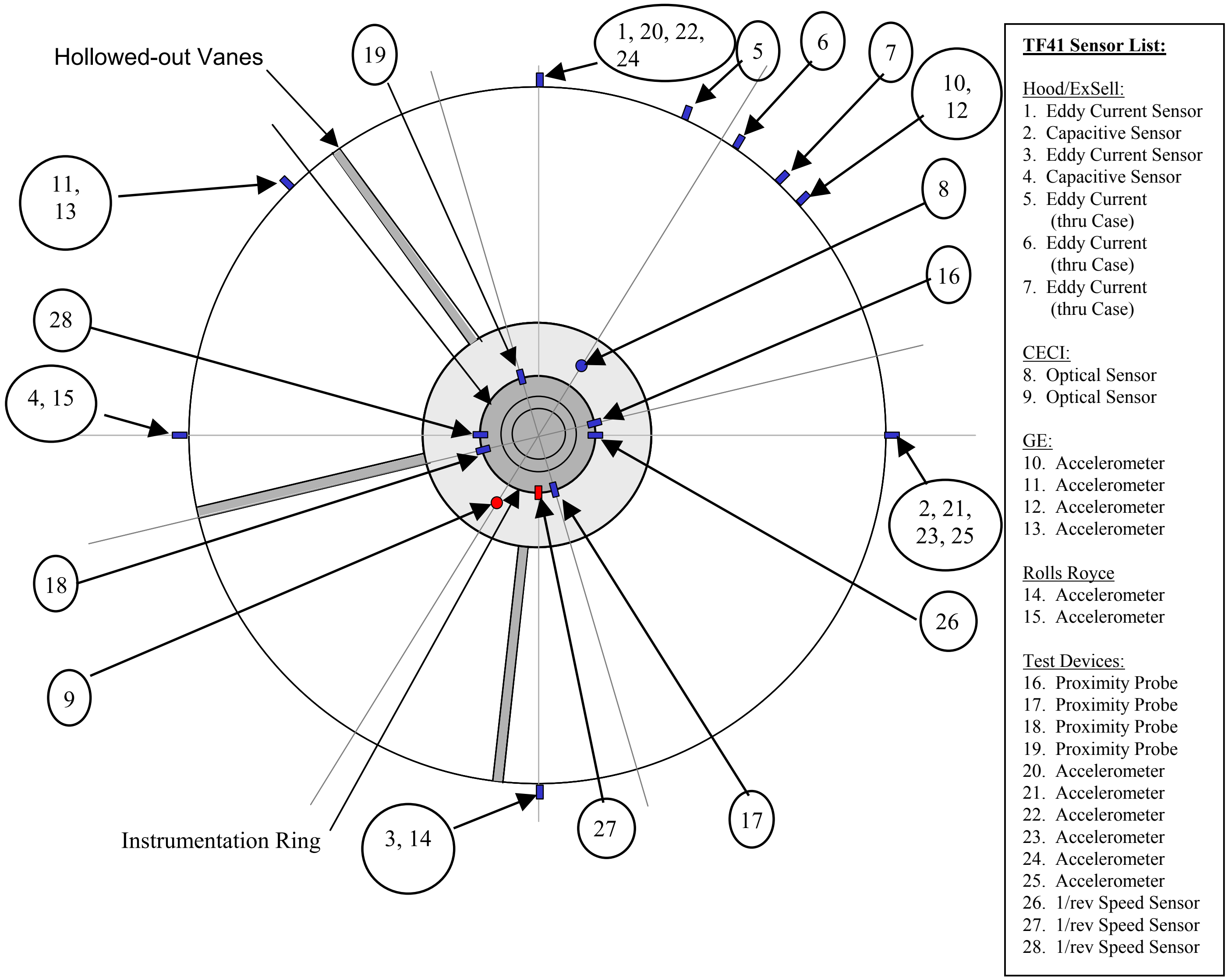

FIGURE 3. SENSOR LOCATIONS
(Front face of the TF41-A-1B engine with the fan removed.)

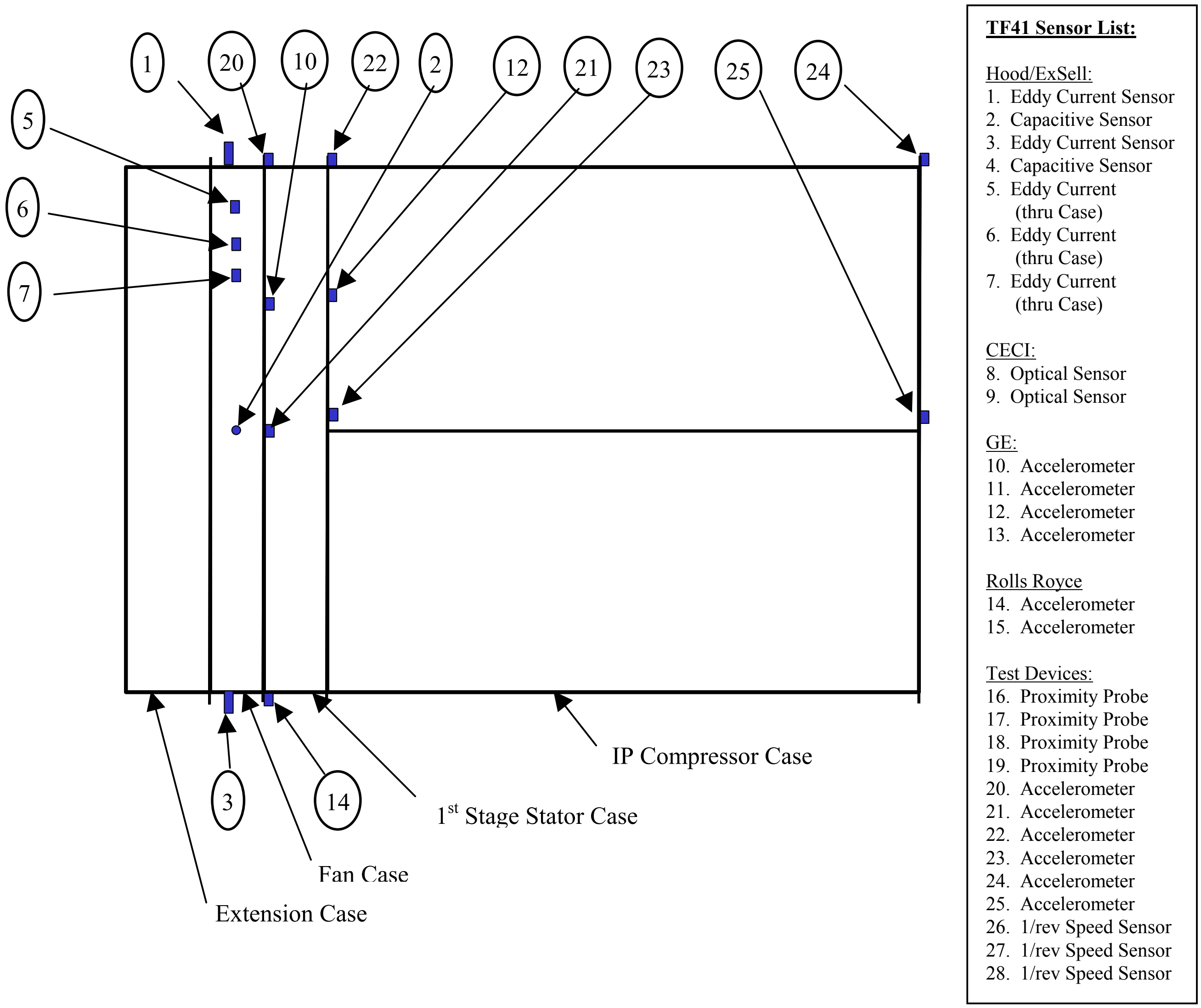

FIGURE 4. SIDE VIEW OF THE TF41-A-1B ENGINE INCLUDING THE EXTENSION AND FAN CASES

4.1.3 First-Stage Fan Modifications.

A notch was made in the first-stage fan of the TF41-A-1B engine. The size and location for this notch were recommended by Impact Technologies, LLC following a stress analysis of the fan. The design requirements for the analysis were to design a seeded fault that would grow, over a 2-week test period, into a critical crack length that was representative of commercial aircraft catastrophic failure size and location. The material properties of the older TF41-A-1B design necessitated that a moderate stress region of the disk be selected to obtain the desired growth. The midweb region was selected because it had been a source of disk failures in commercial engine accidents.

The initial EDM notch was a 0.100-inch radius electron discharge-machined half-penny slot (0.200″ length at the surface) on the forward face of the first stage fan disk. The disk was subjected to a total of 20,140 cycles, each cycle ramping approximately from idle (3000 rpm) to 8500-8800 rpm in the Test Devices Inc. spin pit. These spin pit cycles were intended to initiate a crack in the disk to ensure further crack growth when the fan was on the engine. Fluorescent penetrant was used to periodically inspect the crack during spin pit testing. All inspections conducted with fluorescent penetrant inspection (FPI) were negative in the spin pit. It is important to note that sensors surrounded the EDM notch, therefore polishing was not possible. At 20,140 cycles, a small FPI indication was present in the crack growth sensor but not in the parent material. The team decided to have the disk eddy-current inspected.

The disk was shipped to the Air Force Research Laboratory/Materials Integrity Branch (AFRL/MLSA) where they conducted an FPI, revealing no visible cracks at each end of the EDM slot in the parent material. However, the eddy-current crack inspection revealed that the spin pit cycling of the disk resulted in cracks approximately 0.100 ±0.010 inch long, extending from each end of the EDM slot. The disk was then shipped to NAWC China Lake for full-scale engine testing.

At the conclusion of the test, having completed 4474 on-engine throttle cycles, the fan was removed and sent to the AFRL/MLSA for inspection. The results of the testing and inspection are discussed in section 7.

4.2 TEST SETUP.

The test engine was set up on the C-3 test pad at the WSL.

Engine starts were accomplished using an auxiliary starter. The firing officer was on the test pad during engine start-up. Blast shields were placed between the engine and the auxiliary starter, as indicated in figure 5.

An armored instrumentation box was placed on the test pad near the engine, but outside the ±10° hazard zone for the fan. This box contained the signal-conditioning equipment provided by the participants and a patch panel linked to the control room patch panels.

Five cameras were positioned throughout the test pad to provide video monitoring and safety video (figure 5). In addition, two high-speed digital video cameras were positioned on either side of the engine to provide video in the event of disk failure. The break wire surrounding the fan case was used to trigger the cameras. The cameras were set to center trigger, meant that the cameras would capture a few seconds before and after the break wire was severed. Because there was no disk failure, the cameras did not trigger.

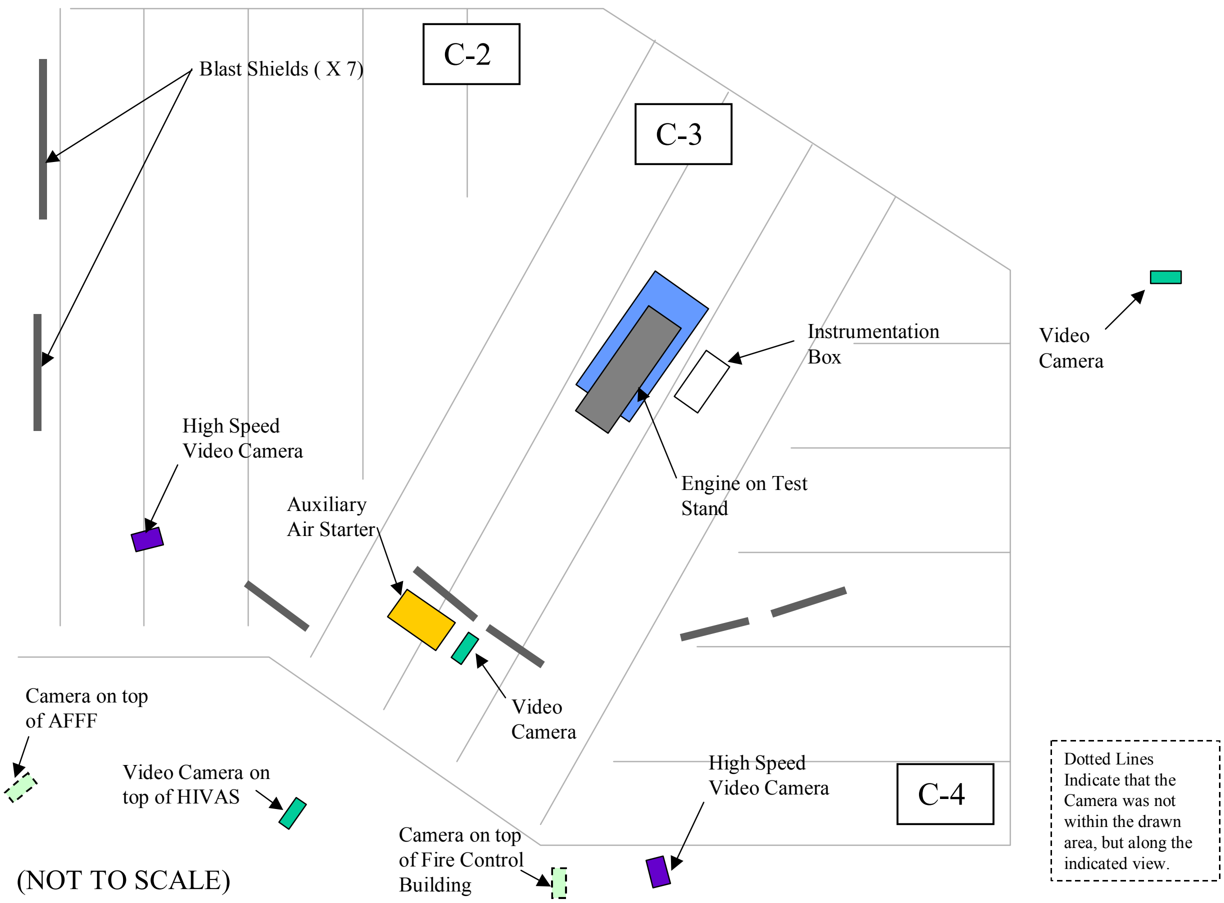

FIGURE 5. TEST PAD SETUP

A throttle cable was installed on the engine throttle controls. A step motor was placed on the engine stand to allow the throttle to be actuated from the WSL control room. A computer program provided the acceleration and deceleration schedule. A switch was provided to transfer throttle control between the manually operated throttle quadrant in the WSL control room and the autothrottle control. The throttle control worked by advancing the throttles to the maximum power level setting and controlling the engine's rpm using the airflow limiter. The T2 engine sensor was fed a false temperature signal to take advantage of the TF41-A-1B airflow limiter, restricting the low-speed shaft rpm to the desired speed. The variability of the resulting speed and the rpm profile observed during testing is discussed in section 7.

5. DATA.

5.1 INSTRUMENTATION.

Instrumentation requirements for monitoring general engine health are shown in table 1.

The participants provided and monitored their own sensors for crack detection. The sensors were positioned, as shown in figures 3 and 4.

TABLE 1. INSTRUMENTATION

Symbol	Range	Frequency (Hz)	Parameter	Output
	Engine Instrumentation			
N1	0-10,000	50	Low-pressure rotor rpm (±10 rpm)	L W
N2	0-15,000	50	High-pressure rotor rpm (±20 rpm)	L W
PLA	0-68.5°	50	Power level angle	L W
Poil	0-200 psig	50	Engine oil pressure	L W
T5	0-2000°F	50	Turbine exit temperature	L W
P7	0-350 psig	50	Exhaust pressure	L W
Wftot	0-15,000 pph		Total fuel flow	W-+
REV	0-10,000 rpm	50	1/rev signal	L
	On-Site Conditions (record in logbook)			
Pa			Atmospheric pressure	W
Ta			Ambient temperature	W
Tf			Bulk fuel temperature	W

L - LabView, T - tape record, W - worksheet (hand recorded)

Due to the number of channels and frequency of the sensor data, not all channels could be recorded at all times. Data were collected at a low sample rate from all sensors routed through the WSL amplifiers (with the gain set to 1, unless otherwise requested). Several sensors were not routed through the amplifiers for fear that the signal would be distorted. Ambient conditions were periodically recorded from the WSL weather station.

5.2 VISUAL AND AUDIO RECORDS.

Five video cameras (including safety video) were used to monitor and record the response of the test engine and certain related equipment and are positioned, as shown in figure 5.

The engine was instrumented with break paper or break wires to trigger the high-speed digital video cameras. These cameras were to be post-event-triggered by the break wire to capture the disk burst. Since this event did not take place, the cameras did not trigger. The locations of the cameras are shown in figure 5 (represented by the purple rectangles).

Color still photographs were taken of the test setup and ancillary equipment before, during, and after the test. These digital images taken by the WSL crew and distributed to the participants on compact disks due to security regulations.

6. TEST PROCEDURES.

6.1 ENGINE CHECKOUT AND BASELINE TESTS.

An engine checkout was performed several months prior to the seeded fault test to ensure nominal engine performance. Preliminary data collection was incorporated into the engine checkout. However, while this provided baseline engine noise and sensor checkout for those participants with sensors installed for the checkout run, the engine was run with an undamaged fan. The undamaged fan's part number matched that of the seeded fault fan. Therefore, the data collected during the checkout runs were preliminary data, rather than real baseline data.

Checkout included normal engine operability runs to ensure nominal engine control and performance. The automatic throttle controls were tested during the engine checkout runs. These checks included the automatic throttle capability, cycle repeatability, automatic and manual switch, and the go-to-idle switch. The data from the checkout runs indicated that the variation in the top end rpm for the engine power cycles was as much as ±150 rpm. This issue will be addressed in greater detail in section 7.

Some of the participant-furnished sensors were installed during the engine checkout. The 1/rev signal was tested to determine if the fidelity of the signal met the participant's requirements. All the participants requesting the 1/rev signal deemed it acceptable.

The test matrix for the baseline testing included several runs with an imbalance applied to the first-stage fan. Test Devices Inc. provided a test matrix indicating the weights they wished to add to various locations on the disk. However, due to time constraints, the number of runs was limited. Several different sized lead weights were added to the disk at various locations to simulate crack-induced imbalance of the disk.

A second engine checkout was conducted 1 week prior to the seeded fault test. The purpose of the second checkout was to ensure the engine was still functioning within allowable limits after almost a year of being in storage and to adjust the K type thermocouple simulator to provide a false temperature signal that would reduce the fan overspeed limit to 8500 rpm and 8800 rpm. The thermocouple simulator was set to various temperatures and the throttle advanced to its maximum position for each setting and the maximum and sustained rpm were recorded. Unfortunately, the airflow limiter allowed both the N1 and N2 (high-speed shaft) to spike before it invoked the limiter. This speed spike occurred both when the throttle was advanced quickly and when it was advanced slowly. The rpm variability is discussed in greater detail in section 7.

6.2 SEEDED FAULT TEST.

The sensors agreed upon by the participants were installed on the TF41-A-1B engine, as shown in figure 6. The disk with the seeded crack was installed on the TF41-A-1B engine with IDINY's crack detection mesh and AADC's MEMS sensors already applied. Installation was performed in accordance with Navy maintenance procedures [12].

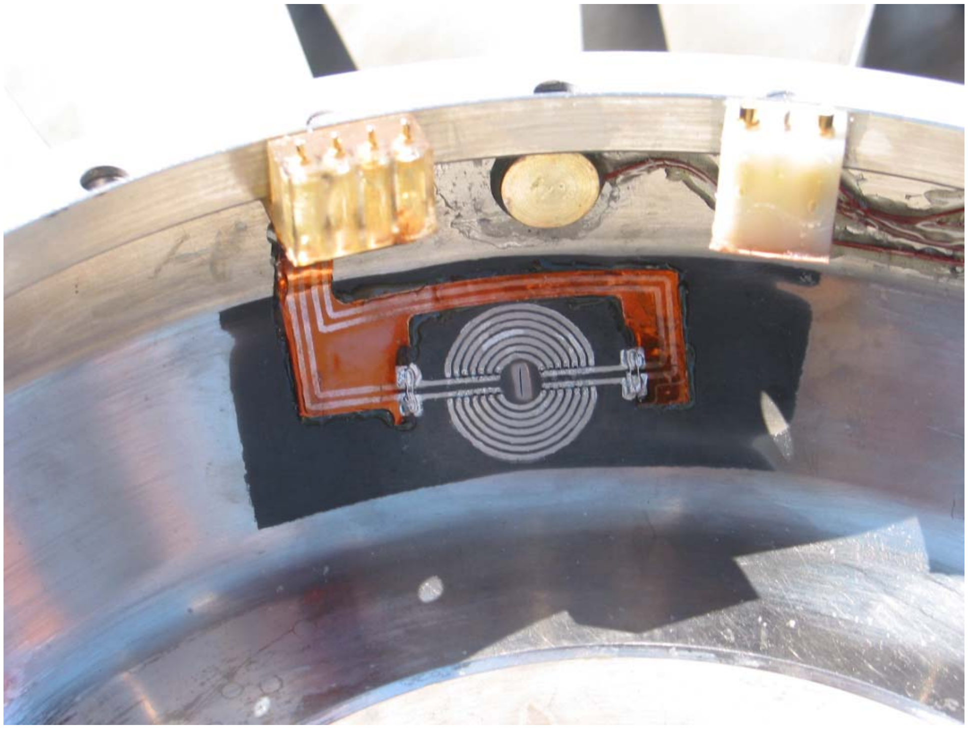

FIGURE 6. TF41-A-1B DISK WITH EDM CRACK
(Shown with the IDINY crack wire sensor and AADC acoustic sensors in place.)

A run sheet was maintained by the test engineer to record any events that occurred during testing. The run sheet included pauses in testing and the number of cycles at each break in testing.

- Morning checkout procedure:

  1. Walk around the engine to ensure all sensor and control connections are intact and remove battery-recharging cables (AADC/IDINY).

  2. Turn on the power to the signal-conditioning equipment in the armored box on the test pad.

  3. Turn on the T2 thermocouple simulator.

  4. Check that the break wire is intact, and turn on the cameras.

  5. Aqueous film forming foam checkout.

- Start-up Procedure:

  1. Turn on the safety video.

  2. Turn on the fuel farm.

3. Open the fuel valve (wall).

4. Check camera view positions.

5. Start data recording.

6. Start the engine.

7. During the 2-3 minute soak at idle, verify that all sensors are functioning correctly.

8. Cycle the engine manually: (the total cycle should be approximately 3 minutes long)

    a. Ensure that no personnel are outside the fire control building.

    b. Advance the throttles smoothly to intermediate-rated power (IRP). Monitor N1 to ensure that the fan speed does not exceed 8550 rpm.

    c. Allow 30 seconds for the engine to stabilize at IRP. Check the engine sensors to ensure normal engine operation.

    d. Retard the throttle smoothly to idle.

    e. Allow the engine to stabilize at idle for 2 minutes.

9. Switch throttle controls to automatic, making sure that the automatic power cycles are consistent.

10. Repeat the power cycles until disk failure or scheduled completion of the test. Monitor the engine parameters at all times to ensure engine health.

The engine was run approximately 9-10 hours per day when possible. The engine was shutdown or held at idle, as necessary, for access to the Fire Control Building, refueling, and at the end of each day.

Throttle cycles were modified during the course of this testing. The throttle cycles at the beginning of testing consisted of a long cycle followed by 27 short cycles.

1. The longer of the two power cycles consisted of a 30-second dwell at idle, a 75-second ramp to maximum speed (8500 rpm, N1), a 30-second dwell at maximum speed, and a 15-second ramp to idle (approximately 2500 rpm, N1) for a total cycle time of 150 seconds.

2. The shorter cycle consisted of a 15-second dwell at idle, a 15-second ramp to maximum speed, a 15-second dwell at maximum speed, and a 15-second ramp to idle for a total cycle time of 60 seconds. The short cycle was repeated 27 times following each longer throttle cycle.

The 75-second ramps were requested by GE prior to testing, while the 30-second dwells at idle and at maximum speed were requested by CECI. Both participants waived this request shortly after testing began, and the cycles were limited to only the short cycles.

The fan endured a total of 4474 on-engine throttle power cycles. At the conclusion of the test, the fan was removed and inspected.

The technologies that were first evaluated in the test experienced some difficulties. The short lead-time for the development of TF-41 installations contributed to these difficulties. Had the systems been available for the earlier checkout runs, adjustments in the systems could have been implemented during the crack growth portion of the test. A posttest inspection discovered the fiber-optic lines for the torsional vibration measurement had been pulled taut across the top of the forward bearing. The coating on the fiber-optic lines had melted and had fused together (figure 7).

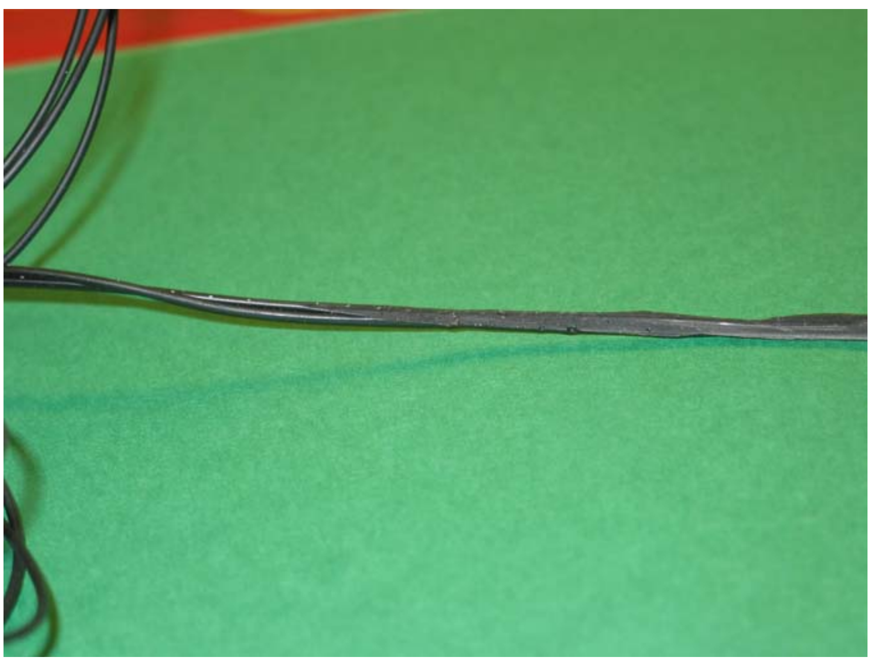

FIGURE 7. CREATIVE ENGINEERING CONCEPTS, INC., FIBER-OPTIC LINES FUSED TOGETHER

The tension on the fiber-optic lines also pulled the line around a corner on the sensor mount and caused the fiber-optic lines to break (figure 8). A red laser pointer was used to detect any breaks in the fiber-optic lines.

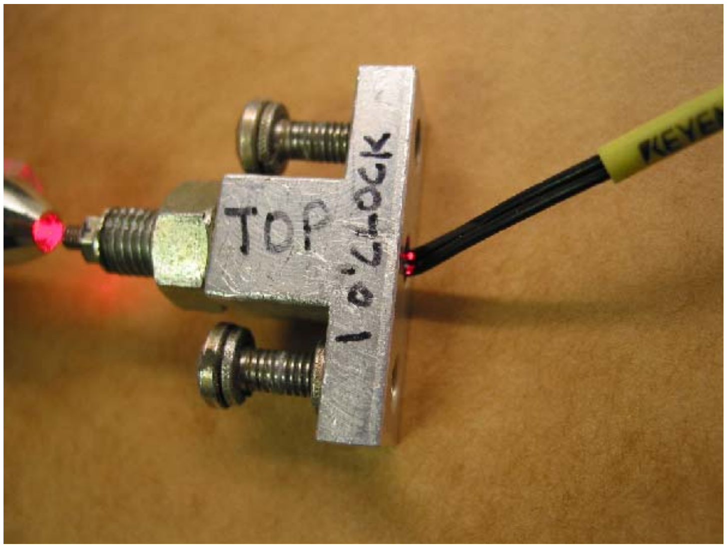

FIGURE 8. CREATIVE ENGINEERING CONCEPTS, INC., SENSOR AND SENSOR MOUNT WITH A RED LASER POINTER ILLUMINATING A BREAK IN THE LINES

The AADC and IDINY wireless telemetry hardware (figure 9) installed in the nose cone also had some problems. Sand got into the electronics of the transmitter in the center post, and the battery seemed to have an intermittent connection. The nose cone was removed at the end of the first test day, and the exposed portion of the electronics was sealed with epoxy. The wiring connections in the electronics were checked and strengthened, and the nose cone was replaced.

FIGURE 9. ALLISON ADVANCED DEVELOPMENT COMPANY AND IDINY TELEMETRY HARDWARE
(Fan with the nose cone removed)

Upon disassembly of the engine, a small piece of debris was found on the aft retention plate on the fan (figure 10). The debris appeared to be a small piece of rubber or plastic that was sucked into the space between the fan and the first-stage stators through one of the hollowed-out vanes. The debris measured approximately 0.8 x 0.45 inch and weighed 5 grains (0.324 gram).

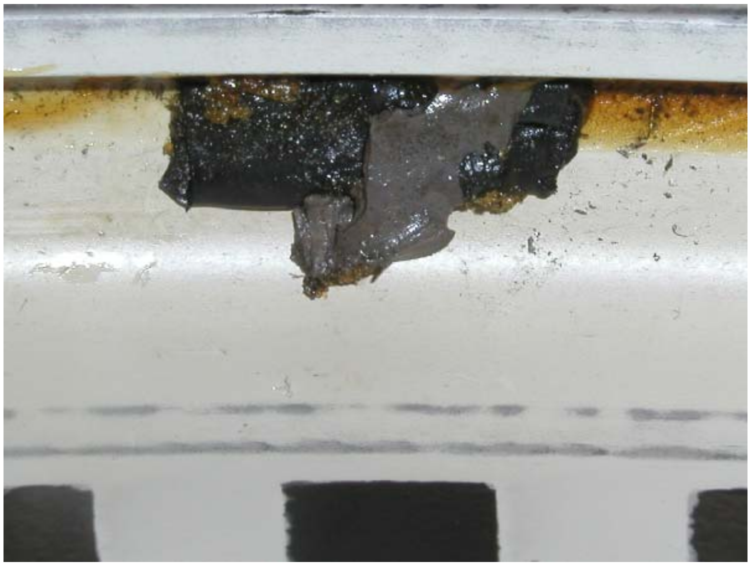

FIGURE 10. DEBRIS ON FAN AFT RETENTION PLATE

7. RESULTS.

7.1 ENGINE CHECKOUT.

The engine checkout runs were conducted May 3-15, 2002. Table 2 contains a summary of the engine checkout run sheets.

Sometime during the first run, the Test Devices Inc. proximity probes rubbed against the aft face of the fan disk. All four proximity probes were damaged and had to be replaced prior to the seeded fault test. This was attributed to the differences between the early and late fan disk designs. The disk employed in the test had a thicker web than the disk used by Test Devices, Inc. to develop the instrumentation ring.

Some irregularities were noted on the N1 tachometer. The output signal from the N1 tachometer seemed to follow the N2 tachometer with almost no lag or lead, indicating an error. The tachometer was changed on checkout run 8, but the replacement tachometer was a different type and resulted in an oil leak and had to be replaced with the original tachometer. It was discovered prior to checkout run 11 that the tachometer frequency was different than what was programmed in the Labview monitoring software.

TABLE 2. ENGINE CHECKOUT RUN SUMMARY

Run No.	Date	Description	Comment
1	5/3	Op Check	Dry Windmill, followed by Start. OVERTEMP
2	5/6	TDI Baseline	OVERTEMP using computer controls, switched to manual. Appeared that all TDI Prox sensors bad.
3	5/7	TDI Baseline	TDI/ExSell/Hood/(GE) Baseline. Autothrottle functioned.
4	5/7	GE Baseline	TDI short throttle cycle, 15s cycles
5	5/7	10 g out-of balance	
6	5/8	30 g out-of balance	Stopped at ~56° PLA-exceeded vibration spec.
7	5/8	20 g out-of balance	
8	5/8	20 g out-of balance	Changed Tachometer. Oil leak at IRP, shutdown prior to idle.
9	5/8	20 g out-of balance	Back to original tach.
10	5/8	20 g out-of balance	
11	5/8	20 g out-of balance	
12	5/9	20 g out-of balance	
13	5/9	50 g out-of balance	
14	5/9	Baseline	
15	5/15	Baseline	TTL check/exhaust nozzle expansion

Although the tachometer was fixed, the variability of the rpm, while holding the throttle steady, was sometimes as much as ±150 rpm (checkout run 11). The rpm also had a tendency to drift upwards. The exhaust gas temperature was approaching the 583ºC limit, with an average fan speed of approximately 8635 rpm. At the time of the engine checkout run, testing was scheduled for September 2002, when ambient temperatures were expected to be higher, possibly reducing the engine fan speed even further. Therefore, a portion of the exhaust nozzle was removed increasing the exhaust nozzle diameter from 24″ to 27″, a 20% increase in exhaust area. This modification reduced the backpressure and allowed the fan to reach higher rpm at lower exhaust gas temperatures. The exhaust gas temperature limiter was not powered on during checkout runs 1 to 14. The problem was corrected prior to checkout run 15. The engine throttle was advanced to the maximum PLA with the limiter switch on and off at various times. When the limiter power was on, the engine approached the maximum-allowable N1 without reaching the turbine temperature limit. The increase in the exhaust nozzle area allowed the N1 rpm to reach 9000+ rpm.

During the engine checkout the week before the seeded fault test, the cutouts made in the static air seal plate were covered with aluminum tape. During this second engine checkout, the aluminum tape lifted up and rubbed against the fan aft retention plate (figure 11). The aluminum tape did not cause any damage to the retention plate, to any of the sensors on the instrumentation ring, or the static air seal plate. The aluminum tape was removed and replaced with thin strips of stainless steel spot-welded into place.

FIGURE 11. ALUMINUM TAPE RUBBED AGAINST THE TF41-A-1B FAN DISK BLADE RETENTION PLATE

7.2 SEEDED FAULT TEST.

The TF41-A-1B fan survived 4474 engine power cycles with an initial crack radius measuring 0.205″ on the front face of the first-stage engine fan without catastrophic failure (figure 12). The crack radius grew to approximately 0.225″ (figure 13). These inspections were made with eddy current. The high residual stress disk exhibited very tight cracks that were not detected with FPI and were only partially visible with polishing and magnification. The visual crack growth was larger than the eddy-current growth, which is attributed to the amount of polishing and the fact that the growth sensor was chemically removed after the test and mechanically removed for the postspin pit inspection.

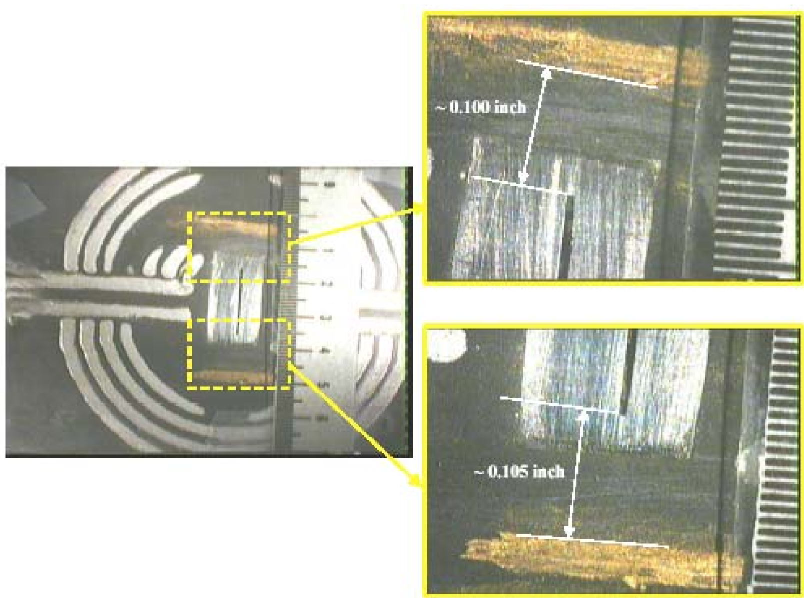

FIGURE 12. TF41-A-1B FAN DISK CRACK AFTER PRETEST SPIN-PIT GROWTH [13]

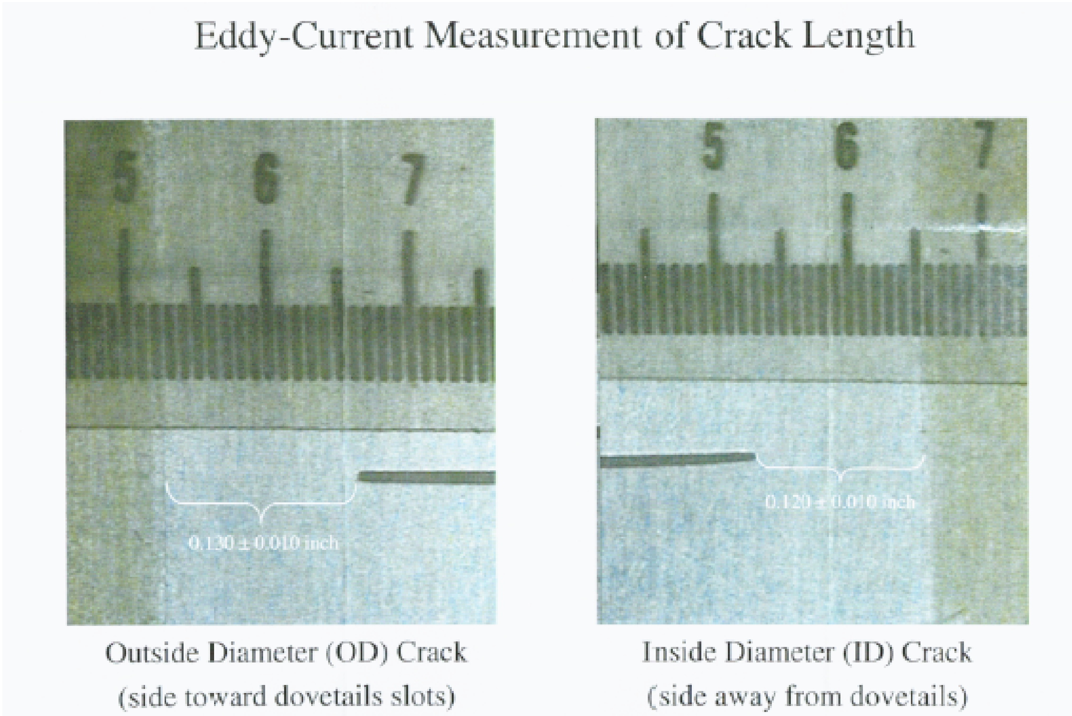

FIGURE 13. TF41-A-1B FAN DISK CRACK AFTER 4474 ON-ENGINE THROTTLE CYCLES [14]

The eddy-current inspection of the crack revealed a crack length of 0.130 ±0.010 inch beyond the EDM notch on the outer diameter side of the EDM notch and 0.120 ±0.010 inch beyond the inner diameter side of the EDM notch on the disk.

The crack grew less than predicted by the analysis. Table 3 describes the predicted crack growth.

TABLE 3. ANALYTICAL PREDICTION OF CYCLES TO FAILURE

Toughness ($KI_c\sqrt{in}$ ksi*in$^{0.5}$)	3000-8500 rpm		3000-8800 rpm	
	Cycles	Crack Radius (in.)	Cycles	Crack Radius (in.)
30	75	0.222	0	0.2
35	844	0.303	334	0.263
40	1896	0.393	1052	0.345
45	3103	0.48	1965	0.425
50	4549	0.583	3075	0.511

The number of cycles performed exceeded the predicted number of cycles to failure of 50 ksi·√inch toughness titanium fan disk.

After the first 285 cycles at approximately 2500-8500 rpm, the T2 simulator setting was changed so that the airflow limiter allowed a higher N1 rpm. The target speed for the airflow limiter was 8800 rpm. However, the T2 simulator temperature was raised in small increments (5°F) to prevent overshooting the desired rpm. The T2 temperature was increased to 40°F after approximately 695 cycles and maintained at that temperature until the conclusion of the test. Figure 14 shows the peak and sustained rpm values throughout the seeded fault testing (courtesy of Hood Technologies). Several spikes are noticeable. A broken T2 simulator wire caused the first spike in the rpm. The N1 speed reached as high as 9050 by one participant's estimation. Several other less severe spikes occurred on start-up. Figure 15 shows the distribution of the maximum N1 rpm for all cycles after the T2 simulator was set to 40°F. The mean peak N1 speed was 8816 with a standard deviation of 31.2 rpm. The ambient temperatures are also plotted in figure 14, but no trends indicating a relationship in N1 speed variation and ambient temperature are evident.

Smaller spikes were present in every engine throttle cycle (figures 16 and 17). This overshoot was a consequence of the method chosen to control rpm speeds. The airflow limiter allowed an overshoot of the N1 and N2 speeds by an average of 300 rpm before invoking the rpm limit. Figures 16 and 17 show N1 and PLA values for typical engine cycles during the seeded fault testing. The data presented was extracted from the data file named 04_03_03a.txt. The overshoot of N1 rpm occurred even when the throttles were advanced slowly.

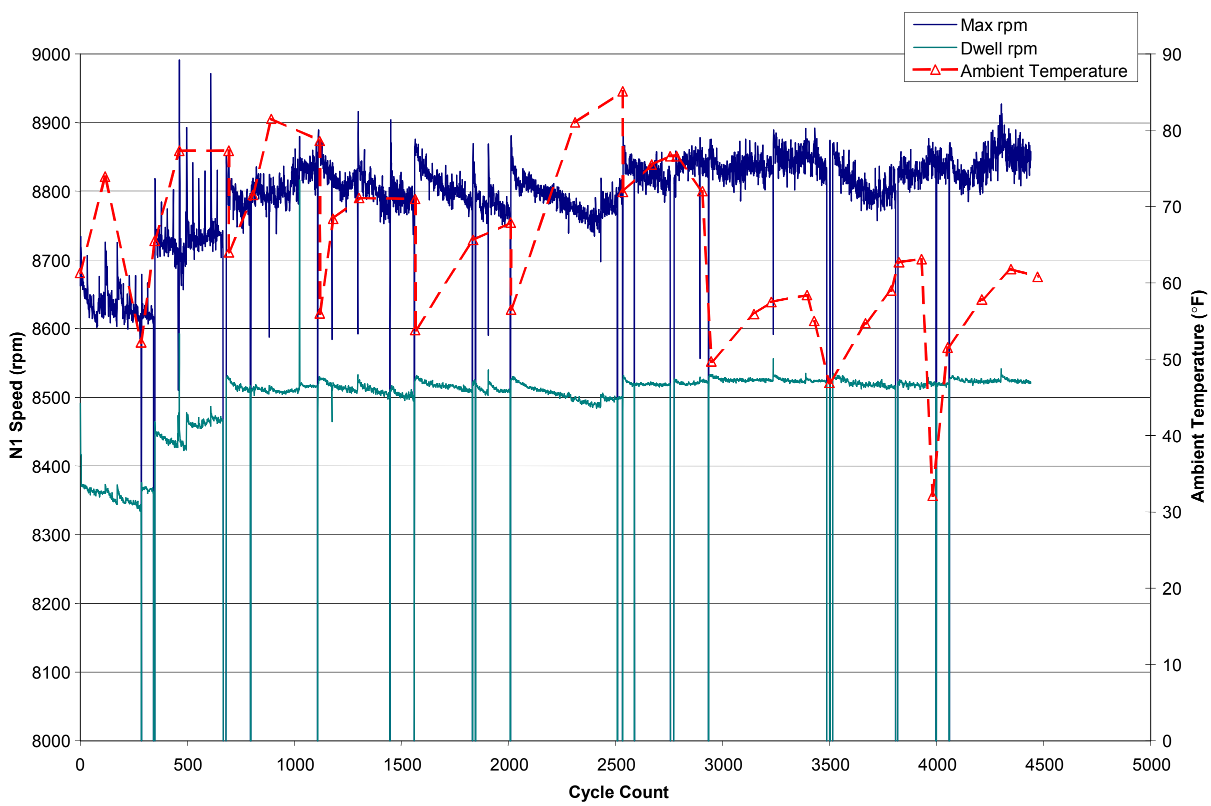

FIGURE 14. N1 SPEED VS CYCLE COUNT

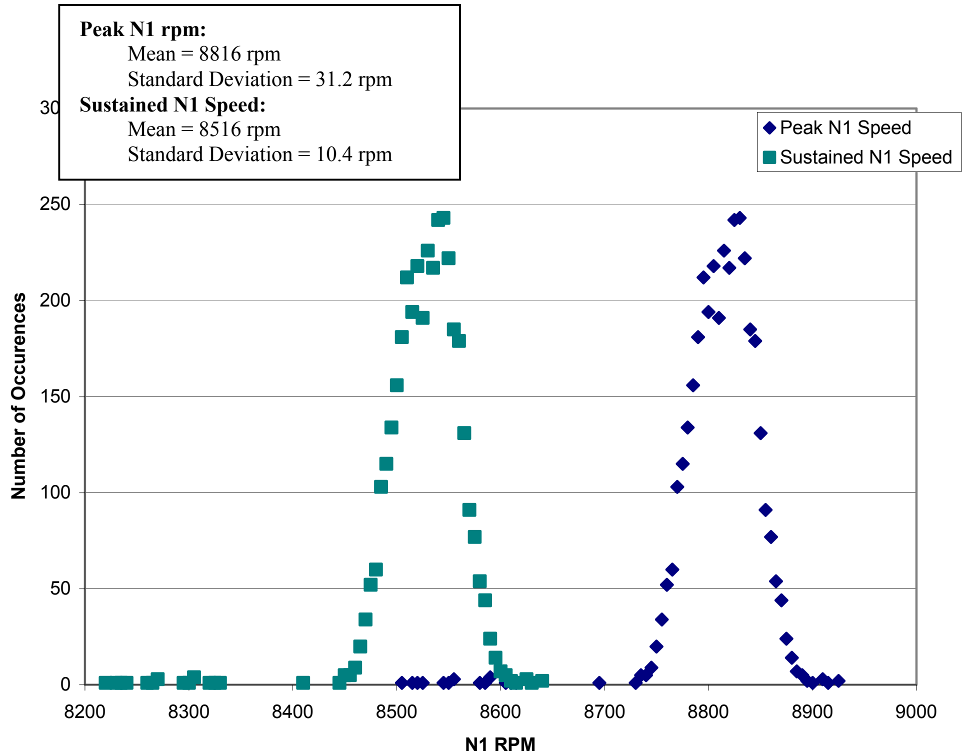

FIGURE 15. SEEDED FAULT TESTING

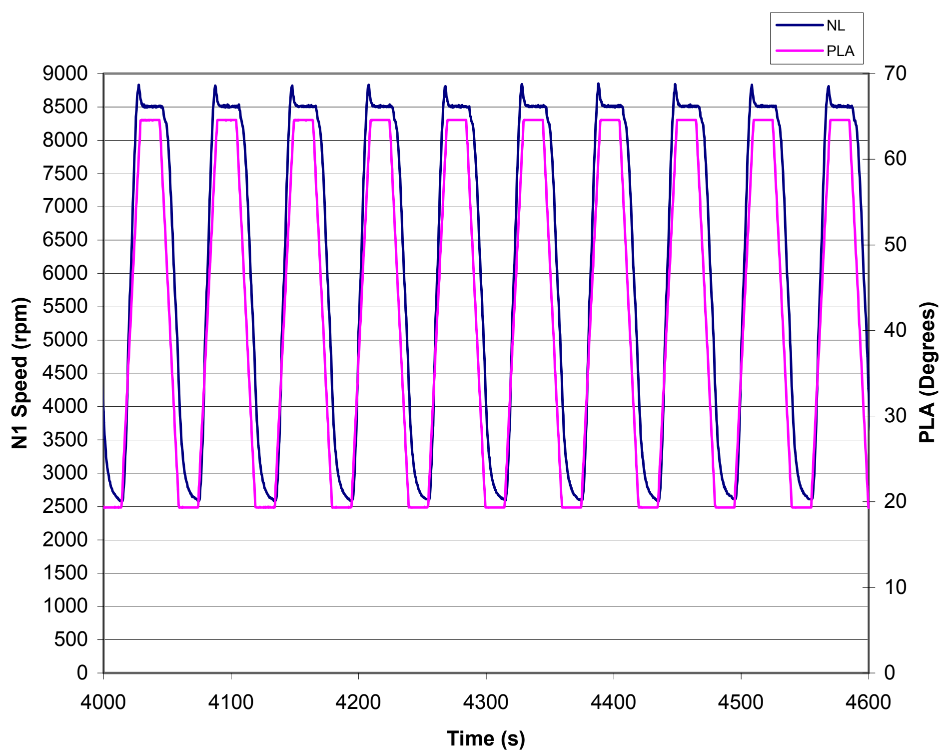

FIGURE 16. SAMPLE ENGINE POWER CYCLE DATA

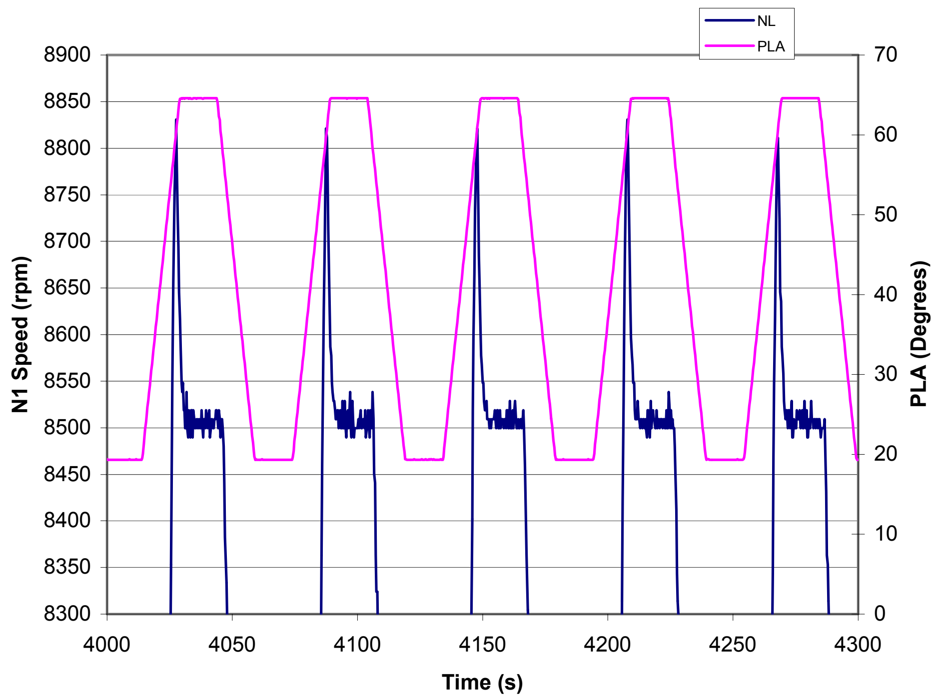

FIGURE 17. CLOSE-UP OF ENGINE POWER CYCLE DATA

8. CONCLUSIONS.

The ability to detect a growing crack in a turbine engine fan disk has the potential to provide significant safety benefit to aviation. The FAA, NASA, DoD full-scale disk crack propagation test has leveraged a significant investment in successful laboratory testing into the first successful demonstration of crack growth in a full-scale engine. Technology developers have experienced the running engine environment and learned from this effort. Modifications to the sensors, data acquisition, and processing were considered based upon the data collected during this test effort.

The TF41-A-1B seeded fault testing successfully grew a seeded fault on a full-up engine. Although the crack did not propagate as much as the analysis had predicted, the test offered a unique opportunity to monitor a crack within a real engine environment and to identify areas of improvement that may not be apparent in a spin pit test.

The limited growth of the crack may have been due to various factors. One was the fact that the growth occurred only at the higher low-speed shaft (N1) speeds. The spikes to 8816 rpm were of very short duration and may not have been sufficient to induce crack propagation. The maximum speed was not increased because doing so would have reduced the size of the critical crack length and may have caused the disk to fail rapidly, not providing the time to identify the trend preceding the failure. To provide a larger critical crack size and sufficient cycles to collect data, the crack was introduced in a moderate stress area. Other factors that could have contributed to the limited crack growth were aerodynamic loading from the fan blades and temperature gradients across the fan. Both of these loads were not present in a spin pit test and were, thus, not included in the analysis.

After analyzing the test results, it was suggested that the crack growth rate be investigated by placing a Vishay crack grid on the disk and cycling the disk in a spin pit. However, the crack growth rate would not help to identify the disk toughness. The discussions also suggested that a better means of controlling the N1 speed needs to be developed to hold the desired rpm, rather than allow the spike seen during each cycle of the seeded fault test.

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APPENDIX A—TF41-A-1B RUN SHEETS SUMMARY

Date	Time (24HR)	Stop Time (24HR)	Run #	Run Data			Ambient				Comments	Total Cycles	Daily Fuel Use	Cycles per Day	Run #	Ambient Temp (ºF)
				Count @ Startup	# Runs	T2 Setting (F)	Temp	Press	Rel. Humidity	V[kts] (dir) sus/gust						
24-Mar-03	08:44	09:55	1	0	4	25	61.3	27.6	44	-	Only set up for 1 set of cycles to allow adjustments. Decreased temp, wanted peak at 8500RPM	285	2500	285	0	61.3
					29	20										0
	10:21	12:00	2	33	84	20					CECI/Hood made adjustments after run. Broke pencil lead to test Acoustic sensors.					0
	13:09	14:14	3	117	56	20	73.9	27.58	26	-	CECI/IDI/AADC made adj after run.				117	73.9
	15:01	17:05	4	173	112	20					IDI/AADC made adj after run. Sand in hardware, when nose bullet disassembled. Cleaned out, epoxied holes on top, reinstalled in the morning.					0
25-Mar-03	07:39	07:52	5	285	8	20	52.2	27.86	58	-	Camera Problems, shutdown and reset.	695	3649	410	285	52.2
	08:07	09:09	6	293	56	25					Speed change (goal was to peak at 8800, T2 change not enough) due to resonance/drift added safety cables.					0
	09:56	12:04	7	349	113	30	65.5	27.88	38	-	Speed change (goal=8800 RPM, still not quite high enough.) CECI still adjusting				349	65.5
	12:46	12:57	8	462	2	30					Hot start, peaks @ 8950, 9050…T2 wire broken					0
	13:14	13:56	8(b)	464	61	30										0
	14:09	16:15	9	525	113	35	77.3	27.29	21	-	Slightly Hot Start CECI still adj.				464	77.3
	16:32	17:38	10	638	57	35					Slightly Hot Start CECI still adj.				694	77.3
26-Mar-03	07:55	10:03	11	695	113	40	64	27.72	34	-		1120	4271	425	695	64
	10:27	12:07	12	808	85	40	71.5	27.2	30	-	CECI finally getting data, but still adj.				808	71.5
	13:03	15:44	13	893	142	40	81.5	27.61	25	16.9/23.3	CECI -1 sensor dead.				893	81.5
		(15:44)								20/30						0
	16:02	17:40	14	1035	85	40	78.6	27.51	24	25.5/36.9					1120	78.6
27-Mar-03	07:43	09:13	15	1120	63	40	56	27.64	39	3/5	Lost NH Tach, shut down, switched amps in control room.CECI adj bad sensor.	1566	4375	446	1121	56
	09:38	11:48	16	1183	121	40	68.4	27.64	26	3/5	CECI adj sensor.				1183	68.4
	12:32	15:12	17	1304	151	40	71.1	27.57	17	11/15					1304	71.1
	15:40	17:40	18	1455	111	40	71								1565	71
28-Mar-03	07:34	12:22	19	1566	271	40	53.8	27.87	18	7/9		2013	4512	447	1566	53.8
	13:14	14:34	20	1837	73	40	65.6	27.84	8	13.9/19.2					1837	65.6
	15:51	17:43	21	1910	103	40	67.9	27.82	8	13/18					2012	67.9
31-Mar-03	0743	14:58	22	2013	421	40	56.5	27.77	30	0/0		2535	4758	522	2013	56.5
		(12:45)					81	27.67	12	3/6					2313	81
	15:36	17:33	23	2434	101	40	85.1	27.55	12	8/11	Hot start, EGT light=momentarily 583				2535	85.1
1-Apr-03	09:37	13:25	24	2535	251	40	66.8	27.46	22	(202) 13/18.8	Auxilary Air Starter failed, had to get replaced, causing 2.5 hour delay.	2948	3587	413		66.8
		(09:45)					71.9	27.47	20	(205) 16.5/20.2					2536	71.9
		(12:00)					75.5	27.41	16	(207) 23.9/31.4					2671	75.5
		(13:25)					76.6	27.38	16	(206) 22.6/29.4					2756	76.6
	14:06	16:25	25	2786	121	40	76.6	27.38	16	(206) 22.6/29.4					2786	76.6
	16:50	17:31	26	2907	41	40	72	27.34	19	(208) 26.7/34.6					2907	72
		(17:31)								(208) 27/38					2948	0

Date	Time (24HR)	Stop Time (24HR)	Run #	Run Data			Ambient				Comments	Total Cycles	Daily Fuel Use	Cycles per Day	Run #	Ambient Temp (ºF)
2-Apr-03	07:19	12:25	27	2948	301	40	49.7	27.45	39	(208) 20.1/25.1		3501	5001	553	2949	49.7
		(10:40)					55.9	27.51	29	(238) 20.7/25.8					3149	55.9
		(12:00)					57.5	27.5	24	(237) 24.8/31.7					3229	57.5
	13:03	15:41	28	3249	151	40									3249	0
		(15:30)					58.4	27.51	26	(253) 21.7/29.8					3397	58.4
	15:56	17:35	29	3400	101	40										0
		(16:30)					55	27.51	32	(247) 22.1/29.3					3430	55
3-Apr-03	07:22	12:31	30	3501	301	40	46.9	27.63	34	(114) 2/3		4053	5026	552	3501	46.9
		(10:00)					54.7	27.67	21	(158) 4.8/8.1					3669	54.7
		(12:00)					59	27.65	18	(171) 3/8.5					3789	59
	13:06	15:43	31	3802	151	40										0
		(13:30)					62.7	27.61	19	(209) 5.9/9.7					3826	62.7
		(15:15)					63.1	27.57	20	(226) 5.7/10.2					3931	63.1
	15:57	17:38	32	3953	100	40									3953	0
		(16:30)					32.1	27.57	22	(274) 10/13.8					3983	32.1
4-Apr-03	07:20	11:31	33	4053	241	40	51.5	27.6	28	(118) 0.2/1.1		4474	3000	421	4053	51.5
		(10:00)					57.8	27.58	22	(239) 16.3/23.7					4213	57.8
	12:03	15:04	34	4294	180	40										0
		(13:00)					61.8	27.5	24	(233) 23.7/31.3					4349	61.8
		(14:30)					60.8	27.49	26	(234) 22.7/29.1					4474	60.8
Total # of Cycles				4474												