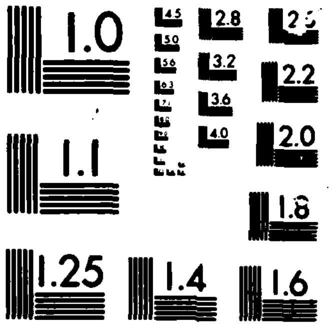
AD-A167 166 RETIREMENT FOR CAUSE INSPECTION SYSTEM DESIGN VOLUME 1 1/2
MAIN TEXT.. (U) PRATT AND WHITNEY WEST PALM BEACH FL
GOVERNMENT PRODUCTS DIV.. J S CARGILL ET AL. OCT 81
UNCLASSIFIED P/W/GPD-FR-15175-VOL-1 F/G 14/2 NL



MICROCOP CHART

12

AFWAL-TR-81-4111
Volume I

RETIREMENT FOR CAUSE INSPECTION SYSTEM DESIGN

Vol I - Main Text

J. S. Cargill, et al.

UNITED TECHNOLOGIES CORPORATION
PRATT & WHITNEY AIRCRAFT GROUP
GOVERNMENT PRODUCTS DIVISION
P. O. BOX 2691
WEST PALM BEACH, FLORIDA 33402

OCTOBER 1981

FINAL REPORT FOR PERIOD JULY 1980 TO JUNE 1981

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

This report has been reviewed by the Office of Public Affairs (ASD/PA) 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.

Joseph A. Moyzis, Jr.

JOSEPH A. MOYZIS, JR.
Nondestructive Evaluation Branch
Metals and Ceramics Division

FOR THE COMMANDER

D. M. FORNEY, JR., Chief
Nondestructive Evaluation Branch
Metals and Ceramics Division

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. Report Number
AFWAL-TR-81-4111, Vol. I

2. Govt Accession No.
ADA 167166

3. Recipient's Catalog Number

4. Title *(and Subtitle)*
RETIREMENT FOR CAUSE INSPECTION
SYSTEM DESIGN
Volume I — Main Text

5. Type of Report & Period Covered
Final Report
July 1980 to June 1981

6. Performing Org. Report Number
FR-15175

7. Author(s)
J. S. Cargill, et al

8. Contract or Grant Number(s)
F33615-80-C-5049

9. Performing Organization Name and Address
United Technologies Corporation
Pratt & Whitney Aircraft Group
Government Products Division
P.O. Box 2691, West Palm Beach, FL 33402

10. Program Element, Project, Task Area & Work Unit Numbers
24180517

11. Controlling Office Name and Address
Materials Laboratory (AFWAL/MLLP)
Air Force Wright Aeronautical Laboratories
Wright Patterson AFB, OH 45433

12. Report Date
October 1981

13. Number of pages
136

14. Monitoring Agency Name & Address *(if different from Controlling Office)*

15. Security Class. *(of this report)*
Unclassified

15a. Declassification/Downgrading Schedule

16. Distribution Statement *(of this Report)*
Approved for public release; distribution unlimited.

17. Distribution Statement *(of the abstract entered in Block 20, if different from Report)*

18. Supplementary Notes
This report is divided into two volumes: Volume I contains the Main Text and Volume II contains the Appendices.

19. Key Words *(Continue on reverse side if necessary and identify by block number)*
Retirement for Cause, Nondestructive Evaluation, F100 Engine, Engine Maintenance, Eddy Current, Ultrasonic Test, Fluorescent Penetrant Inspection, Automated ~~Facility~~

20. Abstract *(Continue on reverse side if necessary and identify by block number)*

A design study has been conducted to establish an engineering specification for an integrated inspection system that will be used to implement the Retirement for Cause (RFC) maintenance philosophy on gas turbine engine disks and spacers. The system specified by this study emphasizes equipment reliability, flexibility, component throughput and accountability required for 1985 overhaul facility implementation through an Air Force manufacturing technology program. NDE technology needs for far term (post-1985) overhaul implementation of optimal RFC inspections are discussed in terms of necessary research programs which should be conducted in parallel to the manufacturing technology effort.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

FOREWORD

This work was performed under Materials Laboratory Contract F33615-80-C-5049. The Air Force project manager was Mr. K. D. Shimmin, AFWAL/MLLP, and the work was contracted to the Materials and Mechanics Technology Laboratories of Pratt & Whitney Aircraft (P&WA) Group Government Products Division, West Palm Beach, Florida. The Program Manager was J. S. Cargill reporting to J. A. Harris, Jr., Supervisor of Mechanics of Structures, who reports to M. C. VanWanderham, Manager of Mechanics of Materials and Structures. R. L. Shambaugh was Program Coordinator.

Dr. James E. Doherty was the original P&WA Program Manager, and the authors wish to acknowledge the many special contributions which he has made.

The authors wish to acknowledge the members of the RFC team, who diligently conducted research for their respective program tasks and prepared thorough engineering specifications for the RFC Inspection System. The contributors and their tasks follow: J. M. La Grotta (P&WA/Commercial Products Division), eddy current equipment, signal processing and interface protocal; Dr. R. V. Harris, Jr. (P&WA/Government Products Division), ultrasonic test instrumentation; Dr. J. E. Doherty and Amos S. Greer (Southwest Research Institute), mechanical scanning subsystem; H. L. Grothues (Southwest Research Institute), control software and data management; F. Trindade and J. Oosterlink (Giffels Associates), parts handling and facility layout; Dr. C. A. Rau (Failure Analysis Associates), inspection system performance; Prof. R. B. Thompson (Ames Research Laboratory), advanced NDE methods; Dr. R. W. Schafer (Georgia Institute of Technology) and Dr. R. S. Williams (United Technologies Research Institute Technology), signal processing.

CONTENTS

LIST OF ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION 1.0

INTRODUCTION

1.1 BACKGROUND

The most common methods used for predicting the life of gas turbine engine rotor components have resulted in conservative estimation of useful life. Most rotor components are limited by low cycle fatigue, generally expressed in terms of mission equivalency cycles. When some predetermined cyclic life limit is reached, components are retired from service. These cyclic life limits are established by a statistical analysis of data indicating the cyclic life at which 1 in 1000 disks will have a fatigue-induced crack of approximately 0.03-in. length. It has been documented that many of the 999 remaining disks, which are also retired at the same time, have considerable useful residual life. Retirement for Cause (RFC) provides a procedure based on Fracture Mechanics and Nondestructive Evaluation (NDE) for screening the one bad part and certifying the remaining 99.9% for additional safe engine service.

Under the RFC concept, the fatigue initiation phase of a critical components total life is fully exhausted and subcritical crack growth is characterized to determine the appropriate conditions for retirement. Referring to Figure 1, an NDE limit, or rejectable crack size, is established for a given set of component, operating, and overhaul conditions. A component is inspected and returned to sevice as long as the largest defect in the component is determined to be below the NDE limit (illustrated by the horizontal dotted line in figure 1.) The return-to-service interval (RTS), illustrated by the solid portion of the crack propagation curves in Figure 1, is determined by a fracture mechanics calculation of remaining crack propagation life from the NDE limit and application of safety factor which produces optimum RFC benefits. The residual propagation life which is guaranteed (by the safety factor) above and beyond the maximum life which may have been expended during the most previous RTS, is designated by the dashed portion of the crack propagation curve in Figure 1. The component is then retired when overhaul inspection indicates that any crack is larger than its respective rejectable limit.

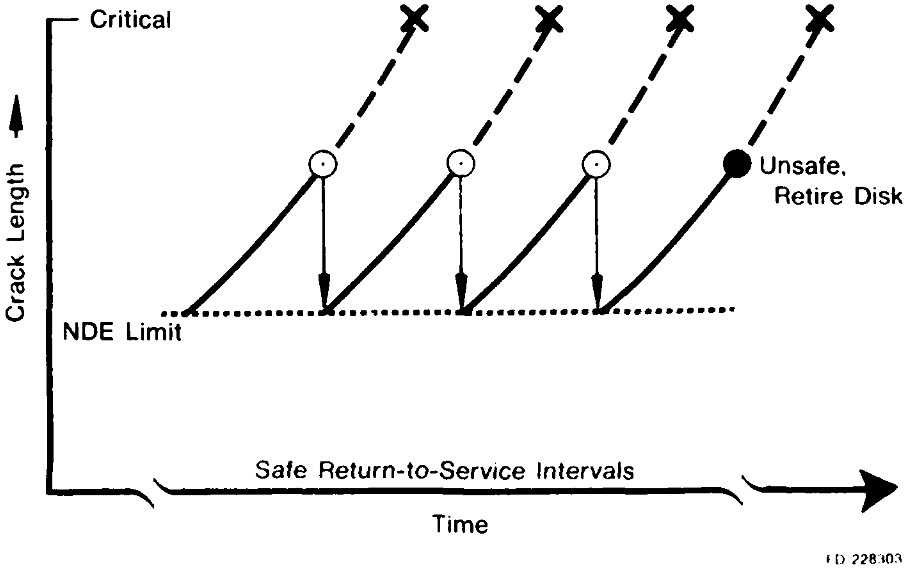


Figure 1. Illustration of the Retirement for Cause Concept

The Metals Behavior Branch of the Materials Laboratory (AFWAL/MLLN) has been conducting in-house research and development activities in the RFC area since 1972. Pratt & Whitney Aircraft Group began extensive research and development programs under corporate, IR&D, and Government contract sponsorship in 1972 to identify and develop the applied fracture mechanics and NDE technologies necessary to realize the RFC concept. We have been convinced that while the life analysis technologies for RFC are obtainable, implementation of an RFC maintenance concept hinges upon the ability to conduct NDE of candidate components. Therefore, this NDE system design study and the following manufacturing technology program become key factors in realizing the life cycle cost benefits of RFC.

During conduct of the "Concept Definition: Retirement for Cause of Engine Components" program during 1979 and 1980, the criticality of NDE was acknowledged, and company-sponsored activities were undertaken to formulate the approach necessary to produce a RFC Inspection System which would address the specific requirements associated with the F100 engine, yet still be applicable to other engine systems. This internal research has been reflected in the "RFC Inspection System Design", and coupled with other technology development programs (Figure 2) to produce a clear picture of suitable objectives and opportunities for the RFC manufacturing technology effort.

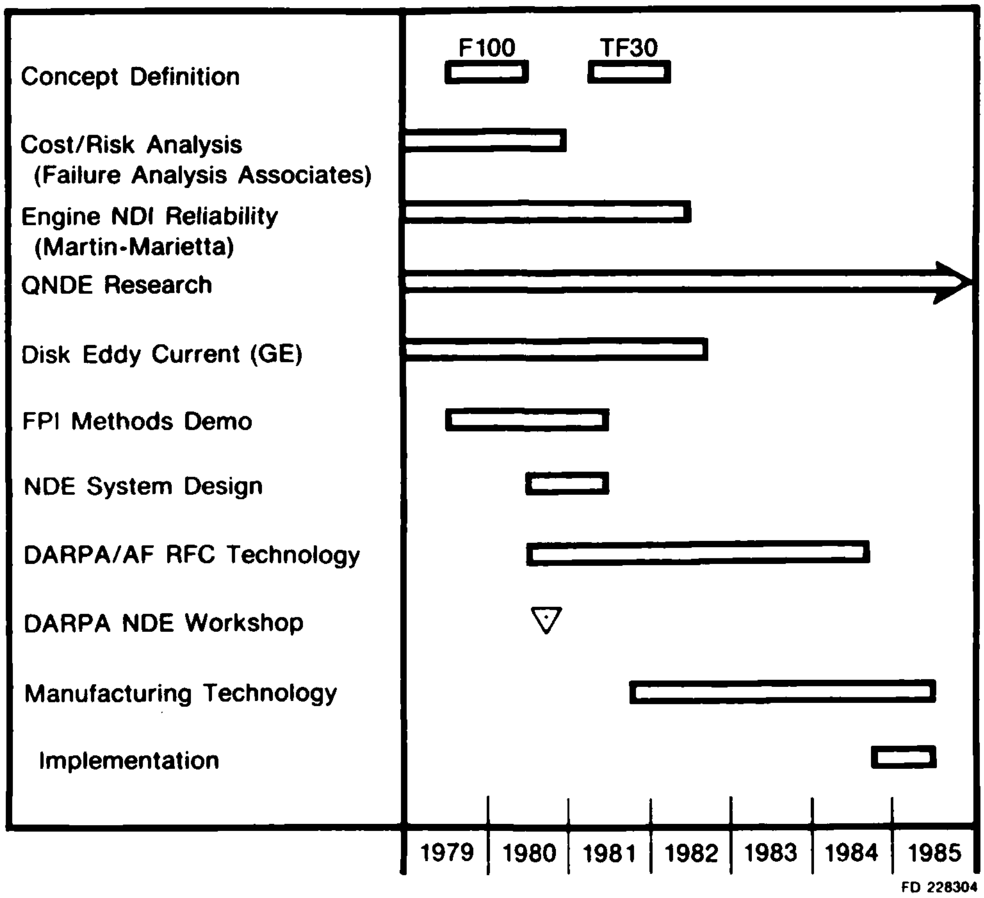


Figure 2. Supporting Activities for Retirement for Cause

1.2 OBJECTIVES

This report details the results and conclusions of an exploratory development program whose primary objective was to establish an engineering specification for an integrated inspection system that will be used to implement the RFC methodology on critical gas turbine engine components. Key features of the specified inspection system include high defect discrimination, repeatability of results, and thoughput capability which is compatible with Air Force overhaul center requirements. This program has formed the basis for a manufacturing technology effort which will demonstrate and validate the integrated system in the Air Force overhaul enviroment.

Specific objectives were divided between overhaul center production requirements and advanced NDE technology requirements necessary for optimum application of the RFC concept. The production requirements, which must be addressed within the initial system implementation in early 1985, include equipment and inspection reliability, parts throughput, system flexibility, accountability of parts and modules, and system maintainability. The NDE technology requirements fall primarily into catagories of increased inspection sensitivity, defect discrimination, and quantitative NDE.

1.3 SCOPE

This final report is composed of two volumes: a general report to summarize program accomplishments and engineering specifications, and an appendix volume of engineering specifications which address primary subsystems.

Within the context of this program, RFC applicability is addressed only for Air Force fighter-type engines, although the RFC concept will ultimately have more widespread application. Upon presentation of the inspection and scanning requirements for the twenty-one RFC candidate components from the PWA F100 engine, the Air Force Technical Manager concluded that the F100 requirements represented a near-complete listing of generic requirements for all Air Force fighter-type engines.

No experimental effort was conducted within the scope of this program. Therefore, specific recommendations regarding applicability of NDE techniques are based solely upon previous experience and engineering judgement. The inability to conduct an experimental effort has been perceived as a handicap in evaluation of ultrasonic test methods, where demonstration of detectability of small internal crack-like defects has received little documentation.

No component life analyses or life cycle cost analyses were considered within the scope of this program. These items are being thoroughly researched in a parallel program: the DARPA/Air Force "Engine Component Retirement for Cause" Program, Contract No. F33615-80-C-5160. The program has been contracted to P&WA/Government Products Division. Mr. J. A. Harris, Jr., is P&WA Program Manager. Dr. W. H. Reimann is the Air Force Technical Manager.

The initial engineering specification is based upon a conventional NDE approach because it was conceded that the follow-on manufacturing technology program would probably only be able to address overhaul center operational needs within the current early 1985 implementation schedule. However, the design study has considered NDE technology gaps which prevent optimum RFC implementation, and the opportunities for parallel exploratory development programs in advanced NDE are discussed.

2.0 TECHNICAL PROGRAM AND ACCOMPLISHMENTS

The Retirement for Cause (RFC) Inspection System Design program was structured into four technical phases. Phase I activities included initial definition of the inspection requirements for RFC candidate components, definition of Air Logistic Command (ALC) operational and nondestructive evaluation (NDE) technology needs, and research of NDE methods for applicability to the system. Phase II activities included selection of specific conventional and advanced NDE approaches to be included in the near term (1985 system implementation), and development of a summary of opportunities for exploratory development of advanced NDE methods which may be implemented as "modules" of the RFC Inspection System in the post-1985 time frame. System design was considered during Phase III. A set of engineering requirements for each major subsystem was developed. In addition to those requirements, specific suggestions for compliance with those requirements were prepared. Design specifications were prepared during Phase IV. Volume II is a compilation of those specifications that represent the technical contributions of many program participants.

2.1 Phase I — Evaluation of the State of the Art

Phase I objectives included the listing of input parameters and general system operational requirements necessary to perform the system design effort. Research of candidate NDE techniques as applied to the RFC requirements was also conducted during the initial phase.

2.1.1 Inspection and Scan Requirements

Four Air Force inventory engines must be considered when listing potential RFC inspection system requirements: The F100, TF30, J79 and TF41. The F100 engine is planned as the first application for RFC and a program is currently underway to develop all the technologies, less NDE, necessary for F100 implementation in early 1985. The Air Force inventory of TF30 engines is also significant, though much smaller than the planned F100 inventory, and a RFC concept definition study is currently underway for this engine. If the RFC Inspection System is to be capable of high sensitivity, high reliability inspections and is to have generic applicability, then it must be assumed that the system will be used to perform evaluations of all critical turbine engine components which have specialized inspection requirements. Therefore, General Electric's TF41 and J79 must be considered within the realm of the RFC Inspection System even though specific RFC implementation may not occur.

Twenty-one F100 components were selected as RFC candidates during the "Concept Definition: Retirement for Cause of F100 Rotor Components" Program (Table 1). The specific locations with highest stresses have been identified for those components and as a collection, they represent geometries that are typically of concern in any high performance gas turbine engine. Some of these typical locations can be identified in Figures 3 and 4, which are, respectively, a composite sketch of typical rotor components and sketches of specific flaw locations in these geometries. Sketches of all the F100 candidate components with designation of critical locations are included as Figures 5 through 25. Also included in the figures are pertinent dimensional details for system design.

Table 2 lists all the RFC eddy current and ultrasonic test inspection operations needed to evaluate the twenty-one F100 parts. This table also gives the time currently estimated for each operation. Each operation is detailed in operation sheets shown as Figures 26 through 33. The operation sheets schematically indicate the scanning actions required for eddy current and ultrasonic inspection.

TABLE 1. RFC CANDIDATE F100 COMPONENTS

Module	Material	Component	Part Number	Abbreviation
Fan	Ti 6246	1st-Stage Disk and Hub	4046741	1F
	Ti 6246	2nd-Stage Disk and Hub	4048902	2F
	Ti 6246	3rd-Stage Disk	4048903	3F
	Ti 6246	2nd-Stage Airseal (2-3 Spacer)	4049087	2/3 CPS
Compressor (HPC)	Ti 6246	4th-Stage Disk	4030604	4C
	Waspaloy	7th-Stage Disk	4041337	7C
	Waspaloy	8th-Stage Disk	4040108	8C
	Waspaloy	12th-Stage Disk	4022612	12C
	Waspaloy	6th-Stage Airseal (6-7 Rim Spacer)	4039846	6/7 CPS
	Waspaloy	7th-Stage Airseal (7-8 Rim Spacer)	4039727	7/8 CPS
	Waspaloy	8th-Stage Airseal (8-9 Rim Spacer)	4050978	8/9 CPS
	Waspaloy	9th-Stage Airseal (9-10 Rim Spacer)	4050979	9/10 CPS
	Astroloy	10th-Stage Airseal (10-11 Rim Spacer)	4043279	10/11 CPS
	Astroloy	11th-Stage Airseal (11-12 Rim Spacer)	4043280	11/12 CPS
	Astroloy	12th-Stage Airseal (12-13 Rim Spacer)	4041591	12/13 CPS
High-Pressure Turbine (HPT)	Astroloy	1st-Stage Front Blade Retainer Plate (TOBI Seal)	4036812	TOBI
	IN100	1st-Stage Turbine Disk	4043321	1T
	IN100	2nd-Stage Turbine Disk	4042922	2T
	IN100	1-2 Rim Spacer	4042715	1/2 TS
Fan Drive Turbine (LPT)	IN100	3rd-Stage Turbine Disk	4041794	3T
	IN100	4th-Stage Turbine Disk	4001857	4T

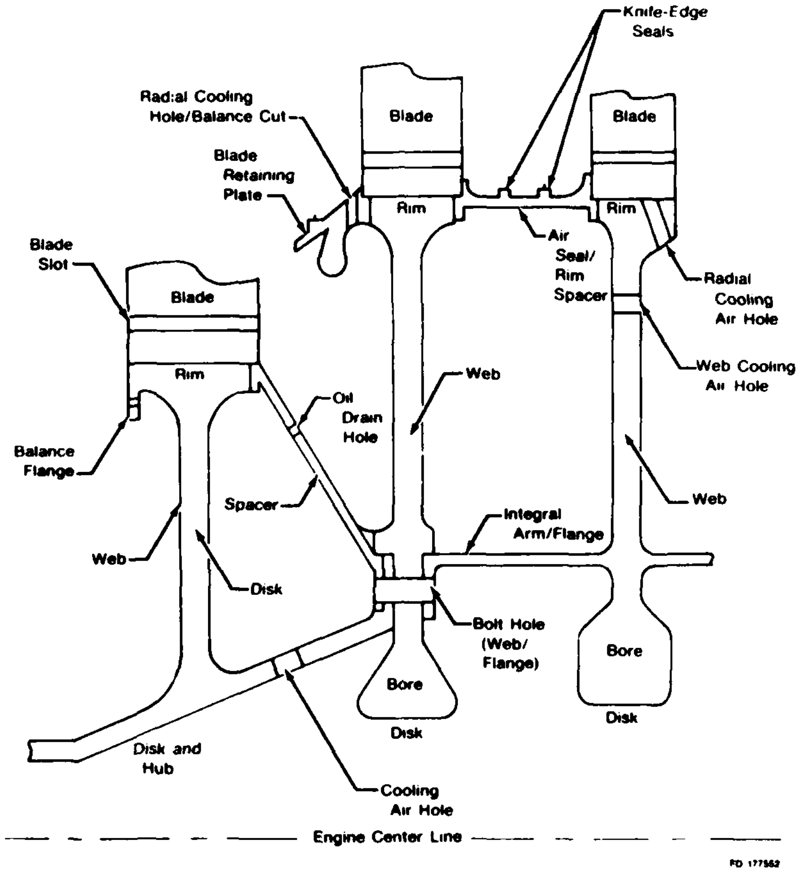


Figure 3. Composite Sketch of Typical F100 Rotor Components and Critical Locations (Not All Features on All Parts)

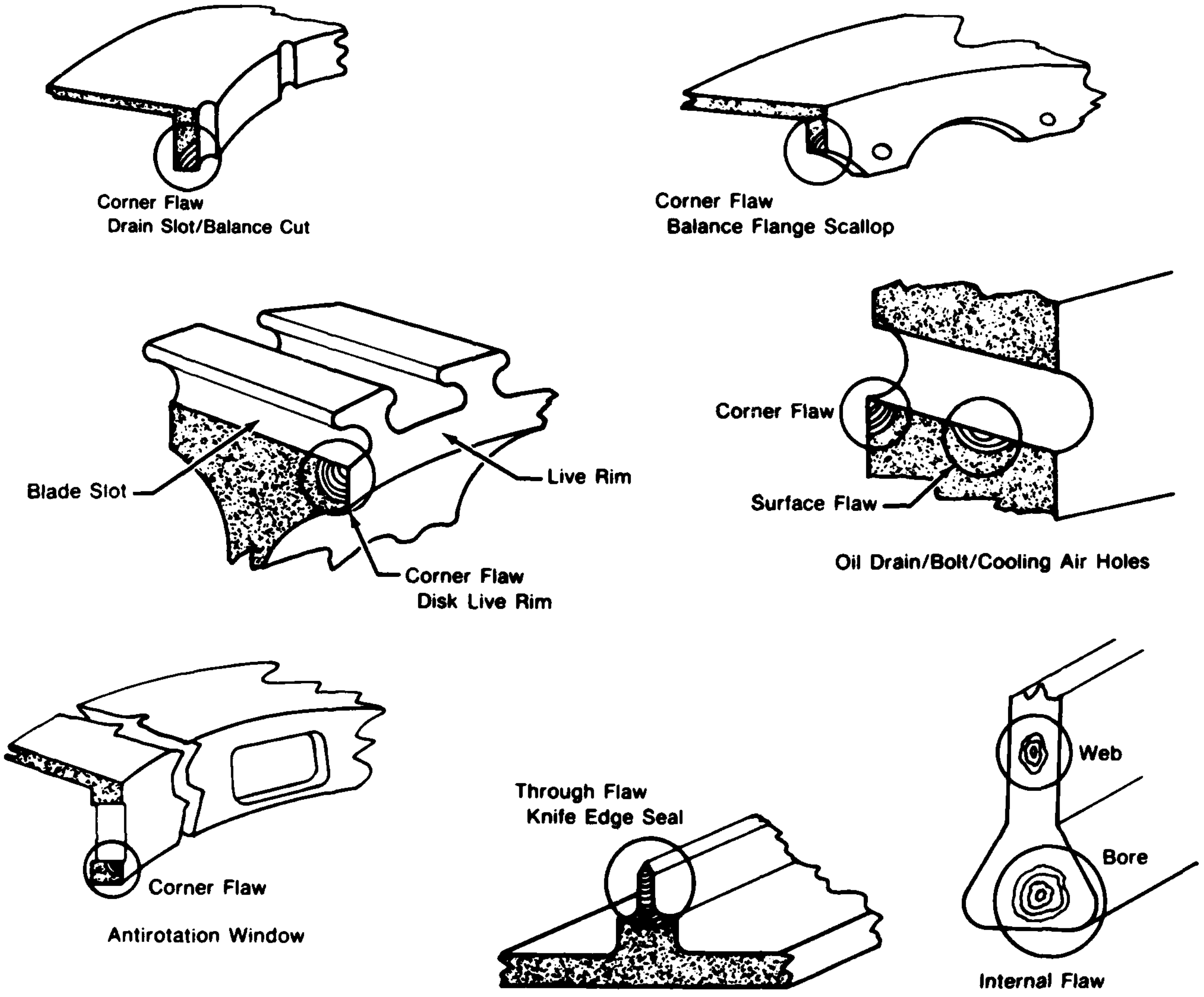


Figure 4. Composite Sketch of Typical Flaw Locations (Not All Features on All Parts)

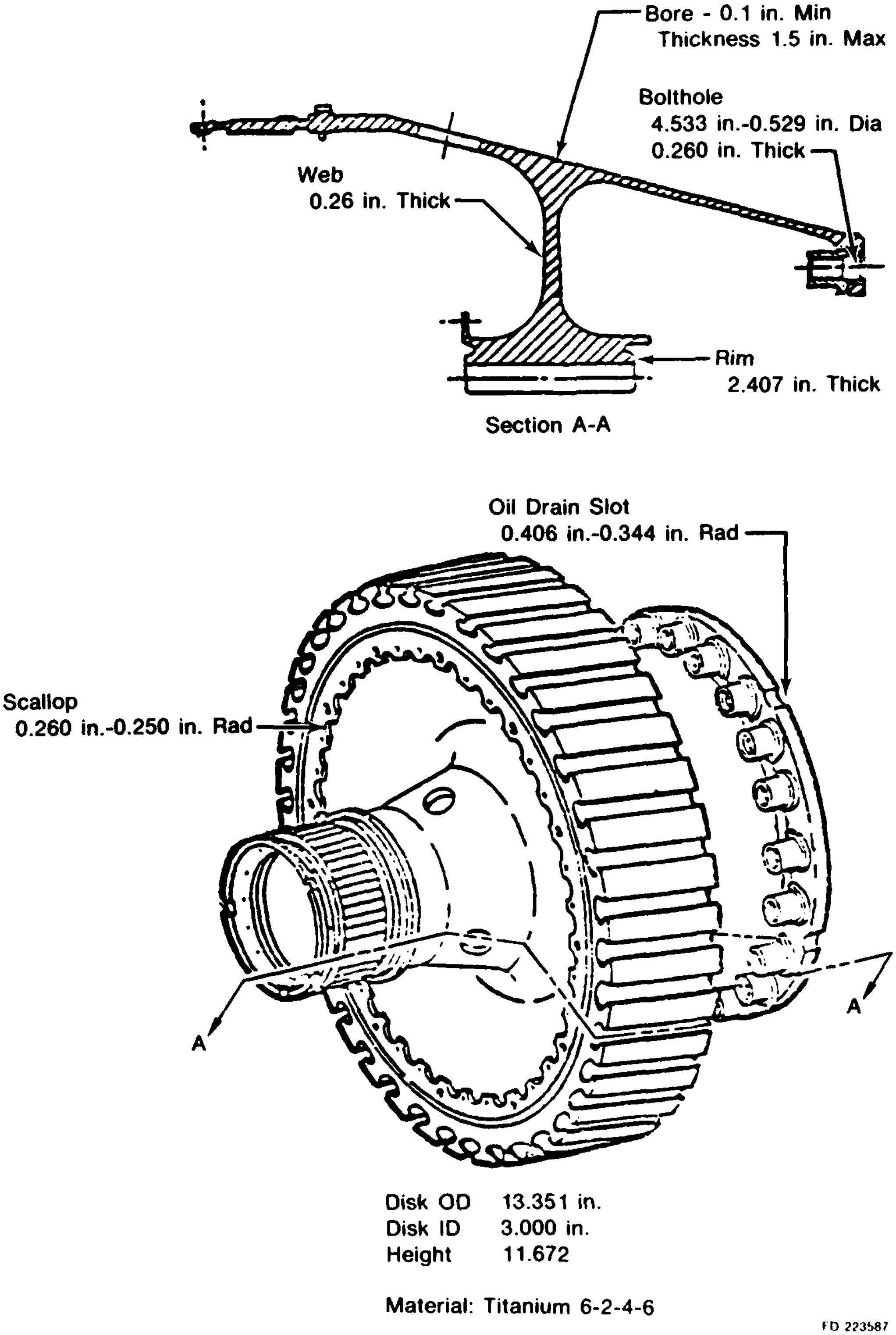
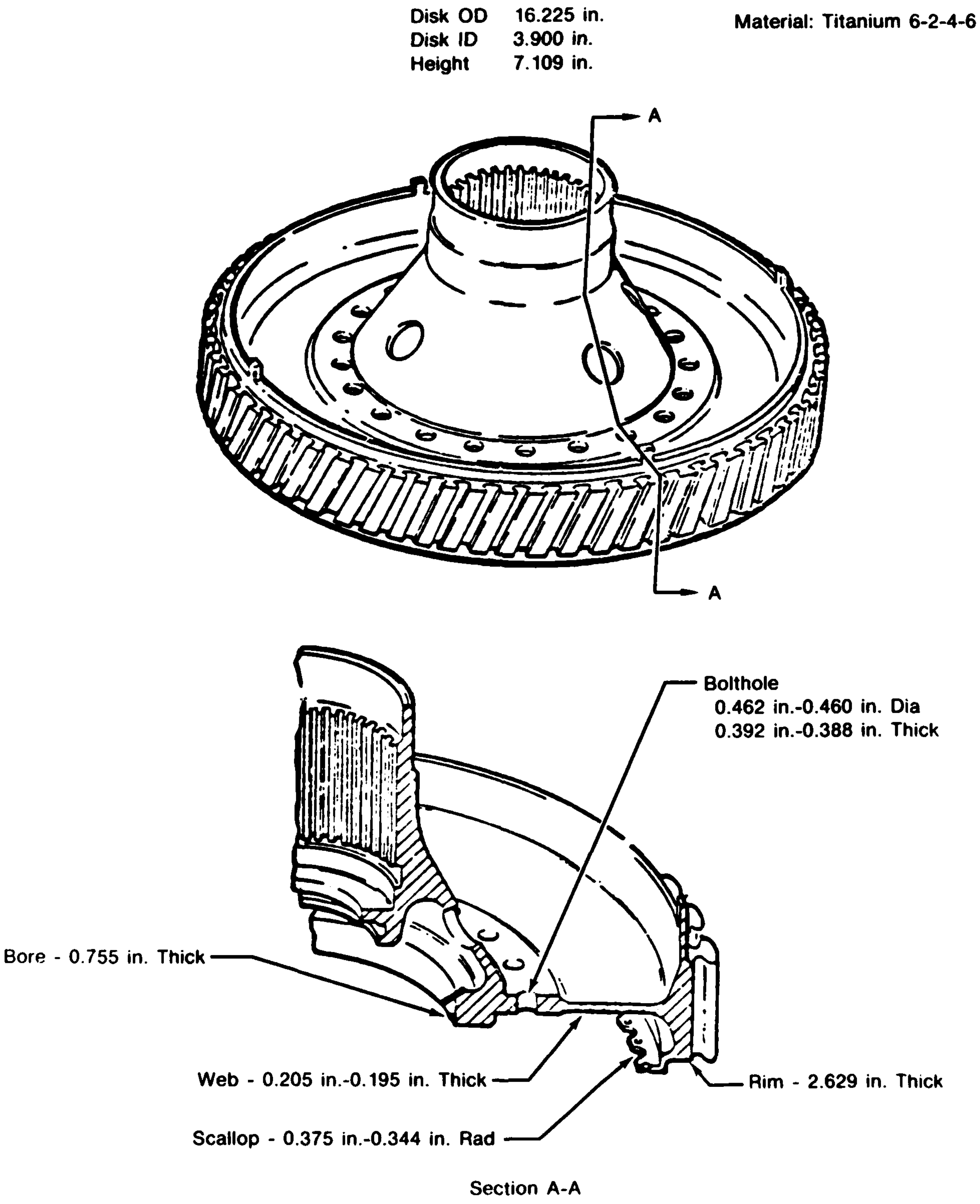
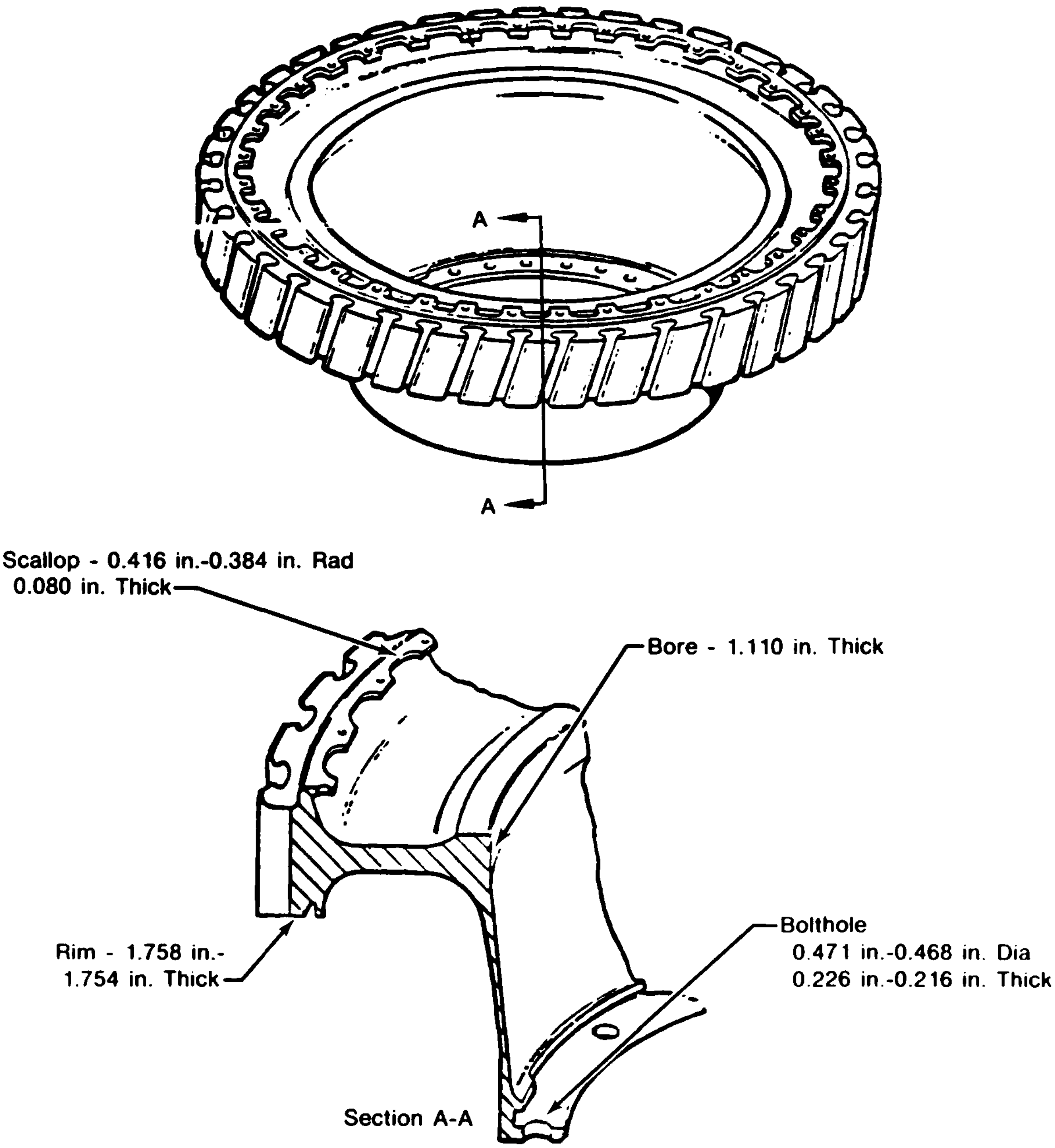


Figure 5. 1st-Stage Fan Disk (P/N 4046741)



FD 223588

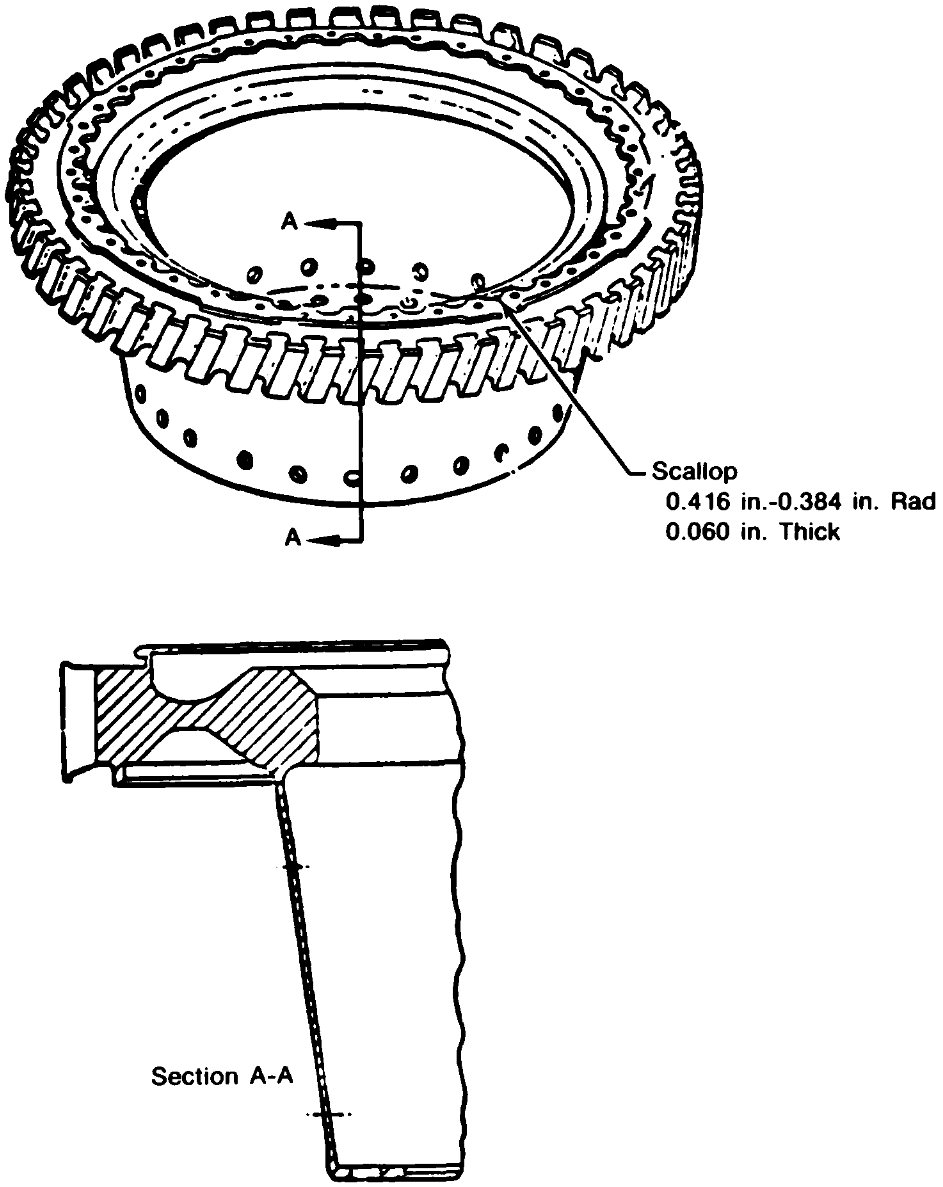
Figure 6. 2nd-Stage Fan Disk (P/N 4048902)



Disk OD	16.865 in.	Material: Titanium 6-2-4-6
Disk ID	9.091 in.	
Height	5.8525 in.	

FD 227589

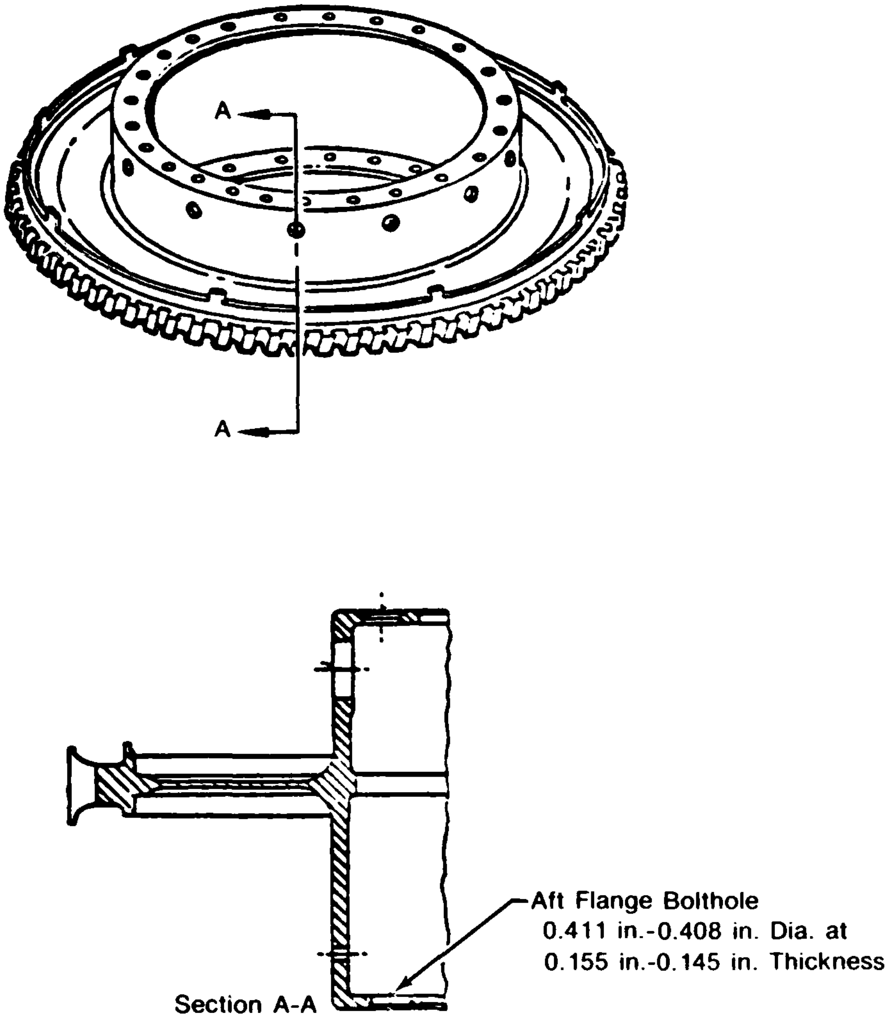
Figure 7. 3rd-Stage Fan Disk (P/N 4048903)



Disk OD	16.865 in.	Material: Titanium 6-2-4-6
Disk ID	9.091 in.	
Height	6.220 in.	

FD 223590

Figure 8. 4th-Stage Compressor Disk (P/N 4030604)



Disk OD	16.776 in.
Disk ID	8.710 in.
Height	4.499 in.

Material: Waspaloy

FD 223591

Figure 9. 7th-Stage Compressor disk (P/N 4041337)

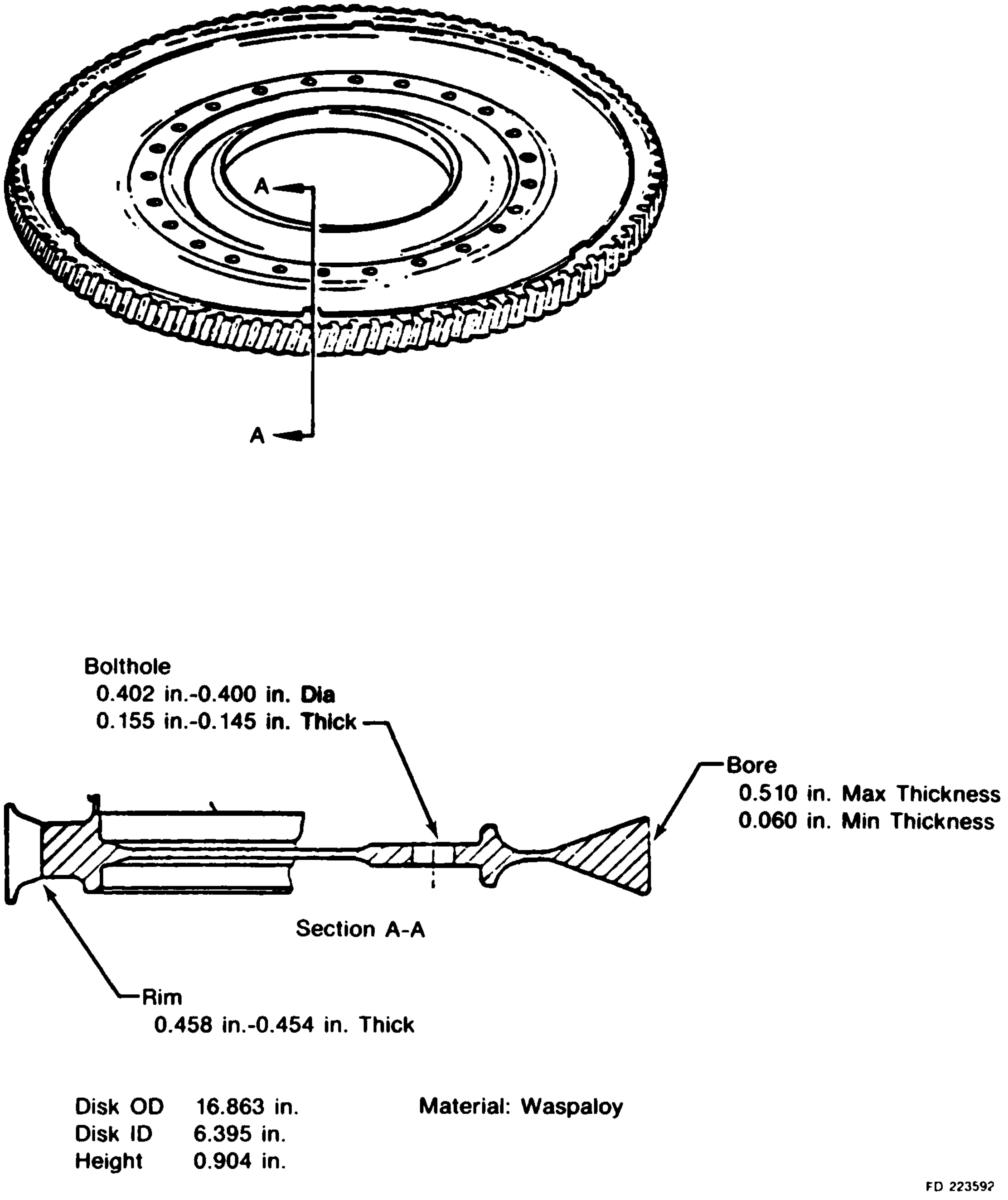
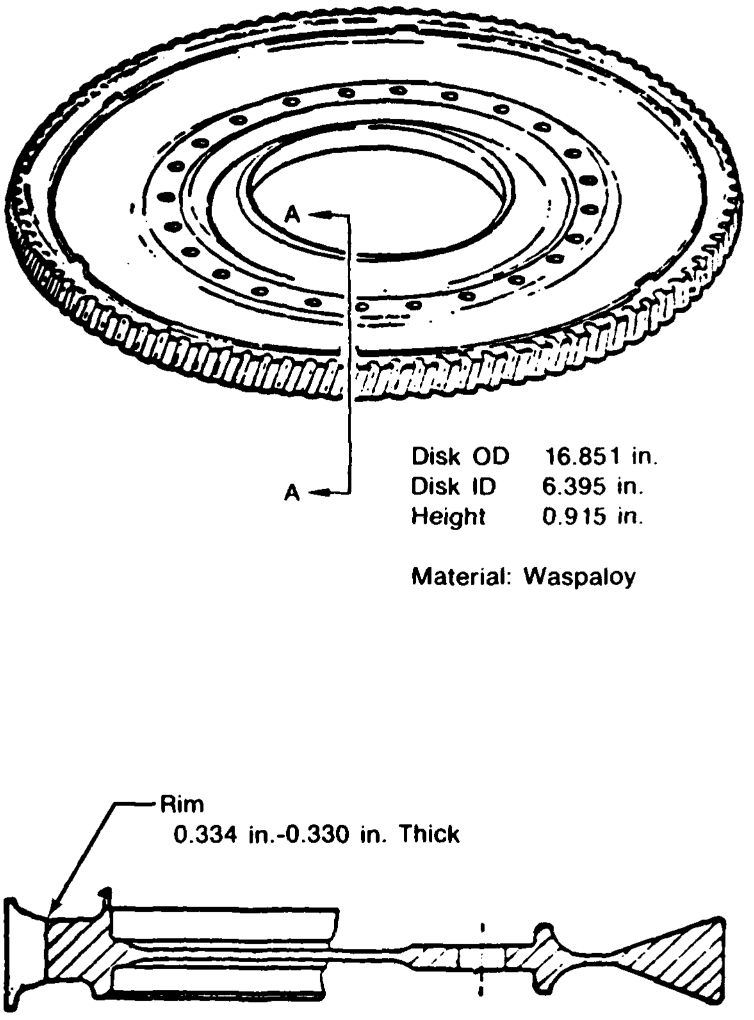


Figure 10. 8th-Stage Compressor Disk (P/N 4040108)



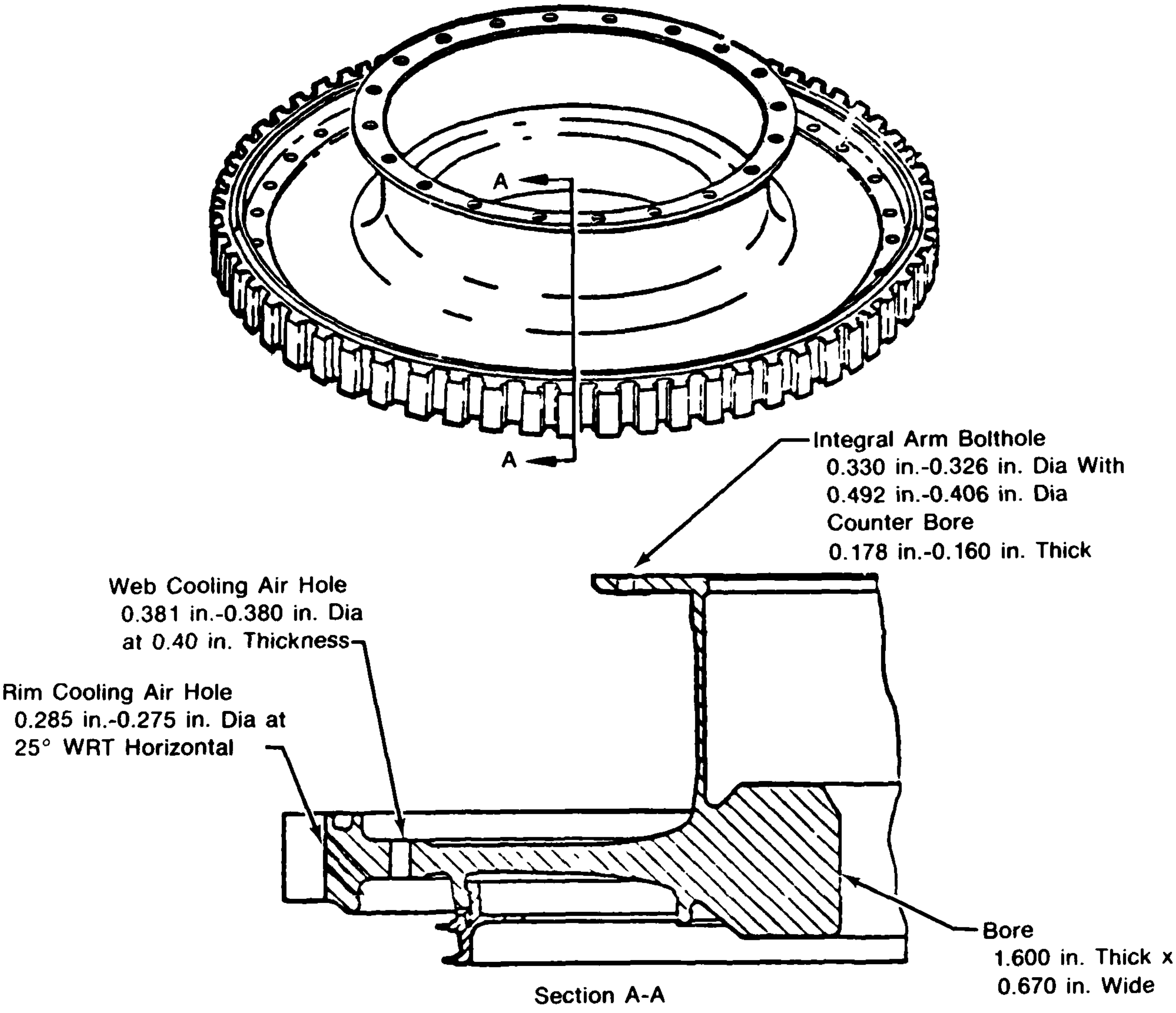
Disk OD 16.851 in.
Disk ID 6.395 in.
Height 0.915 in.

Material: Waspaloy

Section A-A

FD 223593

Figure 11. 12th-Stage Compressor Disk (P/N 4022612)



Disk OD	18.368 in.
Disk ID	6.995 in.
Height	3.832 in.

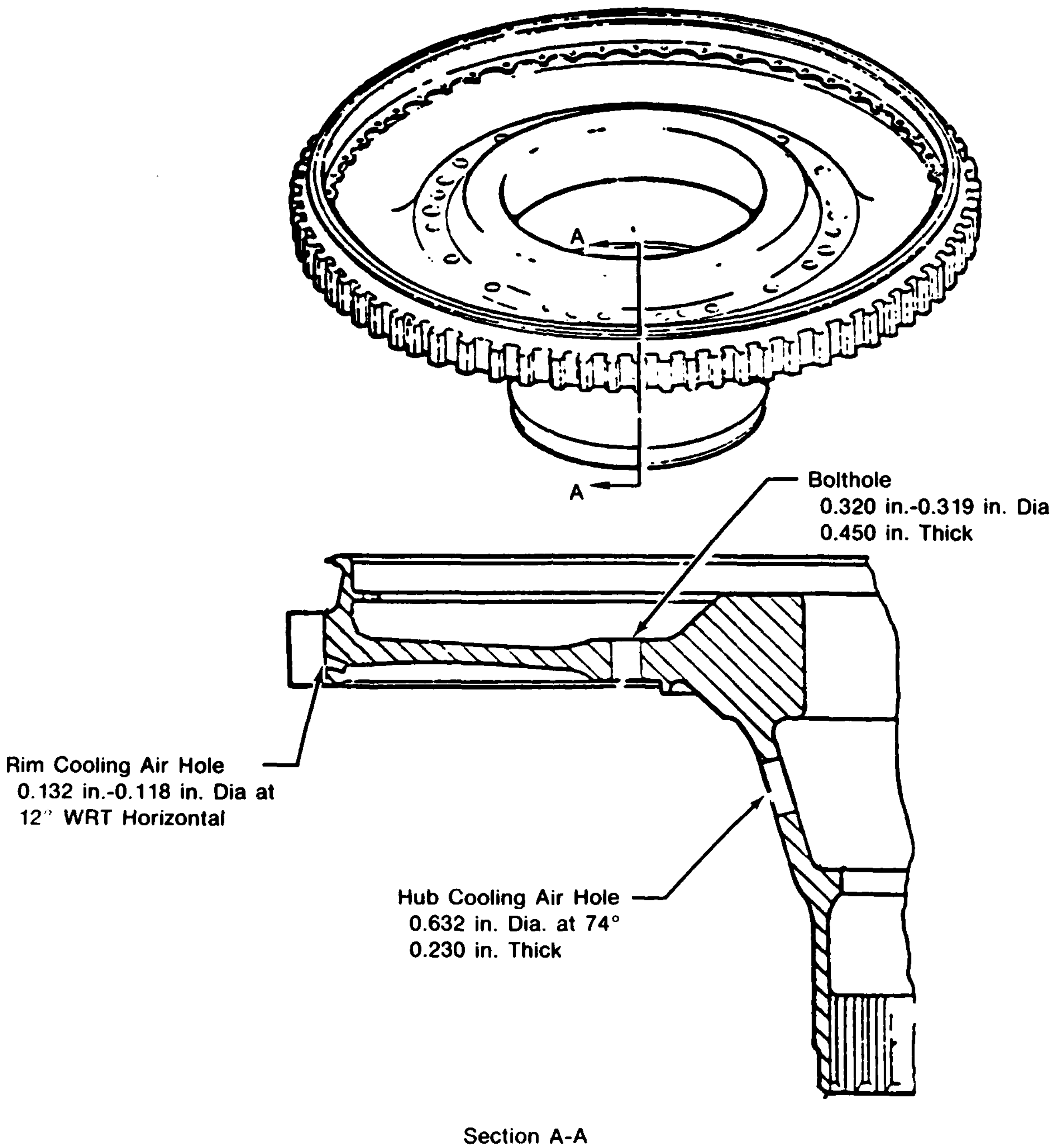
Material: GATORIZED· IN100

FD 223594

Figure 12. 1st-Stage Turbine Disk (P/N 4043321)

Disk OD	16.521 in.
Disk ID	6.685 in.
Height	5.875 in.

Material: GATORIZED® IN100



Section A-A

Figure 13. 2nd-Stage Turbine Disk (P/N 4042922)

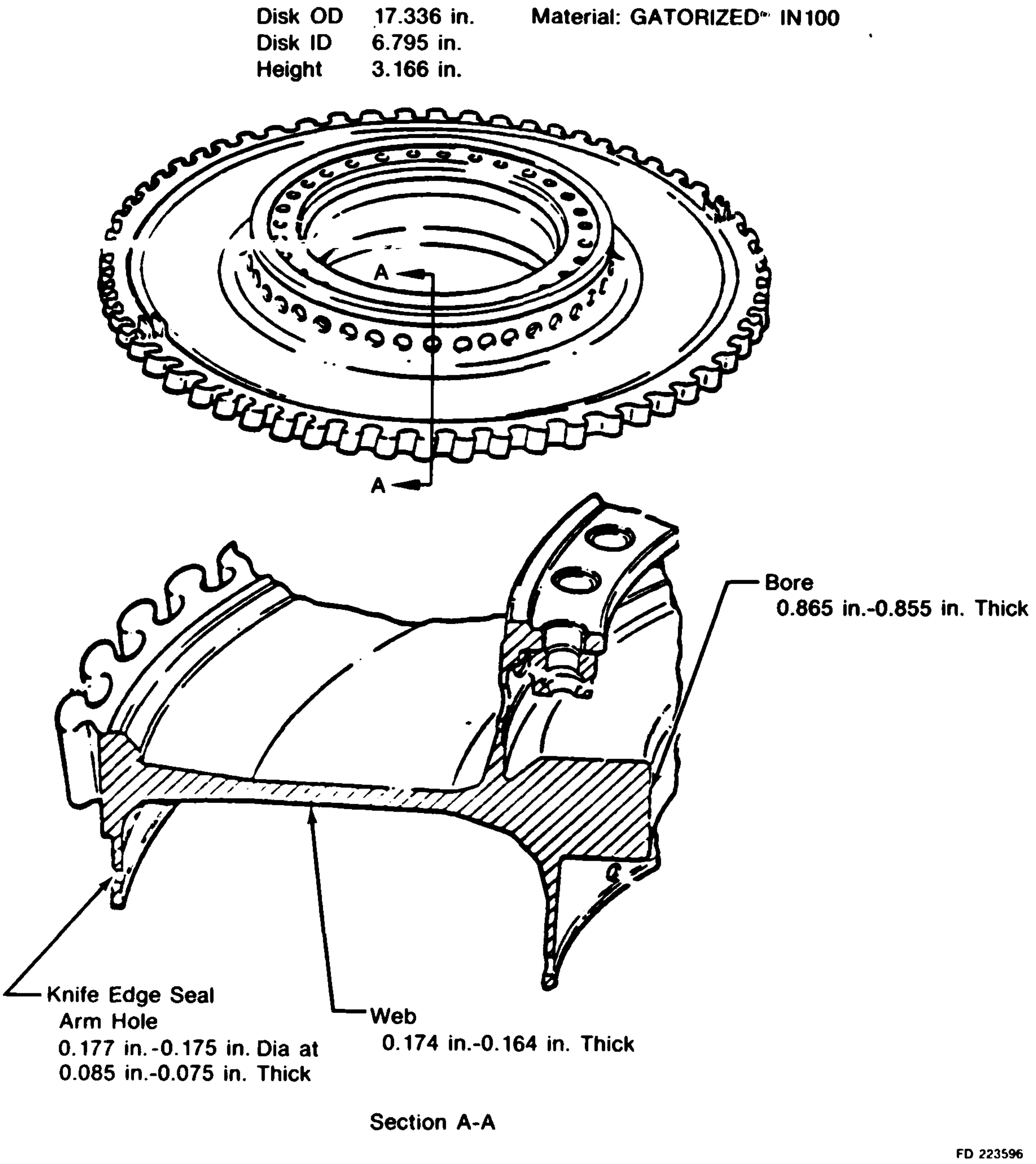
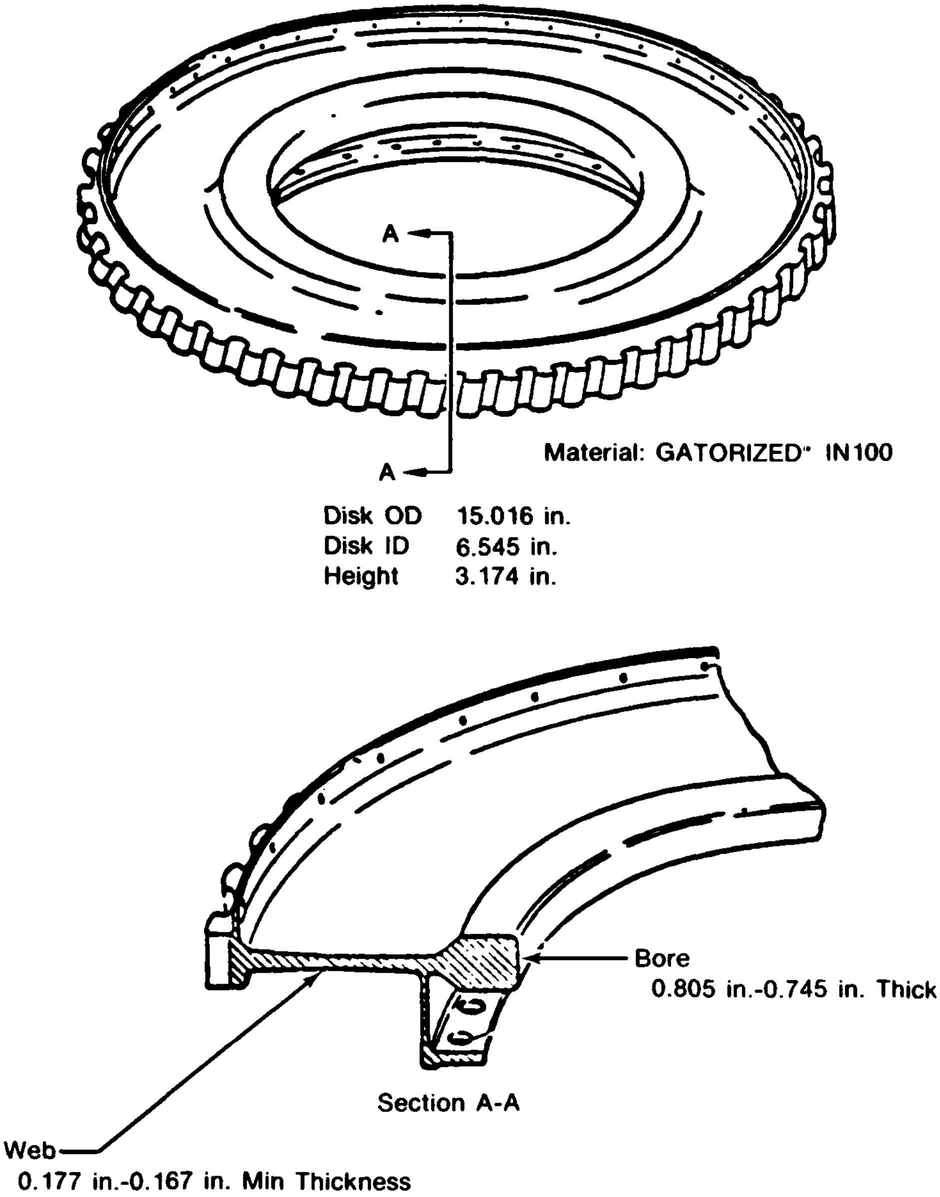


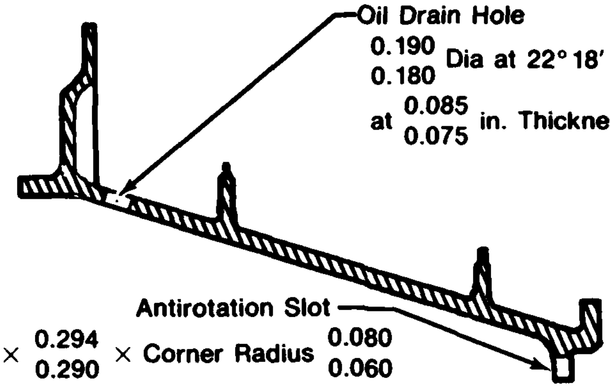
Figure 14. 3rd-Stage Turbine Disk (P/N 4041794)



Material: GATORIZED® IN100

Disk OD	15.016 in.
Disk ID	6.545 in.
Height	3.174 in.

Figure 15. 4th-Stage Turbine Disk (P/N 4061857)



Oil Drain Hole

$\genfrac{}{}{0pt}{}{0.190}{0.180}$ Dia at 22° 18′ WRT Vert

at $\genfrac{}{}{0pt}{}{0.085}{0.075}$ in. Thickness

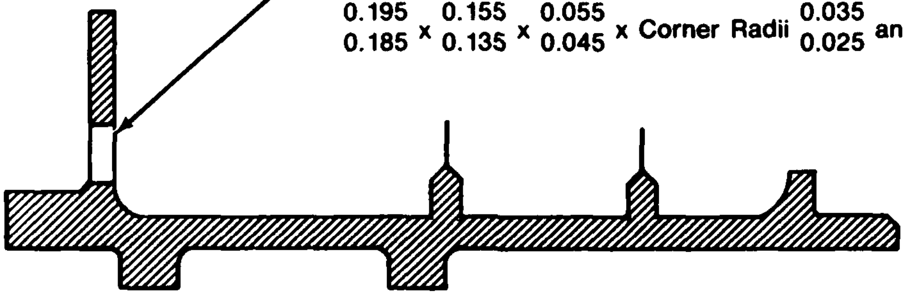
Antirotation Slot

$\genfrac{}{}{0pt}{}{0.305}{0.295} \times \genfrac{}{}{0pt}{}{0.294}{0.290} \times$ Corner Radius $\genfrac{}{}{0pt}{}{0.080}{0.060}$

Spacer OD	19.521 in.	Material: Titanium 6-2-4-6
Spacer ID	15.166 in.	
Height	3.2765 in.	

FD 223598

Figure 16. 2-3 Compressor Spacer (P/N 4049087)



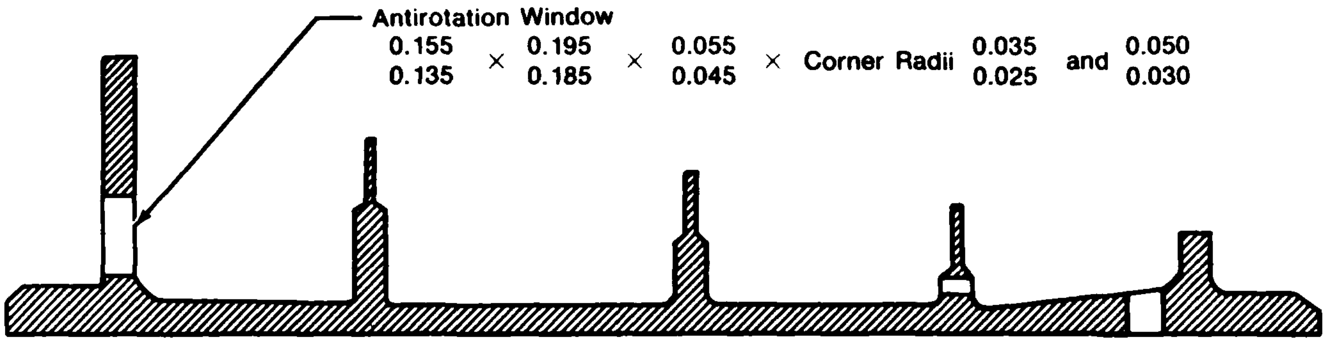
Antirotation Window

$\genfrac{}{}{0pt}{}{0.195}{0.185} \times \genfrac{}{}{0pt}{}{0.155}{0.135} \times \genfrac{}{}{0pt}{}{0.055}{0.045} \times$ Corner Radii $\genfrac{}{}{0pt}{}{0.035}{0.025}$ and $\genfrac{}{}{0pt}{}{0.050}{0.030}$

Spacer OD	16.280 in.	Material: Waspaloy
Spacer ID	15.160 in.	
Height	2.082 in.	

FD 223599

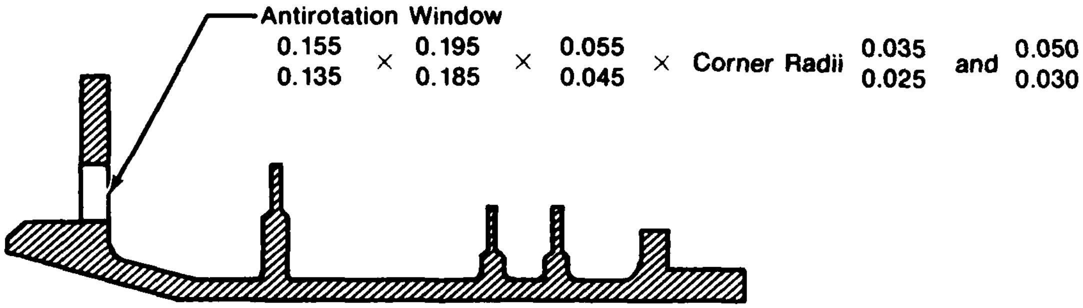
Figure 17. 6-7 Compressor Spacer (P/N 4039846)



Spacer OD 16.270 in. Material: Waspaloy
Spacer ID 15.240 in.
Height 2.323 in.

FD 223600

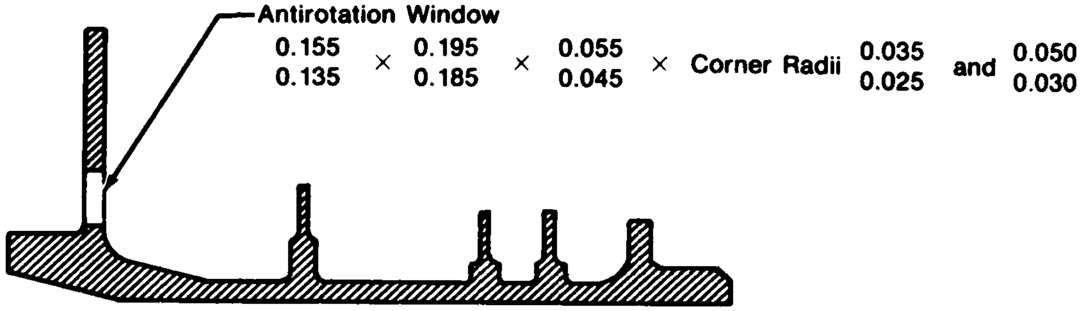
Figure 18. 7-8 Compressor Spacer (P/N 4039727)



Spacer OD 16.270 in. Material: Waspaloy
Spacer ID 15.240 in.
Height 1.760 in.

FD 223051

Figure 19. 8-9 Compressor Spacer (P/N 4050978)



Spacer OD	16.330 in.	Material: Waspaloy
Spacer ID	15.450 in.	
Height	1.763 in.	

FD 223052

Figure 20. 9-10 Compressor Spacer (P/N 4050979)

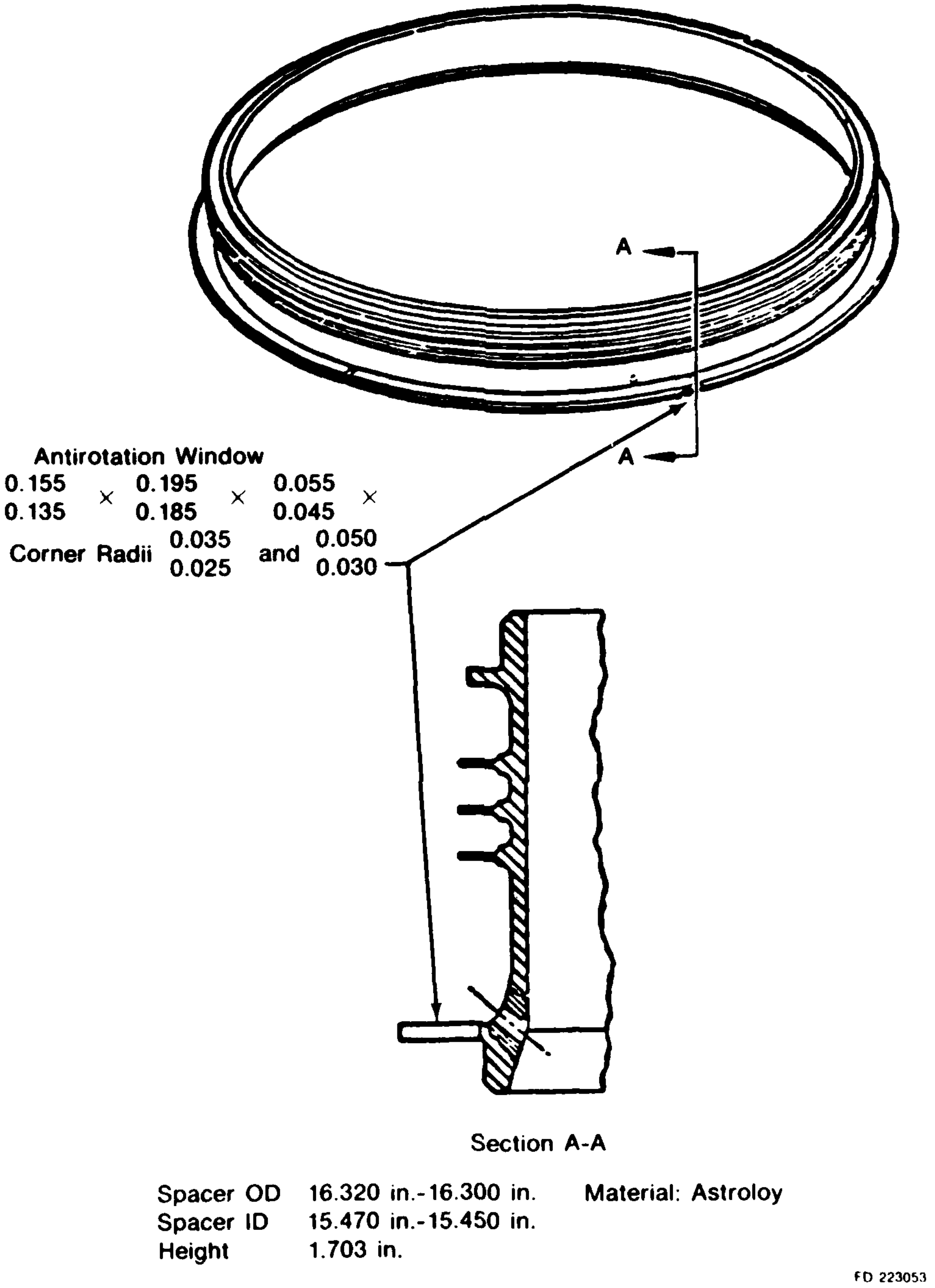
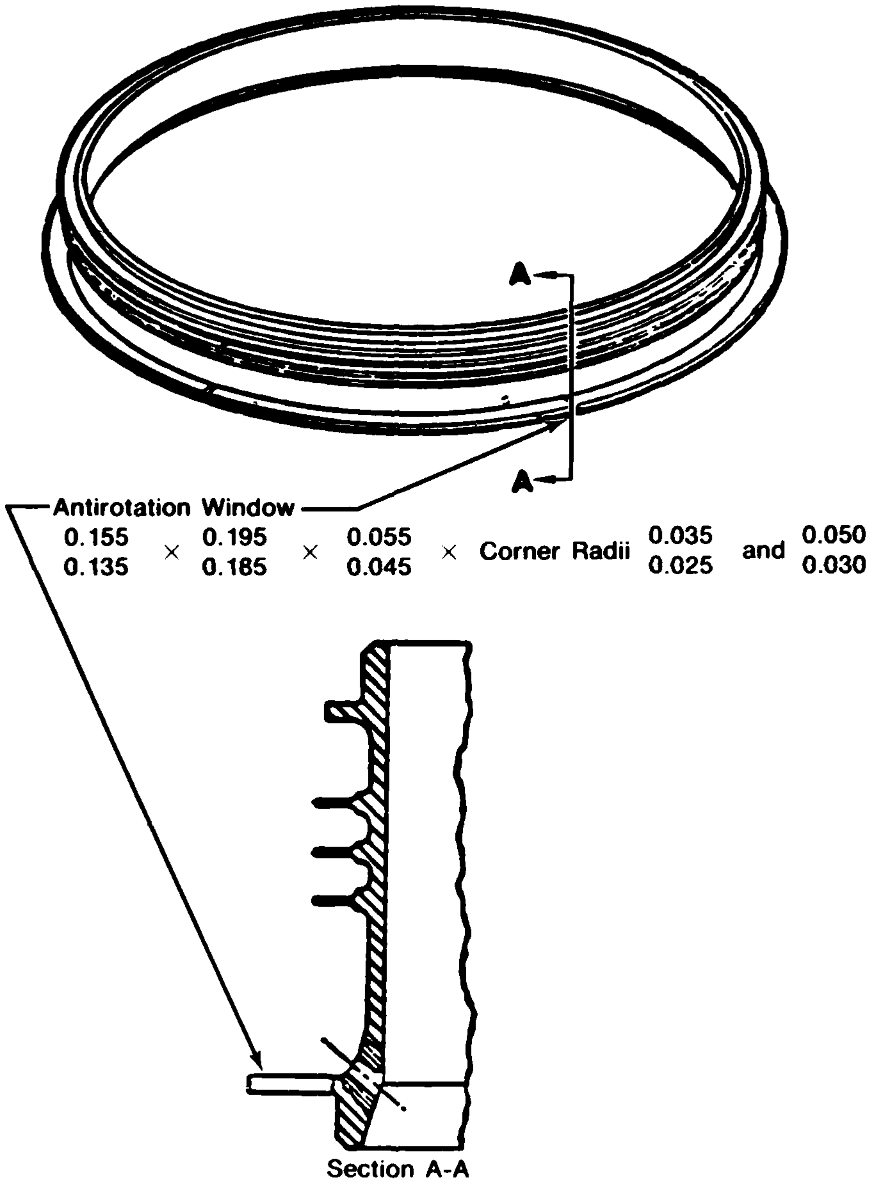


Figure 21. 10-11 High Pressure Compressor Spacer (P/N 4043279)

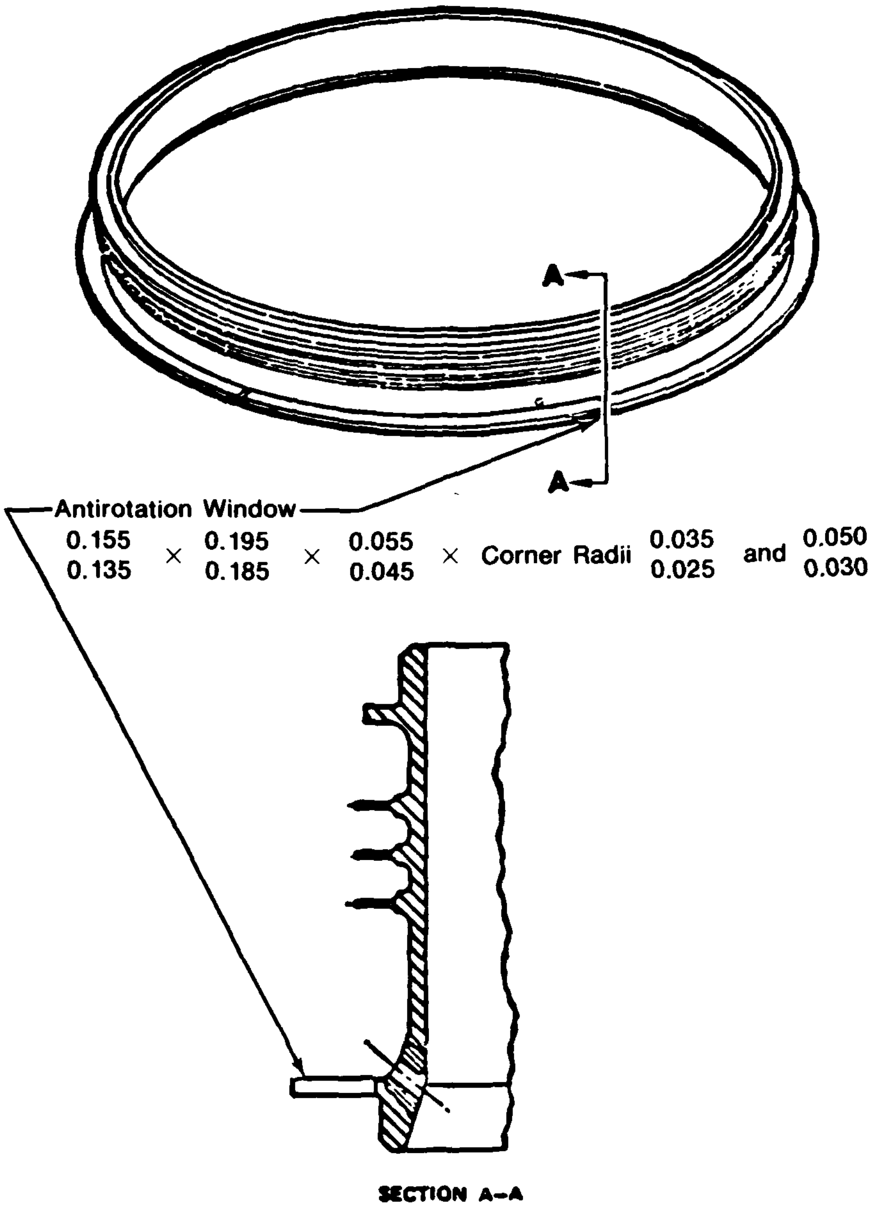


Spacer OD	16.330 in.-16.310 in.
Spacer ID	15.470 in.-15.450 in.
Height	1.705 in.

Material: Astroloy

FD 223054

Figure 22. 11-12 High Pressure Compressor Spacer (P/N 4043280)

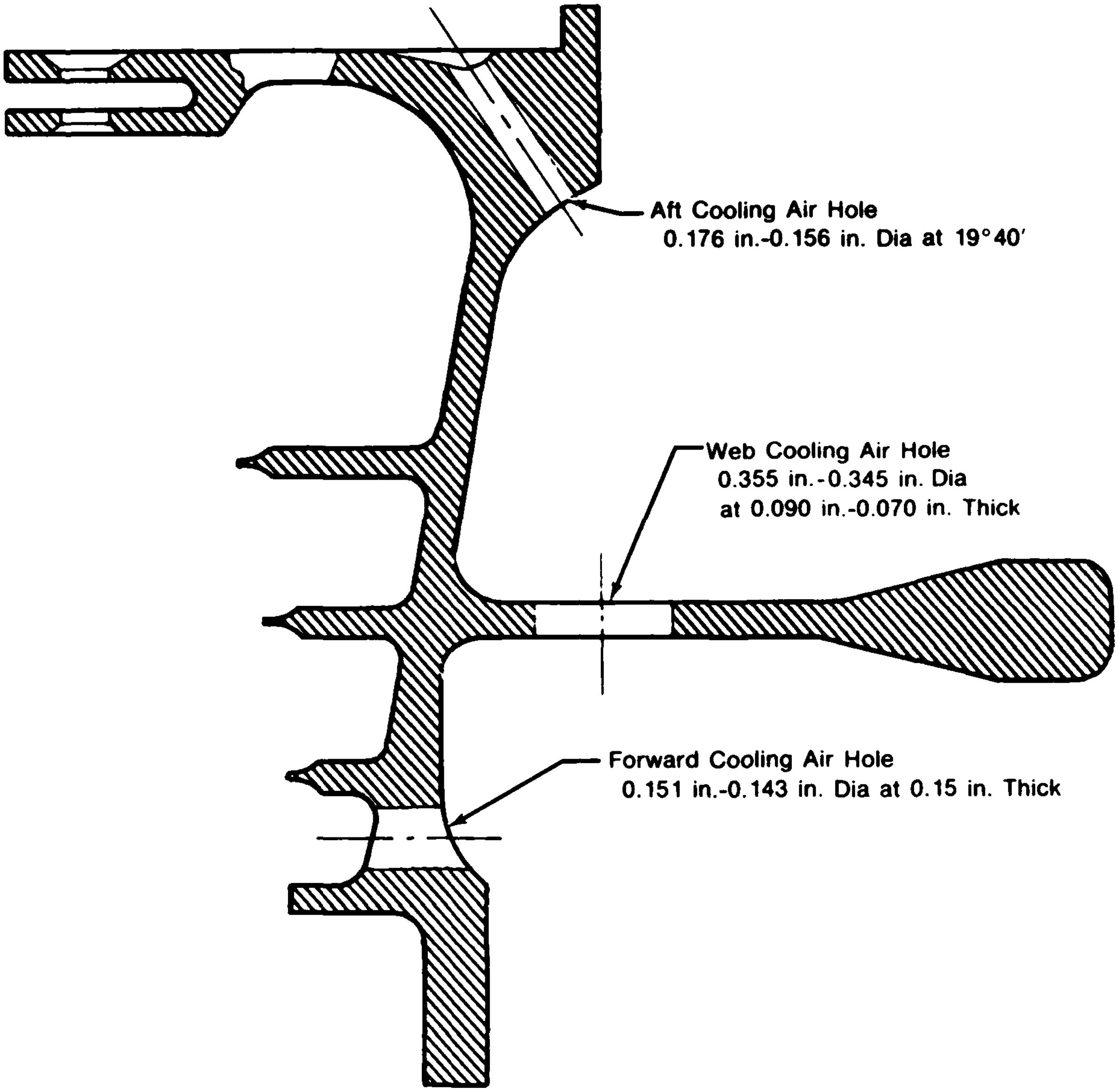


Spacer OD	16.330 in.-16.320 in.
Spacer ID	15.450 in.-15.470 in.
Height	1.612 in.

Material: Astroloy

FD 223055

Figure 23. 12-13 High Pressure Compressor Spacer (P/N 4041591)



Spacer OD 18.863 in. Material: GATORIZED· IN100
Spacer ID 13.395 in.
Height 2.745 in.

FD 223056

Figure 24. High Pressure Turbine 1-2 Spacer (P/N 4042715)

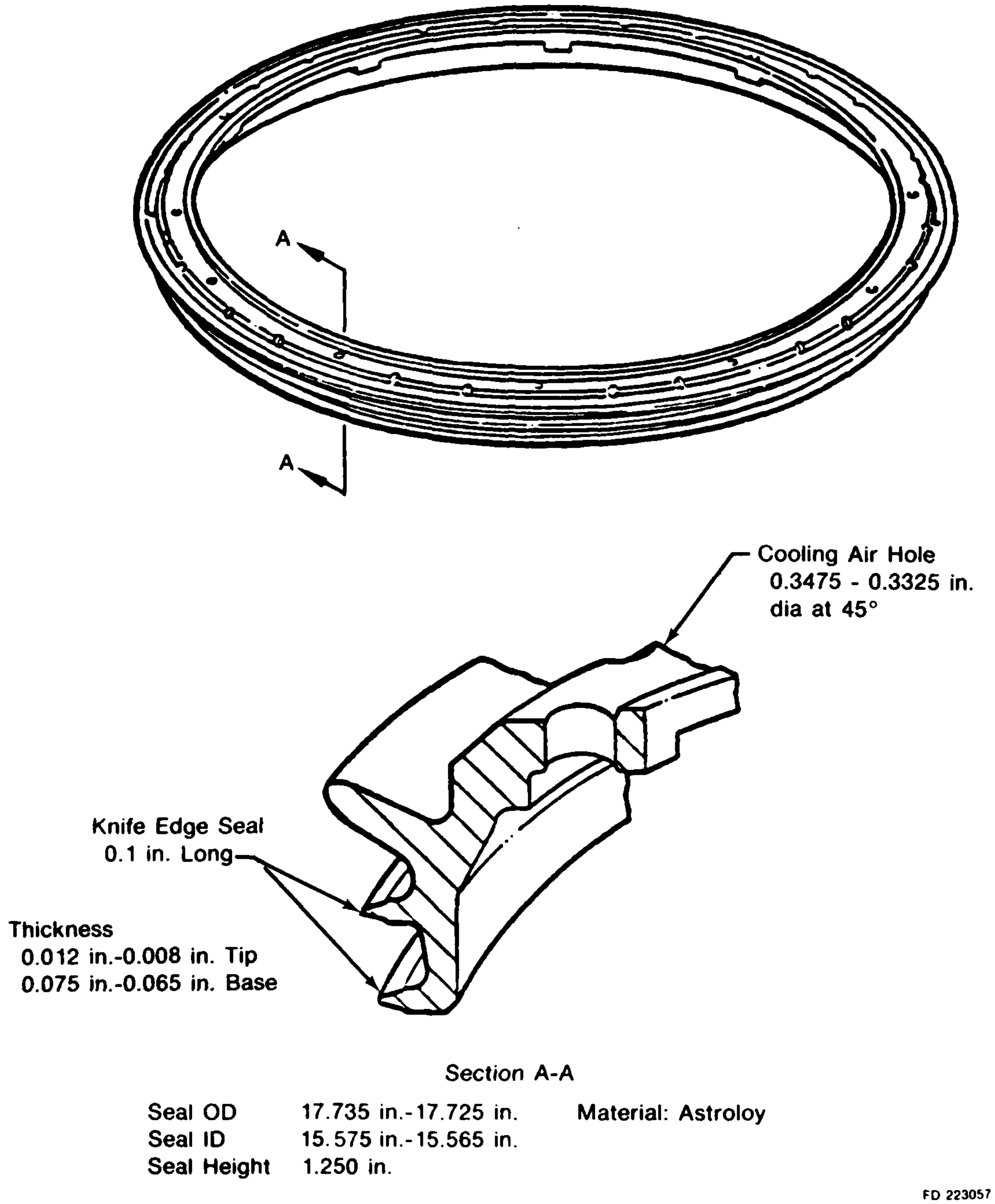
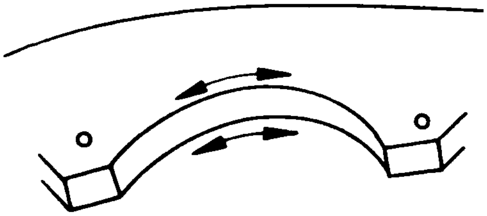


Figure 25. High Pressure Turbine Tangential on Board Injector Outside Diameter Seal (P/N 4036812)

TABLE 2. F100 RFC INSPECTION OPERATIONS

Part Description	*Scallops (Eddy Current) 10 sec/scallop*	*Boltholes (Eddy Current) 15 sec/bolthole*	*Web (Eddy Current, Plus Ultrasonic) 15 min*	*Bore (Eddy Current, Plus Ultrasonic) 15 min*	*Rim Slot Corner (Eddy Current 10 sec/slot*	*Drain Slot (Eddy Current) 10 sec/slot*	*Angle Cooling Hole (Eddy Current) 15 sec/hole*	*Axial Cooling Hole (Eddy Current) 15 sec/hole*	*Radial Hole (Eddy Current) 15 sec/hole*	*Rotation Slot (Eddy Current) 10 sec/slot*	*Knife Edge (Eddy Current 1 min/knife edge*
1st Fan Disk	40	24	X	X	48	6					
2nd Fan Disk	40	24	X	X	64						
3rd Fan Disk	40	24	X	X	48						
4th Compressor Disk	40										
7th Compressor Disk		28									
8th Compressor Disk		28		X	96						
12th Compressor Disk					96						
1st Turbine Disk		20		X			60	30			
2nd Turbine Disk		20					60 20				
3rd Turbine Disk			X	X					30		
4th Turbine Disk			X	X							
2/3 Compressor Spacer					6					6	
6/7 Compressor Spacer										6	
7/8 Compressor Spacer										6	
8/9 Compressor Spacer										6	
9/10 Compressor Spacer										6	
10/11 Compressor Spacer										6	
11/12 Compressor Spacer										6	
12/13 Compressor Spacer										6	
1/2 Turbine Spacer							60	10	30		
TOBI							30				2



Procedure:

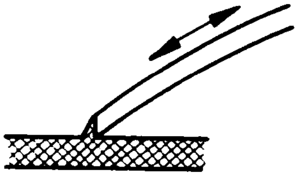
Scan Along the Edge of a Complex Curve with a Contacting Probe, Then Rotate to Next Location

Scan Time: 10 sec

Calibration Time: 20 sec

FD 226726

Figure 26. Scanning Procedure and Time for Scallops



Procedure:

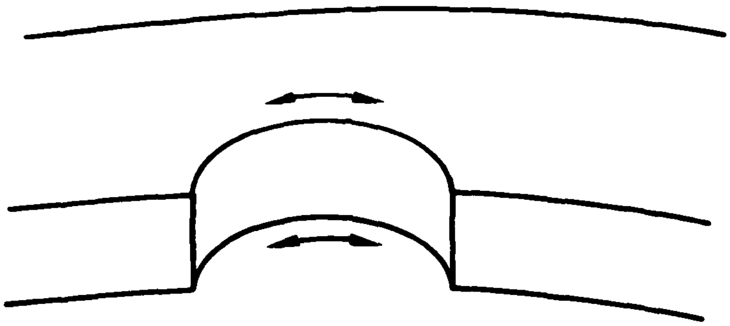
Scan Along the Edge by Rotating Seal Under a Contacting Probe

Scan Time: 1 min

Calibration Time: 20 sec

FD 226727

Figure 27. Scanning Procedure and Time for Knife Edge Seals



Procedure:

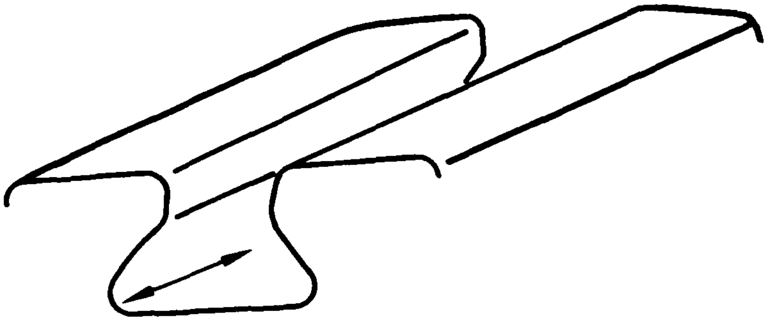
Scan Along the Edge of a
Simple Curve, and Then
Rotate to Next Location

Scan Time: 10 sec

Calibration Time: 20 sec

FD 226728

Figure 28. Scanning Procedure and Time for Oil Drain Slots



Procedure:

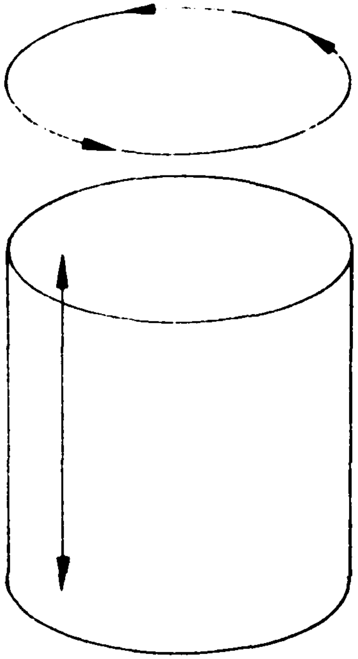
Insert and Withdraw a
Contacting Probe, Then
Index to a New Location

Scan Time: 10 sec

Calibration Time: 20 sec

FD 226729

Figure 29. Scanning Procedure and Time for Rim Slots



Procedure:

Insert and Withdraw a Rotating Noncontacting Probe, Then Index to the Next Location. The Nominal Probe/Surface Clearance Is 0.005 in.

Scan Time: 15 sec

Calibration Time: 30 sec

FD 226730

Figure 30. Scanning Procedure and Time for Boltholes

Procedures:

Two Different Inspections Must Be Performed On Each Side of Disk

1. Scan the Surface by Rotating Disk Under Contacting Eddy Current Probe

   Time: 4½ min per Side

   Calibration Time: 15 sec

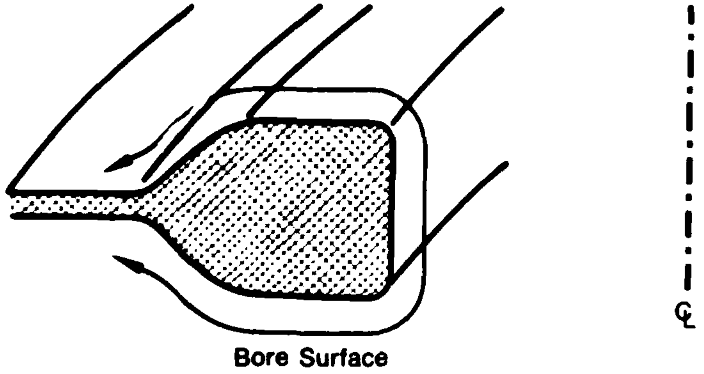
2. Scan the Surface by Rotating Disk Under Noncontacting Ultrasonic Probe Under Water
   Note: A Simultaneous Scan Using Two Probes May Be Necessary To Achieve Inspection Envelope Goals

   Scan Time: 4½ min per Side

   Calibration Time: 2 min

FD 226731

Figure 31. Scanning Procedures and Time for Web Surfaces



Procedures:

Two Different Inspections Must be Performed on Each Side and the ID of the Disk

1. Scan the Surface by Rotating the Disk Under a Contacting Eddy Current Probe

   Time: 7½ min Total

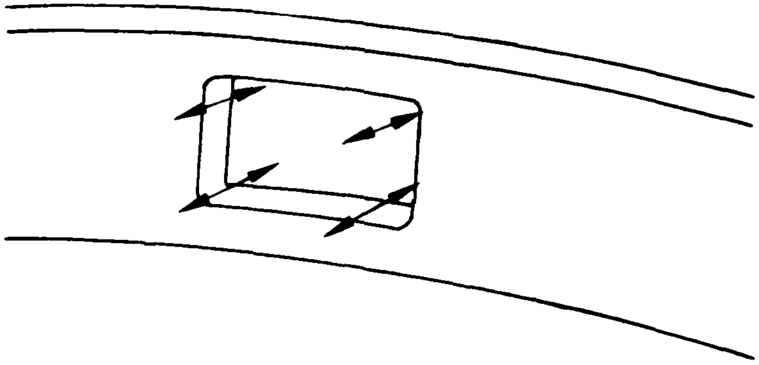
   Calibration Time: 15 sec

2. Scan the Surface by Rotating the Disk Under a Noncatacting Ultrasonic Probe Under Water
   Note: A Simultaneous Scan Using Two Probes May be Necessary to Achieve Inspecion Envelope Goals

   Scan Time: 7½ min Total
   Calibration Time: 2 min

FD 226732

Figure 32. Scanning Procedures and Time for Disk Bore



Procedure:

Scan In and Out Along Each of the Four Corners With a Contacting Probe

Scan Time: 10 sec

Calibration Time: 20 sec

FD 226733

Figure 33. Scanning Procedures and Time for Antirotation Windows

Upon presentation of the detailed F100 inspection and scan requirements to the Air Force Technical Manager, it was concluded that these requirements closely represent the generic requirements for the RFC Inspection System as applied within the scope of this program. Therefore, the selection of applicable NDE methods, system design, and engineering specifications are directed toward satisfying all of the F100 RFC inspection requirements. It is recognized that satisfaction of all the requirements through the production of a 1985-implementable system probably will not be necessary or possible.

The Air Force has specified that, as generic requirements, the RFC Inspection System must be capable of high reliability detection of surface cracks 0.005 in. deep by 0.015 in. long (and larger), located in cooling holes, boltholes, radii, fir tree areas, etc. The system must also be capable of high reliability detection of internal, penny-shaped cracks 0.015 in. diameter (and larger) located within the bore regions of disks. These generic requirements are compatible with F100 RFC inspection requirements.

2.1.2 Air Logistics Command Production/Manufacturing Requirements

RFC Inspection System needs were established by the Air Force and through meetings at the ALC centers at Tinker and Kelly Air Force Bases. No groups of needs have been identified: production/manufacturing and NDE technology needs. The production needs, which relate to the overhaul center environment include maintainability, reliability, throughput, flexibility, and accountability. The NDE technology needs relate to RFC requirements of quantifying, detectability, defect sizing, and measurement stability. Although these needs are all important for establishing RFC, the fulfillment of the operational requirements may represent the greater near-term challenge. RFC implementation crucially depends on inspection equipment working consistently and continuously at the overhaul center.This section summarizes the perceived production/manufacturing requirements as they must be addressed in the RFC Inspection System design.

2.1.2.1 Component Throughput

It has been difficult to obtain definitive information about the number of components that will require RFC-type inspections. A maximum ultimate throughput estimate can be based on current production data and anticipated procurement, but the detailed requirement will depend on the number of components ultimately selected for RFC-type inspection. This number depends on the specific propulsion systems chosen for RFC, the number of critical components in each system, and eventually the number of other engine non-RFC components which may need high resolution inspection for safety purposes.

There are several engine systems in addition to the F100 engine, that are potential candidates for RFC life management. The TF34-GE-100 engine is undergoing a structural assessment effort under the management of Aerospace Systems Division (ASD). As a result of this effort, some components of the TF34 may be identified for RFC application or for other inspection requirements. The TF34 is, however, overhauled by the Naval Air Rework Facility, Alameda, CA, and thus any inspection requirements would not impact the throughput requirements of San Antonio Air Logistics Command or Oklahoma City Air Logistics Command. The TF30-PW engine is the subject of an ongoing RFC concept definition study at Pratt & Whitney Aircraft/Government Products Division (P&WA/GPD). If an RFC maintenance plan is selected for the TF30, the inspection will be implemented at Oklahoma City Air Logistics Command.

There are other engine programs that should be considered if the needed inspection throughput is to be correctly sized. It is reasonable to assume that if the RFC inspection has generic capability that it will be used to perform inspections on all engine rotating components that have specialized inspection requirements. The TF41 and the J69 engines have this type of requirement and they may put an additional load on the production facility.

The current Air Force overhaul production estimates for the F100, J79, TF30, and TF41 are listed in Table 3.

TABLE 3. ESTIMATED PRODUCTION RATE AT TINKER (OKLAHOMA CITY AIR LOGISTICS COMMAND) AND KELLY (SAN ANTONIO AIR LOGISTICS COMMAND) OVERHAUL CENTERS

Center	Engine	Disks/Month
San Antonio-Air Logistics Command	F100	400-1100
San Antonio-Air Logistics Command	J79	180- 270
Oklahoma City-Air Logistics Command	TF30	350- 700
Oklahoma City-Air Logistics Command	TF41	60- 100

For design purposes, an estimate of 2100 disks/spacers per month was selected as the baseline throughput requirement. This represents a potential to inspect the twenty-one RFC candidate components from 100 F100 engines per month, a requirement which may be realized during peak overhaul periods.

2.1.2.2 Maintainability

It was clear from visits to the overhaul centers that the highly automated inspection equipment that would be installed for RFC would be significantly different from the manual or semiautomated inspection equipment now in use. This difference is recognized by Air Logistics Command personnel and is expressed as a fear that an automated system cannot provide the flexibility and assurance of being able to sustain production in the event of a major failure. There is the additional concern that the skill level of operators may not be high enough to be able to identify when and if a failure has occurred.

These concerns generated three specifc design requirements: (1) the system design must be such to assure that a 50 percent throughput capability is available even in the event of a major failure, (2) system elements must have self-diagnostic capability so that equipment malfunction can be readily identified, (3) system elements should be modular to permit a simple replacement repair method to be used.

2.1.2.3 Accountability

The RFC Inspection System will in essence be an accounting capability that establishes the status of components at regular intervals; a component is either retired or reused. A component's status can only be changed by the inspection system. To avoid errors, therefore, care must be taken to keep track of status while a component is being evaluated. A specific system requirement is that the risk of a retired, unevaluated or partially evaluated component returning to service be negligibly small.

2.1.2.4 Flexibility

Inspection requirements, or for that matter inspection equipment ability, will not remain constant in time. It is reasonable to assume that inspection requirements will increase significantly as the high sensitivity RFC-type inspections are extended to other components or component locations. A significant increase in inspection throughput would be required. Meanwhile, if the time to accomplish a whole field eddy current inspection were made considerably shorter (as may be possible), a significant increase in throughput capacity could be realized. A specific design requirement is, therefore, to provide adequate system flexibility so that subsystems may be added or subtracted without major rework. The most likely approach would be a modular system design. The system scanning capability must also have the dexterity to evaluate virtually all locations on a typical engine component. All computer interfacing and communication protocal must also be done according to an industry-wide standard to allow for proper evolution of the RFC Inspection System as advanced technology takes the shape of implementable subsystems.

2.1.2.5 Reliability

Equipment reliability is of primary concern to Air Force and P&WA NDE personnel. Experience indicates that newly designed inspection instrumentation is not highly reliable. In fact, NDE technicians engaged in research and development activities generally spend a large part of their time troubleshooting their equipment. A multistep approach in the manufacturing technology program is suggested (from breadboard, to prototype, to production system) to assure that all equipment meets a rigid set of performance and reliability standards which would be developed and delivered to equipment manufacturers early in that program. A primary method for assurance of reliable production equipment is to devote many operational hours to prototype equipment and encourage malfunctions to appear during that stage of development.

Inspection reliability must also be considered as an operational need. While inspection reliability may not have to be exceptionally high for small defects, the reliability must be quanitifiable and consistent or the entire RFC Inspection System operation may be considered a hoax. Quantification of inspection reliability is also essential for incorportion into the RFC probabilistic analysis for specific components. Therefore a specific requirement of this design program has been to establish the means and the methodology to determine the inspection system defect detectability performance. The requirements to measure performance is more important than establishing a specific minimum detectability because the statistically based life management system will require a knowledge of the frequency a given sized defect will actually be found. It is recognized, however, that it is desirable that the inspection system have a good capablity for finding small flaws.

In summary, specific design requirements identified to meet Air Logistics Command operational needs are:

- Inspection system must have the capacity to process 2100 parts per month
- Inspection system must be capable of operating at least at 50 percent of capacity in the event of a major failure
- System elements must have self-diagnostic capability so equipment malfunction can be identified
- The system must have an accounting and part identification scheme that will allow only inspected and accepted components to reenter service

- System design must permit orderly expansion for greater capability
- All system computer interfacing and communication protocol should be based on industry-side standards to assure ease in upgrading or change of inspection elements
- System elements must be modular to permit quick replacement of malfunctioning elements
- System mechanics and scanning capability should have the inherent capability to inspect all critical locations on F100 disks and spacers
- Ultimate equipment reliability must be assured through rigid performance standards set early in the manufacturing technology program
- Inspection reliability must be consistent enough to readily quantify.

2.1.3 Nondestructive Evaluation Requirements

This section discusses the needs that must be addressed if the RFC maintenance concept is to have optimum implementation. These needs relate to improvements in NDE technology which are required to reliably detect very small flaws with a concomitant low incidence of false calls (Type II inspection errors).

2.1.3.1 Detectability

While it is recognized that conventional aerospace NDE methods may be sensitive enough to meet most RFC flaw detectability requirements, it may be necessary to implement methods with improved small flaw detectability to achieve desired inspection reliability goals at larger, rejectable flaw sizes.

2.1.3.2 Sizing (Quantitative NDE)

The RFC inspection process will consist of two steps: first detection and then sizing. It is likely that, for a high inspection reliability to be achieved at rejectable flaw sizes, much smaller flaws will be detectable using the RFC Inspection System. The ability to detect flaws, accompanied by the inability to quantify them would result in such a high rate of false calls that RFC would become a losing proposition. Classical inspection approaches have focused only on the first step. The second step is important if the criticality of a detected flaw is to be clearly assessed. An estimate of the time it will take a defect to grow to a large size (i.e., an estimate of remaining useful life) requires a knowledge of its current size. The technical capability to make quantitative size estimates from inspection data has been developing over the last ten years. A specific requirement then will be to provide the quantitative sizing capability needed to make more precise estimates of flaw severity.

2.1.3.3 Stability

The RFC Inspection System will be used to manage the life of components over many years. A key element in this management scheme will be the tracking of indications and indication distributions as they increase in size or change shape as time elapses. To provide this tracking capability, it will be necessary to compare measurements that may have been made several years apart. For these comparisons to be meaningful, the respective measurements must have been against the same basis. This requirement of constant basis or system stability will be the key to RFC optimization. A specific requirement will be to establish procedure and standards that will assure constant and uniform system performance, even though system elements are changed, improved, or modified.

In summary, the specific inspection system requirements which must be fulfilled if defect measurement needs are to be met are:

- Inspection techniques must provide for quantitative flaw measurements and high inspection reliability at rejectable flaw sizes

- RFC Inspection System methodology must assure stable performance over long periods of time.

2.1.4 Evaluation of Conventional NDE

Conventional methods which were evaluated for their potential as RFC inspection tools included eddy current, ultrasonic test, and penetrants. The capabilities of present inspection methods are limited by several factors, which include instrumentation, measurement procedures, and data interpretation procedures. A program evaluating the performance of various inspection methods used to assess airframe structures has been completed Reference 1). This program demonstrated that there was a significant degradation in inspection performance when an inspection was applied in maintenance conditions. A similar program evaluating the field performance of turbine engine inspection procedures is underway (Reference 2).

Although this type of program is helpful in identifying the deficiencies in current practices, which are primarily manual, they are not helpful in assessing the potential performance of conventional methods applied in an automatic manner. Unfortunately, it is the knowledge of this performance which we must have to predict the performance of RFC inspection.

Before turning to the specific techniques, it is worthwhile to briefly review the physical reasoning behind the selection of particular forms of energy to be used in detecting and characterizing flaws. Table 4 lists the four types of flaws that are expected and six candidate types of interrogating energy. The last three categories, X ray, optics and thermal waves, are discussed in Section 2.1.5 because the particular RFC-type of applications for these forms of energy are considered to be advanced NDE technology. Table 4 reflects research performed by Professor R. B. Thompson (Ames Research Laboratory) and other program participants.

An entry of D in Table 4 implies that, based on the physical principles involved, the technique should be of high utility in detecting flaws of the particular type indicated. Entries of C and A indicate a strong potential for measuring length and depth, respectively, for surface cracks and for measuring the dimensions parallel to and perpendicular to the web surface, respectively, for internal cracks. In a number of cases, lower case letters are used. This indicates that the technique has potential, but it is deemed to be of less immediate utility either because of complicating physical factors or a lower degree of development.

The table indicates that eddy currents are quite effective for detecting surface flaws and providing important sizing information. These are discussed in greater detail in Section 2.1.4.1.

---

1. "Reliability of NDI on Aircraft Structures," Lockheed-Georgia/Air Force Program AFLC/SAALC/MME 76-6-38-1.

2. "Reliability of Nondestructive Inspection (NDI) of Aircraft Engine Components," Final Report on Phase I, Ward D. Rummel, Martin Marietta, SAALC/MME MCR 79-678.

TABLE 4. CANDIDATE NDE TECHNIQUES FOR RFC-TYPE INSPECTIONS

	Eddy Current	*Ultrasonics*	*Penetrants*	*X-ray*	*Optics*	*Thermal Waves (Photoacoustics)*
Internal flaws		D		d		
		C,A		c		
Through flaws	D	d	D	d	d	d
(knife edge seal)	C,A	c,a	C	c	c	c,a
Corner flaws	D	d	D	d	d	d
	C,A	c,a	C	c	c,a	c,a
Surface flaws	D	d	D	D	d	d
	C,A	c,a	C	a	c	c,a

Code:	Detection	Sizing
Higher potential	D	C,A
Lower potential	d	c,a

Ultrasonics is the preferred technique for detecting and sizing internal flaws. Specific approaches will be discussed later in this section. Ultrasonics can be used, in principle, for surface-connected flaws. However, the complex geometries of rotor components make this quite difficult and it is judged to be a low priority approach for such flaws.

Penetrant inspection is the most common inspection method used for gas turbine engine components. It appears to be a relatively simple, inexpensive process to apply for detection of surface-connected defects. Its capability to detect small crack-like flaws also appears to be good. But, as indicated in the following section, its simple appearance is deceptive, and overhaul inspection reliability can be poor.

X-rays have detection and sizing potential, but this is practically limited by: (1) the fact that the reliability of detecting cracks (rather than volumetric flaws) is low, and by (2) the capabilities of available instrumentation. A brief review of some of the more advanced instrumentation that is presently available or under development is given.

2.1.4.1 Eddy Current

There are several commercially available eddy current inspection systems which are capable of performing high resolution inspection. These state-of-the-art instruments are compact designs, capable of performing inspections over a wide range of frequencies (100 Hz to 6MHz), are of solid state design with integral oscilloscopes, and they all have multiple analog outputs. While the sensitivity of the commercially available instruments appears to be sufficient to meet design criteria for the RFC Inspection System, several problems preclude direct usage of any state-of-the-art instrument. Long term stability is not sufficient to allow very sensitive high throughput RFC inspection; no instrument can claim less than 1.0 percent drift within 2 hr. Also, no commercially available eddy current instrument has digital controls or output necessary to be adaptable to a high throughput computer-automated RFC Inspection System. The one instrument which has a digital input appropriate for computer interface, the Nortec NDT-25, is an order of magnitude too slow for high speed inspection.

There are two major programs which have made assessments of the effectiveness of the eddy current inspection methods: "Quantitative Eddy Current Nondestructive Evaluation/Bolthole Inspection" (Reference 3) and "Cost/Risk Analysis for Disk Retirement" (Reference 4). Both of these programs evaluated detectability of cracks in boltholes of TF33 turbine disks.

In the "Quantitative Eddy Current Nondestructive Evaluation/Bolthole Inspection" program, eddy current inspection of the boltholes was made with a Nortec NDT-15 eddy current scope, a special probe consisting of three coils connected electrically in series and spatially in the same circumferential plane at 120° intervals, and a Nortec PS-2 mechanical scanner. The scanner pitch rate was 0.025 in. of travel per revolution, so that one of the three coils would pass over an axial flaw every 0.008 in. of axial translation.

Coil diameter was 0.125 in., and measurements were made at frequencies of 100 kHz, 200 kHz and 2MHz (electromagnetic skin depths of 0.0 in., 0.3 in., 0.01 in. respectively). The coils were mounted on a 0.625-in. diameter probe.

Experimental samples consisted of boltholes in TF33 turbine disks. Two were in-service disks containing fatigue cracks. From a replication analysis, a relationship of $\ell = 11.12$ exp (0.031x) was established where ℓ is the surface length and x is the maximum depth of the crack, each measured in units of 10^{-3}in. Three disks contained electro-discharge machining notches for calibration. These had a width of 0.006 in., lengths ranging from 0.20 in. to 0.800 in., and depths ranging from 0.010 to 0.300 in. It was concluded from an experimental comparison that electro-discharge machining notches and cracks produced responses that were virtually identical. It was also concluded that the response was essentially independent of frequency in the range selected, and hence 500 kHz was selected as a standard frequency. These results are contrary to experience at P&WA, using similar instrumentation.

Sensitivity of the eddy current inspection (including a semi-automatic crack detector) was not completely established. The smallest flaws reported were detected for the electro-discharge machining notches, this size was 0.020 in. long by 0.005 in. deep. For the fatigue cracks, this was 0.010 in. long by 0.010 in. deep.

The "Quantitative Eddy Current Nondestructive Evaluation/Bolthole Inspection" program did not produce a statistically significant number of inspection opportunities to establish a detection probability curve. Instead a receiver operating characteristic curve has been estimated in terms of a plot of probability curve. Instead a receiver operating characteristic curve has been estimated in terms of a plot of probability of false rejects versus the probability of correct detection with the threshold setting of the detector as a parameter. As shown in Figures 34 and 35 each of these parameters increases, as expected, monotonically when the threshold decreases.

Interpretation of these receiver operating characteristics curves depends upon how the probabilities of detection and false alarms are defined. The researcher defined the probability of detection as the number of cracks detected divided by the total number of cracks inspected; the latter was determined from the replicas used. The same definition was used for the disks with electro-discharge machining notches; the known notch location was used to determine the total number of inspections. In each case, the probability of false alarm was taken as the number of false alarms divided by a number equal to the product of the number of boltholes per disk (10), the number of probe rotations per bolthole (40), and the number of possible

---

3. "Quantitative Eddy Current NDE/Bolthole Inspection," second interim report, 9/77 12/79, Adaptronics, Inc

4. "Cost/Risk Analysis for Disk Retirement," second through seventh interim reports, 12/78 3/30, Failure Analysis Associates.

responses per rotation (60). This number is on the order of 24,000 because each of 60 resolvable angular orientations of the probe in each rotation was viewed as a separate opportunity for flaw detection. The very low probabilities of false alarm shown in Figures 34 and 35 result from this large estimate of the number of detection opportunities in each bolthole.

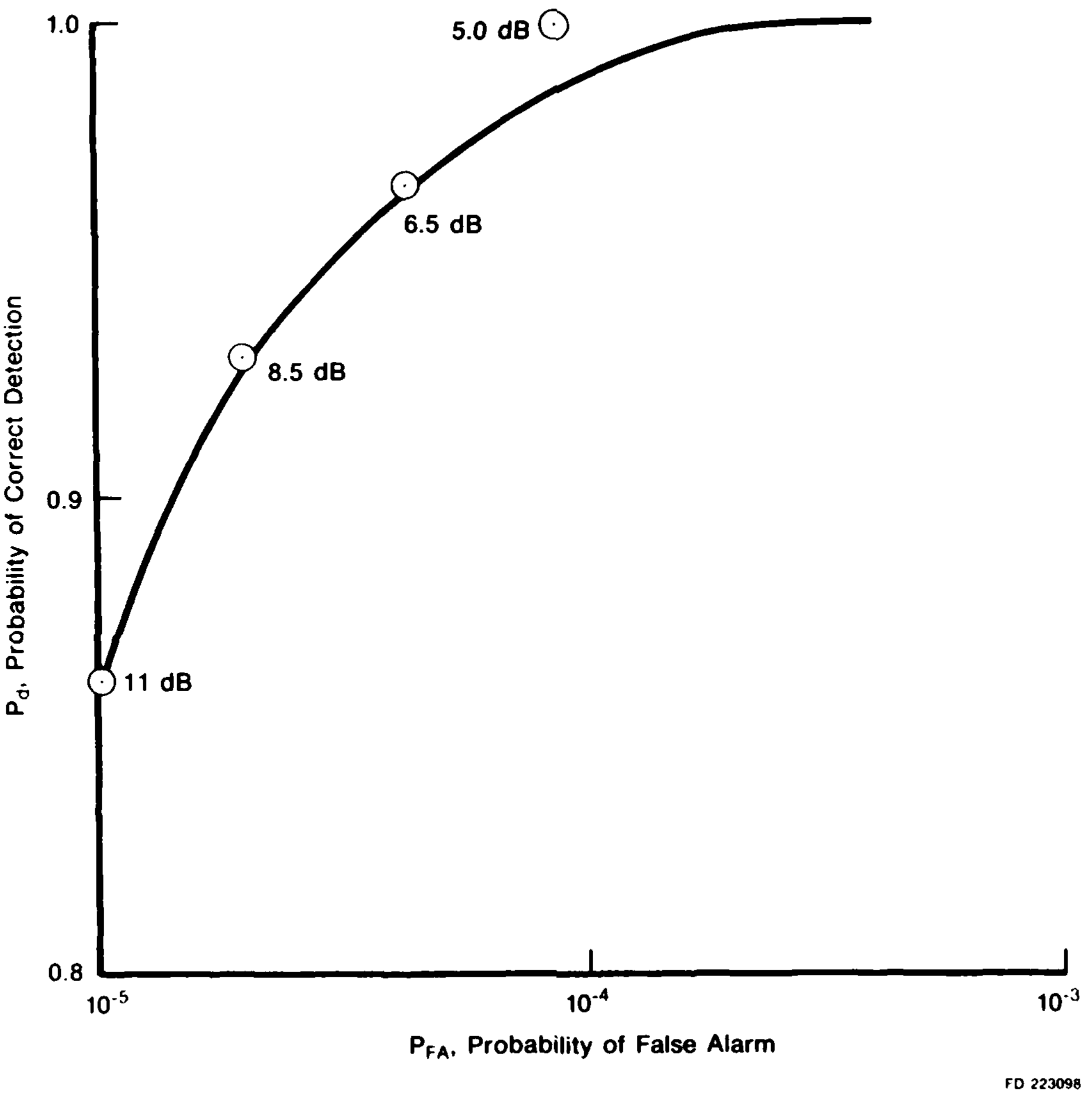


Figure 34. Receiver Operating Characteristic Curve of Automatic Crack Detector for EDM Notches

Based on the receiver operating characteristics shown in Figures 34 and 35 the instrument performance was computed. For example, consider 10,000 disks, containing 100,000 boltholes of which 100 are cracked. The researchers predicted that 89 cracked holes would be correctly identified as cracked, 10 uncracked holes would be incorrectly rejected, and 11 cracked holes would be incorrectly accepted.

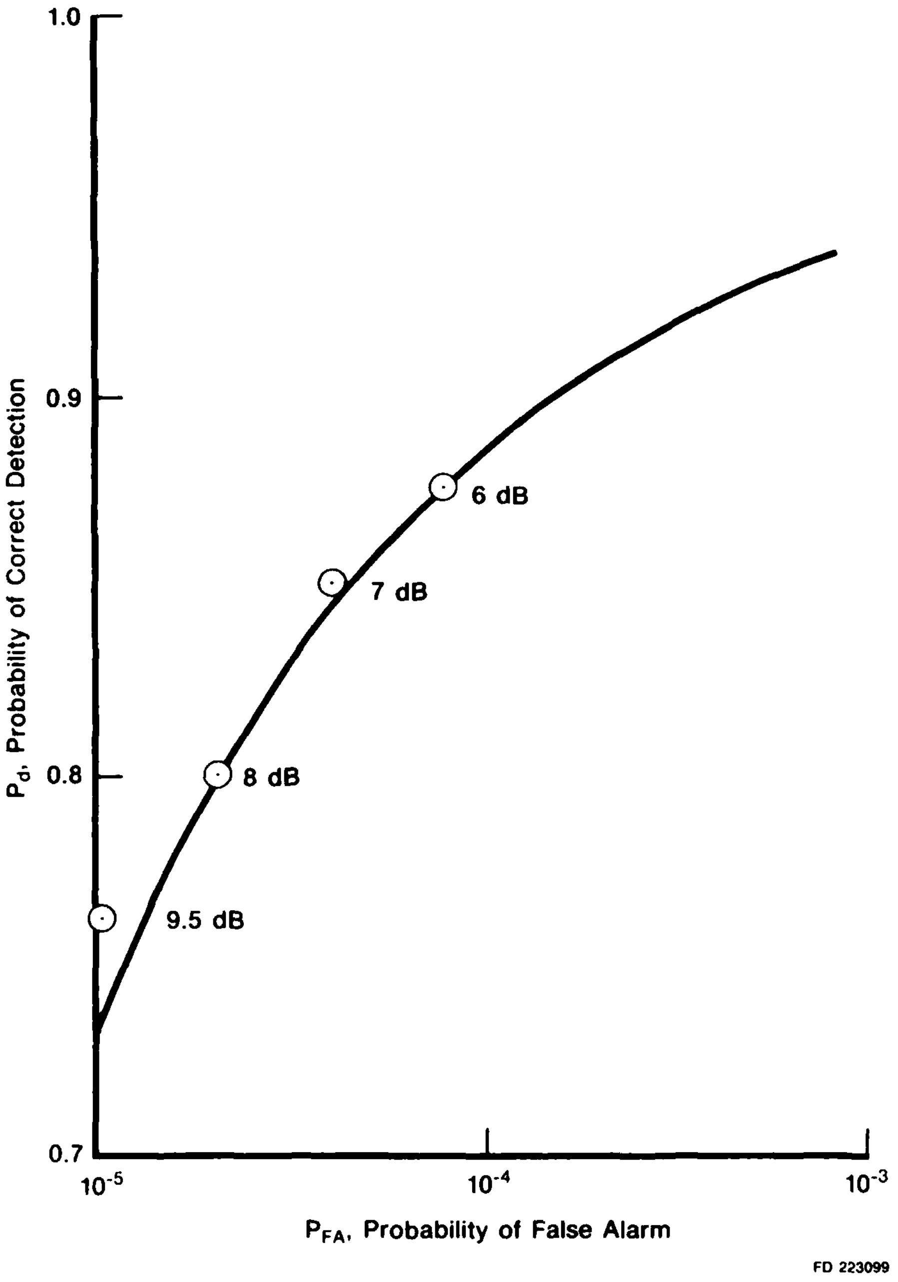


Figure 35. Receiver Operating Characteristic Curve for In-Service Cracks

The conclusions seem to be erroneous because they are based on an improper assumption. The probability of false alarm per bolthole, rather than the probability of false alarm per detection opportunity is the basis that should be used to calculate the false alarm rate. Using this approach, the probability of false alarm per bolthole is 2,400 times the value (40 relations/hole times 60 possible responses per rotation) estimate in Figure 34 and 35. The instrument performance now would be that 88 cracked holes would be correctly identified and 12 uncracked holes would be incorrectly rejected. This result is consistent with the detection estimates arrived at in the program which is discussed next. It should also be noted that to use these results to predict performance in other inspection situations one must assume that the distribution of flaw sizes is the same as it was in the "Quantitative Eddy Current Nondestructive Evaluation/Bolthole Inspection" experiments.

In the course of verifying the basic technologies and methodologies of RFC, Failure Analysis Associates (FAA) has assembled and analyzed eddy current inspection data on a large set of TF33 third-stage turbine disk boltholes (Reference 4). The sample base consisted of a 50-disk population, each of which contained 10 holes, for a total of 500 holes. These were examined in five independent inspections, using a variety of frequencies, instrumentation, procedures, and personnel. It should be noted here that the TF33 disk material, Incoloy 901, characteristically produces multiple cracks of widely varying aspect ratio when initiated from fatigue, as has occurred during engine service.

Two field inspections were conducted at Tinker AFB using Gulton FD-100 units operating with a 0.50-in. diameter coil at 500 kHz. The first was performed by field personnel while the second was conducted by laboratory personnel. Two additional laboratory inspections were conducted by Adaptronics, Inc. using Nortec NDT-15 instrumentation. These differed in frequency, one being at 0.5 MHz and the other at 1.0 MHz. The final inspection was performed by the Reluxtrol Corporation, using a Reluxtrol 700-29 CREG eddy current inspection system. The measurement frequency was 5 MHz, coil diameter was 0.040 in., and the probe advanced 0.0184 in. per revolution. The latter three tests were used as the data base for most of the analysis since the angular and axial positions of the probe was recorded in those cases, but not in the former two tests. This allowed a more complete comparison to the results of the replication studies.

All of the boltholes were replicated to determine the surface length of the cracks. In the 490 boltholes inspected, 847 cracks were found in 280 holes. Cracks ranged from less than 0.005 in. in length to 0.700 in. in length. Figure 36 is a histogram of the crack lengths detected.

Twenty-eight of the boltholes were then destructively sectioned to characterize 56 of the crack indications. As anticipated, a considerable scatter in a plot of depth (from destructive testing) versus length (from replication) was observed (as shown in Figure 37), with a crack aspect ratio of $a/c=0.35$ providing an approximate fit.

Figure 38 presents inspection reliability and false call percentages for cracks greater than a given surface length. These results were computed on the basis of grading a call as correct if an indication was found in the same hole as a known crack, regardless of any agreement between the magnitude and location of the indication and the size and location of the crack. For all cracks, the reliability ranged between 55 and 70 percent for all 5 inspectors, but rose to over 90 percent for cracks greater in length than 0.100 in. If, however, one requires that location (angular), length (to within a factor of 2), and axial position of the indication and actual crack all be in agreement, the results degrade to those shown in Figure 39. Here reliabilities drop as low as 18% and false calls rise as high as 46% for all cracks.

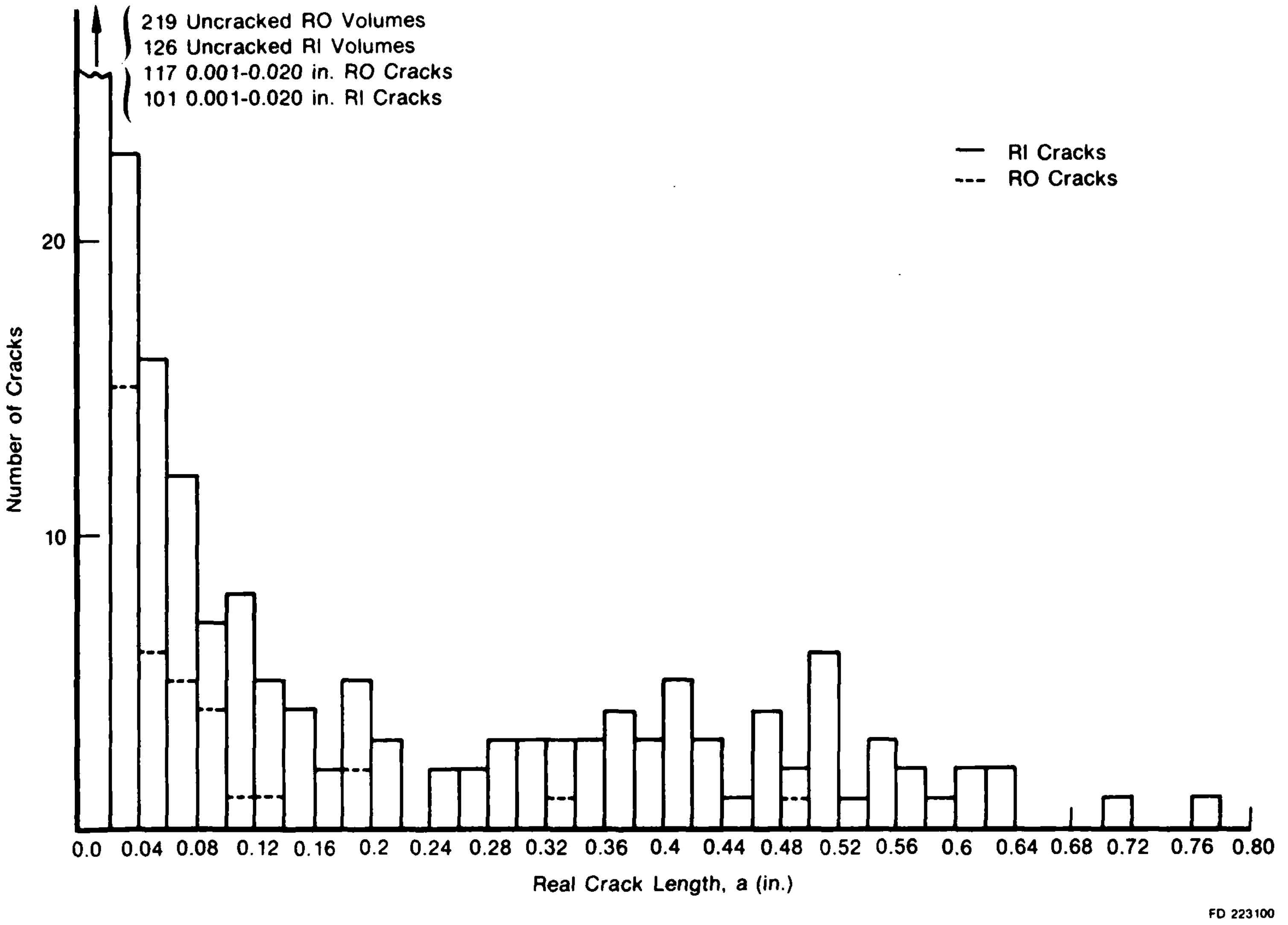
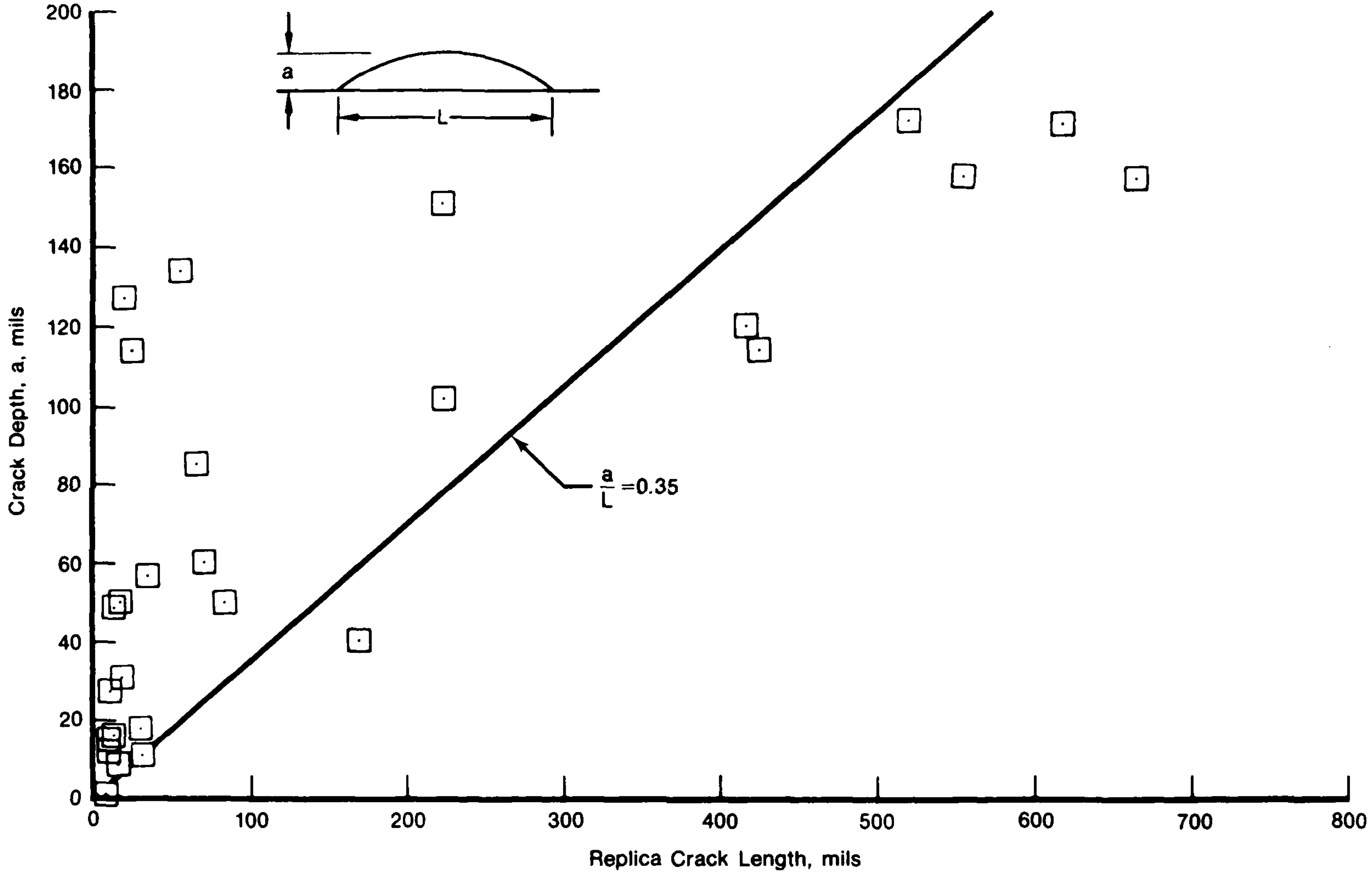


Figure 36. Frequency Distribution of Real Crack Lengths (A) Determined from Surface Replication for the ½ Bolthole Volumes Inspected by the High Resolution Eddy Current System. The Symbols RI and RO Refer to the Inner and Outer Halves of the Boltholes, Respectively



FD 227317

Figure 37. Crack Depth vs Replica Surface Crack Length for ARPA Bolthole Cut-Ups Using the 0.040 Surface Crack Combining Criterion

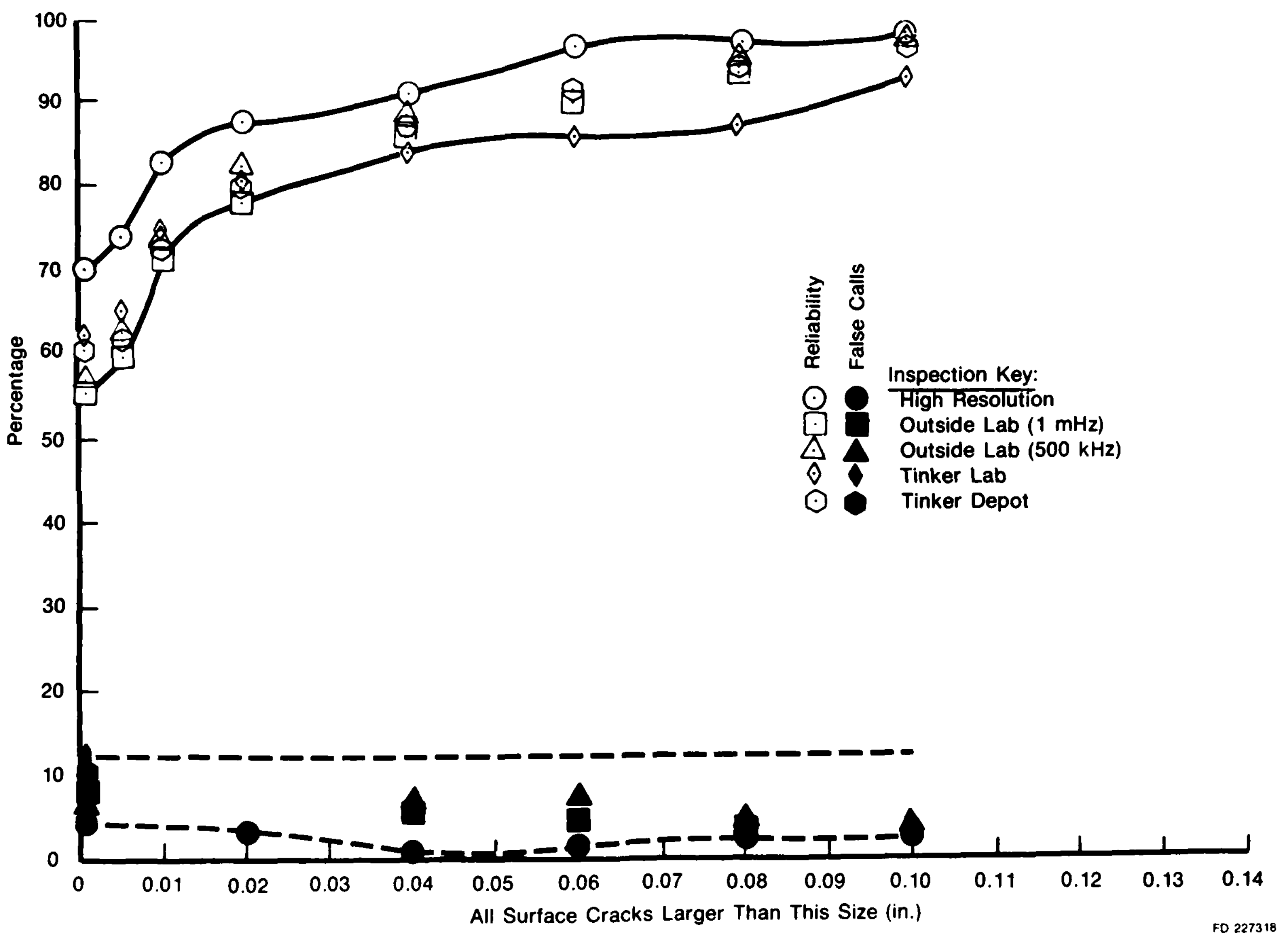


Figure 38. Inspection Reliability and False Call Percentages for Finding Cracks Greater Than a Given Surface Length Using Only the Indication Agreement Criteria

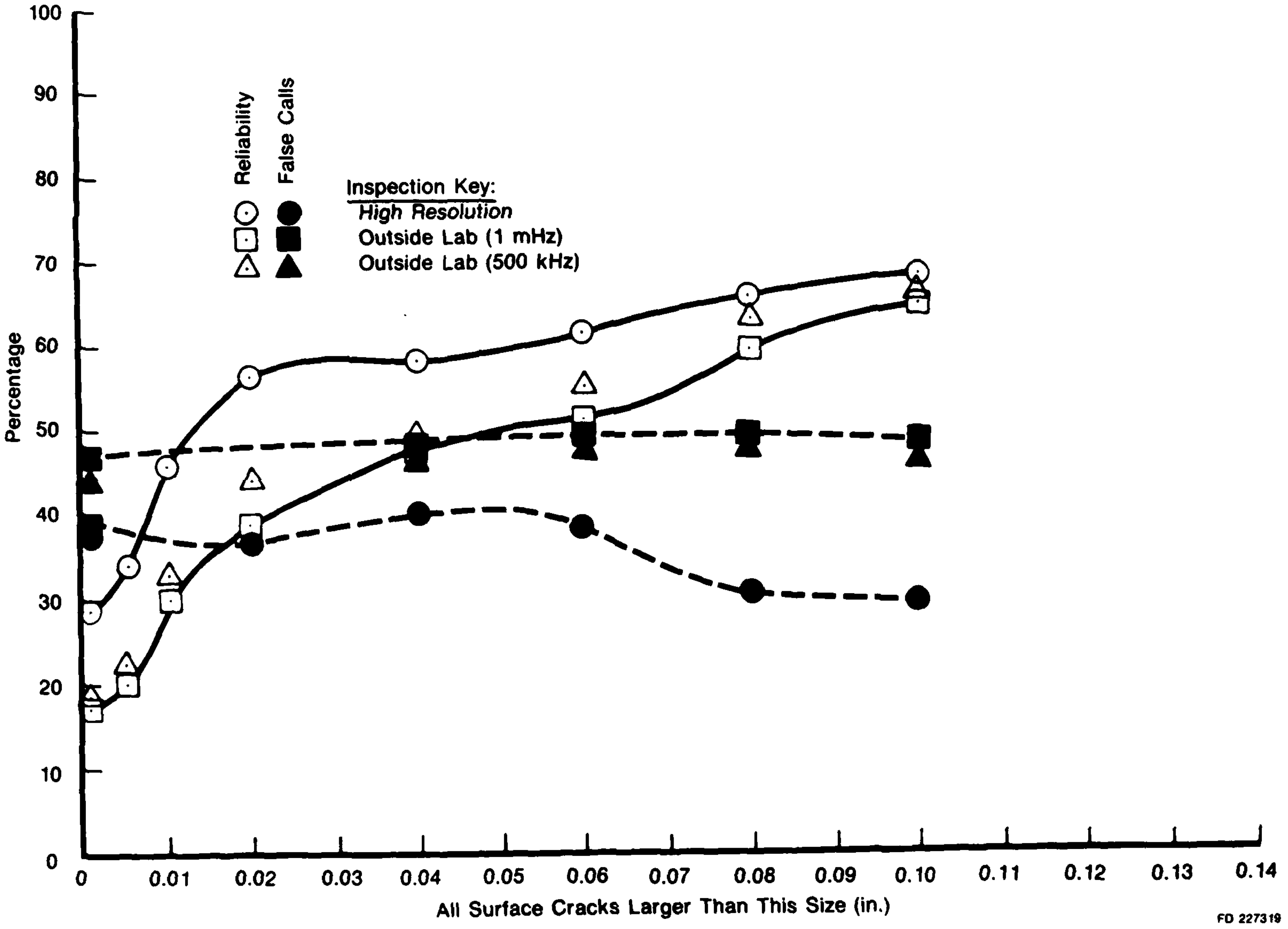


Figure 39. Inspection Reliability and False Call Percentages for Finding Cracks Greater Than a Given Surface Length Using Indication and Location and Length (2X) and Position Agreement Criteria

The above probability of detection results may be somewhat conservative, since they are calculated on a crack population basis (i.e., each crack is considered as an opportunity for measurement, even if there are several cracks per bolthole). Higher probabilities can be expected on a bolthole population basis since there may be more opportunities to detect at least one of a set of multiple cracks. Figures 40 and 41 illustrate this for all cracks and cracks greater than 0.040 in. in length. Not shown in the figures is the false call probability. This will also rise on a bolthole population basis.

From the above plots, it can be concluded that the high resolution probe provided the highest reliability. Figure 42 presents more details on its performance on a 1/2 bolthole population basis as a function of surface crack length and location agreement criteria.

The minimization of false rejects is essential if the full economic benefits of RFC are to be realized. This requires that an accurate sizing of the flaw be obtained from the nondestructive measurement technique. Figure 43 illustrates the observed sizing performance of the high resolution probe. The apparent crack length is determined from the equation

$$a = [1 - e^{-TURNS/5.85}] [2.38 \times 10^{-2} (TURNS)^{0.851} + 3.5 \times 10^{-2})] \quad (1)$$

$$+ [e^{-TURNS/5.85}] [2.48 \times 10^{-2} (AMP)^{1.187} + 6.59 \times 10^{-3}]$$

where TURNS is defined as the number of sequential turns, made by the coil, that produce an indication and AMP is the maximum amplitude of the indication. This empirical form was derived by performing a nonlinear regression analysis of the real crack length a, as determined from replication, versus TURNS and AMP.

From the scatter of the data in Figure 43, it is clear that there was considerable uncertainty in the sizing. This was quantified by the inspection uncertainty function (P(a/a). Figures 44 through 46 present plots of the cumulative distribution of a, i.e., the percentage of the time that the apparent crack length will be less than the size specified on the abscissa, for three different crack range intervals; 0.001-0.010 in., 0.040 to 0.060 in., and 0.100 to 0.700 in., respectively. In these ranges, the 90% point is reached at apparent to real crack length ratios of 9, 2.5, and 2.5, respectively.

This inspection uncertainty can strongly influence the economic benefits of RFC. This is illustrated in Figure 47 in which the increase in economic gain per TF33 third-stage turbine is shown when the inspection uncertainty is reduced by taking the square root of the size ratio. Such a reduction in sizing uncertainty is, of course, one of the major benefits of the quantitative NDE techniques to be discussed later in this report.

In summary, the sensitivity of conventional eddy current is probably adequate to detect cracks 0.005 in. or less in length. For sizes on the order of 0.040 in. or greater, reliability of detection, on a bolt hole basis, can be on the order of 90%. This will be accompanied by a significant probability of false calls. However, for smaller flaws on the order of 0.005 in. or less, such as may be of interest in application of RFC principles to such engines as the F100, reliability of the present eddy current techniques drops to 50% or less. In addition, there may be a significant problem with false calls as illustrated by the following discussion.

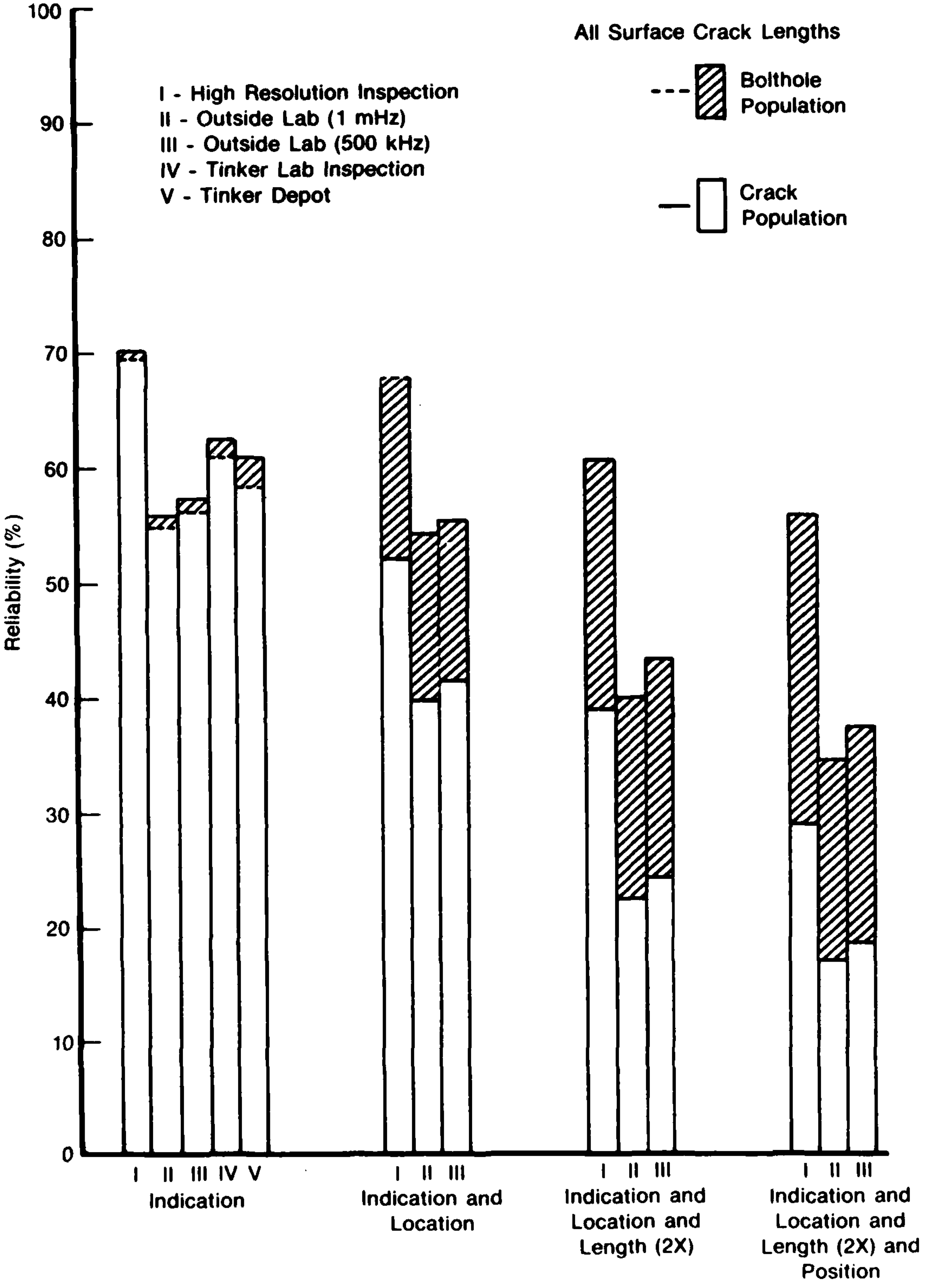


Figure 40. Inspection Reliability of Detecting all Cracks as a Function of the Various Agreement Criteria. Open Bars Are for a Crack Population Basis and Shaded Bars Are for a Bolthole Population Basis

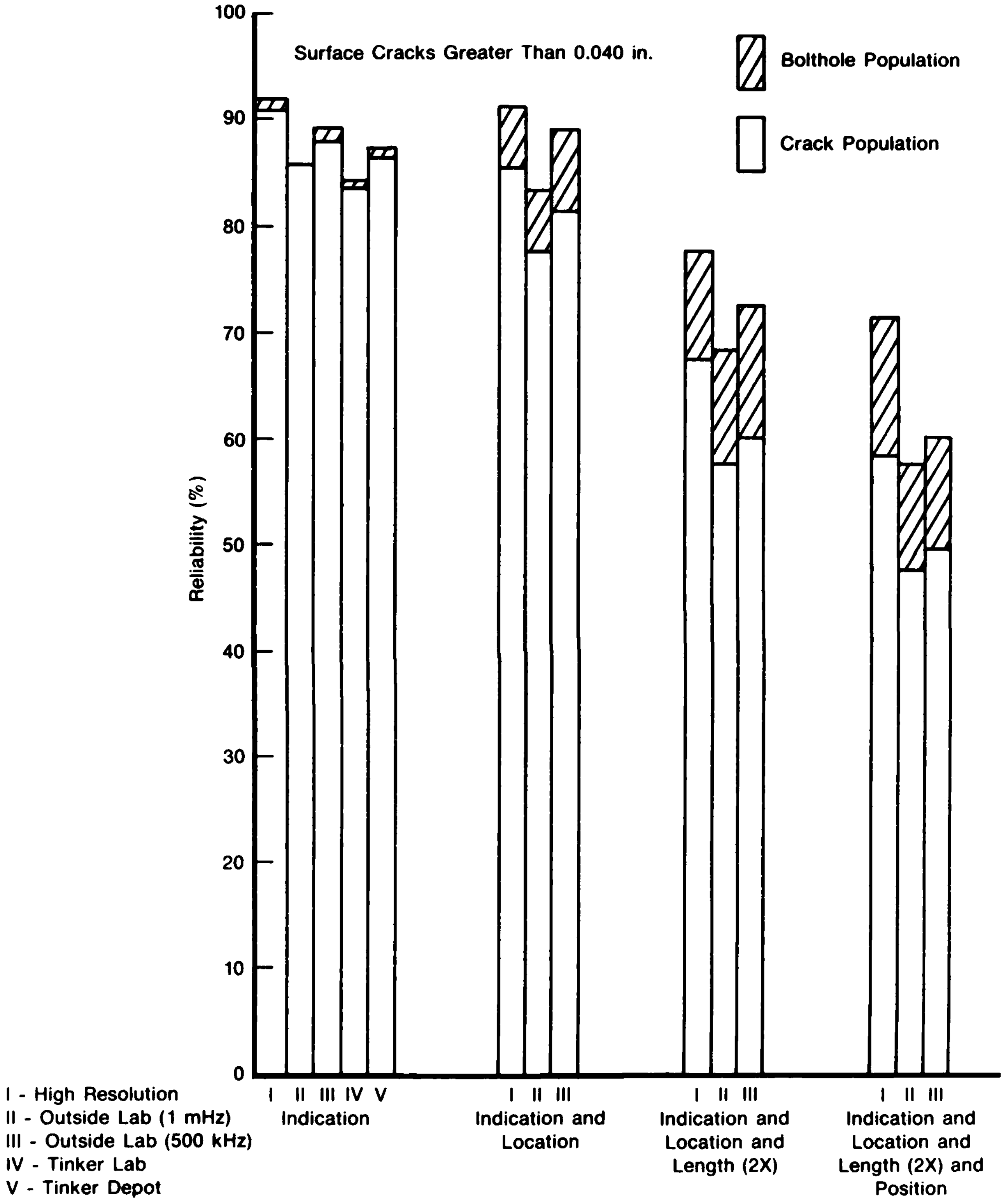
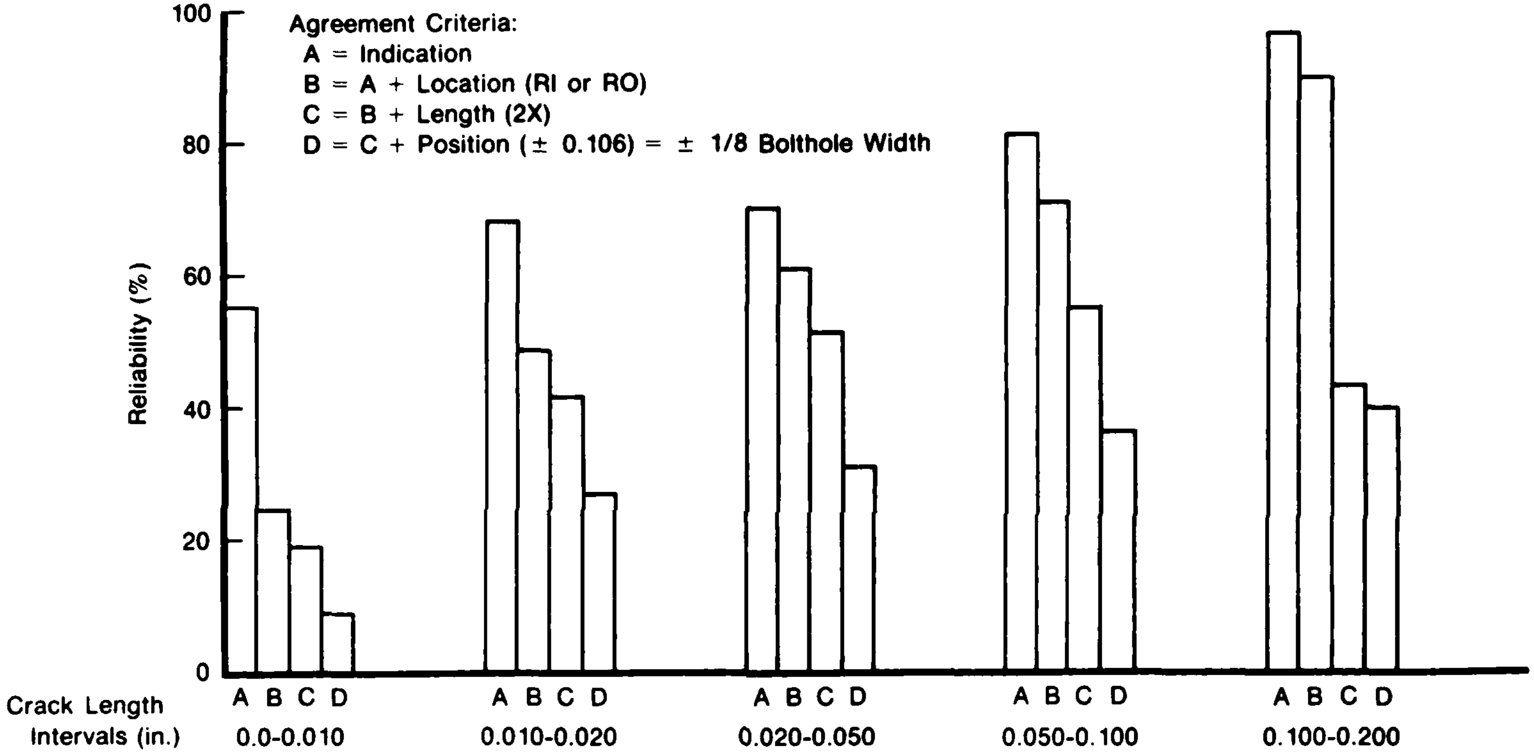


Figure 41. Inspection Reliability of Detecting Cracks Greater Than 0.040 in. in Surface Length as a Function of the Various Agreement Criteria. Open Bars Are for a Crack Population Bais and Shaded Bars Are for a Bolthole Population Basis



FD 227322

Figure 42. Inspection Reliability for a Maximum Crack Within a ½ Bolthole Population for High Resolution Inspection as a Function of Various Agreement Criteria. Selected Surface Crack Length Intervals Are Indicated

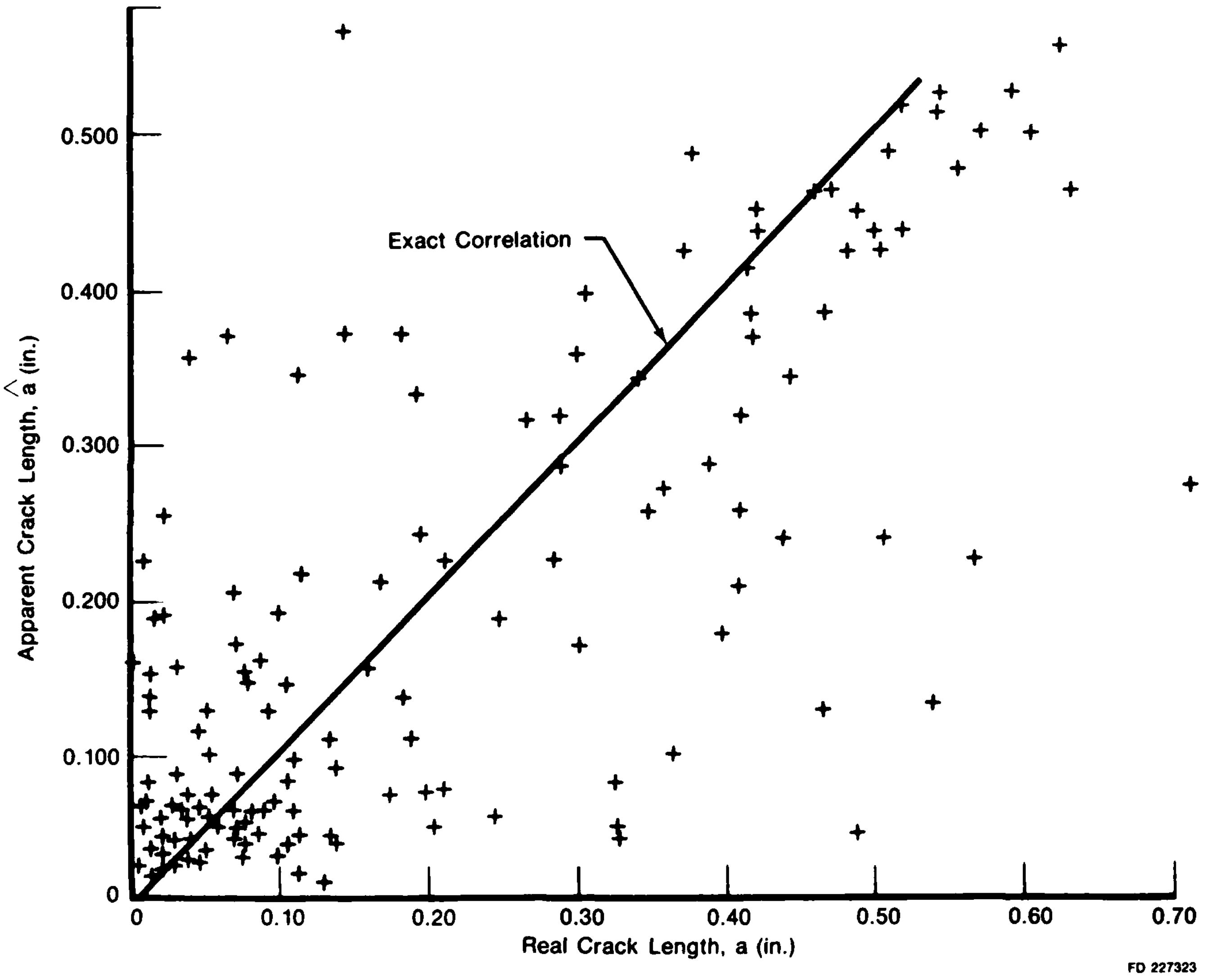


Figure 43. Apparent Crack Length from High Resolution Inspection Signals vs Real Crack Length Measured by Replication. Equation 1 Was Used to Convert Eddy Current Inspection Results to Apparent Crack Length

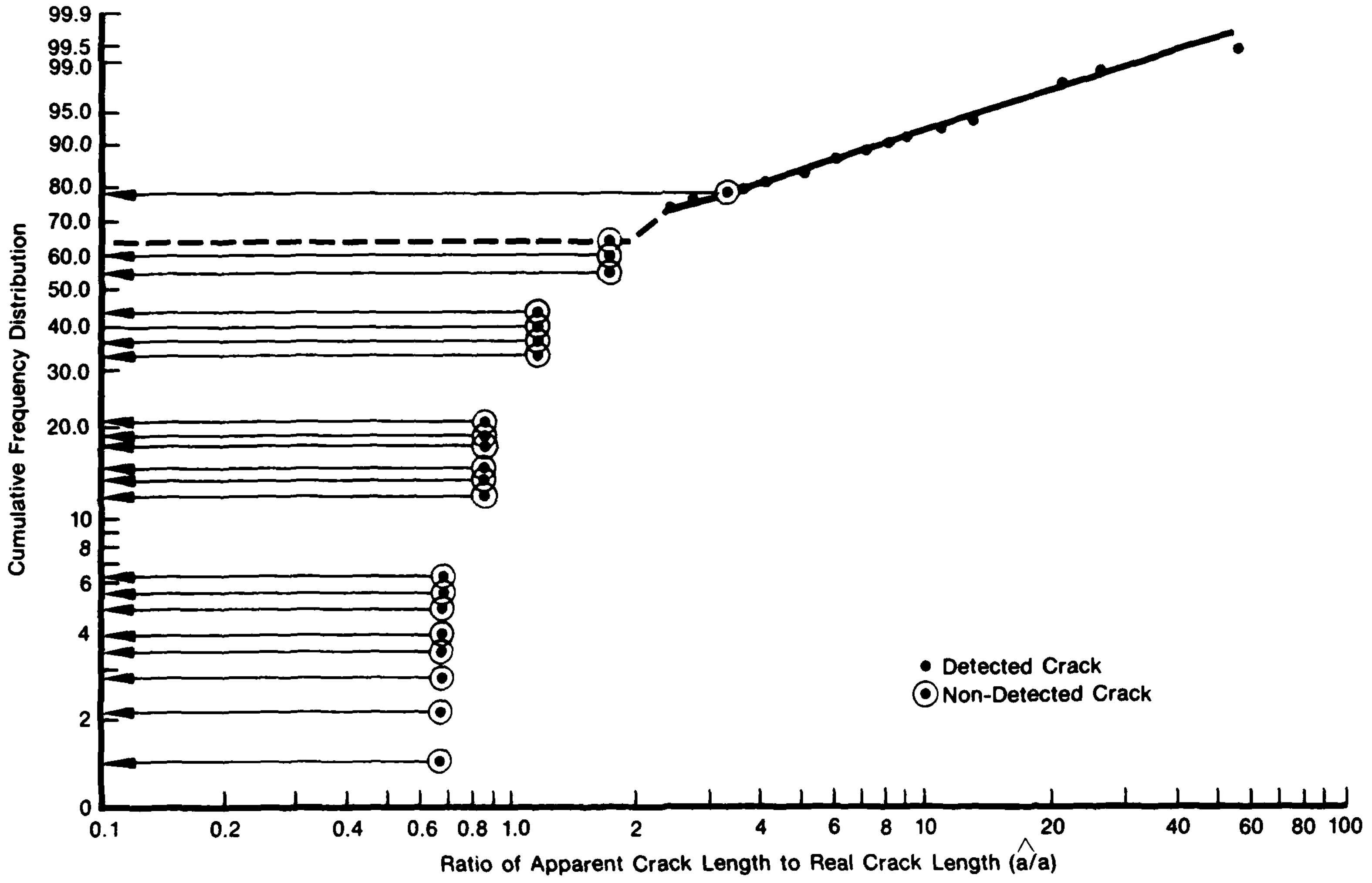


Figure 44. Cumulative Frequency Distribution of Apparent Crack Length to Real Crack Length for High Resolution Inspection. For Clarity Not All Points Have Been Plotted. Only a Representative Sample. Real Crack Length Range: 0.001-0.010 in.

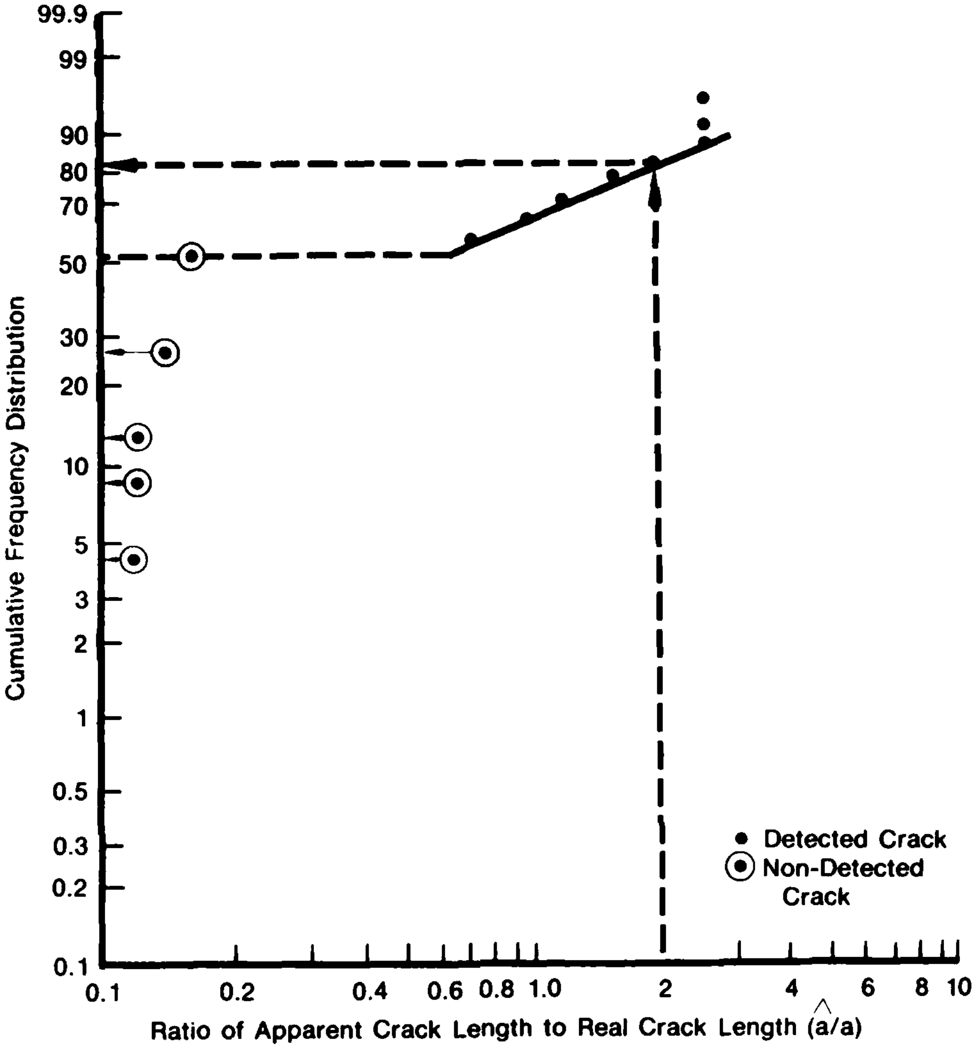
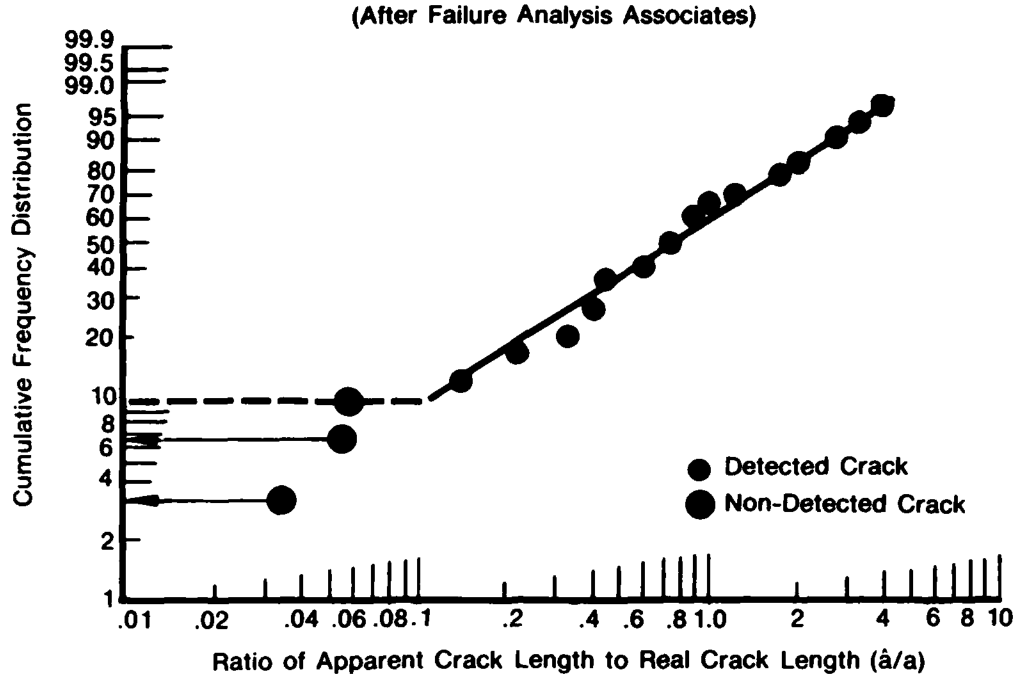


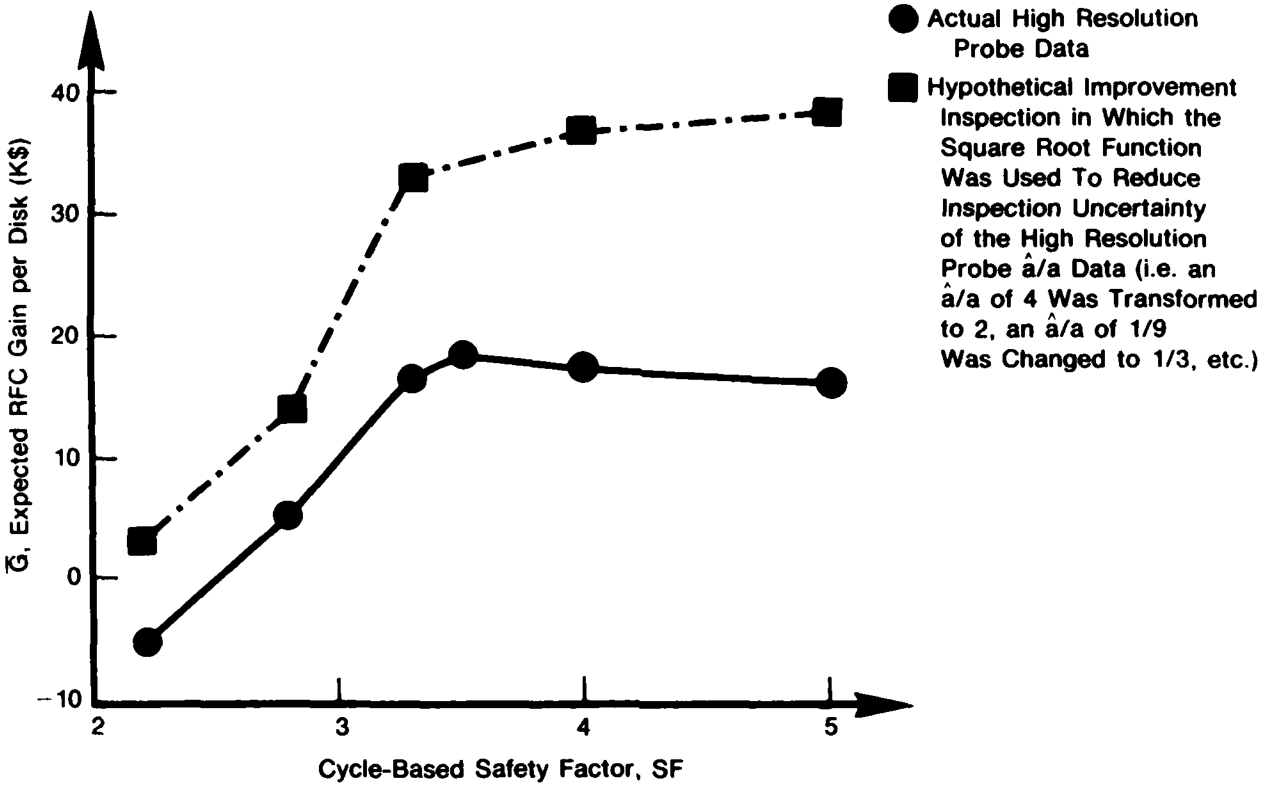
Figure 45. Cumulative Frequency Distribution of Apparent Crack Length to Real Crack Length for High Resolution Inspection. Real Crack Length Range: 0.040-0.060 in.



FD 227326

Figure 46. Cumulative Frequency Distribution of Apparent Crack Length to Real Crack Length for High Resolution Inspection. Real Crack Length Range: 0.100-0.200 in.

(After Failure Analysis Associates)



FD 227327

Figure 47. Effect of Dramatic Reduction of Inspection Uncertainty on RFC Benefits

Suppose first that one wishes to reject all flaws greater than 0.005 in. and the instrument is set up so that rejection occurs when the apparent flaw size is greater than this value. Then from Figure 44, approximately 50% of real 0.005-in. flaws would have apparent size less than this value and would be falsely accepted. Fortunately, as note in the FAA report, the evolution of failure is such that, in a given disk, there are likely to be several cracks of approximately the same size since all boltholes have experienced virtually identical fatigue histories. Consequently, although any particular crack would only be rejected 50% of the time, the probability of rejecting at least one would be considerably higher. Unfortunately, this same reasoning refers to false rejects. Thus, a single 0.001-in. flaw would have an apparent size greater than the 0.005-in. threshold 15% of the time, and if there are several of these, the probabilities are much greater. A high false reject level might ensue. The trade-off between false accepts and false rejects appears to be quite difficult.

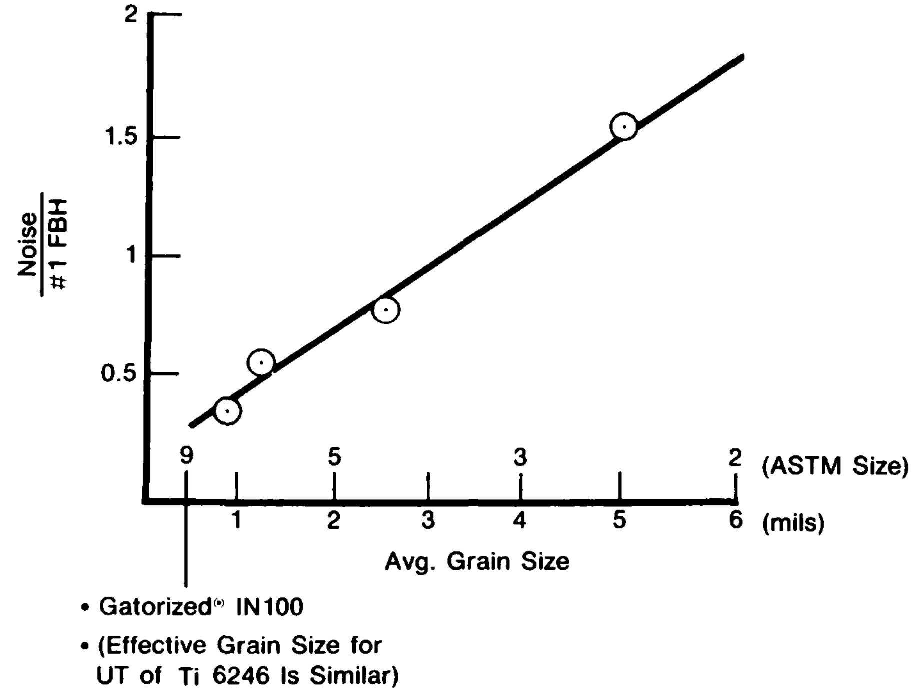
It should be emphasized that these comments are quite speculative since (1) they are making extrapolations to quite small flaw sizes from data obtained on a system designed to detect larger flaws, and (2) they are not based on a full statistical argument such as is contained in the FAA report for the TF33 disk with larger critical flaws. Nevertheless, they do suggest that care should be taken when relying on the state of the art to detect crack sizes on the order of 0.005 in., and that quantitative NDE techniques with better sizing ability may be essential if the economic potential of RFC is to be realized in materials having critical sizes in this range.

2.1.4.2 Ultrasonic Inspection

As shown in Figure 4, the great majority of the generic RFC flaw types are surface connected and localized due to the low cycle fatigue origin of the failure. These are most amenable to eddy current inspection. However, a few examples of volumetric flaws are also given, including cracks in the web and inner bore of the turbine. Hence, ultrasonics will be required and an assessment of the state of the art of that technology is appropriate.

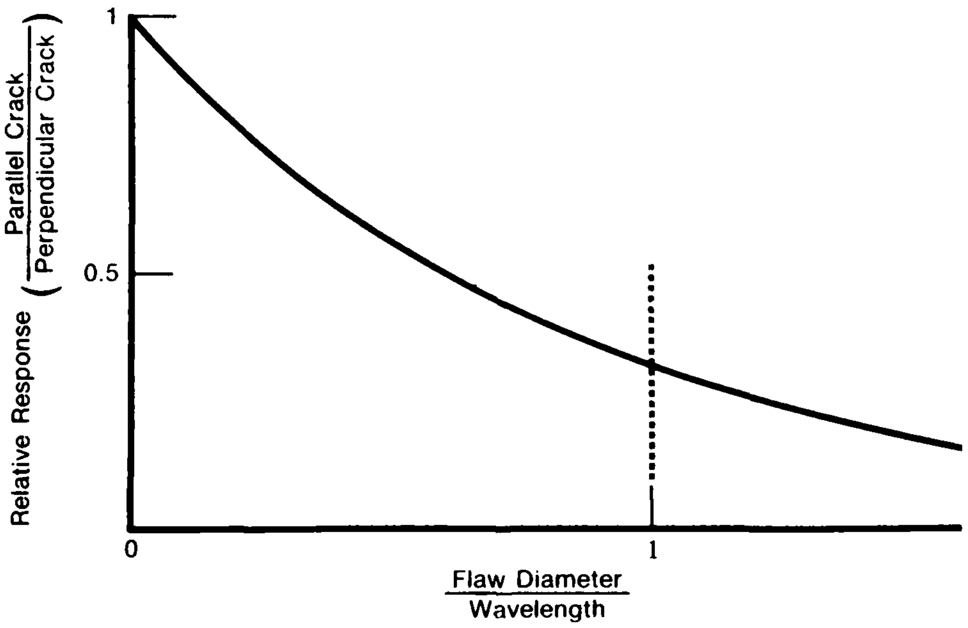
Unfortunately, no programs similar to the above mentioned eddy current efforts have been run for the case of ultrasonic inspection of turbine disks. This is largely due to the relatively difficult task of inserting internal crack-like defects into a specimen population and verifying internal crack-like defects which are present and detected. Therefore, an assessment of inspection performance must be based upon limited experiences. It is apparent that the sensitivity of ultrasound is certainly adequate to detect crack-like flaws with sizes on the order of 0.016-in. diameter or less if several conditions are met. First, the attenuation and grain scattering noise of the material must be sufficiently low that high frequencies can be used. Figure 48 shows partial results of a detectability study conducted by Dr. James E. Doherty for P&WA's Commercial Products Division. It is obvious from the figure that grain noise in the subject F100 materials should not be a severely limiting factor. Also, the geometry and flaw orientations must be such that a pulse-echo or pitch-catch configuration can be defined which detects the specular reflection from the crack surface. Figure 49 shows the dependence of ultrasonic detection of crack-like defects upon the orientation of the interrogating beam. As the ultrasonic wavelength approaches the size of the flaw diameter, the ultrasonic response of a crack which is parallel to the beam is calculated to be 25% of the reflection of a crack which is oriented perpendicular to the beam (based upon a 0.016-in. diameter crack in nickel and an ultrasonic frequency of 15 megahertz).

Ultrasonic inspection, as used to inspect disks in production, is quite advanced. Two programs have been conducted to construct computer-aided systems for production application. Computer compatible ultrasonic instruments appeared commercially soon after these programs were completed, and advanced inspection systems based on these new instruments are now on line at major engine manufacture production facilities.



FD 228302

Figure 48. Scattering Noise Limits Ultrasonic Sensitivity



FD 228301

Figure 49. Relative Response of Cracks Perpendicular and Parallel to an Ultrasonic Beam (Calculated)

The new instruments are to varying degrees compatible with the high data rates needed for high-speed inspections. The capability to modify all instrument operation characteristics during one pulse cycle has been demonstrated, thus permitting complex performance even in a high volume environment.

Transducers compatible with the new instruments are commercially available and have been used to detect and resolve 0.015-in. flat-bottomed holes in fine grain material as close as 0.05 in. to either near or far surfaces. The sensitivity of new systems to detect reflectors in materials used in current gas turbine engines is limited by coherent noise generated in the material and not by instrument noise.

The question of reliability is somewhat more difficult (References 1, 2 and 5). It can be speculated that, because of the known influences of crack closure stresses and crack orientations on state-of-the-art ultrasonics, the reliability of present day equipment will be somewhat less than that for eddy currents. Advances on the state of the art of ultrasonics may bring greater improvements in detection reliability in appropriate areas than advances in eddy current technology.

2.1.4.3 Fluorescent Penetrant Inspection (FPI)

FPI is the most widely used inspection technique, and perhaps the only technique used for some critical component inspections. The apparent simplicity, low cost, and inherently high sensitivity are the main advantages of this inspection technique. FPI capability of engine overhaul facilities in terms of probability of detection is unknown. An AFLC SA-ALC/Martin Marietta study to quantify NDI capability is in progress (Reference 2). A recent study of the maintenance FPI capability of airframe components (Reference 1) revealed that only cracks greater than 0.70 in. (1.78 cm) will be detected with 60% probability of detection at 95% confidence level. Similar FPI capabilities for engine components in an overhaul environment may be assumed. If the assumption is valid, this presents a problem for the demonstration of structural integrity for in-service engine components. It should be emphasized that critical crack sizes for engine components are generally smaller than for airframe components, and engine components are subjected to very high temperatures and severe environmental conditions during engine operations, thus making it more difficult for FPI to detect tight fatigue cracks. Inherent FPI capability in a production or manufacturing environment is higher than that in overhaul inspection; and in the laboratory under controlled conditions, it is possible to detect cracks smaller than 0.032 in. (0.813 mm) with a probability of detection greater than 94% at 95% confidence level (Reference 5). In fact with stress-enhanced (wink) FPI, laboratory capability can be greater than 91% at 95% confidence level for cracks smaller than 0.016 in. (0.406 mm) (Reference 5). Thus, it is immediately obvious that there is potentially great scope for improvements in FPI capability of overhaul inspection. This area of research and development was, however, not addressed in detail until recently (References 6 and 7). An AFWAL/P&WA program, "Methods Improvement of the FPI Process" (F33615-79-C-5021) investigated surface preparation procedures and key FPI process variables for overhaul inspection. The main objective was to develop implementable improvements and enhancements of inspection capability for engine overhaul facilities. A follow-on AFWAL/P&WA program "Improved Penetrant Process Evaluation Criteria" (F33615-80-C-5060) is currently evaluating increased performance in FPI reliability using improvements and modifications to the FPI process identified and evaluated in contract F33615-79-C-5021. This evaluation consists of designing and conducting a demonstration program to statistically quantify the increased performance in terms of probability of detection.

---

5. "Disk Residual Life Studies," Part II of AFML/P&WA Final Report AFML-TR 79-4173.

6. "Methods Improvement of the Fluorescent Penetrant Inspection Process." AFWAL Contract No. F33615-79-C-5021. Final Report, AFWAL-TR-80-4161.

7. "Improved Penetrant Process Evaluation Criteria" AFWAL Contract No. F33615-80-C-5060.

The method of FPI in overhaul facilities is similar to a production environment. The method essentially consists of applying penetrant on the components, and after the penetrant has had time to enter the discontinuities, the excess penetrant is removed, the part goes through a drying process, and then developer is applied to the surface. The penetrant which had been entrapped in the discontinuity is drawn to the surface by the developer and produces characteristic indications which are examined by an inspector.

For over a decade semiautomated penetrant inspection systems have been in use in overhaul facilities. Usually these systems consist of several in-line stations with engine components being transported from station to station by mechanical handling systems. The stations may consist of:

1. Surface preparation
2. Drying to remove any moisture away from the parts
3. Soak in a temperature controlled penetrant tank (varying dwell time is generally used depending on components)
4. Prerinse station to remove some excess penetrant
5. Controlled time dipping in an emulsifier tank
6. Rinse station, usually consisting of water spray
7. Air circulating controlled temperature drying oven
8. Developer station
9. Developer drying station if a wet developer is used
10. Black light inspection booth.

These semiautomated facilities, when properly planned and set up, should provide uniform processing for the same type of components as required in inspection procedures. These units are preferred to hand-processing units, but a small hand-processing unit is always coexistent with semiautomated units to handle small parts and specialized nonroutine inspection items.

Stress-enhanced or wink FPI is sometimes used on selected suitable components. The method was introduced for increased sensitivity and reliability for detecting tight fatigue cracks or cracks filled with contaminants to increase penetrant flaw entrapment efficiency. Unfortunately, often this method is not properly applied or is not considered for fear of the time factor involved in stress-enhanced inspection. Recent work under AFWAL sponsorship has demonstrated that significant improvements in sensitivity and reliability of FPI can be achieved by new advanced stress-enhanced FPI procedures (Reference 5). There has been no study conducted to compare the time and cost factors involved in stress-enhanced FPI vs focused eddy current inspection. In some instances stress-enhanced FPI may be more suitable and capable than other inspections. Also, as a complementary inspection to other inspections such as eddy current, stress-enhanced FPI may increase reliability of the overall inspection and decrease the time involved in evaluating false indications.

Even though the FPI procedure is basically the same for manufacturing and overhaul inspection, the capabilities may vary vastly. The main reasons for lower sensitivity and reliability of overhaul inspection are: (1) poor surface condition of components (nicks, dings, deep scratches, etc.), (2) contaminants such as carbonized oils, oxide films, corrosion and paint on the surface or in the discontinuities, (3) abrasive cleaning procedures used to clean the parts, (4) compressive stresses on the surface of the component, (5) poor process-variable control, and (6) human factors like variability of training, experience, and job interest.

Figure 50, which is reproduced from the interim report for the "Improved Penetrant Process Evaluatioin Criteria" program, shows point estimates of probability of detection of fatigue cracks using a FPI process specified in an aircraft engine manufacturers overhaul technical order. The point estimates are simply the ratio of number of detections divided by the number of inspections for each specimen. Five independent inspectors evaluated each specimen using a small hand processing FPI facility at Kelly AFB. While no statistical analysis is shown, three conclusions may be drawn. First, overall inspection performance was poor. Second, inspector performance was consistent (i.e., if one inspector found the crack, they all did). Finally, flaw detectability was not directly related to flaw size.

Figure 51, also reproduced from the interim report, shows dramatically different results using the modified FPI process which was proposed following the initial research and development activity. The same inspectors evaluated the same group of 100 rectangular bars and compressor blades (approximate 50/50 split between flawed and unflawed specimens). It is apparent that the FPI process is much more effective in this case, yet flaw detectability is still not strongly related to flaw size. This behavior was probably observed because FPI is affected by localized residual stresses, smeared inspection surfaces and residual contamination within the defects.

In summary, the capability of the overhaul FPI process can be quite variable and is generally assumed to be poor for very small fatigue cracks. However, FPI is the only process which is currently applied as a whole field overhaul inspection for fatigue damage in critical gas turbine engine hardware, and could be applied reliably to detect relatively large rogue surface-connected defects.

2.1.5 Evaluation of Advanced NDE Methods

Evaluations of advanced applications of eddy current, ultrasonic test, microfocus X-ray, optical techniques, and thermal waves, as applied to RFC, are reported by Professor R. B. Thompson (Ames Research Laboratory) in Appendix J of the second volume of this report.

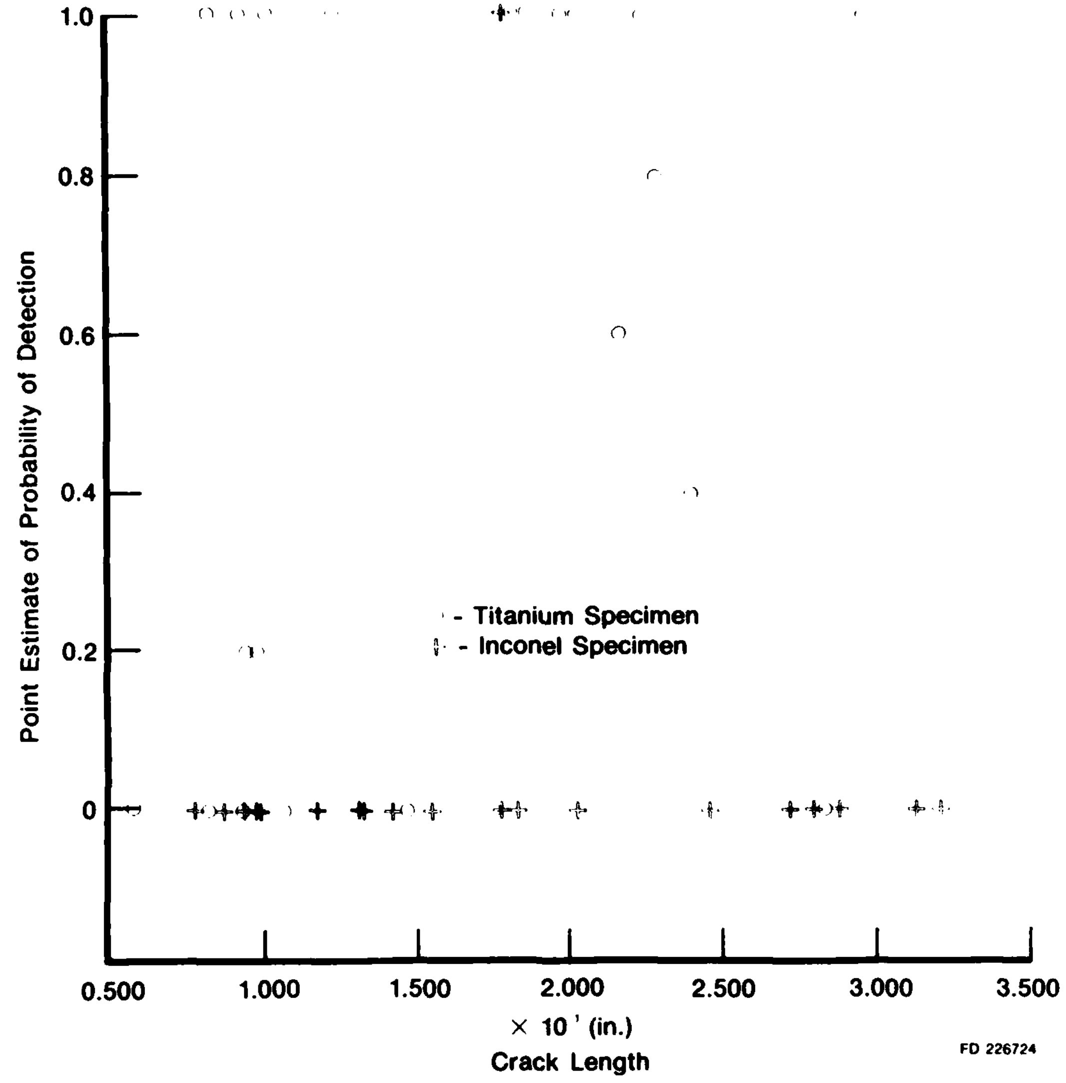


Figure 50. Point Estimates of Probability of Detection for the Baseline Inspections

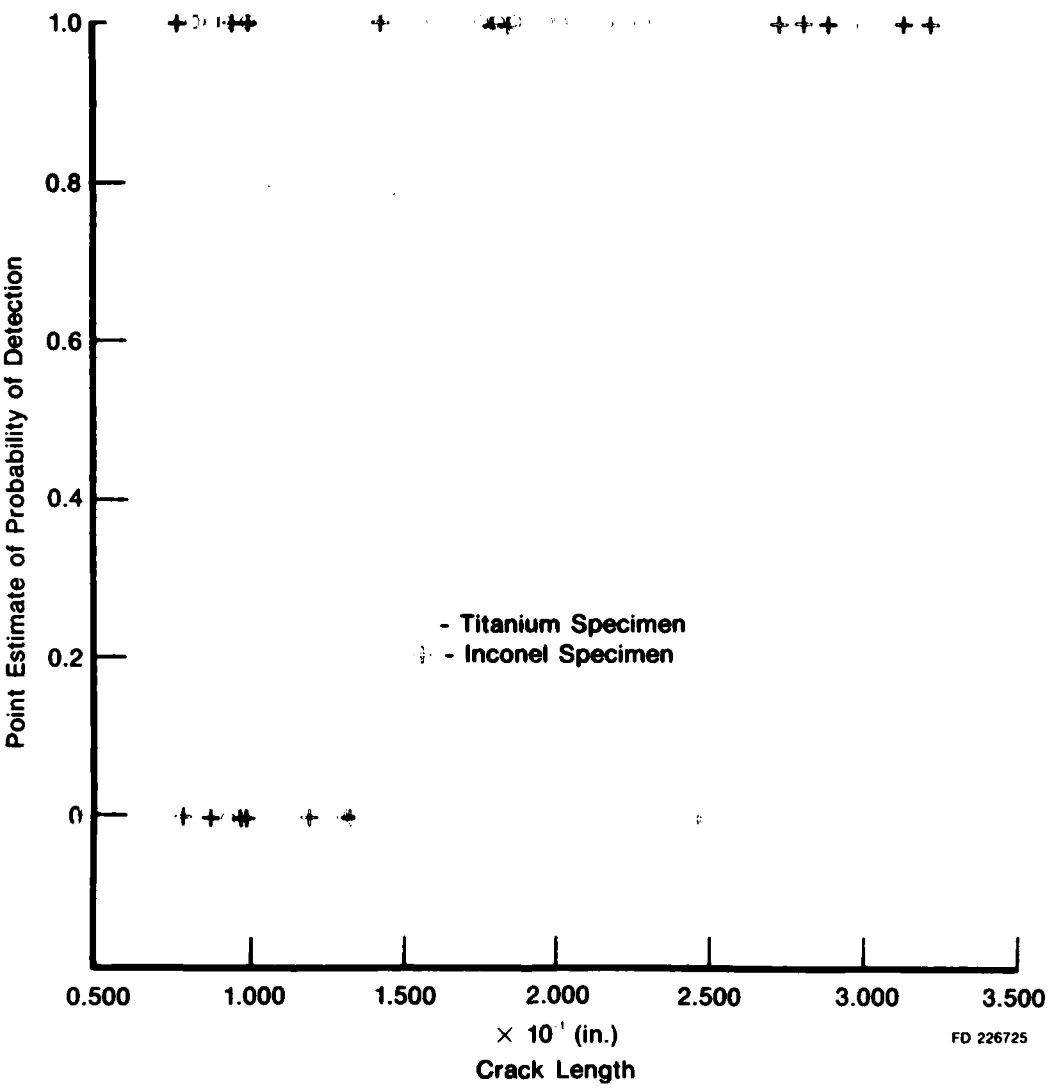


Figure 51. Point Estimates of Probability of Detection for the Improved Surface Preparation and Modified Process Parameters

2.2 Phase II — NDE Subsystem Selection

Criteria for selecting candidate RFC Inspection System NDE methodologies were established during Phase I activities. Those criteria included: (1) the RFC inspection and scan requirements (based upon application to Air Force fighter-type engines); (2) Air Logistics Command production/manufacturing requirements (including component throughput, maintainability, accountability, flexibility, and reliability); (3) NDE technology requirements (including detectability, flaw sizing, and equipment stability); (4) an evaluation of conventional NDE technology; and (5) an evaluation of advanced NDE technology.

In making the subsystem selection, it is anticipated that the RFC Inspection system will be configured as a production unit and be on line at San Antonio Air Logistics Center early in 1985. An NDE technique could impact that system in one of three ways. First, it could be fully evaluated at the present and therfore be ready for direct incorporation in the system. Second, it could be sufficiently well-developed that hardware modules could be available in the time frame of the manufacturing technology program for incorporating in, or testing in parallel with, the RFC Inspection System. In the latter case, exploratory development programs should be nearing completion for the candidate technique and the initiation of a manufacturing technology effort should be contemplated in the near future. In a third situation, new techniques are progressing rapidly, but may not be ready in that 1985 time frame. These techniques could impact the system by being incorporated as additional, or replacement, modules of the system.

It has been concluded that the scope of the upcoming RFC manufacturing technology program would have to be impossibly far-reaching to achieve all RFC objectives by 1985 and within budgetary restrictions. The scope of the ALC operational requirements alone presents an enormous task to the program participants. Therefore, we have decided to primarily address the ALC production/manufacturing requirements in development of a design specification, and make recommendations for parallel exploratory development and manufacturing technology programs which address the NDE technology gaps for post-1985 implementation.

2.2.1 Selection of Conventional Methods

Several conventional inspection technologies were initially addressed during Phase I, but were discounted early as RFC candidates. They included radiography, nonfluorescing dye penetrant, acoustic emission, and optical methods. The first two methods were judged to be relatively insensitive to fatigue damage compared to other techniques under evaluation. Acoustic emission, in its present state, was judged to be too time consuming and complex to apply in the ALC overhaul enviroment for detection of damage in disks. The only optical method, other than the customary overhaul visual inspection, which is considered to have credence was evaluated as an advanced NDE technology.

The conventional NDE technologies which were selected as the basis for the RFC Inspection System, included all three methods which received detailed evaluation: eddy current, immersion ultrasonic test, and fluorescent penetrant inspection. The Phase I detailed evaluation provided necessary information for preparation of the system design. Application of all three technologies is considered to be complementary, as opposed to redundant. Eddy current inspection will be applied primarily as a focused inspection, in the classical sense of RFC, to detect relatively small fatigue cracks in fastener holes and other stress concentrators. It will also be used in a less focused manner to inspect critical bore and web regions for volumetric defects in the locations were immersion ultrasonic test isn't applicable. Immersion ultrasonic test will be used to inspect for internal fatigue damage in some web and bore locations that are deemed critical. In order to avoid leaving an uninspected or grey area during volumetric inspection, two simultaneous ultrasonic scans may be made to achieve a near surface resolution on the order of 0.03 in. while inspecting through the volume. Fluroescent penetrant inspection will be performed to detect relatively large rogue defects which may occur in locations that aren't considered by the former two techniques. The design specification recommends fully automated approaches to eddy current and immersion ultrasonic test, and a modified manual approach to fluorescent penetrant inspection.

2.2.2 Selection of Advanced Methods

Evaluation of advanced NDE techniques was performed by Prof. R. B. Thompson of Ames Research Laboratory, Iowa State University, and is reported in Appendix J of the second volume of this report. Techniques were grouped into the three categories discussed in Section 2.2, and selections were made for immediate application and parallel development.

The first category pertains to techniques which have been fully evaluated at the present time, and thus are ready for direct incorporation in the system. Such techniques could become an integral part of the system. The second category pertains to techniques which have not yet been fully evaluated, but which are sufficiently well developed that hardware modules could be available in the 1983-1984 time frame for testing in parallel with the automatic inspection system. In order for a technique to fall into this category, 6.2 development programs should be nearing completion for the candidate technique and the initiation of 7.8 manufacturing technology programs should be contemplated in the near future. In some cases, new techniques are rapidly advancing, but may not be quite ready in that time frame. These fall into a third category of techniques which may be available for incorporation into a second generation RFC system.

2.2.2.1 Techniques Ready for Direct Incorporation in RFC System

None of the techniques discussed in Appendix J for quantitatively evaluating flaw sizes has been evaluated with a sufficiently large and varied sample base to establish the reliability and confidence levels necessary for direct integration into an RFC inspection system. As noted in the following section, many of these techniques could take the form of stand alone modules by the 1984-1985 time frame. Skipping the steps leading to the development and evaluation of these modules and directly integrating the techniques in the automated NDE system at this time would be possible. However, the risk of premature deployment before proper evaluation would only be warranted if it were believed that the objectives of RFC could not be adequately reached with state-of-the-art technology.

It does appear, however, that the analytical scattering models developed to attack the quantitative NDE problem could be used as computational tools in the RFC system design. For example, as discussed in Appendix J, Section 3.2.5, it is anticipated that numerical results will be available by the time of the 1981 AF/DARPA Review of Quantitative NDE which predict the response of a circular eddy current coil to half-penny shaped cracks. Such models would be useful in choosing coil dimensions and in estimating the reliability of the resulting subsystem. Similarly, as noted in Appendix J, Sections 3.2.3 and 3.3.3, scattering calculations can be used to model the ultrasonic repsonse to internal flaws. These can aid in the selection of transducer frequencies and positions.

It is therefore recommended that a task be included in the NDE system construction program whereby these present tools are incorporated into the detailed design and evaluation procedure. Such a task is summarized in Table 5.

TABLE 5. TASK FOR SCATTERING MODEL INCORPORATION IN RFC SYSTEM CONSTRUCTION PROGRAM

Technique	*Present Status*	*1982 Effort*
Modeling of eddy current system performance	Response of circular coil and bridge to half-penny shaped crack available in summer 1981	Use this analytical capability to select coil geometry and measurement frequency
Modeling of ultrasonic response	Scattering formulae are available for scattering from penny shaped and elliptical cracks as a function of frequency and angle	Use these models to select probe configurations and measurement frequencies

2.2.2.2 *Techniques Which May Be Ready for Evaluation in 1984-1985 Time Frame as Stand Alone Modules*

As noted in Appendix J, several electromagnetic and ultrasonic techniques have shown considerable promise for sizing flaws. As noted above, these have generally reached the level of successful feasibility studies and hence have not received instrumental developmental and evaluation efforts to warrant immediate incorporation in the RFC system. However, in many cases, it does appear that modular hardware could be available in the 1984-1985 time frame which could be evaluated in parallel with a state-of-the-art RFC system. Programs that would lead to these modules are summarized in Table 6.

In general, the programs involve the steps of (1) more detailed laboratory evaluation of existent techniques, and (2) construction of semi-automatic instruments for evaluation in an ALC. The first two are eddy current programs, the next two are ultrasonic programs, and the fifth is an optical program. In addition to these experimental/hardware development efforts, two modeling tasks are included, one for eddy currents and one for ultrasonics. These are extensions of the efforts described in Table 5, and are aimed at developing a capability for predicting system reliability. This may be necessary, since the performance of enough experiments to establish the required reliability may be economically impossible.

2.2.2.3 *Techniques Which Are Candidates For Future RFC Systems*

Among the techniques discussed in Appendix J, Paragraph 3.0, microfocus X-rays and thermal wave imaging were not identified as having the potential to be ready in the 1984-1985 time frame. In the former case, this judgement was made on the basis of the technological difficulties anticipated in achieving sufficient penetration. In the latter case, the state of evolution of the technology was judged to be too early. Although detailed program plans are not presented, it should be emphasized that both techniques are considered to have considerable long term promise.

TABLE 6. CANDIDATE PROGRAMS FOR DEVELOPING ADVANCED NDE TECHNIQUES TO LEVEL SUITABLE FOR TESTING IN PARALLEL WITH RFC SYSTEM IN 1984-1985 TIME FRAME

Technique	*Present Status*	*1982 Program*	*1983 Program*	*1984 Program*
Microwave EC inspection with YIG sphere	Theoretical analysis at Stanford in QNDE program. Instrumentation development at Battelle NW in AF6.2 program. Limited data on fatigue cracks at Rockwell in DARPA RFC research program	Evaluate instrumentation developed on present 6.2 program as it performs in the detection of fatigue cracks. Include replication studies of a sufficient number of samples to establish reliability	Build semi-automatic instrument, including probe designed to inspect particular region of rotor component	Evaluate instrument at an ALC in parallel with automatic inspection system
Small, multiple coil EC inspection	Array concepts demonstrated at Northrop on second layer fastener problem. Demonstrations of crack detection in boltholes at SWRI	Design and construct small coil eddy current probe or probe array and evaluate on limited sample base	Evaluate probe or probe array on sample base used previously for YIG sphere evaluation (first 6 months). Begin construction of an instrument	Complete instrument construction and evaluate at ALC
Long wavelength ultrasonics	Stanford/Berkeley ONR program establishes that roughness not important but closure effects significant in ceramics	Experimentally assess effects of closure in disk materials. Develop procedure to compensate for interference from surface reflected signals.	Develop instrument incorporating knowledge learned in previous years	Evaluate instrument at an ALC in parallel with automatic inspection system
Inverse Born	Much of 1982, 1983 program contained in program for Quantitative NDE module presently under procurement at AF	Develop improved, automatic technique for measuring T_c. Evaluate performance on tight cracks. Develop protocol to properly position transducer bandwidth with respect to general flaw	Develop instrument incorporating knowledge gained in previous years	Evaluate instrument at an ALC in parallel with automatic inspection system
Optical detection of cracks	Experimental effort in progress at Rockwell in DARPA RFC research program	System developed in DARPA program should be evaluated on an extensive data base of such as described for YIG sphere program	Build semi-automatic system suitable for evaluation in an ALC	Evaluate instrument in an ALC in parallel with automatic inspection system

TABLE 6. CANDIDATE PROGRAMS FOR DEVELOPING ADVANCED NDE TECHNIQUES TO LEVEL SUITABLE FOR TESTING IN PARALLEL WITH RFC SYSTEM IN 1984-1985 TIME FRAME (Continued)

Technique	*Present Status*	*1982 Program*	*1983 Program*	*1984 Program*
Modeling of eddy current system reliability	Response of circular coil and bridge to half-penny shaped crack developed jointly by SRI Internatinal, Stanford, and General Electric in QNDE program	Extend analytical techniques to treat more general flaw and probe configurations	Use models to estimate reliability of RFC system	Develop estimation procedures to probabilistically predict flaw parameters from measurements
Ultrasonic modeling to predict system reliability	Limited start at Iowa State in QNDE program	Develop models for inspection of disks	Use models to estimate reliability of RFC system	Develop estimation procedure to probabilistically predict flaw parameters from measurements

2.3 Phase III — System Design

2.3.1 Eddy Current Device

This section deals with the specific design requirements of the eddy current device for the RFC Inspection System. It covers design features, communications media, and performance of a fast, high-resolution, high-reliability, digital eddy current instrument.

2.3.1.1 Device Architecture

The eddy current device described in Eddy Current Device Specification, Appendix A is inherently a digital instrument. This instrument is designed to communicate commands, status, and data to a host computer. The digital design and communication capability of this instrument offers several advantages over conventional analogue instruments. These advantages include: improved stability, greater noise immunity, greater dynamic range, direct computer control, and improved maintainability. The digital nature of the instrument and the internal micro-processor allows the instrument to possess functions not economically feasible in an analogue instrument. These include self-diagnostics, simple high-level command structure, and flexible communication protocol.

A second key element of the instrument architecture is the choice of communication media. The nature of the test and the anticipated operating environment dictate several constraints on the media. The choice of communication media must provide a reasonably high bandwidth channel (at least 30K bytes/second) in order to accommodate data transfer between the computer and instrument. In addition the device must be capable of bi-directional transfers and have interrupt capability. For the reasons stated and others discussed in Section 2.3.6, the IEEE 488A/1978 was chosen as the instrument/computer interface specification. This specification describes the hardware requirements of the link, while the protocol requirements are included in the draft specification of IEEE 488A Code and Format Conventions (Appendix D).

In addition to the feature already noted, the instrument must operate in an environment that requires exacting stability and accountability. This constraint is imposed by the RFC concept itself. For RFC to be operable with reasonable certainty, the inspection results must be consistent from inspection to inspection and from year to year. Three design requirements have been incorporated to aid in this endeavor. First, the instrument will have an output variability of less than 1% under worst case operating conditions for a period of two hr. Second, the instrument will incoporate self-diagnostic capabilities for at least 80% of the circuits in their active state; and third, each instrument will posses a unique electronic identification (Serial No.) which is accessible by the host computer. It is the intent of these and other design requirements to ensure that accurate and stable data is collected from a known, identified source.

It should be recognized that the performance of the eddy current test is highly dependent upon the probe configuration and part surface preparation. Recent experience with the F100 Structural Assessment Team (SAT) inspection has demonstrated the need for improved probes and surface preparation. The SAT experience emphasizes the need to do local surface preparation to minimize Type II errors (false calls). In this regard, it is strongly recommended that each eddy current station have provisions for local cleaning and polishing operations. The procedures developed for SAT are directly extendable to satisfying RFC requirements.

2.3.1.2 Summary

The instrument features summarized in this section and detailed in Appendix A provide a basis for an automated eddy current instrument. The instrument's primary intent is to satisfy the anticipated needs of the Air Force RFC facility; however, most functions are of a generic nature to accommodate other applications. The design is intended to serve as a basis for a series of NDT instruments which are computer controllable. The concepts presented are not new; they have been successfully implemented by a number of U.S. electronic instrument manufacturers.

In summary, the key aspects of the eddy current module design are outlined below. (See Appendix A for specific detailed descriptions).

- Special cleaning and preinspection preparation will be required for eddy current inspection. Very exacting parts preparation procedures must be established to minimize Type II errors (false calls).
- The instrument must respond to simple functional commands from the module controller.
- The system should be designed to stringent stability standards. Drift should be limited to less than 1 percent in two hr of continuous operation.
- The instrument must have internal diagnostics and be accessible to the remote processor to initiate and report.
- Calibration should be totally automatic and controlled by the remote processor.
- The remote processor must be able to identify individual eddy current instruments with each data set.
- Considering the anticipated high-noise operating environment, A/D signal conversion must be made internal to the instrument.
- The interface should be of a configuration that conforms to the IEEE instrument bus standard, IEEE 488A/1978. This standard is known as the General Purpose Interface Bus (GPIB).
- Communication protocol should conform to the preliminary draft of the Code and Format Conventions for IEEE 488.

2.3.2 Dimensional Inspection

A variety of dimensional inspections is now being performed on F100 parts considered RFC candidates as part of routine overhauls. There are two basic types, with respect to RFC: (1) inspection of those areas that can be routinely repaired (e.g., snap diameters, bearing mating surfaces), and (2) inspection of those areas that cannot be repaired, resulting in part scrappage (e.g., live rim diameters, knife-edge seals).

The first type is not considered to be classically RFC. It is generally an inspection for wear, galling, and gouging which requires subjective visual interpretation in addition to actual measurements. Repairs are accomplished by machining away parent material, coatings, and dressing to original tolerances. This type of inspection does not lend itself to automation, at least not with current state-of-the-art technology.

The second type will result in possible part retirement. If the part is outside of tolerances in certain areas, generally as a result of excessive growth or unrepairable wear, it must be scrapped.

Another type is made up of areas not covered in the routine overhaul inspection. These inspections would pick up dimensional irregularities expected to occur in extended life periods. For the F100 engine specifically, all relevant dimensions, including those that would change as a result of prolonged life, are checked as a part of routine overhaul. Any dimensional inspection done in the automated facility for RFC of the F100 engine would be redundant to existing overhaul procedures.

It is recommended, therefore that no specific provisions be made in the RFC facility for dimensional inspection at this time. It should be kept in mind that the mechanical scanning equipment specified for eddy current systems would likely be capable of performing several of the required dimensional inspections. And, in combination with advanced dimensional inspection techniques (e.g., optical, sonic), the RFC facility could perform complete dimensional inspections in the future.

2.3.3 Ultrasonic Test Instrument

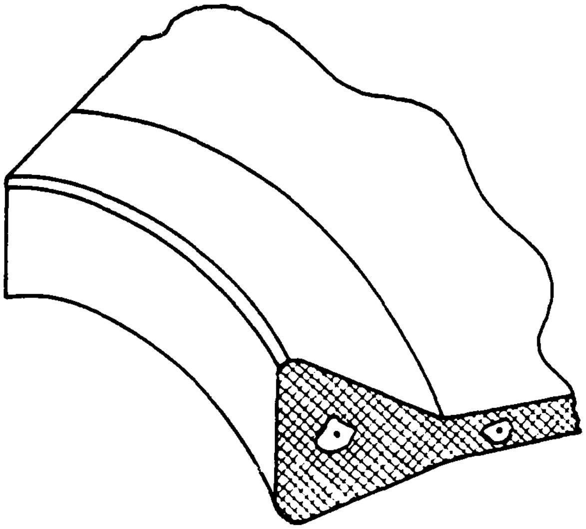
The detailed specific requirements for immersion ultrasonic inspection of jet engine disks in RFC are not known at this time. The specifications herein (and in Appendix B) are intended to permit inspection for all anticipated flaw types in all required disk geometries (specifically, PWA F100 RFC candidate disks). These anticipated inspections are described in the following paragraphs.

2.3.3.1 Inspection Requirements

The system must at least be able to perform the usual inspections applied to premachined disk shapes, but at higher sensitivities and better resolution, through flat, cylindrical, conical, and radiused surfaces. In particular, in a single-pass inspection, it will detect defects equivalent to a No. 1 flat-bottomed hole (FBH) (i.e., a planar, disk-shaped flaw 0.015 in. (0.38 mm) in diameter, lying in a plane parallel to the sound beam entry surface) at depths from 0.050 in. (1.3 mm) to 4.0 in. (10 cm). Moreover, it will be capable of detecting defects equivalent to a No.1 FBH between 0.030 in. (0.76 mm) and 0.050 in. (1.3 mm) from the sound beam entry surface, in a near-surface zone inspection. This latter capability will bridge the gap between conventional eddy current and conventional ultrasonics.

The system is also required to detect penny-shaped defects lying in the axial-radial plane in bore and web areas as shown in Figure 52. This type of defect will originate at an ultrasonically nonrejectable site, propagating in the axial-radial plane as a disk-shaped defect centered at the originating site. Minimum required detection size is 0.015 in. (0.38 mm) diameter. The difficulty with this defect is that it is perpendicular to the available sound beam entry surfaces, so that only a backscattered wave, not a specular reflection, will return towards the transmitting transducer as shown in Figure 53.

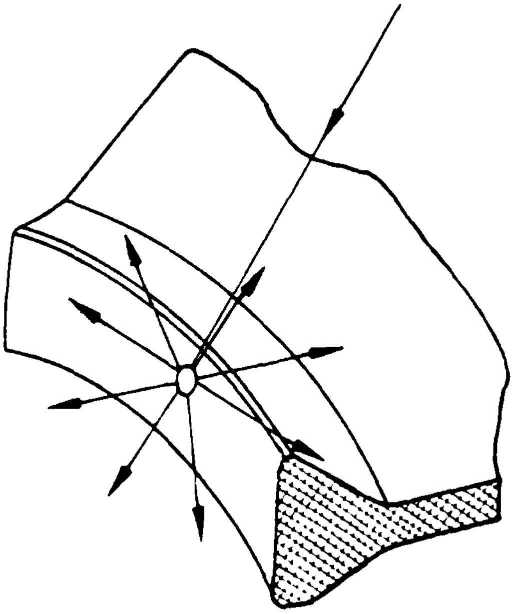
- Internal to Bore or Web
- Penny-Shaped Crack
- Axial-Radial Orientation (Perpendicular to Beam Entry Surfaces)
- 0.015 in. (0.38 mm) Diameter and Larger



FD 227339

Figure 52. Critical Flaw for Ultrasonics

- Scattered Energy



FD 227340

Figure 53. Inspection Geometry Single Transducer

2.3.3.2 Inspection Approach

Development of a method using the backscattered wave for detection of the penny-shaped defects would result in the simplest instrument and mechanical configuration (single transducer, either normal to the surface or angulated); if a specular reflection is required, the situation becomes more complicated. The situation is similar to that encountered in butt and seam weld inspection (Figure 54). As seen in Figure 55, the return path of the sound beam depends on the depth of flaw in the part. At a 45 deg beam path (in the material), the return paths for near and far surface flaws are separated by twice the material thickness, as measured along the material surface (Figure 56). With the transducer angled at either 9 deg (longitudinal) or 20 deg (shear), the beam separation along the transducer surface is 90% or 75% of that amount. Part thicknesses for the F100 range up to 1.5 in. (3.8 cm), necessitating a transducer face length of approximately 2.7 in. (6.5 cm) or 2.2 in. (5.6 cm), with the face width chosen to optimize beam characteristics. Since it is difficult to drive a large transducer at high frequencies with sufficient power to obtain high sensitivity, it seems advisable to use a small transmitting transducer (which will also be the receiving transducer for far-surface flaws), and a large receiving transducer (Figure 56). In order to enhance inspection reliability, it maybe desirable to monitor the back-face signal (Figure 57). Thus the instrument requires three receiver inputs: one for the transmitting transducer, one for the flaw echo receiving transducer, and one for the backface monitoring transducer. The three transducers can share common receiver circuitry, provided the excitation pulse is decoupled from the receive-only transducers; the signals from the three transducers will be added for input to the common receiver circuitry. This requirement is specified in Appendix B. Another possible inspection configuration is excitation from one direction, and detection of a preferentially scattered wave in a different direction (Figure 58). This also requires two or three transducers and therefore a two or three input receiver.

Operating frequencies are expected to be primarily between 10 and 15 MHz. However, the near-surface resolution will probably require 20 or 25 MHz, and penetration in coarse-grained materials may require frequencies as low as 1.0 MHz.

In order to optimize signal characteristics, impedance mismatches should be minimized. This is achieved by using matched outputs, cables, connectors, and inputs. The matching of the transducer(s) to the pulser and receiver is not so simple, however, since the transducer impedance is typically 2 to 10 ohms, while the cable impedance is 50 ohms or more. The ideal solution is to eliminate the cabling between the transducers and the pulser and receiver. This specification is included in Appendix B, since it is not a standard item and will require development; the two features are designated as "satellite pulser" and "satellite receiver". Each will consist of miniature electronics, mounted to the submersed end of the search tube (both in a single enclosure, for pulse-echo mode). The power supply should be low voltage for safety. The advantages to be gained by the satellite pulser are elimination of cable ringing, increase in transmitted power, simplification of transducer construction, and increased reproducibility in transducer performance. The advantages of the satellite receiver are increased signal level and reduced electrical noise.

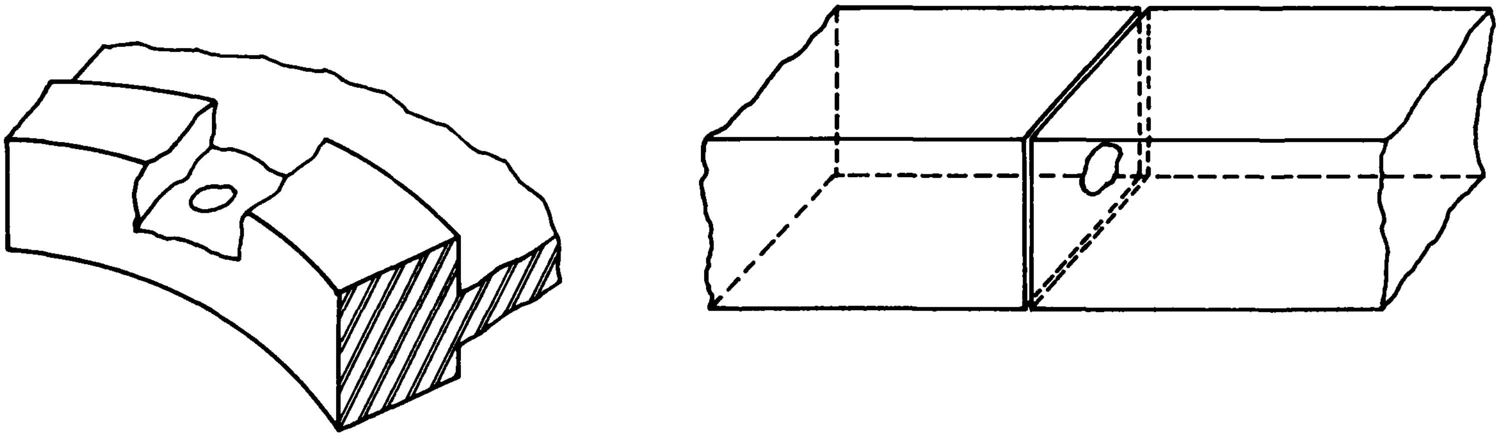
In order to provide ease of interpretation in areas with holes, where the front face signal will periodically disappear, a front face monitor gate is required. This gate need only indicate the presence or absence of a signal above 50% screen height at the expected location.

Disk Inspection

- 0.015 in. (0.38 mm) Diameter
- Radial-Circumferential Orientation
- Sonic Shapes (Surface Parallel to Plane of Flaw)

Butt Weld Inspection

- 0.050 in. (1.2 mm) Diameter
- Perpendicular to Beam Entry Surface
- Parallel Back Surface



FD 227341

Figure 54. State of the Art in Ultrasonic Inspection

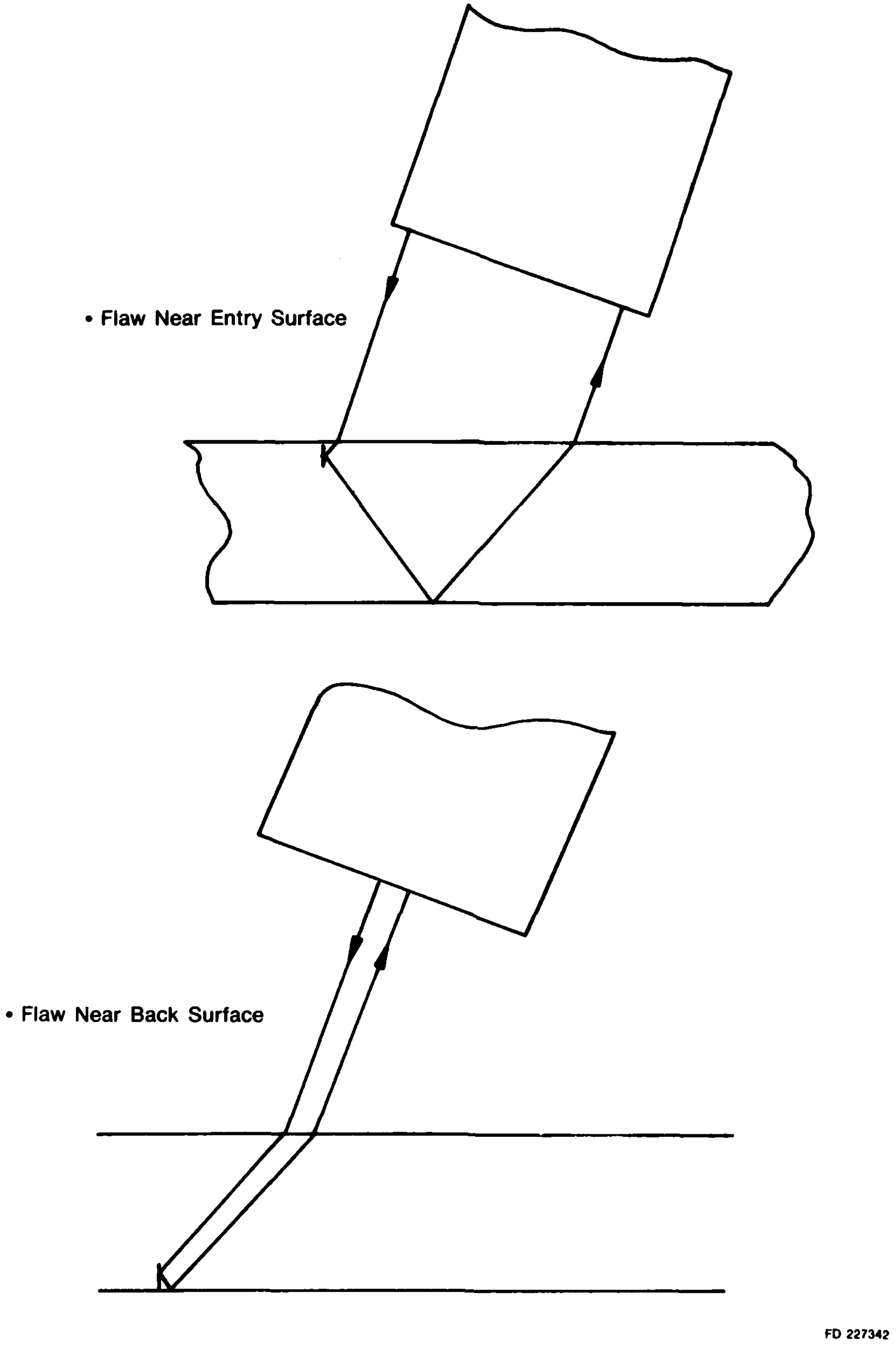


Figure 55. Beam Return Depends on Flaw Depth

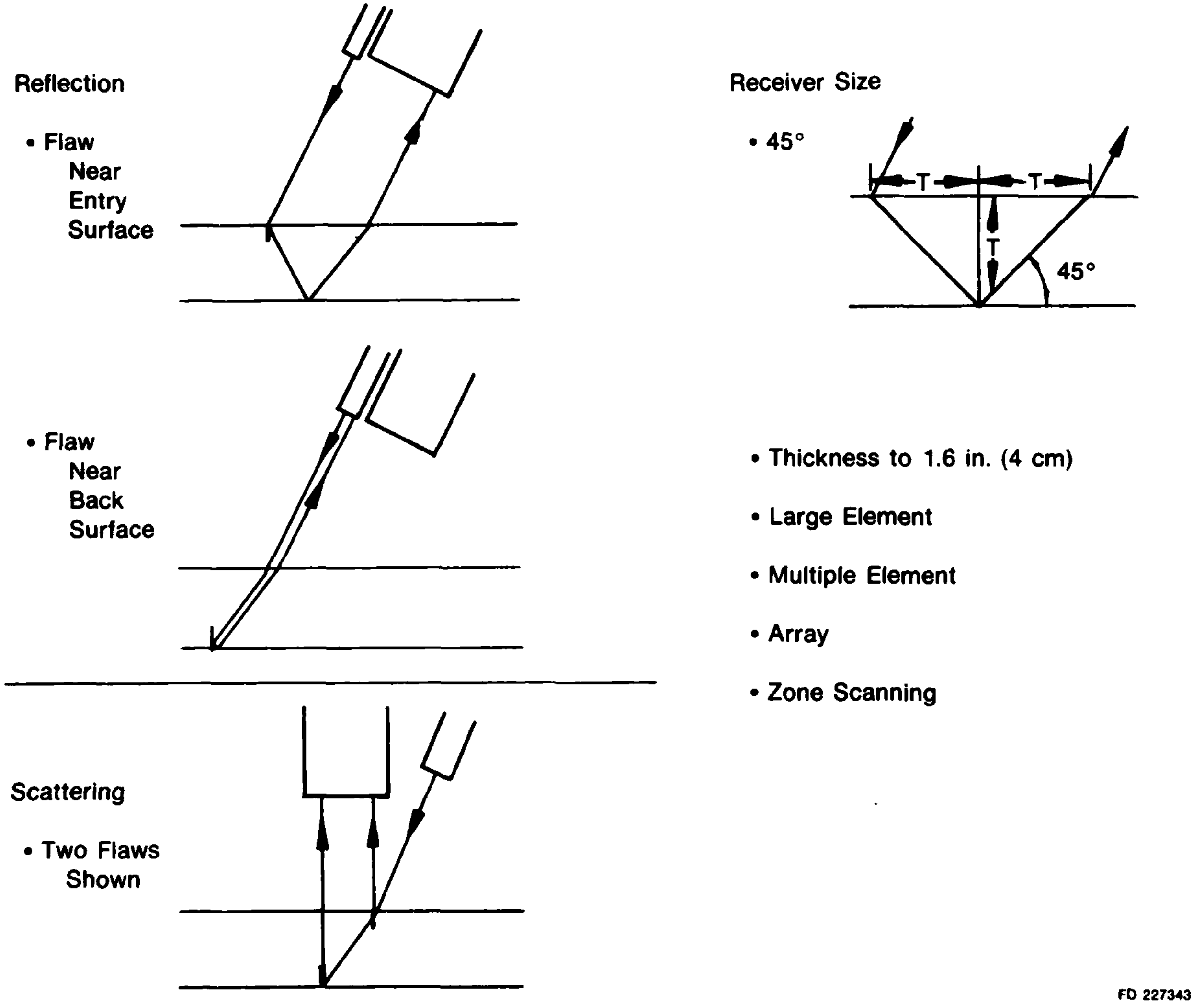


Figure 56. Receiving Geometry

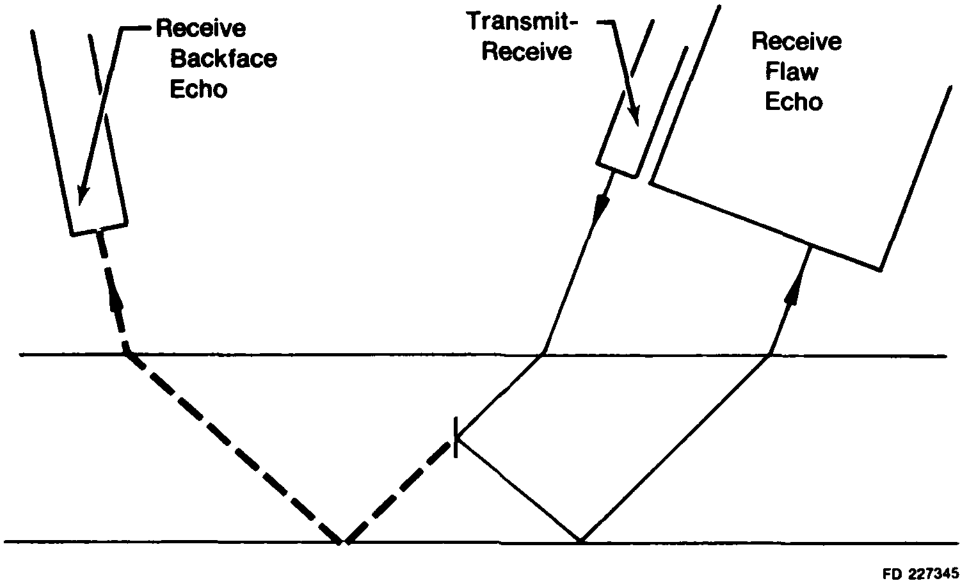


Figure 57. Flaw Interrupts Backface Echo

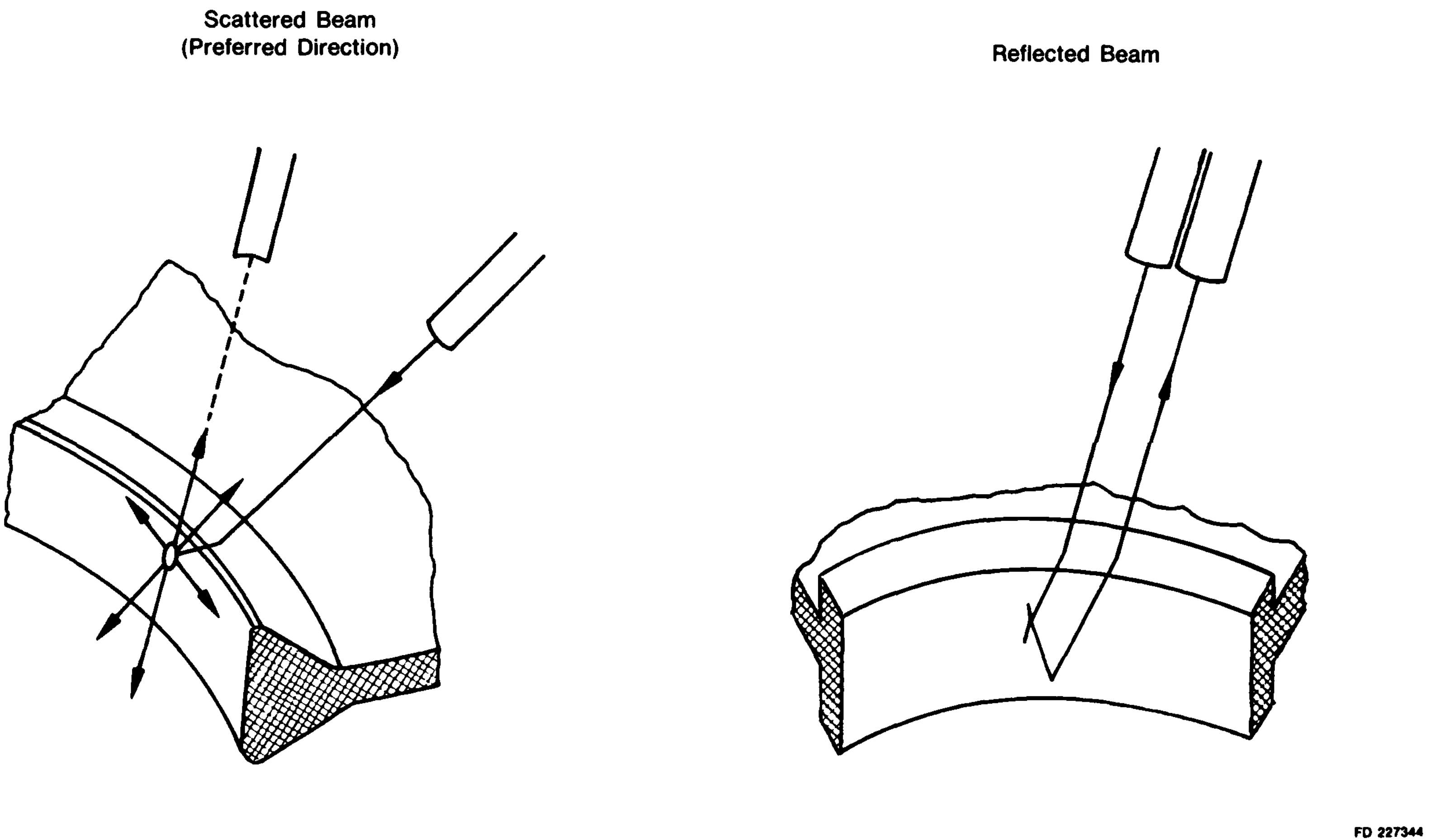


Figure 58. Inspection Geometry Multiple Transducers

2.3.4 Fluorescent Penetrant Inspection

A whole field technique will be an essential part of the RFC Inspection System. The utility of this technique will not be for ultra-sensitive focused inspections, but it will be necessary to search for relatively large rogue defects which may occasionally occur from handling damage, fabrication problems, or material flaws. The whole field technique which is most commonly used for critical turbine engine components is fluorescent penetrant inspection (FPI). Although it is well known that FPI has serious drawbacks as a primary tool for overhaul inspection, this basic method is the most logical choice as the near-term whole field RFC inspection method.

Both Kelly AFB and Tinker AFB have constructed sophisticated FPI facilities. The specification detailed in Appendix C addresses procedural modifications which will be made to overhaul FPI, as performed according to manufacturers' technical orders (T.O.s) to produce an optimum manual whole field penetrant inspection. It is assumed that existing Air Force FPI facilities will be used for the RFC inspections, and all additional material which will be required for technique modifications will be described herein.

The specification addresses FPI process modifications which will be implemented within the context of the first-generation RFC Inspection System, but a better long-term solution is desirable. It is recommended that exploratory development be conducted upon: (1) automated scanning for FPI, and (2) eddy current inspection as whole field method. In addition, there are other whole field methods, such as Krypton Exposure Technique (KET) which will continue to be investigated using P&WA Corporate funding and may produce higher reliability inspections.

The suggested overhaul FPI modifications which are described in this specification have been shown to improve FPI capability during performance of two Air Force R&D Programs and P&WA internal research.

This specification follows MIL-STD-490, Appendix VII only in a general sense because the military standard is meant to describe a piece of equipment rather than a process modification.

While this specification will address the FPI process as applied to RFC inspections, it is not meant to bypass the many implementation aspects of these proposed modifications which must be thorougly satisfied during a manufacturing technology effort. The final T.O.s, which will be tailored for specific engine components, must include restrictions on process variables, such as penetrant, emulsifier and developer materials, dwell times, and processing temperatures. Surface preparations must also be addressed from the standpoint of specification of suitable chemical milling operations for specific components. The surface preparation task must include a study of the effects of chemical preparations on material properties and a sensitivity study of the process variables (e.g., chemical depletion, solution temperature, dwell time, chemical neutralizers) associated with chemical preparations.

2.3.4.1 Background

FPI is the most widely used inspection technique, and perhaps the only technique used for some critical engine component inspections. The apparent simplicity, low cost, and inherently high sensitivity are the main advantages of this inspection technique. FPI capability of engine overhaul facilities in terms of probability of detection is unknown. An AFLCSA-ALC/Martin Marietta study to quantify NDI capability is in progress (Reference 2). A recent study of the maintenance FPI capability of airframe components (Reference 1) revealed that only cracks greater than 0.70 in. (1.78 cm) will be detected with 60% probability of detection at 95% confidence level. Similar FPI capabilities for engine components in an overhaul enviroment may be assumed. If the assumption is valid, this presents a problem for the demonstration of structural integrity for in-service engine components. It should be emphasized that critical crack sizes for engine components are generally smaller than for airframe components, and engine components are subjected to very high temperatures and severe enviromental conditions during engine operations, thus making it much more difficult for FPI to detect tight fatigue cracks.

Inherent FPI capability in a production or manufacturing enviroment is higher than that in overhaul inspection. In the laboratory under controlled conditions, it is possible to detect cracks smaller than 0.032 in. (0.813 mm) with a probability of detection greater than 94% at 95% confidence level (Reference 5). In fact with stress-enhanced (wink) FPI, laboratory capability can be greater than 91% at 95% confidence level for cracks smaller than 0.016 in. (0.406 mm) (Reference 5). Thus, it is immediately obvious that there is potentially great scope for improvements in FPI capability of overhaul inspection. This area of research and development was, however, not addressed in detail until recently (Reference 6). An AFWAL/P&WA program, "Methods Improvement of the FPI Process" (F33615-79-C-5021) investigated surface preparation procedures and key FPI process variables for overhaul inspection. The main objective was to develop implementable improvements and enhancements of inspection capability for engine overhaul facilities. A follow-on AFWAL/P&WA program "Improved Penetrant Process Evaluation Criteria" (F33615-80-C-5060) is currently evaluating increased performance in FPI reliability using improvements and modifications to the FPI process identified and evaluated in contract F33615-79-C-5021. This evaluation consists of designing and conducting a demonstration program to statistically quantify the increased performance in terms of probability of detection.

The method of FPI on overhaul facilities is similar to a production enviroment. The method essentially consists of component surface preparation, penetrant application with associated dwell time, excess penetrant removal, component drying, and developer application. The penetrant which has been entrapped in the discontinuity is drawn to the surface by the developer and produces characteristic indications which are examined by an inspector.

For over a decade semiautomated penetrant inspection systems have been in use in overhaul facilities. Usually these systems consist of several in-line stations with engine components being transported from station to station by mechanical handling systems. The stations may consist of:

1. Chemical and/or mechanical surface preparation
2. Drying to remove any moisture away from the parts
3. Soak in a temperature controlled penetrant tank
4. Prerinse station to remove some excess penetrant (only for hydrophilic system)
5. Controlled time dipping in an emulsifier tank
6. Rinse station, usually consisting of water spray
7. Air circulating controlled temperature drying oven (for dry developer) only at this stage
8. Developer station
9. Developer drying station if a wet developer is used
10. Black light inspection booth.

These semiautomated facilites, when properly planned and set up, should provide uniform processing for the same type of components as required in inspection procedures. These units are preferred to hand-processing units, but a small hand-processing unit is always coexistent with semiautomated units to handle small parts and specialized nonroutine inspection items.

Even though the FPI procedure is basically the same for manufacturing and overhaul inspection, the capabilities may vary vastly. The main reasons for lower sensitivity and reliability of overhaul inspection are: (1) poor surface condition of components (nicks, dings, deep scratches, etc.), (2) contaminants such as carbonized oils, oxide films, corrosion and paint on the surface or in the discontinuities, (3) abrasive cleaning procedures used to clean the parts, (4) compressive stresses on the surface of the component, and (5) human factors like variability of training experience and job interest.

2.3.4.2 Summary of FPI Specification (Appendix C)

The specification addresses implementation of modified surface preparations and FPI process modifications to the perceived current overhaul FPI system used by the San Antonio Air Logistics Command. These modifications may be relatively easily implemented to the current overhaul facility, so we anticipate that the existing facility will be used for RFC inspections. The specification specifically lists materials and equipment which will be required to make necessary modifications to an existing overhaul FPI facility. It does not list all materials and equipment required to assemble complete facility.

Controls are discussed for the recommended chemical mill surface preparation. This is a critical issue and may result in a requirement for fully automated administration of chemical milling to completely assure safety of inspection personnel and engine components.

Design, construction and implementation of modifications are discussed, including recommended sensitivity studies of all chemical mill parametric variables and mechanical properties tests to assure component structural integrity. Finally, procedural aspects for the modified surfacer preparation and FPI process are also discussed in Appendix C.

2.3.5 Advanced NDE Methods

This section introduces the work of Professor R. B. Thompson, et al., regarding quantitative NDE methods for RFC. Although his written presentation of research in application of advanced NDE methods to RFC does not constitute an engineering specification, it is very pertinent to the overall effort in terms of planning for RFC Inspection System growth beyond current state-of-the-art technology.

In Appendix J, Professor Thompson discusses the applicability of quantitative NDE techniques to RFC systems. A review of the state-of-the-art first establishes that more quantitative techniques are needed to realize the full economic benefits of RFC. This is followed by a detailed discussion of the potential offered by advanced methods for quantitative NDE. The report concludes with an outline of programs which would bring the advanced NDE techniques to the state of development necessary for incorporation into an RFC system. These are divided into three categories: (1) those which can be directly incorporated in the design and construction of a first generation system; (2) those which could be brought to a level suitable for testing in parallel with this system by 1984-1985; and (3) those which will not be ready until a second generation system is constructed.

2.3.6 Interface Recommendations

This section will specifically address three generic interfaces required for the system as a whole and the recommendation. The three interfaces a most aptly defined by the devices they connect. They are as follows: processor-to-processor, processor-to-instrument, and processor-to-display device. In subsequent sections each of these interfaces will be discussed.

2.3.6.1 Background

When viewed as a whole, the RFC system has three major hierarchical computer elements which are described in detail in Appendix E. It is crucial that the interface between these elements be accurately defined. It is the recommendation of this design study that all interfaces (both hardware and protocal) fall into one of two categories: either an accepted industry standard or a defacto standard. The recommendations of this report span both categories since recognized industry standards do not presently exist for the interprocessor communication link. However, a defacto standard exists for a specific choice of computational equipment.

2.3.6.2 Processor-to-Display Interface

The interface between the operator display and the station computer is deemed to be a local (less than 50 ft) relatively low speed link (less than 1000 char/sec). The requirements of this interface can be satisfied by the RS-232-C standard of the Electronics Industries Association. The specific minimum requirement of this interface, as defined by RS-232-C, is a 9600 baud full duplex primary asynchronous channel. The speed specified is in excess of the expected initial requirements; however, almost all standard communication interface and display terminals can accomodate this requirement.

2.3.6.3 *Processor-to-Instrument Interface*

The choice of interface between the instrument and the station processor is crucial because it potentially limits both system performance (i.e., how fast can the inspection be done) and future expansion. For this reason, careful consideration was given to the choice of interface. A particularly well-suited selection is the IEEE 488A-1978 instrument bus standard. This interface offers a half duplex bit parallel byte serial link which is capable of speeds in excess of 1 megabyte/sec. The interface is commercially available and, at this writing, is used in over 200 instruments and over 30 processors. The link is limited in length to 20 meters, which is sufficient for the station computer-instrument communication. In addition the address structure of the interface allows up to 14 instruments (31 with hardware repeater) to be connected to a single bus.

The IEEE 488A-1978 specification provides an excellent definition of the actual link hardware; however, a consistent protocol specification is required. Appendix D of this report contains a draft of the proposed Code and Format Convention for IEEE-488A-1978. Although not an accepted industry standard, the draft specification is consistent with most current practices. It is strongly recommended that the instruments used adhere to both the hardware and protocol specification discussed herein.

2.3.6.4 *Processor-to-Processor Interface*

A specific processor-to-processor link is difficult to define without prior knowledge of the processors to be used. Currently, no industry standard exists for such a link. A multiplicity of protocols (hardware and software) exists; however, no specific choice has yet emerged as a defacto standard for the industry as a whole. Therefore, the choice of processors should be closely coupled with the choice of processor-to-processor communication link.

Although a specific recommendation cannot be stated succinctly, a generic description of the link attributes is possible. A list of major attributes is given in Table 7. A number of commercially available protocols satisfy these requirements, including DDS-1000 (Hewlett-Packard) and DDCMP (Digital Equipment Corp).

Two elements described in Table 7 are vital to sucessful implementation of RFC: the error rate equipment and the speed. If the interface chosen does not meet both of these requirements, the possibility exists that either corrupted data will be stored or the communication speed will adversely impact the system operation.

TABLE 7. PROCESSOR-TO-PROCESSOR COMMUNICATION

Speed	Greater than 50K bytes/sec
Error rate	Less than 1 in 10^{10}
Error recovery	Automatic
Host processor overhead	Minimized by interface design

2.3.7 Control Software and Data Management

In developing the computer hardware/software specification, it was necessary to assess current and anticipated inspection techniques, day-to-day operational requirements of the ALC's, and the overall objectives of the RFC system. Currently used and anticipated inspection techniques require a high degree of system flexibility so as to permit incorporation of new methods and equipment. The day-to-day operational needs of the ALC's require reliability and reproducibility of results, as well as adaptability to meet new requirements as implemented through less skilled operations. The RFC systems concept requires emphasis on control and accountability as well as centralized data base management of the ever growing historical information required for system operation.

The detailed specifications are presented in Appendix E.

2.3.7.1 Specification Overview

The RFC system consists of three levels of computer interaction as shown in Figure 59: the master parts records system, the inspection master systems, and the inspection station systems. The master parts records system is now an Air Force requirement, and is assumed to exist for use by the RFC system. The functional requirements of all levels are discussed to clarify the role each plays in the system operation. The salient points of the RFC computer hardware/software system are:

- Three independent levels of hardware/software
- Multiple tasks per level
- Modularity of task organization
- Control/accountability at each level
- Flexibility/adaptability at each level
- Self diagnostics
- Standard interfaces and protocols
- Commonality of processors
- Redundancy/backup in design
- Restart/recovery mechanisms
- Interaction with existing AF tracking software.

By design, the RFC computer hardware/software functions as a loosely coupled network. Each computer system in the network performs several well defined tasks, requiring only minimal interaction with other computers to ensure proper system operation and control.

The master parts records system (Figure 60) essentially functions in a data base access-retrieval mode for the inspection master systems and other authorized users. It permits additions, deletions, and updates to the information base that is operated on by the inspection master systems. Basically this is the formalization of initial inspection requirements and all subsequent modification.

The inspection master system provides all local control of RFC activities at an ALC installation. This is illustrated in Figure 61. The inspection master system provides upward and downward communication, ensures tracking and accountability of parts and inspections, and provides local data storage for intermediate operations. This system also reports its results to the master parts records system so the inspection history of the part can be properly maintained and accessed as required when the part recycles through for future inspections.

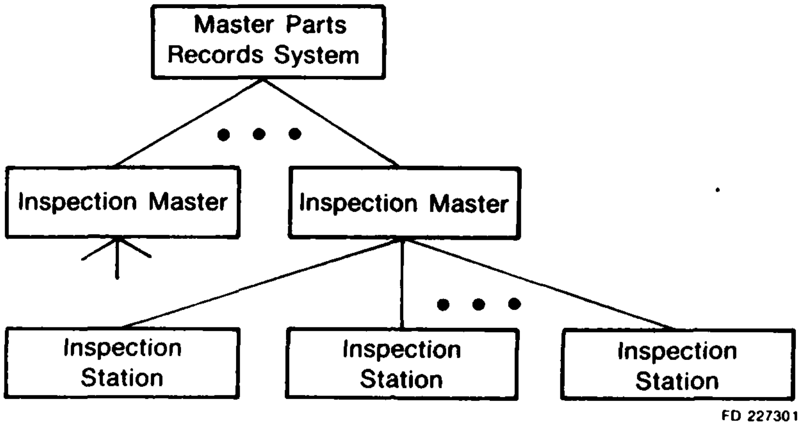


Figure 59. RFC Computer System Configuration

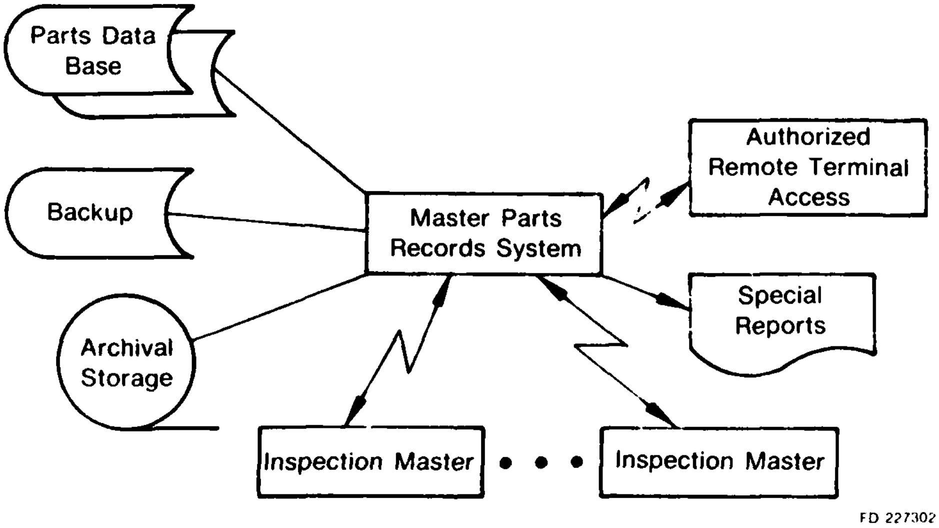
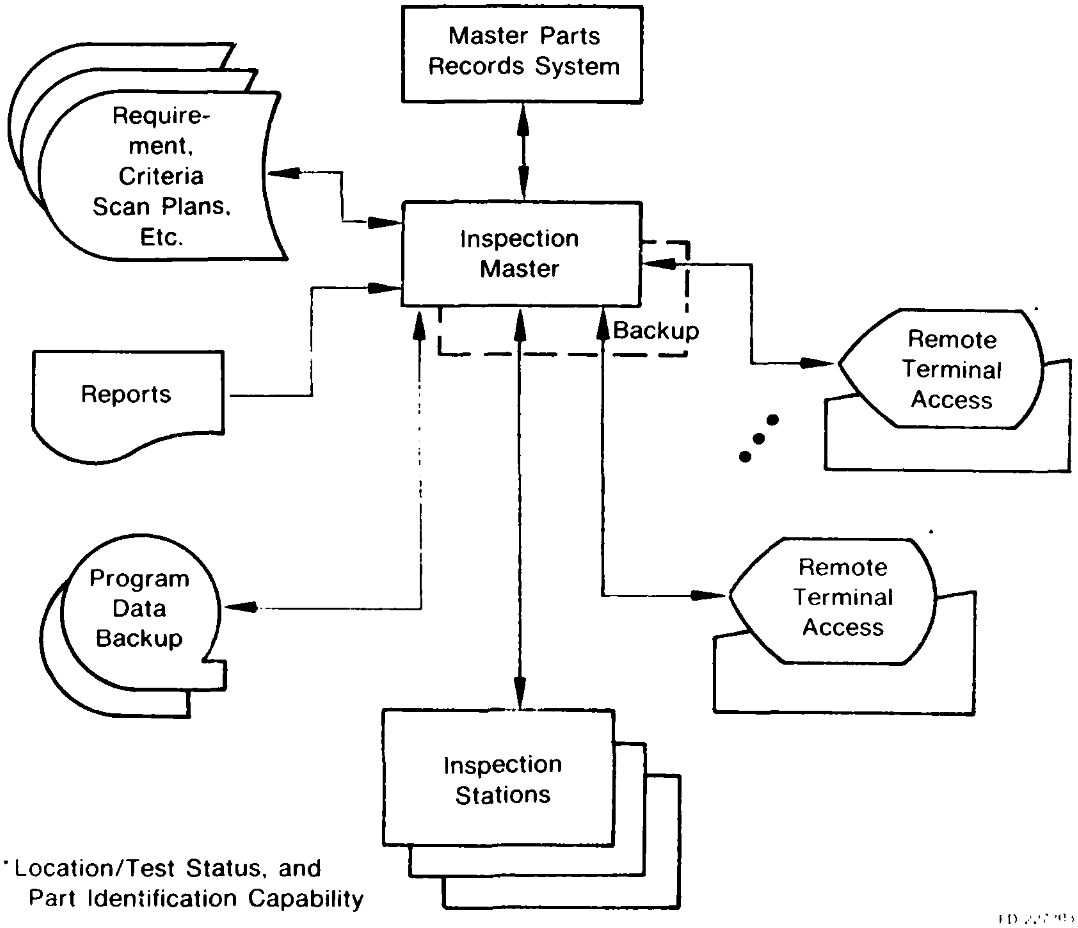


Figure 60. Master Parts Records System



*Location/Test Status, and Part Identification Capability

Figure 61. Inspection Master Computer System

The inspection station system (Figure 62) ensures that the details of the inspection are properly performed and the results are reported to the inspection master system. All interaction with special purpose hardware is accomplished at this level. Here the final details of the control of the inspection process, data acquisition and storage, as well as data processing and reporting requirements are carried to completion. Figures 63, 64 and 65 illustrate the multiplicity of tasks at each level and the associated modularity of function.

Each level within the RFC system has associated requirements for control and accountability. Each is required to fully control its activities; however, accountability for interaction with other computers in the system is required as well. Essentially this is a followup function to determine that no loose ends exist in the system operation. Similarly, all systems incorporate features to enhance their flexibility and adaptability. While these are generic features, they are addressed from the standpoint of availability of general purpose utilities and system configurability to accomodate new requirements incurred in subsequent system upgrades.

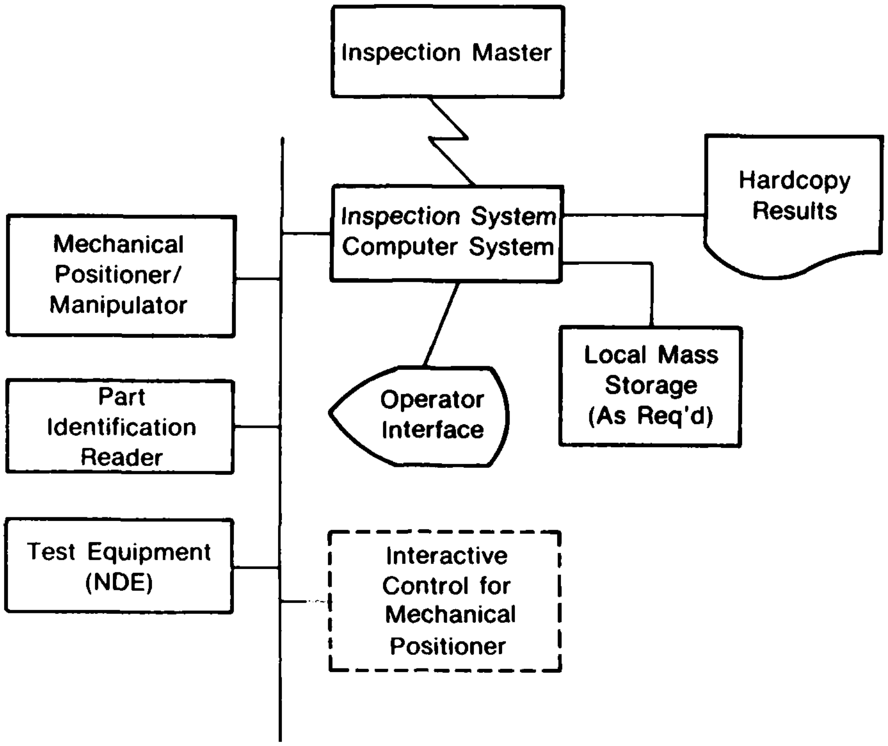
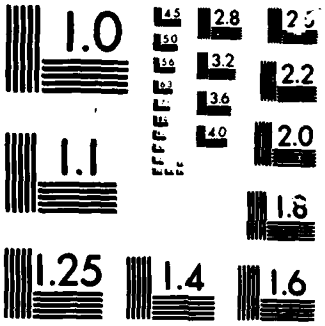


Figure 62. Inspection Station Computer System

AD-A167 166 RETIREMENT FOR CAUSE INSPECTION SYSTEM DESIGN VOLUME 1 2/2
MAIN TEXT..(U) PRATT AND WHITNEY WEST PALM BEACH FL
GOVERNMENT PRODUCTS DIV.. J S CARGILL ET AL. OCT 81
UNCLASSIFIED P/W/GPD-FR-15175-VOL-1 F/G 14/2 NL



MICROCOP CHART

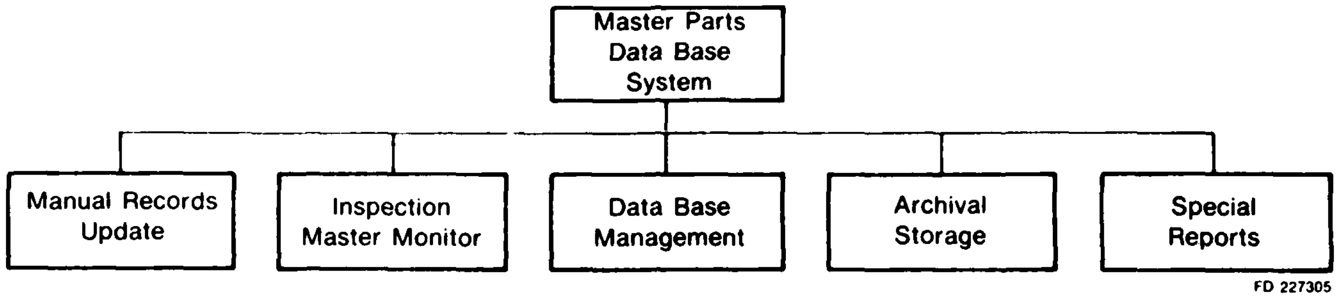


Figure 63. Block Diagram of Master Parts Data Base Software

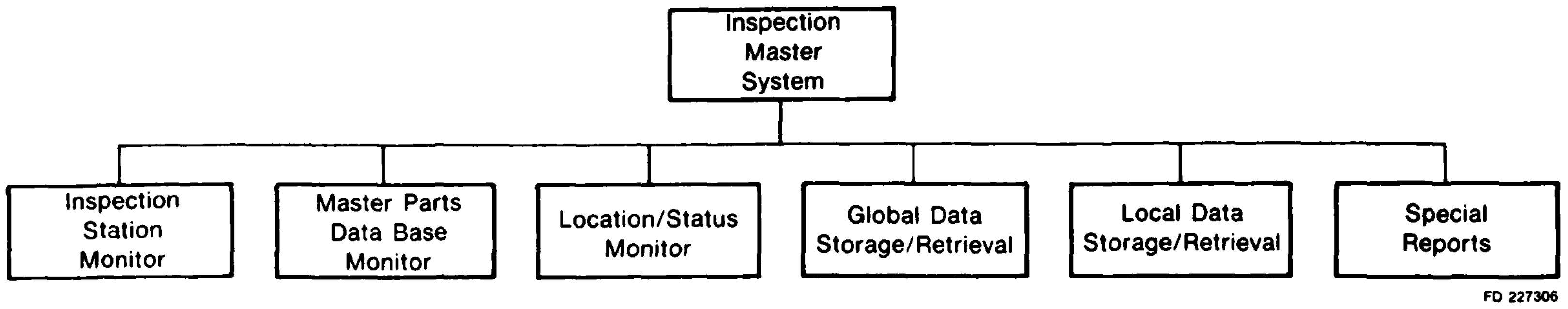


Figure 64. Block Diagram of Inspection Master Software Functions

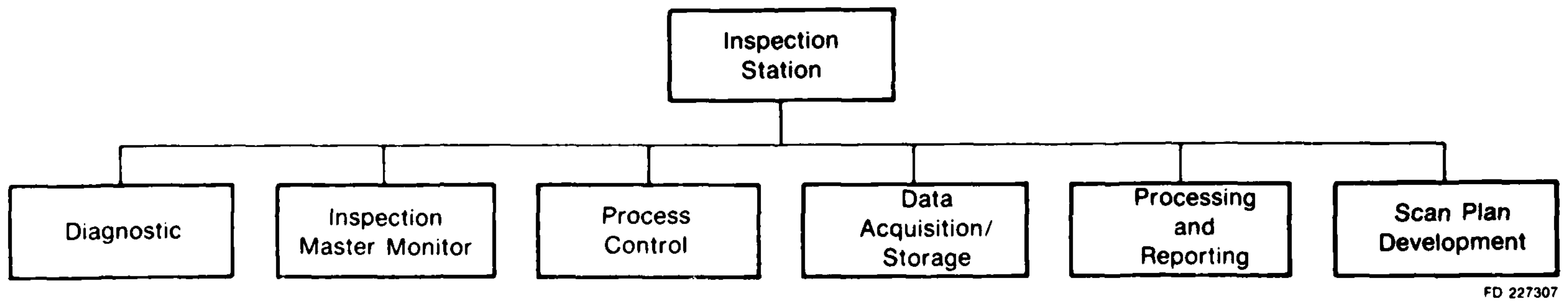


Figure 65. Block Diagram of Inspection Station Software Functions

Each of the systems must have self-diagnostic capability. This essentially ensures the fundamental operability of the system hardware. Diagnostic capability must address the interface between systems as well, to assist in finding problems which are not explicitly related to a single system. The use of standard interfaces and communication protocols eases system development and simplifies the system integration process. It adds further capability in the area of flexibility and permits interchangeability of subsystems along well defined ground rules.

To the largest extent possible, the system is constructed around a common processor type. Aside from the obvious advantages of providing backup as well as commonality of spare parts, interaction between different levels in the system becomes simplified. A single vendor can supply the computers, communications hardware, and communication software to support the entire system operation. This is an advantage particularly in the area of communication interface and protocol, since most computer manufacturers support their own particular networking software. When processors of different manufacturers are used, only minimal networking software is available.

The software for the RFC system reflects human engineering features. This is normally seen as effective and consistent prompting for operator interaction. In this system, however, the human engineering features must be integrated into the design of the software rather than in its implementation so as to simplify response to user needs as they develop. Specifically, generalized reporting packages and scan plan development software must exist for this purpose. While generalized reporting packages for data base systems have existed for some time, simplified control of mechanical apparatus has not. Work in the robotics area has explored approaches where computers are used to monitor operator guided motions and recreate the movements based on this input. Sensor feedback from the various motions provide "fine-tuning" of motions allowing for slight variations in course due to localized inconsistencies. In the case of the RFC system, this enables an end user (NDE person) to create and implement new inspection procedures with minimal or no help from a hardware or software specialist. In essence, the objective is to have the tools available to permit the user to solve his own problem with minimal assistance.

Each computer system has some measure of redundancy or backup designed into it. The master parts records system and the inspection master system, because of their size and function, must have redundant subsystems to enable response to system needs in the event of failure. The inspection station systems are basically identical except for particular inspection related hardware. The fact that these systems are identical permits interchange as required. This provides several benefits and options to the user: reduced number of spare parts and subsystems, as well as possible rearrangement of existing systems to meet shifting production requirements. Another option permits rearrangement of inspection station resources in the event of subsystem failure to permit complete operation at a reduced rate rather than complete shutdown.

All of the software in the system must provide some form of restart/recovery mechanism enabling restart of function (after some failure) with minimal effort. At the inspection station level this is perhaps the most simple, as interface to this system is very localized and the function performed at this level is fairly specific. At this level, the particular task or activity can be restarted from initiation. At the master parts records system and inspection master levels, restart and recovery is more complex due to the increased number of activities and interfaces. In particular, the data bases must be recoverable to sustain operation.

2.3.7.2 Available System Consideration

In preparation of the RFC specification, the implication of existing AF parts tracking systems has been considered. Principally two systems are known to exist: Comprehensive Engine Management System (CEMS) and the Maintenance Job Tracking System (MJT). The CEMS system addresses the overall logistic issues of engine management of which inspection is only one element. It is believed that the RFC system could benefit in initial data base development from information available in CEMS. Similarly, CEMS will benefit from the results of the RFC System because it can provide data needed to build engines from life compatible components. The MJT system is being prepared as a tracking system used to monitor parts within ALCs. The MJT would interface with the RFC system by establishing the inspection system as a specific ALC process or location. Actual location of a part in the inspection cycle would be a function of the RFC system. Interface of the RFC system to either the CEMS or MJT system simply involves either the receipt of or reporting of specific information already within the RFC system. Implementation of these features is trivial with respect to the development of the RFC system itself. Actual mechanisms of interface must evolve as both of the other systems become more of a reality.

2.3.8 Signal Processing Systems and Automatic Pattern Classification

This section discusses digitial signal processing and pattern recognition techniques, such as adaptive learning networks, that can be applied to nondestructive evaluation (NDE) methods. The discussion is divided into three parts. The first part is a review of the general problem of automatic classification of signals or patterns. The second part is concerned with some of the specific problems that are likely to be important in the design of a NDE system. The final part offers some comments upon some related work that has been done on adaptive learning networks.

2.3.8.1 Automatic Pattern Classifications

The basic components of an automatic pattern classification system are depicted in Figure 66. The first stage, object location, is rather obvious but nevertheless extremely important. This usually takes the form of positioning the sensor so as to acquire a signal that represents the object of concern. Careful attention to the design of this part of the system can lead to great simplifications in the design of later stages. The sensor generates a signal which contains information about the object in question. The sensor can be either passive, relying on signals inherently generated by the object, or active, incorporating a probe signal which is modified in characteristic ways by the object. Here again it is obvious that careful attention to the sensor design can pay great dividends in performance and simplification of later processing stages. It is worth pointing out that in many cases, object location may be of concern after the sensor as well as before. For example, the sensor may generate an electrical waveform where the desired information is confined to a limited time interval. Precise location of this part of the waveform can be essential to efficient implementation and high performance.

The next stage depicted in Figure 66 is a digitizer/quantizer. This stage is included in recognition of the fact that the final stages of any system will generally involve a digital information processing machine. The digitizer for pattern classification will generally involve either temporal or spatial sampling as well as quantization of the resulting samples. Both the sampling and quantization processes can distort the signal, so care must be taken so as not to destroy or confound the information in the signal (Reference 8).

---

8 Oppenheim, A. V. and R. W. Schafer, *Digital Signal Processing*, Prentice Hall, Englewood Cliffs, NJ, 1975.

Figure 66. General Form of Automatic Pattern Classifier

The feature extraction stage is a signal processing system whose purpose is to transform the sensor signal into a form which is convenient for use in classification. (Note that feature extraction could be done before the digitization if analog signal processing techniques are desirable.) Generally, feature extraction involves the computation of a set of parameters or features which are characteristic of the possible states of the object of concern. That is, the feature extractor attempts to reduce the information content of the signal by discarding all but the essential information required for reliable classification of the signal. It should be pointed out that design of this stage of processing is also very important. By using sophisticated digital signal processing techniques (Reference 8), it may be possible to compensate for certain kinds of deficiencies in earlier stages; e.g., noise introduced in the sensor stage can be removed by digital filtering. However, it should be emphasized that it is clearly wishful thinking to place too much of a burden upon this stage of the system. The most sophisticated processing will not be able to uncover information that is not present at the beginning. A classifier system will not compensate for poor signal to noise environments.

The final stage of any automatic system is the classification stage. The classifier generally takes a form similar to Figure 67, which depicts the computation of a set of decision or discriminant functions d(i,x), (i = 1, 2...,M) one for each of M possible classes. For a given input feature vector x, each decision function is computed. The pattern is then assigned to the class corresponding to the decision function whose value is the greatest. Decision functions can have many forms, the simplest perhaps being linear decision function of the form.

$$d(i,x) = w\ x$$

where w is a vector of weighting coefficients. Such a decision function is simply a weighted sum of the features. Such decision functions can give correct classifications if the feature vectors for each class lie in nonoverlapping simply connected regions. If this is not the case, it may be necessary to use nonlinear decision functions (e.g. quadratic functions). Unfortunately, in most cases of practical interest, we will not be able to find a set of decision functions which will correctly classify all possible patterns since the pattern overlap. In such cases a statistical approach may be useful. If a statistical point of view is adopted, then the decision functions are expressed in terms of probabilities. For example, if

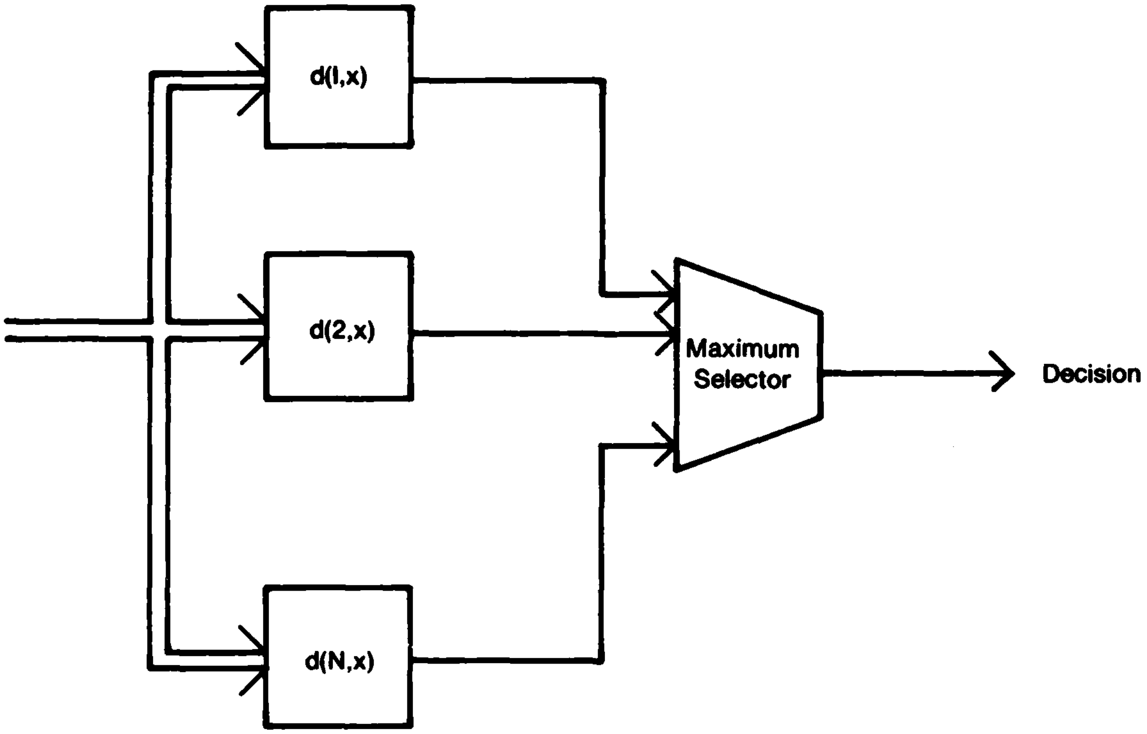
$$d(i,x) = \text{Prob } x \text{ belongs to class } i \ ! \ x$$

then it can be shown (References 9, 10) that the average probability of misclassification is minimized. Using Bayes therorem (References 9, 10), other forms of the decision functions can be found in terms of conditional probability density functions and a priority probabilities of the classes.

---

9 Tou, J. T. and R. C. Gonzalez, *Pattern Recognition Principles*, Addison-Wesley Pub. Co., Reading, MA, 1974

10 Duda, R. O. and R. E. Hart, *Pattern Classification and Scene Analysis*, Wiley Interscience, New York, 1973.



FD 228306

Figure 67. General Form for Classification Stage

In general the design of a pattern classifier consists of choosing the basic form of the decision functions, followed by a "learning" phase in which variable parameters of the decision functions area are adjusted so that a set of labelled "training" samples is correctly classified with minimum error. It is then assumed that the classifier can be applied to new samples with comparable success. The question naturally arises as to the number of samples required for training the classifier. Since collecting training data is often very expensive, the minimum number of training samples required for training is of great interest. Unfortunately it is not possible to give a general answer to this question since it clearly depends on the amount of variability of the features. However, a rule of thumb appropriate for linear decision functions is that we need a number of samples of each class equal to at least twice the number of features in order to be assured of reasonable training of the classifier (References 9, 11).

The final step in the design of a pattern classification system is the evaluation of performance. This is an area where there is little theoretical guidance and much opportunity to obtain confusing or misleading results.

Generally, the system is evaluated by testing it on a set of samples that are distinct from the original training set. The results of such tests can be used to estimate error rates for the system.

---

11 Cover, T. M., "Geometrical and Statistical Properties of Linear Irregularities with Applications to Pattern Recognition," IEE Trans. Electronic Computers, Vol. EC-14, pp. 326-334, 1965.

It is clear from the previous discussion that a pattern classification system involves a set of interacting component systems and deficiencies in the performance of any stage can severely degrade overall performance. The design of such systems clearly involves the following sub-problems:

1. Pattern locator design
2. Sensor design
3. Digitizer/quantizer design
4. Feature extractor design
5. Feature selection
6. Classifier design
7. Classifier learning
8. Evaluation system performance.

All of these aspects must be given careful attention in the design of any automatic classification system.

2.3.8.2 Automatic Crack Detection

The preceding discussion attempts to provide perspective on the important aspects of automatic classification systems. In what follows we shall discuss the design problems in the context of automatic crack detection using eddy current probes.

2.3.8.2.1 Object Location

The problem of object location seems relatively straightforward if attention is directed toward bolthole cracks. Systems for scanning angularly and axially are available (Ref 12).

2.3.8.2.2 Sensor

Sensor design is extremely important since the resolution and a sensitivity of the eddy current probe will ultimately determine the ability to reliably detect and determine the size of cracks. Sensors should be designed with cognizance of the features to be extracted from the sensor signals. It does not necessarily follow that a probe which is optimized for human observers will give best performance in an automatic system. In any case the physics of the eddy current phenomenon should be understood so as to obtain theroretical models for the effect of cracks on the probe response. Such physical models may lead to a natural parameterization of the response which in turn could serve as a basis for definition of features to be used in the classification process.

---

12 Shankar, R., S. N. Vernon, and A. N. Mucciardi, "Quantitative Eddy Current NDE/Bolthole Inspection," Second Iterim Report, Adaptronics Inc., January 1980.

2.3.8.2.3 Digitization

With the present state of microprocessor and minicomputer technology, it seems abundantly clear that the probe response signals should be digitized immediately with no analog signal processing save anti-aliasing lowpass filtering prior to sampling. The required sampling rate depends straight-forwardly upon the scanning speed, and it is well known that the sampling rate should be at least twice the highest frequency of the signal. Even if the signal is determined to be bandlimited, a low pass filter should be used to eliminate high frequency noise prior to sampling. In determining the necessary quantization accuracy, there are two issues: (1) What is the required accuracy of representation? (2) What is the dynamic range of the signal? These factors interact since if signal amplitude decreases while leaving quantization step size constant, the percentage error increases. It is quite likely that a 12-bit A/D converter would provide adequate accuracy over a suitable dynamic range. Such A/D converters are readily available at very modest costs for sampling rates of interest in this application.

2.3.8.2.4 Feature Extraction and Selection

If the eddy current probe scans axially and angularly in a bolthole, then distance is represented by the time dimension of the resulting waveforms. The waveforms will be relatively constant in regions of homogeneous properties with transition regions corresponding to movement from air to metal. As the probe moves past a crack or other anomaly in the metal, a periodic train of pulses will be generated. The amplitude, shape, and number of these pulses will depend upon the size of the crack. A specific advantage of digitizing early in the information collection processes is that digital information is less corruptible than analog information by traditional noise processes to be expected in shop environment. With the probe signals in digital form, there are a multitude of digital signal processing techniques such as digital filtering, discrete Fourier analysis, and linear predictive analysis that can be applied to enhance the data and to extract a set of parameters or features from the signals (Reference 8). It should be emphasized that such techniques should not be applied blindly without guidance from physical models, and we should not rely too heavily on signal processing techniques to recover information lost in the transduction process. For example, deconvolution is perhaps useful, but it cannot completely compensate for physical limitations imposed by probe design.

Even if features are initially defined on the basis of a physical model, it is quite likely that some of the features will not be effective in classification either because they convey little information or are highly correlated with other features. Techniques exist for selecting features or reducing the dimensionality of patterns without severely reducing their information content (Reference 9).

2.3.8.2.5 *Classifier Design and Training*

The eddy current probe signals contain information about both the presence of and the size of cracks in metal. If it is only necessary to detect the presence of a crack, a simple classifier may suffice. For example, a type of correlation or template matching scheme could be used to detect pulses corresponding to cracks. If the size of the crack is to be determined, then the entire pattern of pulses must be analyzed and the size inferred from the number and size of the train of pulses. One approach is to record many waveforms from boltholes containing cracks, extract features, and develop decision functions from these examples. Another approach would be to develop a detailed physical model for the production of the eddy current waveforms and to try to work backwards from the waveform to a set of physical parameters which would define the crack shape. The former approach is the classic pattern recognition approach, and it requires the measurement of many boltholes with cracks in order to "learn" the parameters of a classifier. The latter approach might be preferred if a detailed physical model were possible. Practically speaking, a combination of these approaches is probably necessary, with the physical model providing insight into the type of features to use and the amount of variability to be expected in these features.

In any case, it is absolutely essential to obtain a large "library" of turbine disks with boltholes containing cracks of known size and location. This "library" should be as large as possible and it should contain a representative set of examples since it will be necessary for both training and evaluation of a classifier system.

2.3.8.3 Comments on the Adaptive Learning Network (ALN) Approach

The use of adaptive learning network classifiers in NDE processes is documented in Reference 12. The approach followed is essentially that described above. This application uses hardware implementation of a general trainable pattern classifier algorithm which takes a set of features as input and produces a decision as output. This system is called an "adaptive learning network" (ALN). Although the details of this algorithm do not seem to be readily available in any literature or reports, it seems likely that the algorithm consists of an iterative scheme for adjusting coefficients of a nonlinear (probably quadratic) decision function. The parameters can be adjusted so that certain features have little or no effect on the decision while others may be dominant. Thus, the feature selection process is in a sense built into the training classifier. It is tempting, therefore, to define a large set of conveniently measured features and then rely upon the training algorithm to discard the useless features. As pointed out above, it is preferable to pay closer attention to physical models if useful models are available. Nevertheless, once the coefficients of the decision making matrix are defined, the classifier operates as a deterministic, rather than a statistical estimator, since no information is provided about the validity of the estimate.

In general, the ALN approach is sound if applied in a reasonably noise-free, well-specified environment. The following points should be made: (1) Adaptronics (Reference 12) wishes to sell systems based upon a generic pattern recognizer. The approach is therefore, defined by what their machine can do. The price paid for standardization is the loss of flexibility to tailor an approach to the specific problem of crack detection. Other, well-documented classification structures are available at the United Technologies Research Center (UTRC) including the RESID algorithm, which is based upon the same theory as ALN. These structures have the flexibility to tailor the classifier algorithm to the specific problem. (2) More attention should be paid to physical models in defining and extracting features. This is the key to successful applications of advanced signal processing and pattern recognition to NDE methods. (3) The amount of data available for training and testing of the system is small. This is not surprising in view of the difficulty involved in obtaining detailed measurements of cracks. Expansion of the data base should be of highest priority in future work on automatic crack detection system. The RESID algorithm has a key advantage here of requiring much less training data than other classifiers (Reference 13).

Other, well-founded statistical approaches such as the leave-one-out training method also can be used to minimize data requirements. The UTRC has assembled, over the past several years, a comprehensive set of software tools for digital signal processing and pattern recognition (References 15, 16, 17). The IEEE Signal Processing Library (Reference 14) is acknowledged as being the state of the art within the community. Likewise, the ARTHUR81 pattern recognition package (Reference 16) is widely known and was used in the eddy current work discussed above. In addition, Ivakhenenko's polynomial classifier methodology has been implemented in UTRC's RESID algorithm (similar to the Adaptive Learning Network (Reference 17)).

2.3.8.4 Summary

Automatic crack detection is technically feasible and researchers have made good headway on the problem. Future work should focus on all phases of the design problem from the sensor through the classifier. It is essential to develop a large set of carefully documented cracks for development and evaluation of automatic classifier systems. The work of Adaptronics, Inc. and UTRC demonstrates that it may be possible to automatically and reliably detect cracks. However, much remains to be done in investigating the sources of error and improving and evaluating performance before a viable system is available.

2.3.9 Mechanical Scanning

This section provides an overview of the scanning equipment specification and additional information on the availability of equipment that can be used to meet the specification. A discussion of special problems that must be addressed to meet the specification is included. Details of the specification for mechanical scanning equipment are presented in Appendix F.

---

[13] Swicke, P. E., "Ship Classification Using Recursive Structure Identification and the Mellin Transform," UTRC, Report R80-192109, January 1981.

[14] IEEE, *Programs for Digital Signal Processing*, John Wiley and Sons, New York, 1979.

[15] Kowalski, B. R., "ARTHUR81 Users Manual," Distributed by Infometrix, Inc., Seattle, WA, January 1981.

[16] Zwicki, P. E., "Interactive Signal Processing Package Users Manual," UTRC Report UTRC81 14, Revised May 1981

[17] Shankar, R., et al., "Feasibility of Using Adaptive Learning Networks for Eddy Current Signal Analysis," NP 723, Electric Power Research Institute, Palo Alto, CA.

2.3.9.1 Equipment Requirements

The program approach was to review the preliminary inspection requirements established during Retirement for Cause Concept Definition to identify scanning motion needs, to visit Air Force Logistics Centers to identify the characteristics of equipment that can function effectively in an overhaul environment, and to transform these needs into requirements that could be described in terms of a specification.

2.3.9.1.1 Motion Needs

Inspection requirements were developed by evaluating the shape and orientation of all areas of F100 parts which require NDE for RFC. Each part was reviewed to determine the kinds of generic motions needed to inspect them. Figures 68, 69, and 70 are typical work sheets used in this process. These figures specifically identify critical areas and the kind of defect that must be detected for each component. These diagrams have been summarized in Table 2 and Figures 26 through 33 which group components by common types of geometries and by the generic kinds of motion required to inspect each type of critical area. These areas and geometries are typical of areas known to be critical on other military power plants although specific dimensions may differ. F100 inspection geometries in themselves represent a generic set of geometries so that any scanning system specified to inspect F100 components will have the capability to scan any gas turbine disk or seal.

2.3.9.1.2 Air Force Logistics Center Needs

The eventual application RFC NDE equipment will be in an ALC and therefore this environment had to be understood before specific requirements were established. Interview meetings were conducted at Tinker and Kelly Air Force Bases where most Air Force engine overhaul work is done. These meetings established the methods currently used to inspect components and the difficulties that had been encountered in the past when new equipment was introduced and placed into service. Program plans for new and improved equipment and approaches were also identified.

Both logistic centers strongly emphasized that they were production operations and that throughput and manpower requirements were the main concern. They indicated that most personnel could be classified as operators. They were reluctant to introduce any new equipment that would require higher skilled personnel such as computer operators. Although it was desirable for all equipment to be capable of operating in the production environment, some specialized inspection equipment was now contained in special rooms with independent environmental control.

Equipment repair and maintenance are a concern since a large number of expert personnel are not available and service contracts are hard to establish. In general there was a great desire to have equipment that could easily be reconfigured to accomplish new inspections; each logistic center frequently established new inspections in response to newly identified problems.

These needs are applicable to all components of the NDE facility.

2.3.9.1.3 Performance Requirements

Specific equipment performance requirements were developed from the identified motion and logistic center needs.

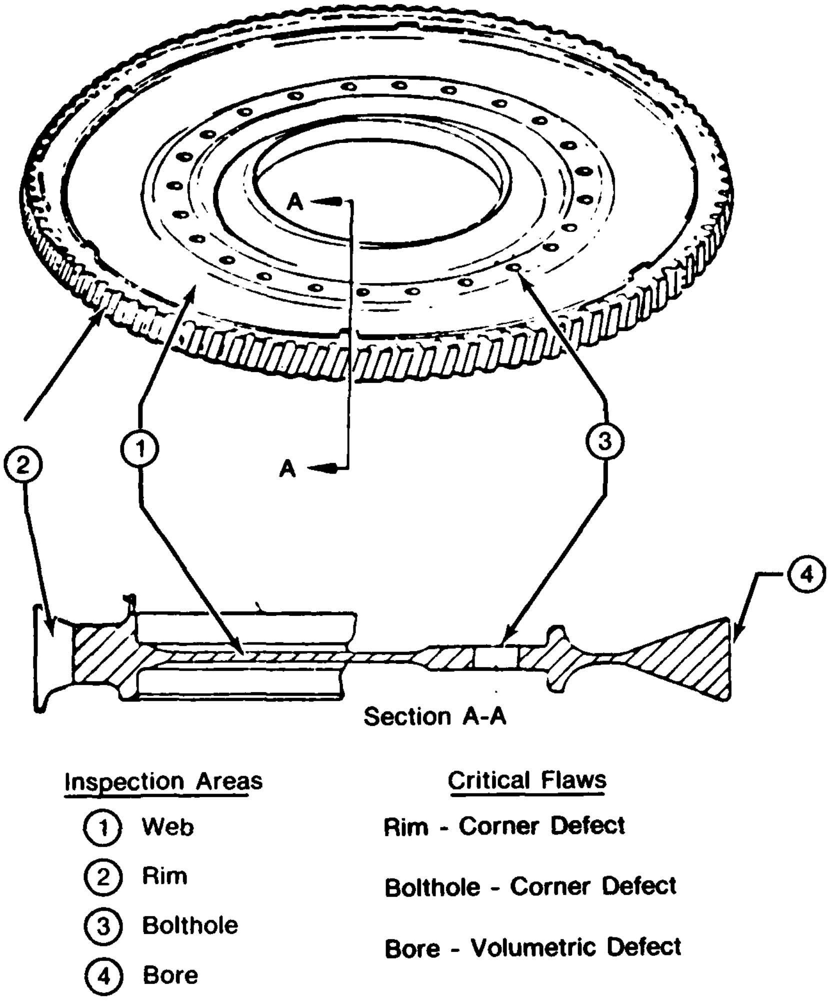
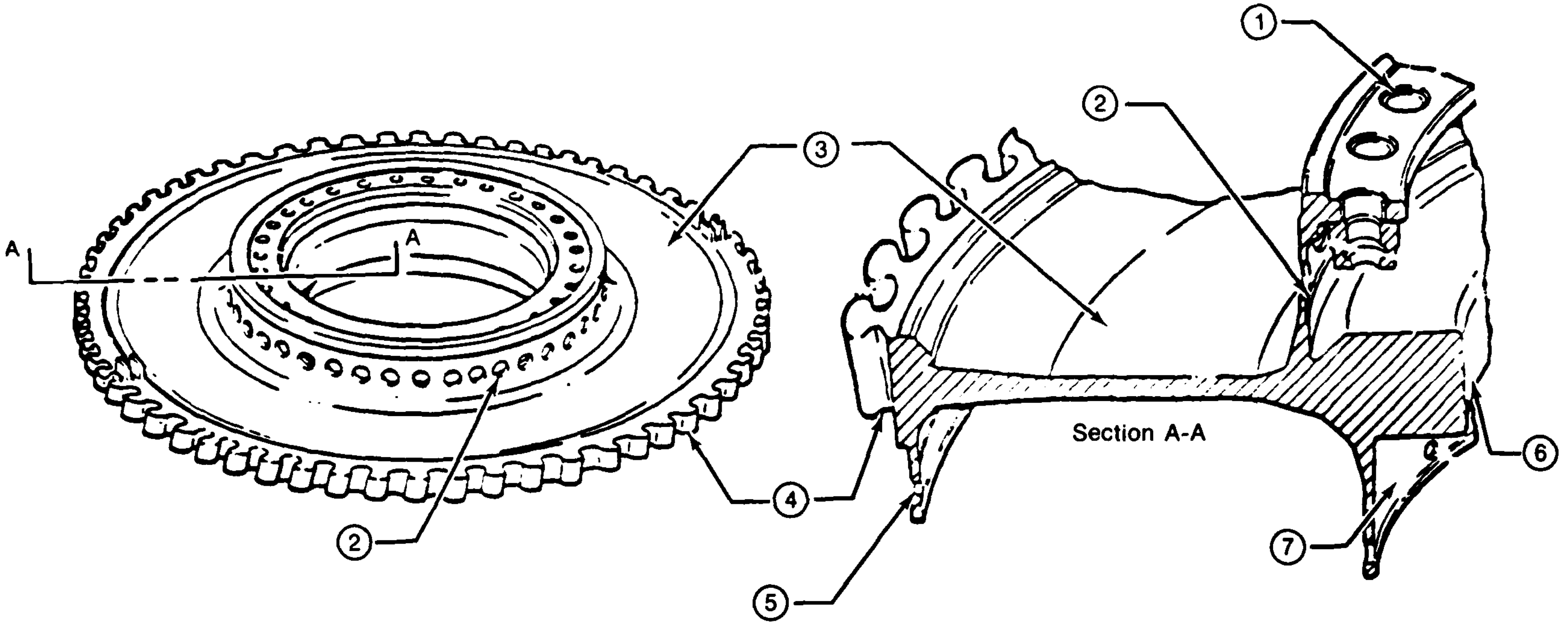


Figure 68. Work Sheet Summarizing Inspection Required for Eighth Stage Compressor Disk. This Figure and Others Similar Were Used to Establish Generic Inspection Motions



<u>Inspection Areas</u>

① Bolthole

② Cooling Hole

③ Web

④ Rim Slot

⑤ Knife Edge Seal Arm Hole

⑥ Bore

⑦ Hub

<u>Critical Flaws</u>

Web - Volumetric Defect

Knife Edge Seal Arm Hole -
Corner Defect

Bore - Volumetric Defect

FD 228310

Figure 69. Work Sheet Summarizing Inspections Required for Third Stage Turbine Disk. This Component is Typical of a Turbine Disk from an Advanced Engine and It Contains Geometry in Addition to That Found on Compressor Disks

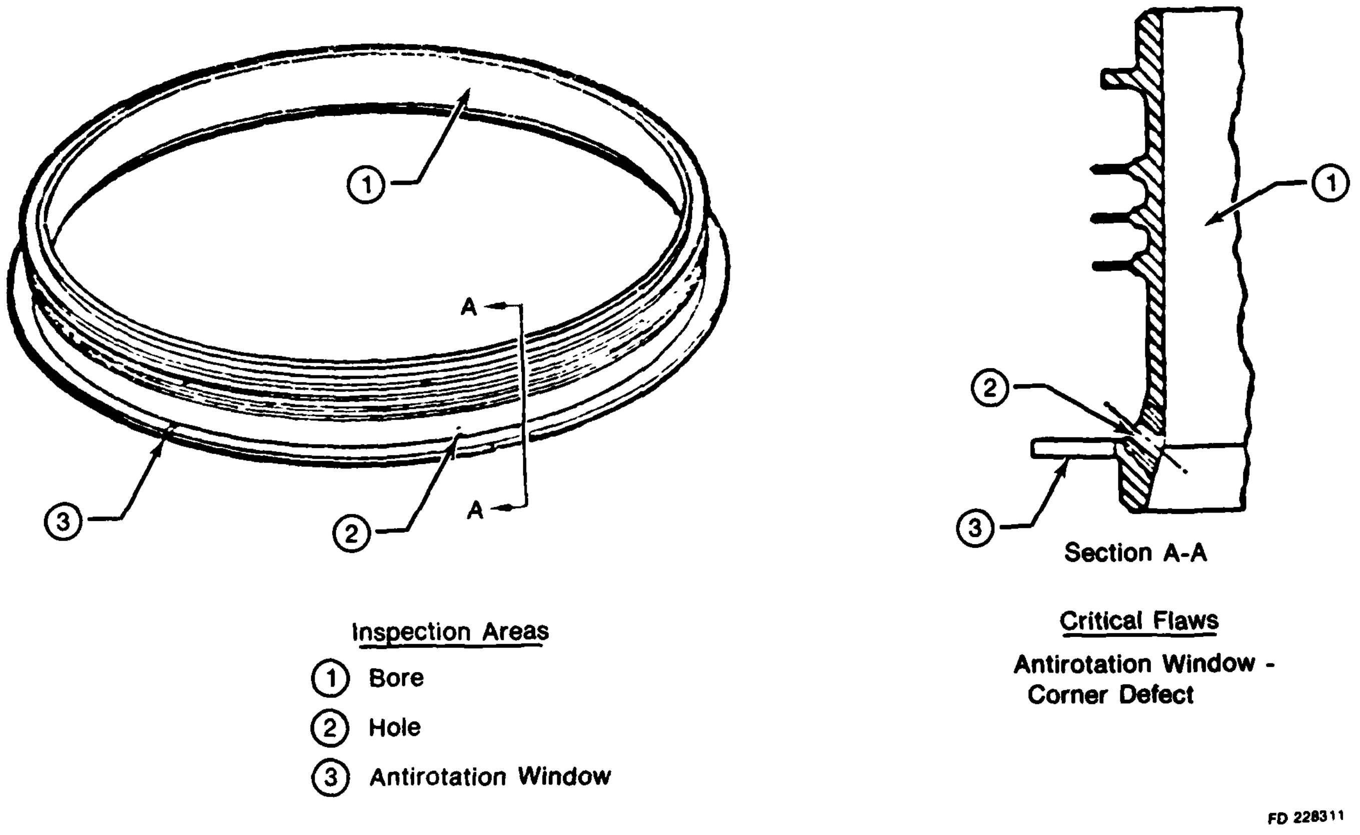


Figure 70. *Work Sheet for the Tenth to Eleventh Stage High Pressure Compressor Spacer. This Part is Typical of Spacer/Seals Used in Compressors and Turbines and Contains Some Additional Geometries*

The ability to maintain some inspection system throughput in the event of a major element failure is a fundamental ALC need that was identified. This need has been articulated in a requirement for sufficient equipment redundancy to maintain 50 percent throughput in the event of a single point failure. This redundancy requirement can be met by simple duplication of equipment or by using common equipment elements to the greatest extent possible.

Equipment maintenance was identified as a key concern of ALC personnel. The RFC inspection system will be a complex and highly automated facility so the typical system operator will not necessarily have the skill to know whether or not equipment is operating within specification. A self diagnostic capability is a system capability that can address this need. It will be required that each system element have a means of indicating to system operating computers whether or not it is functioning properly. A second requirement which parallels this is the need for a modular design where modules are small enough to support a simple replacement maintenance approach. The self diagnostic capability must exist at the module level if this maintenance approach is to be truly effective.

The RFC inspection system will be operational for many years, and therefore, it must have a flexible design to accommodate changing inspection requirements and new inspection equipment and methods. This flexibility can be established if equipment and software use modular design and use a standard communication protocol, and if adaptive scanning control is used to implement inspection motions. The use of standard communication systems such as IEEE 488A will greatly simplify the task of upgrading and altering equipment to meet changing conditions because each element is considered independent with all information transfer between the elements handled in a prescribed way.

Adaptive scanning control has been demonstrated as an effective means to reduce inspection system development and operation costs. New inspection procedures can be added without the used of specially trained personnel if adaptive control is used. This method of scanning control will use spacing information, derived from inspection instrumentation, to fine tune scanning motions.

An essential requirement of RFC is that inspection data must be identified specifically with location and part serial numbers. The inspection system in essence is the accounting capability that changes component status from suitable for service to unsuitable. These decisions may be based on comparison with results of earlier inspections stored on higher level processor systems. To assure that inspection data is properly identified by part and location, serial numbers and reference locations must be determined automatically, because manual entry is prone to error.

In summary, the specific mechanical scanner design requirements identified for meeting both inspection and Air Logistics Command operational needs are: (1) the equipment must have the capacity to meet production quantity throughput, (2) it must have self-diagnostic capability so that equipment malfunction can be identified, and (3) it must have an accounting and part identification scheme that will allow only inspected and accepted components to reenter service. Equipment elements must be modular to permit quick replacement of all functioning elements and the equipment must have the inherent capability to inspect all critical locations of F100 components.

2.3.9.2 Specification Overview

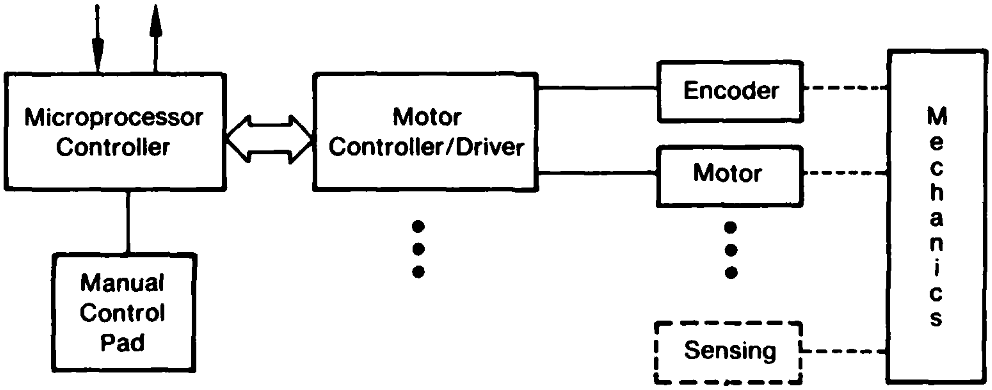
Specifications for scanning equipment were prepared on the bases of the established needs and requirements. Each specification was preapared as a self-contained document so that it could be more easily integrated into the final system specification that includes elements prepared by other team members.

2.3.9.2.1 Scanning Equipment

A scanning system schematic is provided in Figure 71. The major elements of the system are: mechanical motions which move inspection probes; encoders which indicate the position of an inspection motion; motors which drive the inspection motion and a motor controller/driver which controls inspection motion between two points. The scanning system microprocessor receives direction from an assumed inspection module computer, coordinates these overall motion requirements and implements them on the scanning system mechanics. A control pad has been provided to establish manual control. A sensing capability has been assumed for determining the relative relationship between inspection probes and inspection surfaces; this input is for an adaptive scanning algorithm.

Two classes of motion, each associated with ultrasonic and eddy current inspection, respectively, were identified. Figures 72 and 73 summarize motions for ultrasonic and eddy current inspection, respectively. In general, eddy current inspection requires greater precision and accuracy than ultrasonic inspection. Therefore, the mechanical specification for each is listed separately, although it is conceivable that the same equipment could be used for both. It is not required that the same mechanics be capable of performing both inspections, since it is felt that it would be an undue burden with excessive cost. In addition, mechanical equipment tends to be very reliable and the increased redundancy that may be obtained with truly common mechanics cannot be justified by this cost increase. The mechanical specification can be met with modifications to existing equipment.

The specification requires that the scanning system will operate on the basis of simple commands such as move, step, that can be addressed in a high-level language. In addition, the scan system control pad can be used to adaptively develop inspection scan plans by simply walking the inspection system through the required motions because of the requirement for direct position feedback information. Most of the software that would implement this adaptive motion would be developed on the inspection module computer; however, the specification requires that the microprocessor inspection scanning controller must have the capability to directly communicate motion position and interpret simple commands.



FD 227309

Figure 71. Scanning System Schematic Diagram. The Control System Elements Are Interchangeable Between Ultrasonic and Eddy Current Inspection Modules

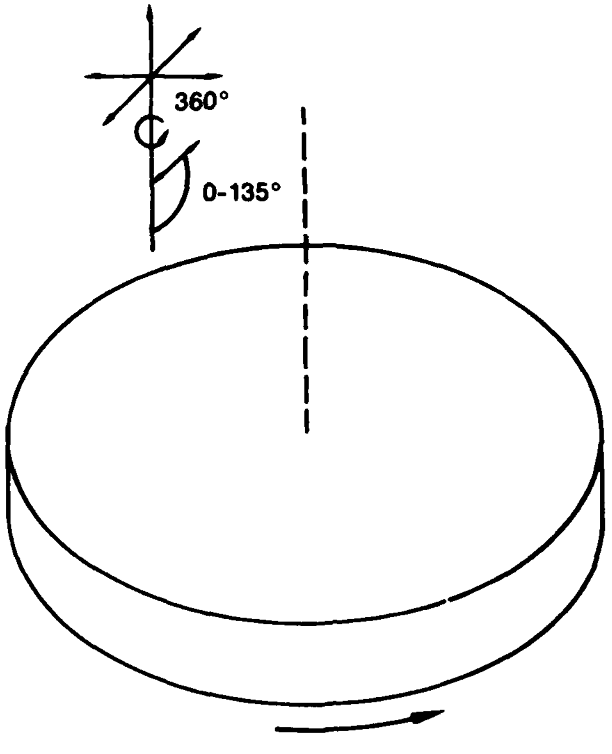


Figure 72. Schematic Embodiment of Ultrasonic Scanning Motions. The Exact Combination Motions Shown Are Not Required. Only Resultant of These Motions Is Required. Other Combinations May Be Appropriate

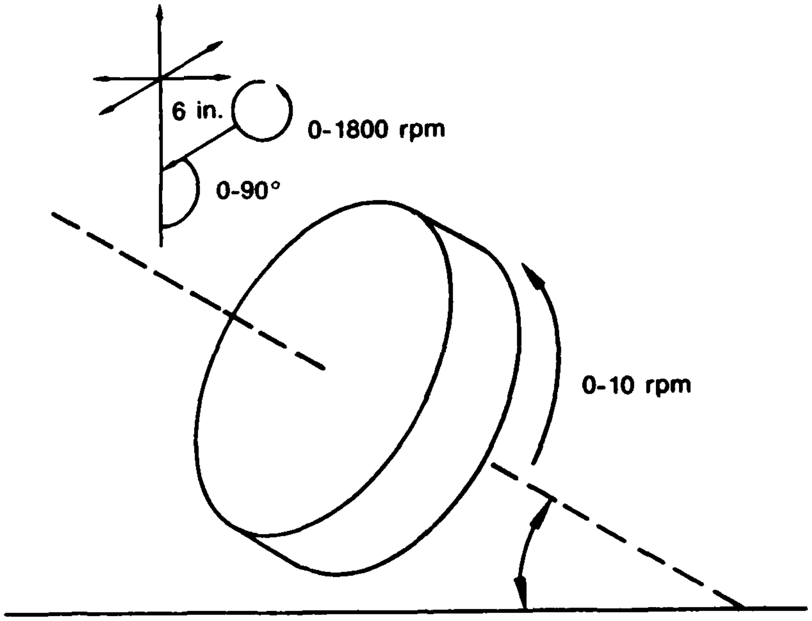


Figure 73. Schematic Embodiment of Eddy Current Scanning Motions. The Exact Combinations Shown Are Not Required. Only Their Resultant Is Required. Other Combinations May Be Appropriate in Meeting Specifications. All Motions Are Not Necessary to Inspect All Locations and Therefore Need Not be Available at All Times

The requirement that the inspection system function in a manufacturing environment with low skill operators has been addressed by establishing requirements for self-diagnostic capability which can evaluate 80% of the electrical components used in the control system. The self-diagnostic mode should be either initiated manually, on power-up, or on direct computer command. An additional requirement has been established to check the performance of the mechanical equipment. It is anticipated that this requirement would be met by assessing the repeatability of the mechanical equipment approaching and positioning itself over certain reference points as it is very difficult to establish indirect methods for indicating wear or changes in mechanical backlash.

The equipment commonality has been assumed as the primary means of introducing redundancy into the mechanical scanning system. A specific requirement is that the control system, including the processor, the motors, the encoders, and the control pads used for all scanning systems be of the same type. The only difference between the eddy current and ultrasonic systems will be the specific mechanical motions established to implement those individual inspection requirements. This commonality in control equipment will significantly reduce the maintenance and spare parts costs as well as provide flexibility in using control modules in any inspection station.

The specification also requires a probe changing capability so that the varied inspection probes needed for the many different part geometries can be used in a high throughput environment. This probe changing capability requirement has been described in general terms since it may be prudent in some cases to not only change the probe but also to change a larger element or scanning head which also includes specific motions. An area where this approach might be useful is the scanning equipment needed to establish bolthole inspections; the rotary motions and axial indexing motions might be included on the scanning head rather than having this capability be a general requirement of the overall scanning equipment. This allows special motions to be implemented in an easy and direct way. The probe changing requirement also indicates that there is a general concern about how electrical and mechanical interfaces associated with probes are addressed. Inspection probes and equipment operate at high frequencies and if the probes are not connected with care, the efficiency with which inspection signals can be transmitted may be greatly reduced. Therefore, special attention must be given to all electrical and mechanical connections in the probe changing equipment.

The specification also addresses the requirement or the need to inspect components from two sides. It is required that some components must be directly accessible from both sides or be capable of being turned over. In addition, the specification also requires automatically operable fixturing equipment. This equipment is also required to have a general capability to fixture several parts. Fixturing systems have been designed with multi-stepped chucks where the diameters of several parts can be easily chucked if they are inserted at the proper elevation. Although there is some desire to have a self-centering capability it has not been made a requirement because the benefit may not offset the cost. Self centering would possibly permit contactless eddy current probes for the inspection of cylindrically symmetric surfaces, but self centering will not give additional assistance in eddy current inspection of special geometries such as holes and blade slots because motion requirements will be adjusted using an adaptive control feature. In general, every attempt has been made to develop mechanical requirements that do not require overly strict accuracy in the motions required to perform the inspection. Significant relief in mechanical tolerance has been achieved by using the concept of adaptive control. The inspection system obtains information on the closeness of the inspection probe and inspection surface from inspection instrumentation. In the eddy current area, this information will be provided through a measurement of the liftoff, and in the ultrasonic area this distance is the time of sound travel between the front face and the probe.

Adaptive control also addresses the concern of meeting variable tolerances in components; this would be difficult to do using completely predetermined scan plans. Also, it provides the opportunity to use contactless inspection probes. The advantage with these kinds of probes is that inspection wear and life-limiting effects can be reduced and inspection probes will last considerably longer than if they must operate in a contact mode. It is still anticipated that contact probes will be used for eddy current inspection of cylindrically symmetric surfaces. It is extremely difficult to provide the high-speed reactivity needed to adaptively contour-follow cylindrically symmetric surfaces at reasonable scanning rates unless parts are well centered. The option to contour-follow is available, however, if one is willing to reduce the scanning speed on the order of 1 in. per second. An additional benefit of collecting adaptive information is that it can also be used to establish uniform inspection sensitivity by adjusting inspection gain to reflect standoff distance change. The overall effort in developing a specification has been to spread the burden of requirements which affect inspection reliability and sensitivity as equally as possible between inspection system elements. This distribution of burden will also provide for a more flexible and reasonable capability. In addition, in the case of the mechanical system, it will provide a reasonable range of choice in the equipment that can be used to meet the specifications.

2.3.9.3 Additional Information — Available Equipment

Available equipment was reviewed based on a schematic set of motions that is consistent with the scanning system specification. These schematic motions are shown in Figures 72 and 73 . These motions indicate all the capability that would be needed to meet the specification. These can be met using several manipulator approaches: dimension measuring machines, robotic arms, and machine tools.

2.3.9.3.1 Dimension Measuring Machines

Dimension measuring machines usually consist of a granite slab support base and an air-bearing supported gantry that supports vertical arms. Normal operation is to use a probe which, when it contacts the surface of a component, stops gantry motion. Contact switches sensitive to various directions have been developed. Dimension measuring machines definitely have the accuracy of motion needed to meet the inspection system requirements. Some of these machines have been established with rotary turntables for part rotation. An area where there has not been significant development, however, is the ability to angularly articulate the inspection head. To use a dimension measuring system for RFC inspection, specific elements would have to be developed in order to provide this capability. These articulation systems would require careful design, otherwise, the overall tolerance benefits of the gantry dimension measuring machine would be reduced significantly.

Dimension measuring machines may not be suitable for ultrasonic inspection because this equipment has not yet been designed to operate under water. In addition, it is not clear whether or not the additional mechanical loads associated with moving water would provide distortion, and subsequently, reduce the positional accuracy of the mechanical arm. Most of these systems also do not have automatic probe capability. Many of them, however, have been established and interfaced with control computers and manual control pads.

2.3.9.3.2 Robotic Arms

The increased availability of robotic arms at reduced cost makes these machines attractive as mechanisms for moving inspection probes. It is possible to contemplate an inspection system that embodies several robotic arms positioned around a turntable to implement more than one inspection at a time. Robotic arms have been shown to be capable of changing tools and probes; however, in most cases, this is a simple grasping that may not be adequate for establishing the electrical contacts needed for the RFC inspection system. A few of these arms have been demonstrated but because they use hard stops to indicate position resolution on the order of 1 mil they may not meet system flexibility requirements. In general, the accuracy capability for most machines is limited to ±30 mils with resolutions near to ±10 mils. A review of the accuracy limit has identified that this limitation, for the most part, is due to an encoder resolution limit and is not a physical limitation of controlability over the machine. Many of these machines are not particularly stiff and it is unclear at this time whether or not they could meet the settling time requirements. They do have the capability of implementing all the angular articulations that would be required for both ultrasonic and eddy current inspection. None of these machines have been developed with the concept of placing any element under water and it appears that most machines would required some redesign in the other extremity of the arm if it is to be operated under water. The interfacing of these machines to computer control systems has been done basically in simple direct control methods where motion sequences are downloaded from other sources. This control system would have to be modified and reestablished to provide the direct feedback information and the high-speed information flow required by the specification.

2.3.9.3.3 Machine Tool System

Machine tool systems have demonstrated the capabilities needed to move the inspection probes. They have a long history of reliable functioning in a production environment. They are definitely rigid and it is clear that they can meet both the settling time requirements and also the scanning time requirements. Many machine tools now come with automatic probe changing capabilities. The question of mechanical and electrical coupling to tools has been addressed, at least in some cases, since several machine tool systems are now on the market which, in addition to tool holding capabilities, have the ability to accept a dimension determining head. Although the electrical requirements for installing these kinds of heads are not as severe as that for the inspection probes, at least this problem has been considered. Machine tools are also like the robotic arm in that high-speed data links are usually not used; they operate by receiving downloaded scan plans or motion plans from some higher level of intelligence. For this feature, the scanning system, control motor drivers, etc. would have to be reestablished in order to make use of these kinds of machines.

Overall, the cost to implement each of these three different scanning approaches appears to be comparable. Very large scale complex machine tools and dimension measuring machines sell for on the order of $250,000. Smaller equipment is available for 1/5 to 1/4 the cost. These smaller machines may be adequate in meeting scanning requirements for some locations but they do not have the size nor the flexibility to meet the requirements of all components. Tables 8, 9, 10 list the comparative advantages and disadvantages of the three kinds of available scanning equipment.

TABLE 8. SUMMARY OF XYZ COORDINATE MEASURING FEATURES FOR RFC SCANNING

Advantages	*Disadvantages*
● High Resolution, High Accuracy	● Will Not Operate in Water
● Moderate Positioning Speed	● High Ceiling Required Clearance for z Axis Travel
● Easily Adaptable to Computer Control	● Angular and Linear Motions Must Be Built Into Probe Assembly
● Ease of Access for Loading/Unloading Parts	● No Probe Changing Capability
● Can Also Be Used as a Coordinate Measuring Machine to Perform Dimensional Checks on Parts	

TABLE 9. SUMMARY OF ROBOTIC ARM FEATURES FOR RFC SCANNING

Advantages	*Disadvantages*
● High Throughput, Several Different Features Can Be Inspected Simultaneously	● Moderate to Low Resolution/Accuracy
● More Articulation Can Be Built Into Robot Arm, Less Required of Probe Assembly	● Developing Technology
● Moderate Positioning Speed	● Does Not Operate Underwater
● Relatively Easy to Adapt to Computer Control	
● Efficient Use of Floor Space	

TABLE 10. SUMMARY OF MACHINE TOOL FEATURES FOR RFC SCANNING

Advantages	*Disadvantages*
● Rigidity, Stability	● Limited Range of Angular Motion
● Built in Auto Tool Changer	● Large Power Consumption
● Demonstrated Performance	● Moderately High Noise Level
● Moderate Resolution and Accuracy	● Many Machine Features Not Usable for Inspection (e.g., Spindle Rotation) Which Add to Basic Cost of Machine
● Moderate Positioning Speed	

At this time it is difficult to select between the three commercially available mechancial systems. None of these systems have control equipment with self diagnostic capability. The motor controller/driver system currently used would require a redesign in order to meet overall specification requirements. This means that any negative view of robotic and machine tool equipment because of a need to reconfigure control systems should not be taken too seriously. The selection of a mechanical scanner should be made primarily on the basis of cost, flexibility, and a proven operational capability. Machine tools are attractive in that their ruggedness and dependability have been established over many years. It is unclear that the development program to provide articulated heads in the dimension measuring machine would be of a low enough cost and low enough risk to warrant their undertaking. The robotic systems are extremely attractive because of their inherent low cost and flexibility. It is not clear, however, whether or not they can attain or provide the rigidity needed that the other systems can. Since newer robotic designs are appearing on the market regularly, it would be reasonably unwise to make a specific recommendation at this time, considering that actual implementation would not occur until the 1984 and 1985 timeframe.

2.3.10 Inspection Sequence

This section addresses the order in which the RFC Inspection System will perform inspection and how that fits with existing overhaul procedures.

The routing will be generally governed by surface conditions of parts. Those inspection procedures requiring the cleanest surface conditions will be done first. In addition, the existing overhaul inspection sequence will not be altered, preventing interface with non-RFC inspection procedures. With these criteria in mind the sequence will be as presented in Table 11.

TABLE 11. RFC INSPECTION SEQUENCE

Existing Overhaul Sequence

- Cleaning and Surface Preparation
- Fluorescent Penetrant Inspection — Modified With RFC Improvements
- Overhaul Dimensional Inspection

RFC Inspection

- RFC Eddy Current Inspection
- RFC Ultrasonic Inspection
- Ready for Further Disposition

2.3.11 Inspection Performance

This section of the report addresses inspection data analysis and performance requirements for the RFC Inspection System. Specifically, the following paragraphs will discuss: (1) identification of important inspection data, (2) definition of data collection and use requirements, (3) impact of redundant inspection on inspection reliability, and (4) establishment of a plan to evaluate inspection system performance.

2.3.11.1 Identifying Important Inspection Data

Although successful RFC can be based upon either a deterministic or probabilistic method, it is generally accepted that higher payoff and return on investment (ROI) will result from use of the probabilistic method.

Because statistical variations and uncertainties exist in some loading, inspection, and materials parameters, a probabilistic RFC anlaysis will be required to quantify the risk of implementing RFC, independent of whether that implementation is deterministic or probabilistic. Furthermore, a probabilistic RFC approach is more likely to produce a higher ROI because it accounts more accurately for those statistical variations and uncertainties which actually exist.

The life cycle cost estimates and corresponding ROI calculations produced in the concept definition phase of the RFC of F100 Rotor Components (AFWAL-TR-80-4118), are based upon the assumption of a perfect deterministic inspection, that is, an inspection which rejects all parts with flaws larger than some specified accept/reject size(s) and rejects no parts with defects smaller than that same size. Everyone agrees that real inspections are not perfectly reliable at any specified size. Consequently, it will be necessary to evaluate and define, for each inspection method, part detail, and inspection size(s), the inspection reliability for a range of crack sizes both larger and smaller than the accept/reject size(s). Specifically, the inspection reliability can be defined in various ways. One convenient way is to develop the probability that the inspection will reject a part, $P(R/a, s)$, given that a flaw size a actually exists and given that the inspection (accept/reject size) has been set at some specified levels. Figure 74 shows that when the real crack size $a < s$, any nonzero probability corresponds to a false call (Type II error) probability, whereas when $a > s$, the difference between unity and the actual inspection rejection probability is the false acceptance (Type I error) probability.

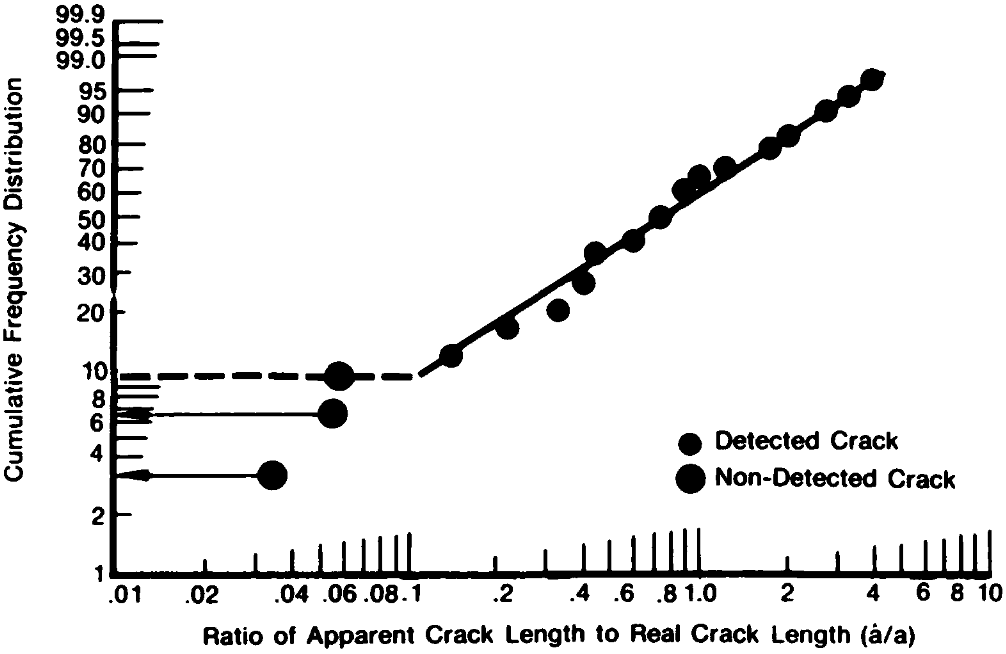


Figure 74. Cumulative Frequency Distribution of Apparent Crack Length to Real Crack Length for High Resolution Inspection. Real Crack Length Range: 0.100-0.200 in.

The inspection reliability (uncertainty) must be quantitatively evaluated for flaws developed under actual service conditions and depot inspection conditions. The inspection reliability under realistic conditions will be much lower than that measured under laboratory conditions. We are particularly concerned that this will be true for the very small flaw sizes that will be required to implement RFC on some of the F100 engine components already identified as candidates. Both the false detection and false acceptance probabilities must be maintained at reasonable levels for the crack sizes of concern.

RFC can still be successfully used even with significant or even large inspection uncertainty. However, as the inspection uncertainty at a specified inspection size increases, the safety factor on the inspection interval must also be increased to assure that those larger defects which will, in fact, slip through the inspection (false accept, Type I errors) do not lead to a castastrophic failure before a subsequent inspection where the cracks are larger and the inspection therefore more reliable, can detect the crack and enable safe removal of the part.

2.3.11.2 Inspection Data Collection and Use Requirements

In the operational RFC system, the inspection data may be used in several ways. First and foremost, each indication is evaluated by the RFC system to make a part accept/reject decision. The basis of each such decision or the accept/reject criteria is a probabilistic (fracture mechanics) engineering evaluation of the probability that the defect causing that indication could grow to cause failure during the interval between this and the next inspection. For this reason, the inspection data collected should be those parameters which define those defect characteristics which determine its impact on the remaining life of the component. For surface, crack-like indications, the crack depth (a), surface length (2c), location (r, θ, z), and orientation are important. Inspection signal characteristics which define any of these should be collected and stored. The precise range of concern for each signal characteristic will vary with location in the component, dependent on the specific stresses, cycles, temperatures, and materials properties.

Although the specific inspection parameter will vary with the specific technique and part geometry, the relevant signals from the most critical part location should be stored in near raw form. The cost of analog or digital storage is already low and is decreasing so rapidly that we believe it will be cost-effective to store all indications (perhaps up to some limit, like 100 for each region) which are clearly above the average background noise level, and it may even be useful to store some signals which are marginally in the background noise level since improved correlation or filtering techniques may become available. It is not envisioned that most of this raw data will ever be examined again; however, specific marginal, accept/reject situations may benefit from more detailed comparison of raw data with that of previous inspections of the same area.

In general it is recommended that raw data be immediately processed to a few key parmeters (e.g., a, 2c, θ, z) and that these parameters would both be used for RFC calculations and stored in readily accessible locations for other RFC analyses or for comparison with inspection results from future inspections.

A second way, in addition to the accept/reject decision, in which inspection results can also be used is to improve estimates of the stresses or number of cycles of loading. More specifically this can be accomplished by recording and analyzing the distribution of indication sizes below the accept/reject size(s). Using probabilistic fracture mechanics analyses, changes in the probability density of indications of different size can be used to estimate more precisely the duty history of that particular component as well as the entire part-population or some subset of the fleet. For these reasons, there is a benefit possible from obtaining reliable inspection data at sizes below the accept/reject size.

Because of the already small sizes of concern for many F100 components which are candidates for RFC, reliable inspections at smaller sizes may not be realistic. In any case, the inspection system *goal* should be to provide reliable inspection data below the accept/reject level with a *specification* that it provide reliable inspection at the accept/reject size and larger. Reliable does not mean 100% probability of detection but the final specification will probably require greater than 50% probability of rejection at the accept/reject size and at least 90% probability of rejection should be *required* (specified) at the size whose median crack propagation life is one inspection interval.

The precise specification of accept/reject sizes and inspection reliability should be established only after sensitivity analyses have been performed with the probabilistic RFC computer codes now available. In this context, the concept development phase estimates of inspection size requirements should be updated to account for the probabilistic variation in crack growth rate which results from mission variability (stress amplitude and number of stress cycles) and materials properties scatter, before a final inspection system specification is attempted. As a minimum, the unspecified conservation used in the fracture mechanics analysis to generate a vs N in the Structural Assessment Program results should be removed so that the crack size which will have a high probability of growing can be established. Even better, probabilistic RFC analyses can be performed with existing codes, and it is recommended that they be performed to provide a quantitative basis for the final inspection specifications of size and reliability.

It appears likely that the small size resolution requirements with high inspection reliability may not be realistically obtainable given the 1985 schedule requirements and resources allocated to this project. For this reason, specifications for higher inspection reliability at larger crack sizes should also be used in conjunction with the best effort reliability produced at smaller flaw sizes.

2.3.11.3 Impact of Redundant Inspections on Reliability

It is realistic to expect considerable inspection uncertainty at the small accept/reject flaw sizes even after the industry's best effort to develop the NDE system. There are many sources of inspection unrealiability (uncertainty), some of which are more strongly associated with the specific indication site while others result from inspection station variability, part cleaning variability, or dimensional variability.

Performing repeated (redundant) inspections can sometimes improve the overall inspection reliability substantially. For example, if all uncertainty resulted from statistical variations which were not strongly dependent on the defect site-to-site variations, then repeating an identical inspection *n* times would decrease the probability of acceptance (R) from P(R/a, s) to $[P/)R/a, s]^n$. For a > s, this suggest that *n* multiple inspections would reduce the probability of false acceptances (Type I errors). However, since the P(R/a, s) also increases when a < s, the number of *correct* acceptances would also decrease [to $P(R/a, s)^n$] due to multiple inspections. Furthermore, the use of multiple inspections will increase the inspection time and direct cost and the total costs both of direction inspection costs and by the additional part replacement cost due to false rejections.

There are many instances where a major contribution to the inspection uncertainty results from differences between flaw sites themselves. In these cases, repeating the inspection may have little or no impact on inspection reliability because the same site peculiarity which caused the first inspection to miss the flaws will have a high probability of causing subsequent inspections to miss the same flaws. It is therefore necessary to understand the major causes of inspection uncertainty for each specific inspection type and procedure applied to a specified location (See Table 12). If these are not well understood, then it will be necessary to actually perform redundant inspections and measure the actual changes produced by repeated nominally indentical inspections.

2.3.11.3.1 Impact of Multiple, Nominally Identical, Crack Initiation Sites

In many of the F100 components considered RFC candidates, there are many of the same features (e.g., a bolthole, or cooling hole, blade rim slot) on each disk. In this common and important case, the full inspection of one disk may produce results similar to multiple inspections of one region. Probabilistic simulations have been made of the effect of multiple, nominally identical crack initiation sites on each RFC component.

Four temporary modifications were made to the RFC software, developed by Failure Analysis Associates (FAA), in order to simulate the effect of multiple crack initiation sites. First, the three different structural details simulated by the available software were each used to simulate a nominally identical site of the same structural detail (e.g., three radial cooling holes); the software was modified to use the same stochastically generated "real" stress for each site. The input data for the radial cooling hole was then used for all three locations. The radial cooling hole was chosen because it was identified as the most critical location from previous analyses. Second, a high-scatter (SHAPE = 1.) Weibull cumulative probability distribution of the ratio of "perceived" crack length, $\hat{a}/a$, was used to simulate NDE inspection errors in place of the low-scatter (SHAPE = 5) Weibull distribution of $\hat{a}/a$, used in previous analyses. Third, the usage estimation (cycle counting error) was exaggerated in the study. These modifications were made as a cost saving measure to increase the simulated failure rates so that a small fleet size of 100 engines could be used to estimate use of experimental data for $\hat{a}/a$, which had previously been fit from our TF-33 (ARPA) RFC project using a piecewise Weibull distribution. Fourth, the effect of introducing a minimum inspection error, representing the finite probability of randomly missing a crack of any size, was included in the simulation.

TABLE 12. PARTIAL LIST OF CONTRIBUTIONS TO INSPECTION RELIABILITY

Defect Variables

- Defect
- Crack COD
- Crack Surface Condition (Oxide, Roughness)
- Crack Orientation and Location (r, θ, z, Surface, Subsurface)

Local Geometry/Transducer Variables

- Local Geometry (Radius, Roundness, Index Detail)
- Part Surface Condition (Roughness, Oxide, Flatness)
- Part Cleaning
- Probe Positioning Subsystem
  - — r
  - — θ
  - — z

Overall Geometry Variables

- Total System Positioning and Recording
  - Probe r, θ, z Average Positioning
  - Vibration — Mechanical Stability

Signal Errors

- Electrical Noise
- Mechanical
- *Signal Drift (Electrical Instability)*
- Calibration Error
- Recording and Storage Errors

The inspection error distribution used in the simulation is shown in Figure 74, reproduced from a previous FAA report on the ARPA project. The cut-off at 12.9 percent (dashed line) indicates that 12.9% of the cracks were not detected. The "Real Crack Length Range" of 0.100 to 0.200 inches, listed for the figure, is typical of, or somewhat larger than the crack lengths present at one inspection interval prior to failure as determined by previous simulations using the P&WA RFC software.

The results of the multiple initiation site simulation are shown in Figure 75 for one, two, and three nominally identical sites per disk using various safety factors and three different values of the inspection error cut-off percentile. An increase in the number of initiation sites per disk produces two competing effects. The increase in the number of crack initiation areas tends to increase the failure rates while the increased probability of finding a crack in a disk tends to decrease the failure rates. (Increasing replacement rates due to more Type II errors will also occur). The failure rates do not increase linearly with the number of cracking sites. The curves show an appreciably higher reliability than expected from single-site "prediction" as the number of identical initiation sites increased. For example, in simulations with two failure sites, a disk is often retired for a medium-sized crack at one site rather then for a larger crack (which is missed or badly underestimated) at the second site. The increase in the probability of detection seems to predominate at lower failure rates as evidenced by the nearly horizontal curves for safety factors of four and five; however, as stated on the figure, the simulation fleet of 100 engines did not provide very reliable results for these comparatively low failure rates.

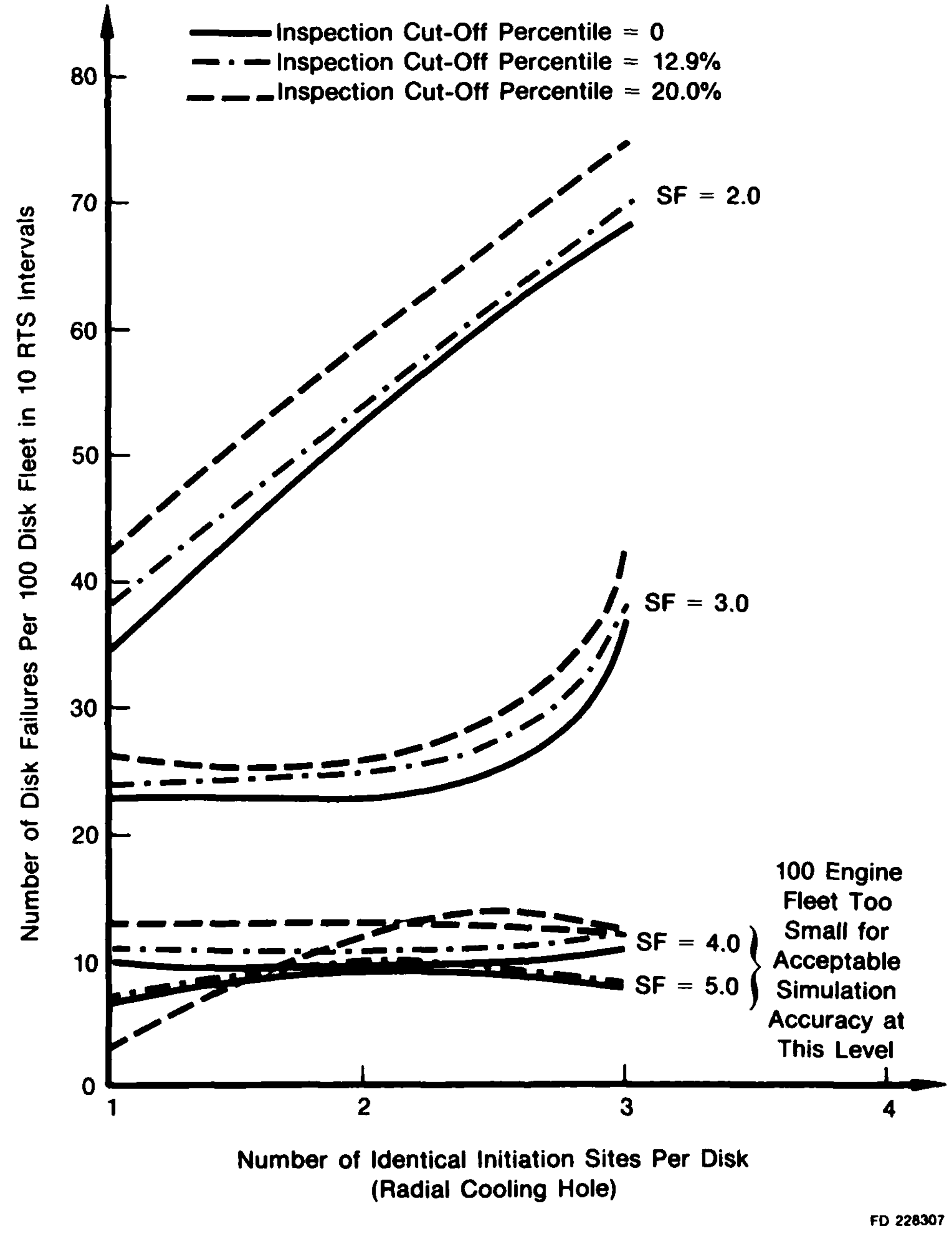


Figure 75. Number of Identical Initiation Sites Per Disk (Radial Cooling Hole)

The fact that there is *any* increase in the total number of failures with an increase in the number of crack initiation sites, as shown for the lower safety factors of two and three, may itself be an artifact of the unrealistically high failure rates imposed for cost savings in this preliminary evaluation. Results of ongoing simulations performed on a more statistically reliable fleet size of 1500 TF-33 engines, using realistic input data (including an improved inspection uncertainty for larger cracks), resulted in *component failure rates which decreased monotonically with an increasing number of initiation sites.* Figure 76 shows two typical curves from the TF-33 simulation which represents a significant failure-rate reduction (and replacement-rate increase) in the RFC procedure. These preliminary results should be interpreted cautiously because the analysis assumed that the major cause of inspection uncertainty is site-to-site variations rather than disk-to-disk, time-to-time, or inspector-to-inspector.

2.3.11.3.2 Use of Inspection Data to Continually Improve RFC Predictions

A key aspect in obtaining an optimum RFC approach will be the use of inspection data to update the initial component life-predictions automatically as field and proof test data becomes available. These changes will be negligible for those components and component-failure modes which were modeled accurately by the original "design" algorithms. However, the changes may be quite significant for some important cases in which the design analysis does not agree with field experience. It is realized that analytical, other improvements, and updates are generally introduced for resolving field problems; however, by necessity these updates are often made under high-pressure and short-time circumstances and are often quite subjective. The inspection results can be used in an algorithm to provide objective and instantaneous update of the life predictions and to signal the user whenever field and proof test experience differs by a statistically significant amount from the design analysis models.

Monte Carlo simulation can be used to represent "actual" field performance on the computer and simulate various levels of analytical and inspection errors. The error levels may range from slight changes in the inspection uncertainties to total misdiagnosis of the component failure mode. This will provide the opportunity for a complete and systematic sensitivity study of and the ability to improve the RFC model used to establish accept/reject criteria. The tuning consists of changes in the RFC model to account for any desired levels of analysis, logistics, and inspection errors. The aspects and errors considered can include optimization of proof test and/or lead-the-fleet parameters, inspection uncertainty in both detecting and sizing cracks and other signs of damage, systematic and stochastic errors in material characterizations and errors in stress analysis, fracture mechanics analysis, estimation of component usage and exposure time, and misdiagnosis of failure modes.

2.3.11.4 A Plan for Evaluating Inspection System Performance

The general procedures which would be used to evaluate inspection system reliability have been developed and verified in the evaluation of cracked bolthole eddy current inspection of TF-33 3rd-stage disks (Reference 18). They simply require comparison of actual defect sizes with the size (if detected) indicated by the inspection system performance, P(R/a, s), under actual depot usage conditions from anything short of actual depot inspection of numerous parts and destructive examination to confirm actual crack sizes.

[18] Interim Reports 1-7, March 1978 - March 1980 -- by S. W. Hopkins, C. A. Rau, Jr., D. E. Allison, P. M. Besuner, J. W. Eischen, Cost/Risk Analysis for Disk Retirement.

Although there are no guarantees that subsystem inspection performance evaluations on specimens or parts will precisely simulate the full inspection system under depot use conditions, it is recommended that the procurement specification include an evaluation of the transducer/electronics (or penetrant reading device) subsystem prior to assembly of the full system. This is desirable from several viewpoints. First, it will enable identification of these parameters (Table 12) which most strongly affect the inspection reliability for each part region and flaw type. Second, it will provide a preliminary upper bound on inspection reliability, and enable reevaluation of the viability of RFC for some candidate components if the inspection reliability is less than the preliminary specifications called for. Thirdly, it will provide experience which may reduce the effort and time required for depot evaluation of the completed inspection system. This is important because the inspection system may not be completely assembled and available for quantitative evaluation until very near the 1985 RFC implementation date.

Based upon our analyses of the impact of inspection reliability on RFC effectiveness, we have attempted to: (1) estimate the number of cracked components which must be inspected, and for which actual crack sizes must be determined independently, to quantify the inspection reliability; and (2) estimate the inspection reliability goals and specifications to assure a financially viable RFC program for many of the candidate components.

2.3.11.4.1 Number of Cracked Parts Required for Evaluation

The inspection system reliability must be evaluated for at least three crack size ranges; (1) unsafe (large) crack sizes which could grow to failure over about one inspection interval, (2) marginal crack sizes, near where the accept/reject size will be set, and (3) safe crack sizes which will definitely not grow to failure in several inspection intervals. For each of these crack size ranges, the probability of the inspection rejecting that part must be estimated. The probability of false rejection must simultaneously be determined. Our experience indicates that about[*] ten (10) actual cracks of each size range must be inspected to determine the probability of rejection to acceptable accuracy for the RFC procedure. Since at least three crack size ranges are required, thirty (30) or more specimens must be used to fully evaluate the inspection reliability for a specific type of defect and geometric detail. Each different region will require a similar number of actual cracks to establish [P(R/a, s)].

2.3.11.4.2 Preliminary Inspection Reliability Goals (Specifications)

Based upon numerous sensitivity studies performed, a preliminary estimate of the inspection reliability which will be required for each of the three size ranges (safe, marginal, and unsafe) to successfully implement RFC has been determined. Since most of the high stress locations occur in a number of equivalent places in each component, the inspection reliability required is not as high as intuition suggests.

Figure 77 summarizes our estimates of a reasonable inspection goal which might also form a preliminary specification, to be finalized only after additional probabilistic analysis of specific F-100 components. Three bars are shown for each of the three crack size ranges to be evaluated. The first bar indicates the subsystem (i.e., transducer/electronics) reliability required. The second bar indicates the reliability of the balance of the inspection system (e.g., manipulators, position locations, vibration, human factors, etc.). The third bar shows the total system reliability which results from the combination of both contributions at each crack size range. The curve shows the change in the total system probability of rejection as a function of actual crack size [P(R/a, s)].

Further details of the preliminary specification are presented in Appendix G.

---

[*] If the inspection reliability is much too low, it may take far fewer than 10 specimens to identify the inadequacy. However, about 30 specimens would be required to evaluate the expected reliability level inspection, and 50 to 100 specimens might be more cost-effective depending upon the specific inspection reliability impact on total RFC.

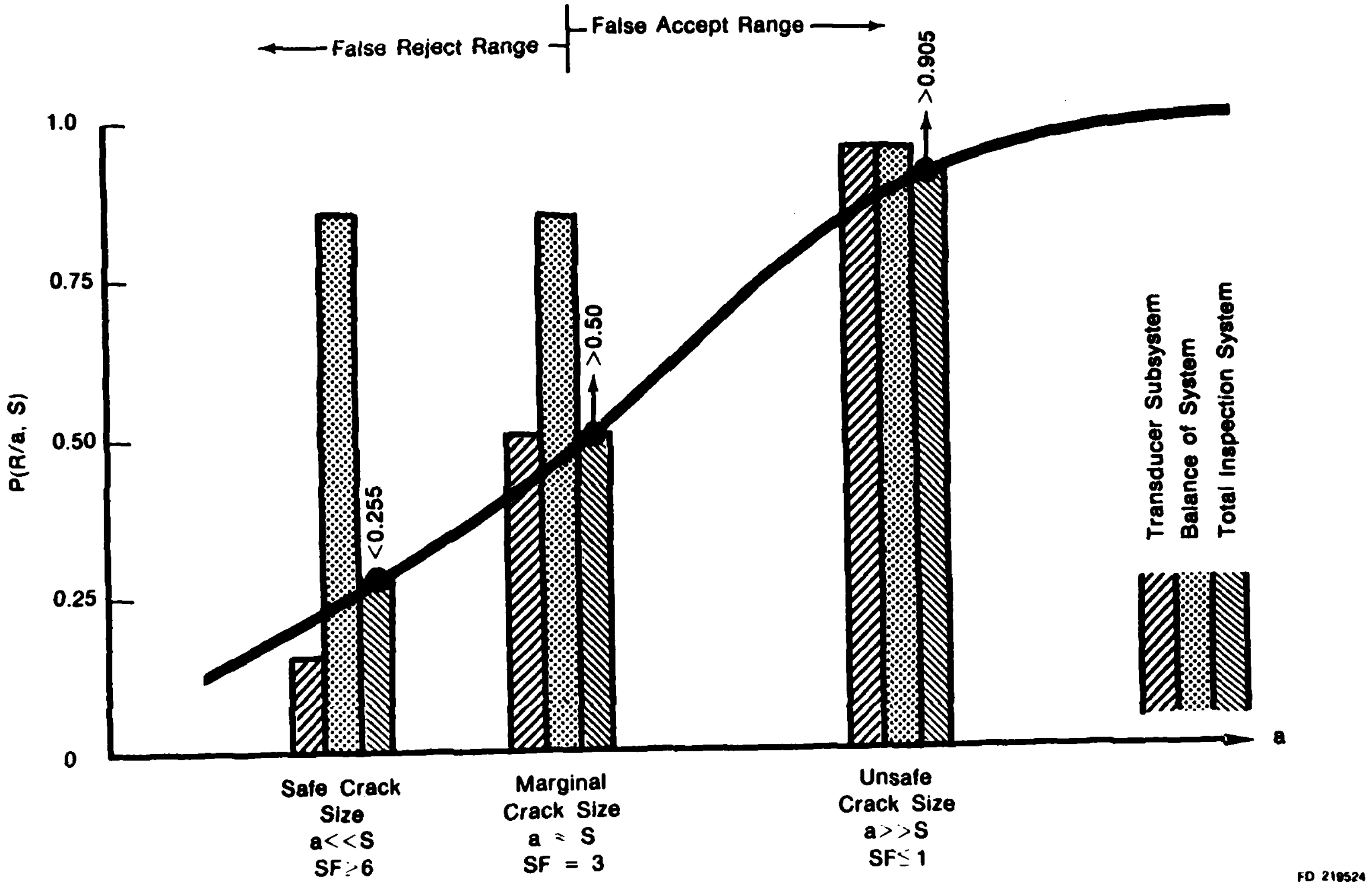


Figure 77. Initial Recommendations for Probability of Rejection Specifications at Various Crack Sizes, a

2.3.12 Parts Handling Subsystem

A primary feature of the RFC Inspection System necessary to accommodate the high volume throughput requirements is the facility parts handling subsystem. This automated system must identify the parts, safely move them to the proper inspection modules while maintaining an orderly progression for the facility as a whole, position the parts for inspection, and assign the proper disposition, either for reassembly with other module components or for further evaluation.

Three configurations were investigated for various throughput capacities and objectives:

System I — This system is configured to process RFC candidate disks and spacers for 100 PWA F100 engines per month. Parts loading and unloading and setup of the inspection machines will be manual. Each machine is totally automatic and suitable to inspect any of the parts.

System II — This system is configured to process RFC candidate disks and spacers for 200 PWA F100 engines per month with fully automatic operations. Machines are typically dedicated to one type of inspection except when requirements are low. In this case the machine is set up for more than one type of inspection.

Pilot System — This system is configured with two eddy current and one ultrasonic inspection machines. The purpose is to set up a minimal operation to test and verify systems capabilities.

These configurations were laid out based on current F100 RFC requirements. A total of 21 parts would be grouped according to their engine modules or submodules:

Module	*Part Description*	*Part No.*
I. Fan Module	1st Disk	4046741
	2nd Disk	4048902
	3rd Disk	4048903
II. Compressor Submodule	4th Disk	4030604
	7th Disk	4041337
	8th Disk	4040108
	12th Disk	4022612
	2-3 Spacer	4049087
	6-7 Spacer	4039846
	7-8 Spacer	4039727
	8-9 Spacer	4050978
	9-10 Spacer	4050979
	10-11 Spacer	4043279
	11-12 Spacer	4043280
	12-13 Spacer	4041591
III. High Turbine Submodule	1st Disk	4043321
	2nd Disk	4042922
	1-2 Spacer	4042715
	TOBI Seal	4036812
IV. Low Turbine Module	3rd Disk	4041794
	4th Disk	4001857

These parts would enter the facility in modules and, regardless of the system type or testing sequence, would be brought back together following inspection for further disposition.

Time available for processing was established on the basis of a seven-hour, one shift per day operation, 22 days per month, for a total of 154 hours per month.

The specifications and detailed explanation of parts handling requirements for all three system types are presented in Appendix H.

2.3.13 Facility Layout and Space Requirements

Determination of layout and space requirements for the RFC Inspection System facility was based on numerous considerations:

- Number of inspection machines
- Inspection machine grouping
- Method of parts transportation
- Storage and transport buffers
- Office areas
- Computer room
- Aisles and circulation areas.

The most significant consideration, however, was the overall facility capacity in terms of parts throughput and facility objective.

As described in Section 2.3.12 Appendix H, three basic systems have been configured for this design study. Each has a different parts rate requirement and/or objective affecting each of the facility design considerations listed above. The three system alternatives for which facilities were designed, with a summary of basic requirements of each are presented in Table 13. Detailed specifications for each configuration including the inspection line and building requirements are presented in Appendix I.

2.3.14 Facility Cost

Capital funding requirements for the installation of the three facility configurations addressed in this report are presented in this section. Estimates for individual inspection system components were gathered from report contributors familiar with specific requirements and available equipment in their area of expertise.

TABLE 13. LAYOUT REQUIREMENTS FOR THREE SYSTEM ALTERNATIVES

System	*Parts Rte*	*EC Stations*	*UT Stations*	*Station Loading Unloading*	*Support Facilities**
I	2100	6	3	Manual	Yes
II	4200	14	4	Automatic	Yes
III	(Demo)	2	1	Manual	Yes

*Support facilities include computer room, short term engine component storage, office space, and maintenance/spare parts storage.

2.3.14.1 Basis of Estimate

Due to the conceptual nature of this phase of the RFC program, this capital cost estimate for the facilities and equipment should be used for budget and planning purposes only. The estimates reflect current costs and include no escalation factors.

The estimates include equipment fabrication, shipping, installation, and checkout. Software development is not included as a capital cost. Building costs are estimated on a unit cost per square footage based on prevailing construction cost for the southwest region of the United States. The number of spares was set to maintain the required operational capacity of the NDE facility.

2.3.14.2 Cost Tabulation

The total estimated cost for the three subject facilities, described in Appendix I, including equipment, building and spares is as follows:

Pilot System	$ 2,216,000
System I	6,350,000
System II	14,843,000

The major categoreis of equipment and spares and their estimated costs are presented in Tables 14 and 15.

TABLE 14. CAPITAL COST ESTIMATE SUMMARY (FIGURES IN $1,000)

		Pilot System		*System I*		*System II*	
Description	*Cost*	*Units*	*Cost*	*Units*	*Cost*	*Units*	*Cost*
Eddy Current Equipment							
Multipurpose Scanner	300	2	600	6	1,800	—	—
Dedicated Scanner	250	—	—	—	—	14	3,500
Peripherals	—	—	120	—	360	—	840
Ultrasonic Equipment							
Scanner	250	1	250	3	750	4	1,000
Peripherals	—	—	88	—	204	—	262
Computer Hardware	—	—	390	—	1,100	—	1,640
FPI Modifications	—	—	150	—	150	—	300
Part Handling Equipment							
Conveyors	—	—	26	—	384	—	789
Industrial Robots	163	—	—	—	—	18	2,934
Total Equipment			1,624		4,748		11,265
Building Construction			230		576		1,305
Subtotal			1,854		5,324		12,570
Contingencies			185		532		1,257
Total			2,039		5,856		13,827

TABLE 15. SPARES COST ESTIMATE SUMMARY (FIGURES IN $1,000)

		Pilot System		*System I*		*System II*	
Description	*Cost*	*Units*	*Cost*	*Units*	*Cost*	*Units*	*Cost*
Eddy Current Equipment							
Multipurpose Scanner	—	10%	60	10%	180	—	—
Dedicated Scanner	—	—	—	—	—	10%	350
Peripherals	—	—	5	—	60	—	114
Ultrasonic Equipment							
Scanner	—	10%	25	10%	75	10%	100
Peripherals	—	—	10	—	55	—	55
Computer Hardware	60	1	60	1	60	2	120
Part Handling Equipment							
Conveyors		5%	1	5%	19	5%	39
Industrial Robots			—	—	—	5%	150
Subtotal			161		449		928
Contingencies			16		45		93
Total			177		494		1,021

2.3.15 Preliminary Hazard Analysis

The facility and parts handling equipment as proposed require no special precaution in reference to the MIL-STD-882A - SYSTEM SAFETY PROGRAM REQUIREMENTS due to the nonhazardous nature of the operation and type of equipment to be provided.

Normal safety precautions during construction and equipment installation will be provided as specified in other sections of these Specifications.

2.3.16 References

1. "Reliability of NDI on Aircraft Structures," Lockheed-Georgia/Air Force Program AFLC/SAALC/MME 76-6-38-1.

2. "Reliability of Nondestructive Inspection (NDI) of Aircraft Engine Components." Final Report on Phase I, Ward D. Rummel, Martin Marietta, SAALC/MME MCR 79-678.

3. "Quantitative Eddy Current NDE/Bolthole Inspection," second interim report, 9/77 - 12/79, Adaptronics, Inc.

4. "Cost/Risk Analysis for Disk Retirement," second through seventh interim reports, 12/78 — 3/30, Failure Analysis Associates.

5. "Disk Residual Life Studies," Part II of AFML/P&WA Final Report AFML-TR-79-4173.

6. "Methods Improvement of the Fluorescent Penetrant Inspection Process." AFWAL Contract No. F33615-79-C-5021. Final Report, AFWAL-TR-80-4161.

7. "Improved Penetrant Process Evaluation Criteria" AFWAL Contract No. F33615-80-5060.

8. Oppenheim, A. V. and R. W. Schafer, *Digital Signal Processing,* Prentice Hall, Englewood Cliffs, NJ, 1975.

9. Tou, J. T. and R. C. Gonzalez, *Pattern Recognition Principles,* Addison-Wesley Pub. Co., Reading, MA, 1974.

10. Duda, R. O. and R. E. Hart, *Pattern Classification and Scene Analysis,* Wiley Interscience, New York, 1973.

11. Cover, T. M., "Geometrical and Statistical Properties of Linear Irregularities with Applications to Pattern Recognition," IEE Trans. Electronic Computers, Vol. EC-14, pp. 326-334, 1965.

12. Shankar, R., S. N. Vernon, and A. N. Mucciardi, "Quantitative Eddy Current NDE/Bolthole Inspection," Second Interim Report, Adaptronics Inc., January 1980.

13. Swicke, P. E., "Ship Classification Using Recursive Structure Identification and the Mellin Transform," UTRC, Report R80-192109, Januay 1981.

14. IEEE, *Programs for Digital Signal Processing,* John Wiley and Sons, New York, 1979.

15. Kowalski, B. R., "ARTHUR81 Users Manual," Distributed by Infometrix, Inc., Seattle, WA, January 1981.

16. Zwicki, P. E., "Interactive Signal Processing Package Users Manual," UTRC Report UTRC81-14, Revised May 1981.

17. Shankar, R., et al., "Feasibility of Using Adaptive Learning Networks for Eddy Current Signal Analysis," NP-723, Electric Power Research Institute, Palo Alto, CA.

18. Interim Reports 1-7, March 1978 — March 1980 — by S. W. Hopkins, C. A. Rau, Jr., D. E. Allison, P. M. Besuner, J. W. Eischen, Cost/Risk Analysis for Disk Retirement.

U.S.Government Printing Office: 1986 — 646-067/40759

END
FILMED

DTIC

6-86