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In-Service Ultrasonic Inspections for Turbine Engine, Life-Limited Rotating Parts

January 2026

Final report

U.S. Department of Transportation
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The aero gas turbine industry has collaborated with the Federal Aviation Administration (FAA) to study and provide guidance and make recommendations about the implementation of requirements for in-service, sub-surface inspections through the Aerospace Industries Association (AIA) team AIA A-18-004. Data from across a broad spectrum in the industry is needed for this work since the probability of an uncontained rotor event from any cause has proven to be extremely low. Following an uncontained event from a melt anomaly in a nickel high pressure turbine (HPT) disk in 2016, industry teams including this team, team AIA A-18-003, the AIA Jet Engine Nickel Consortium (JENQC), and the AIA Rotor Integrity Steering Committee (RISC) have collected data and considered ways to improve rotor damage tolerance through improvements in inspection technologies, melting and manufacturing practices, and part design and lifing. This report documents the data collected and the findings from the evaluation of in-service inspections. The inspection guidance and recommendations provided here are considered as part of a larger critical part damage tolerance strategy. A comprehensive damage tolerance strategy considers the part manufacture, service management, and engineering design characteristics in order to minimize threats.
The position of AIA A-18-004 is that aircraft safety is augmented by the inclusion of subsurface, ultrasonic (UT) inspections. The most effective and desirable means to detect subsurface anomalies and cull suspect material is by original equipment manufacturer (OEM) UT inspection of the billet and forging prior to finished part machining. However, industry field experience suggests in-service UT inspection, implemented at piece part opportunity exposure, may also be helpful. Such in-service inspections provide the most value on large blade carrying HPT disks and some intermediate pressure turbine (IPT) disks while other component types are currently well served by the surface inspections already in place. For some specific applications, a part may be available for piece part inspection at multiple times within its service life. The in-service inspections should be conducted each time one of these safety critical parts is completely disassembled, unless otherwise agreed to with the Authority.</td></tr>
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AIA A-18-004
JULY 2023

In-Service Ultrasonic Inspections for Turbine Engine, Life-Limited Rotating Parts

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1.0 Executive Summary

The aero gas turbine industry has collaborated with the Federal Aviation Administration (FAA) to study, provide guidance, and make recommendations about the implementation of requirements for in-service, sub-surface inspections through the Aerospace Industries Association (AIA) team AIA A-18-004. Data from across a broad spectrum in the industry is needed for this work since the probability of an uncontained rotor event from any cause has proven to be extremely low. Following an uncontained event from a melt anomaly in a nickel high pressure turbine (HPT) disk in 2016, industry teams including this team, team AIA A-18-003, the AIA Jet Engine Nickel Quality Committee (JENQC), and the AIA Rotor Integrity Steering Committee (RISC) have collected data and considered ways to improve rotor damage tolerance through improvements in inspection technologies, melting and manufacturing practices, and part design and lifing. This report documents the data collected and the findings from the evaluation of in-service inspections. The inspection guidance and recommendations provided here are considered as part of a larger critical part damage tolerance strategy. A comprehensive damage tolerance strategy considers the part manufacture, service management, and engineering design characteristics in order to minimize threats.

The position of AIA A-18-004 is that aircraft safety is augmented by the inclusion of subsurface, ultrasonic (UT) inspections. The most effective and desirable means to detect subsurface anomalies and cull suspect material is by original equipment manufacturer (OEM) UT inspection of the billet and forging prior to finished part machining. However, industry field experience suggests in-service UT inspection, implemented at piece part opportunity exposure, may also be helpful. Such in-service inspections provide the most value on large blade carrying HPT disks and some intermediate pressure turbine (IPT) disks while other component types are currently well served by the surface inspections already in place. For some specific applications, a part may be available for piece part inspection at multiple times within its service life. The in-service inspections should be conducted each time one of these safety critical parts is completely disassembled, unless otherwise agreed to with the Authority.

2.0 Introduction

2.1 Background

Turbine engine rotating parts are high-energy components governed by strict regulatory oversight and requirements. When the failure of these parts could result in a hazardous engine effect, as defined by 14 CFR §33.75, they are subject to the requirements of 14 CFR §33.70. 14 CFR §33.70 requires that parts have:

a) An engineering plan that contains the steps required to ensure each engine life-limited part is withdrawn from service at an approved life before hazardous engine effects can occur.
b) A manufacturing plan that identifies the specific manufacturing constraints necessary to consistently produce each engine life-limited part with the attributes required by the engineering plan.
c) A service management plan that defines in-service processes for maintenance and the limitations to repair for each engine life-limited part that will maintain attributes consistent with those required by the engineering plan. These processes and limitations will become part of the Instructions for Continued Airworthiness.

This team was tasked with considering items pertaining to point “C” above. The tasking letter, attached in Section 4.0, contains specific requests of the team, which have been paraphrased as follows:

1. Evaluate whether in-service ultrasonic inspections should be recommended for critical high-energy, life-limited rotating parts.
2. Review current techniques, best practices, and practical challenges for sub-surface inspection implementation on finished machined hardware.
3. Provide guidance for how to evaluate an in-service UT implementation strategy and its benefits.

In reference [1], the US National Transportation Safety Board (NTSB) documents that:

> *On October 28, 2016, about 1432 central daylight time, American Airlines flight 383, a Boeing 767-323, N345AN, had started its takeoff ground roll at Chicago O’Hare International Airport, Chicago, Illinois, when an uncontained engine failure in the right engine and subsequent fire occurred… The uncontained engine failure resulted from a high-pressure turbine (HPT) stage 2 disk rupture. The HPT stage 2 disk initially separated into two fragments… Examination of the fracture surfaces in*

the forward bore region of the HPT stage 2 disk revealed the presence of dark gray subsurface material discontinuities with multiple cracks initiating along the edges of the discontinuities. The multiple cracks exhibited characteristics that were consistent with low-cycle fatigue. (In airplane engines, low-cycle fatigue cracks grow in single distinct increments during each flight.) Examination of the material also revealed a discrete region underneath the largest discontinuity that appeared white compared with the surrounding material. Interspersed within this region were stringers (microscopic-sized oxide particles) referred to collectively as a "discrete dirty white spot." The National Transportation Safety Board's (NTSB) investigation found that the discrete dirty white spot was most likely not detectable during production inspections and subsequent in-service inspections using the procedures in place.

Following this event (herein referred to as "the Chicago event") and the subsequent accident investigation, the NTSB requested the FAA work with the industry, via the AIA to evaluate potential improvements in rotor in-service inspection strategies. This report documents those findings, specifically answering the questions listed above.

3.0 In-Service Inspection Findings

3.1 Current Fleet Experience with In-service Sub-Surface Inspections

Prior efforts to understand materials or manufacturing related disk cracking or fracture events have found success in gathering data anonymously through AIA members including melters, forgers, and OEMs. In most of these cases, the OEMs are also the Type Certificate (TC) holder which provides them unique knowledge into the part stress and temperature environment. The collaboration on these prior efforts has resulted in significant improvements in the durability of titanium parts and circular hole manufacture with lessons being captured in Advisory Circulars (AC) 33.14-1, 33.15-1, and 33.70-2. This collaboration is critical because these materials and manufacturing related issues may affect supply chains and may be rare enough that the combined experience of industry is necessary to ascertain useful information about failure or infection rates.

The next few sections outline the effort to collect and analyze data to be used for ascertaining the value of in-service, sub-surface inspections on life limited rotating parts.

3.1.1 Rotating Parts with Melt Anomaly Field Cracking or Fracture Experience

Following the Chicago event, RISC conducted a field survey to capture negative field experience connected to cast & wrought nickel melt anomalies.

Nickel was selected for inquiry in the aftermath of the Chicago event because the uncontained event occurred on a cast & wrought nickel disk and because nickel inspection and design damage tolerance had not been previously addressed by industry efforts. Titanium melting, manufacture, and design have been studied exhaustively with corrective actions in place since the 1990s.

The data collected identified 25 components where a crack had been associated with a melt anomaly; 6 components where a fracture had occurred. Only one of the parts was reported as having been manufactured from triple melt material.

The field experience collected shows that the blade carrying disk hub has the highest quantity of identified crack finds and disk fractures. A schematic of a simple disk with zones labeled is provided for reference (Figure 1). The hub may also be commonly referred to as the disk bore. Given the distribution of stressed volumes within high-energy rotating parts, these survey results are not surprising.

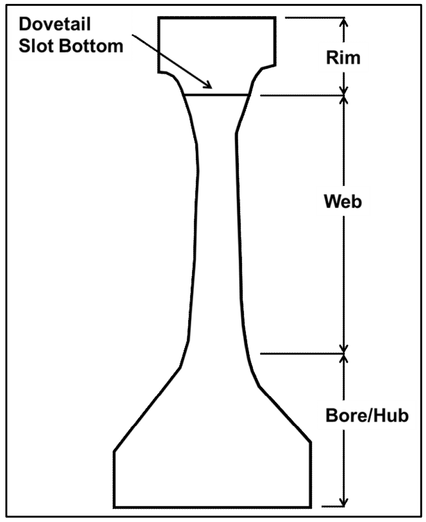


Figure 1. Basic Schematic of Simplified Disk

Along with the data above, specific information (where available) was collected to provide information concerning whether the fractured parts had any opportunities for inspection prior to the fracture event and whether a sub-surface inspection may have been able to catch the crack/anomaly. Figure 2 contains a breakdown of the collected data.

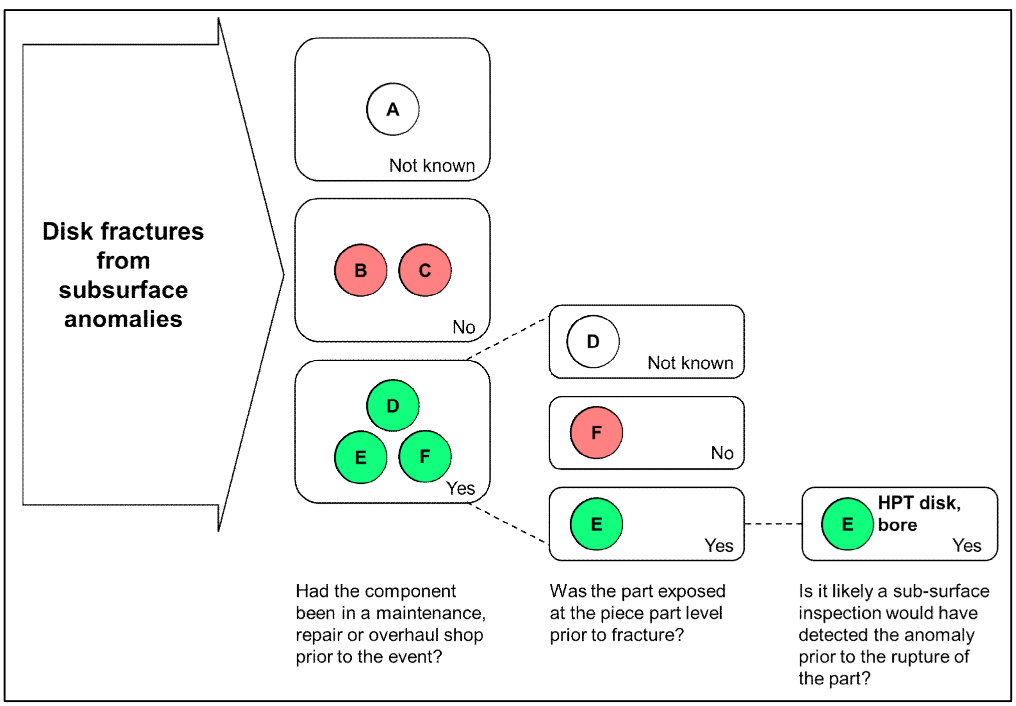


Figure 2. Inspection Opportunities and "Catch" Assessment for the Six Cast & Wrought Fractured Parts Reported in the Field Survey

Not all engines with fractured disks had a shop visit prior to the event. Three out of the six did have a shop visit. Of the three disks that had a shop visit, only one of the parts had a piece part exposure.

The OEM that submitted the part "E" experience indicated the anomaly had nucleated a crack during service and that the piece part shop visit opportunity occurred after the anomaly had nucleated the crack. They indicated that the bore region was well suited towards UT inspection and that an in-service inspection could have detected the anomaly pre-nucleation* and certainly would have detected the anomaly with the crack present. A fluorescent penetrant inspection (FPI) and eddy current inspection (ECI) was conducted at the piece part shop visit opportunity at the surfaces nearest to the initiation site and did not detect the crack because it had not yet broken through to the surface of the part.

As part of the data collection, additional information regarding the disk geometry and part type were provided. For geometry, disks were reported using a simplified representation of the finished part shape. Figure 3 provides an example of this geometry. In the left side of this figure, a HPT disk is shown with 3D features on the disk. An axisymmetric simplification is shown in the cross-hatched region on the right side of the figure. The OEMs were requested to submit the surface area of the revolved, cross-hatched geometry as well as the volume of that revolved section. The results showed trends that are discussed in this section and others.

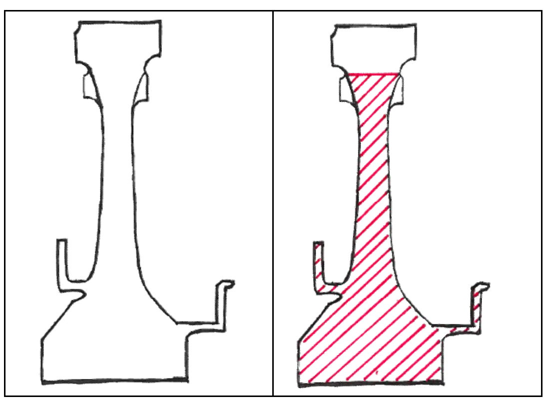


Figure 3. Representation of Simplified Disk Geometric Parameters (left: HPT disk with 3D web features and disk posts, right: axisymmetric representation; cutoff at disk slot bottom)

* This indicates an enhanced OEM UT inspection method (the subject of the AIA A-18-003 task) may also have detected the anomaly pre-nucleation.

Figure 4 contains geometric information for each of the submitted parts. The disk volume is plotted against the revolved surface-to-volume ratio (SA:V). The disk volume is a measure of the likelihood of an anomaly being present in one part versus another; a larger part is more likely to have an anomaly than a smaller part. The SA:V metric provides a measure of how "skinny" or "slender" a part may be. Thin parts such as high pressure compressor (HPC) or LPT disks have a larger SA:V and are less likely to have subsurface anomalies when compared to a part of the same volume with a lower SA:V. This metric does a reasonable job of segregating part types. HPT disks, which may benefit more from an in-service UT inspection than other parts tend to congregate, at a value of SA:V < 4/inch.

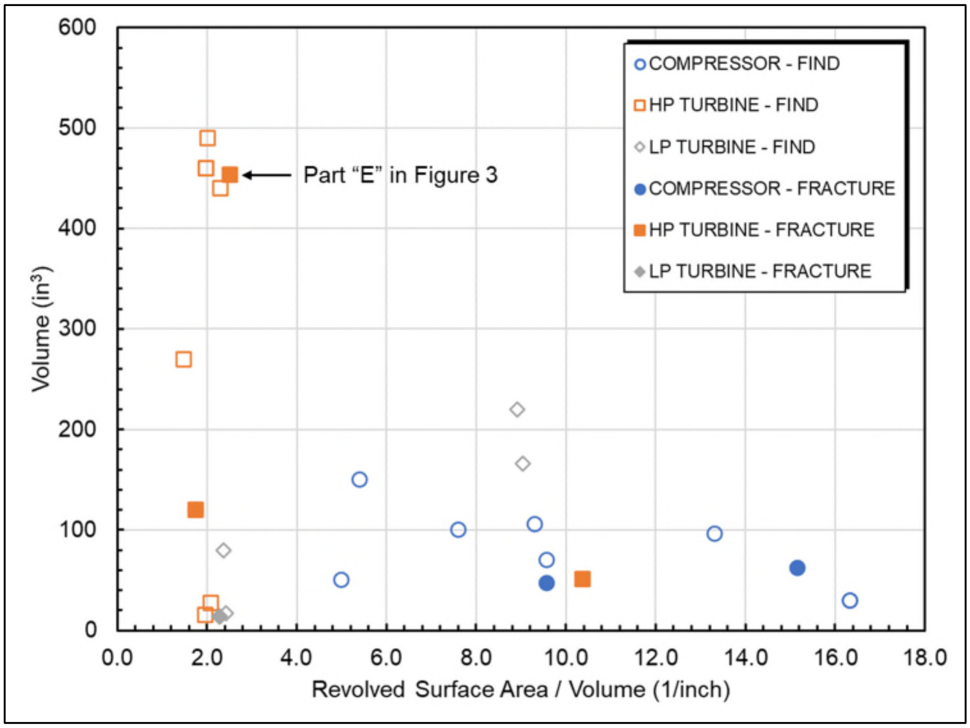


Figure 4. Cast & Wrought Nickel Find and Fractures by Disk Geometric Characteristics

3.1.2 Experience with Anomaly Detection in Fielded Rotors

The field and fracture experience, described in Section 3.1.1, suggests an in-service, subsurface UT inspection can detect propagating cracks in parts. However, this data gathering focused on cast & wrought alloys of a vintage which may overstate the benefit of an in-service inspection as compared to modern designs and manufacturing practices. In addition, cast and wrought alloys are dwindling in usage for HPT designs. HPT designs now favor powder nickel alloys.

To address the powder nickel alloys, a survey was created by Team 004 and executed by the RISC team. The questionnaire focused on nickel alloys including both cast & wrought and powder metallurgy components.

Table 3-1 represents the data submitted to the FAA and provided to the team. Two inspection strategies are represented:

- Special cause: Inspections conducted on limited populations for safety corrective actions
- Fleet sampling: Inspections conducted on part populations at piece part exposure

Table 3-1. OEM Submissions to Recent UT Field Inspection Survey

Aircraft Segment	Alloy Type	Inspected Population	Number of Pieces Inspected	Total Volume of Parts Inspected (in^3)	Qty Parts Rejected	Anomaly Description	Judge the ability of an Enhanced New Make Inspection to Catch The Anomaly Observed in the Field?	If answer is "Yes: to question at the left: What type of inspection could have detected the anomaly in production?	Would Anomaly Have Been Caught by an Existing (ex. FPI, ECI) In-Service Inspection?	Would Anomaly Found Be Detrimental to Part Life?
Wide Body	IN718	Fleet Sampling	1045	347,700	2	Coarse Grains	Highly Likely	Conventional - Refracted Angle Shear	Highly Unlikely	Unlikely
Wide Body	Other C&W	Fleet Sampling	548	256,200	1	Oxide/Carbonitride Cluster	Highly Likely	Conventional - Refracted Angle Shear	Highly Unlikely	Likely
Wide Body	Other Powder	Fleet Sampling	1028	583,100	2	Crack/Void	Unlikely		Highly Unlikely	Highly Likely
Narrow Body	Other Powder	Special Cause	400		1	Crack/Void	Likely	Conventional - Refracted Angle Shear	Highly Unlikely	Unsure
Narrow Body	Other Powder	Special Cause	700		1	Crack/Void	Highly Likely	Conventional - Refracted Angle Shear	Highly Unlikely	Unlikely
Narrow Body	Other Powder	Special Cause	217		12	Crack/Void	Highly Likely	Conventional - Refracted Angle Shear	Highly Unlikely	Unlikely
Narrow Body	Other Powder	Special Cause	108		1	Crack/Void	Highly Likely	Conventional - Refracted Angle Shear	Highly Unlikely	Unsure
Narrow Body	Other Powder	Special Cause	62		0	Crack/Void				
Narrow Body	IN718	Fleet Sampling	271	108,000	0					
Narrow Body	Other C&W	Fleet Sampling	36	4,300	0					
Regional Jet	IN718	Fleet Sampling	34	8,500	0					

The data in the Table 3-1 represents inspections conducted on 4449 disks. Not all part inspected volumes were recorded but at least 1.3 million in^3 is included in the submissions.

For cast and wrought parts reported with finds (3), all were evaluated as “likely to have been caught” via an improved new make inspection. One of those parts had a finding that was reported likely to have a detrimental impact on part life. The location of the anomaly was not requested nor specified.

The data collected on powder metallurgy disks proved to be more interesting. Powder disks, while not subject to the same types of anomalies as their cast & wrought counterparts, are at risk to inherent and rogue particle contamination. Both the inherent foreign particles and rogue anomaly types should be characterized and considered within the approved lifing system of the OEM using powder metallurgy disks. Specific guidance on this topic was published by the European Aviation Safety Agency (EASA) in 2017 [2]. The accepted approach for setting life limits on these disks is to employ a probabilistic fracture mechanics approach, analogous to those employed for hard alpha in titanium [3].

Given the presence of the known (and rogue) inclusions in powder and the potential for crack growth from those inclusions, powder disks are an interesting study.

Altogether, 19† powder parts with cracks or voids were found with field inspections. 15 of those 19 were identified through special cause inspections and were reported to be unlikely or unsure to have detrimental effects on the ability of the part to meet its approved life limit. Those 15 could also have been caught at new make with an improved new make inspection. The remaining parts were classified as undetectable at new make and “highly likely” to be detrimental to the ability of the part to meet its approved life limit.

This supports the continued industry effort on improving new make inspections as a priority. Following the future publication of guidance and recommendations for enhanced new make inspections from AIA A-18-003, it is anticipated that some parts may not have incorporated each aspect of those recommendations at their time of production. In-service inspections will have more importance for parts that do not incorporate the AIA A-18-003 best practices. Implementation of enhanced new make inspections will render in-service inspections less beneficial.

Team 004 requested additional information about the data points where an enhanced new make inspection would have been unlikely to catch the cracks that were observed in the field. A summary of the response from the OEM is below:

- Four powder parts were found cracked out of approximately 1300 inspected. This is an additional two finds and approximately 300 inspections compared to Table 3-1.
- All rejectable sonic indications in the fielded parts had cracks initiated from inherent anomalies within the disks. The anomalies found varied between partially cracked to fully cracked with additional growth into the base alloy. The initiating anomalies ranged in size from 100 square mils to 600 square mils. The cracks found ranged from 22 square mils to 1270 square mils.

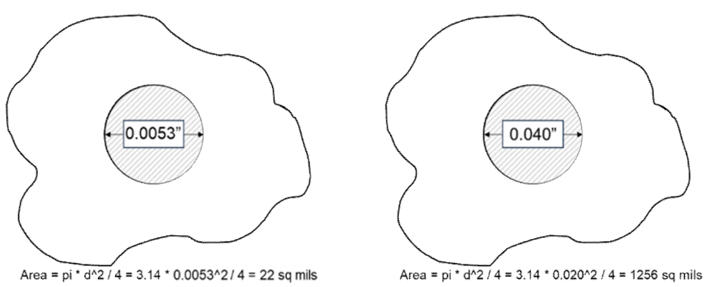


Figure 5. Crack Sizes Found in Field UT Inspected Hardware

- At least one of the cracks found would likely have propagated to failure within the lifetime of the part.

† The initial Team 004 survey had 17 crack finds reported (Table 3-1). One OEM augmented that data with two additional finds that occurred after the initial data collection effort.

- The cracks were found during piece part inspection ranging between 1/3 to 1/2 of the approved life limits for the parts.

The subsurface anomalies noted in 3.1.1 and 3.1.2 are combined into one dataset in Table 3-2 and are further filtered to only include instances where:

1) The anomaly present was reported detrimental to the part's ability to meet its approved life limit and…
2) A piece part opportunity for an in-service inspection occurred and…
3) An in-service inspection had (or may have had) the capability of detecting the anomaly, thus potentially preventing a fracture.

Table 3-2 represents seven serial numbers across four part numbers. Within this subset, all reported locations are within the disk bore (hub).

Table 3-2. Known Subsurface Cracks or Anomalies, Detectable, and Piece Part Opportunity Available, and Potentially Detrimental

Instance #	Section of Report	Qty of Parts	Part Type	Alloy	Condition	Detectable by Enhanced New Make UT?	In-Service Inspection Opportunity	Detectable in Field by UT?	Region of Component where Anomaly Located	Would Anomaly Found be Detrimental to Part Life?
2	3.1.1	1	HPT Disk	IN718	Fracture - Uncontained Failure	Not specified but inferred "Yes" from field response	Yes	Highly Likely	Bore (Hub)	Yes
3	3.1.1	1	LPT Disk	Waspaloy	Fracture - IFSD	Not specified	Yes	"Maybe"	Bore (Hub)	Yes
5	3.1.2	1	Not Reported	Other C&W	UT Find - Oxide/Carbonitride Cluster	Yes	Yes	Yes	Not Reported	Likely
6	3.1.2	4	Not Reported	Other Powder	UT Find - Cracks	No	Yes	Yes	Bore (Hub)	Highly Likely

3.1.3 Analytical Studies Conducted to Evaluate Sub-surface Inspection Potential and Locations

The fielded part experience described in Section 3.1.1 and Section 3.1.2 is the best source of data for making observations on the efficacy of in-service UT inspections. While field data is always the most valued, analytical models are often used to augment understanding.

One OEM volunteered a series of probabilistic fracture mechanics assessments to better understand the SA:V data points previously described. A series of parts, belonging to different engine sizes and modules were assessed. These part and engine types are shown in Table 3-3.

Table 3-3. Part Types Considered for Probabilistic Fracture Mechanics Studies

Engine Class	HPC Spool	HPT Disk	IPT Disk	LPT Disk
Large Narrow Body	X	X	-	-
Wide Body	X	X	-	X
Regional Jet	X	X	-	X
Small Turboshaft/Turboprop	-	X	-	-

A probabilistic fracture assessment, like those conducted for titanium hard alpha, was conducted for a sample of cast and wrought nickel parts using anomaly distributions and rates reasonable for nickel.

In this report, these probabilistic studies are not used to establish part reliability against a design target risk metric but are used to evaluate the fractional portion of total part risk associated with subsurface anomalies. Anomalies, sampled from an observed distribution for cast & wrought nickel, were randomly placed throughout the studied parts and grown to failure. If the initial anomaly size and position was such that it intersected the part surface it was considered as “surface associated risk”. Otherwise, it was considered “sub-surface associated risk”. The summation of the surface and sub-surface risk calculations defines the total risk. A schematic of this is shown in Figure 6. This split is important because parts with the balance of the total risk associated with the part surface may see less benefit from in-service subsurface inspections compared to parts where the subsurface fraction is larger.

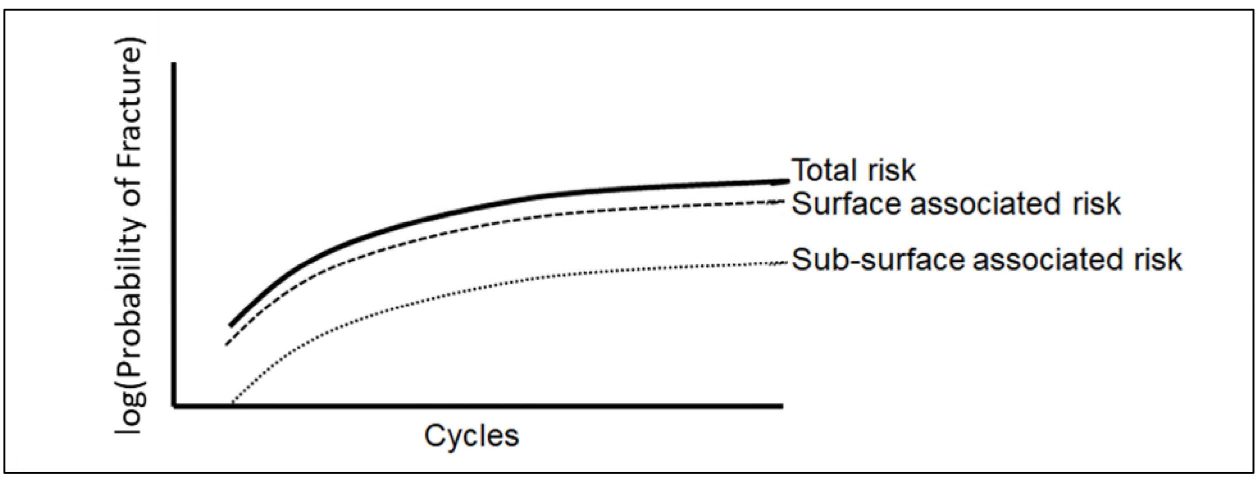
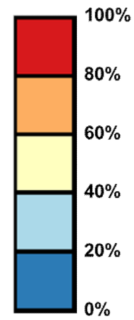


Figure 6. Schematic of Probabilistic Fracture Mechanics Model Output

The probability of fracture (POF) split shown in Table 3-4 is shown at 25% of the approved life limit for the assessed parts. 25% was selected as a representative fraction of life when a piece part shop visit might occur.

Table 3-4. Fraction of POF at 25% of Life Limit

Class	Location	HPC Spool	HPT Disk	LPT Disk
Large Narrow Body	Subsurface	20%	70%	-
Wide Body	Subsurface	30%	70%	25%
Regional Jet	Subsurface	15%	50%	5%
Turboshaft / Turboprop	Subsurface	-	20%	-



These predictions are combined with the field collected data from Figure 4 and are shown in Figure 7 and Figure 8. Figure 7 shows the fraction of risk contained within the subsurface portion of the disk. This plot shows a connection between the SA:V parameter and indicates where an in-service UT inspection may provide value. As SA:V increases, surface-connected anomalies become the dominant part risk. Figure 8 overlays the analytically assessed parts with the RISC collected field data. Numbers are provided as a reference to be able to identify some points common to both Figure 7 and Figure 8.

The data further indicates that a condition where SA:V < 4/inch highlights parts most likely to benefit from in-service UT inspections. This segregates HPT disks from others. A vertical line is shown at SA:V < 4/inch as well as a horizontal line drawn at 100 in^3. In this study, 100 in^3 represented where the proportions of subsurface risk in a HPT disk became similar to disks in other modules.

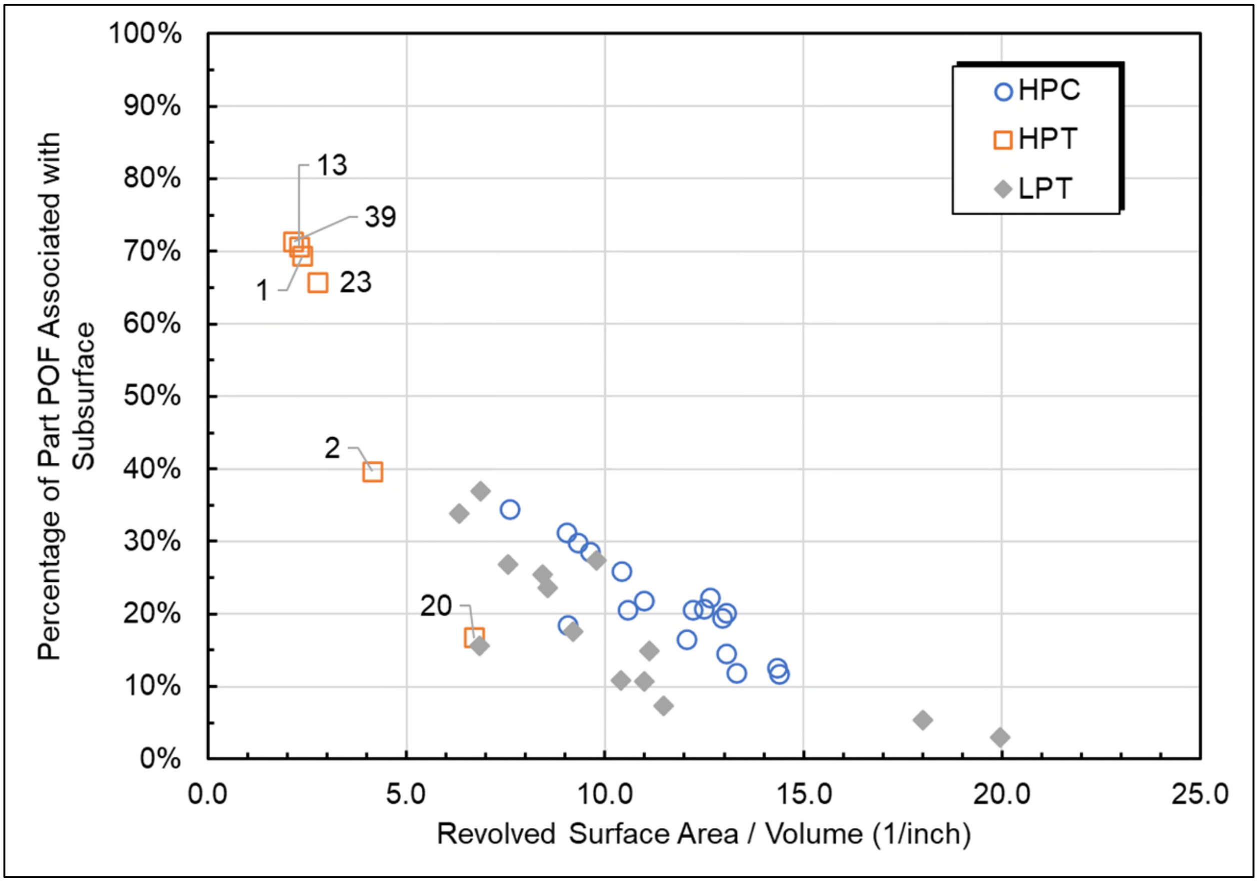


Figure 7. OEM Simulation of Part Subsurface Risk as Compared to SA:V

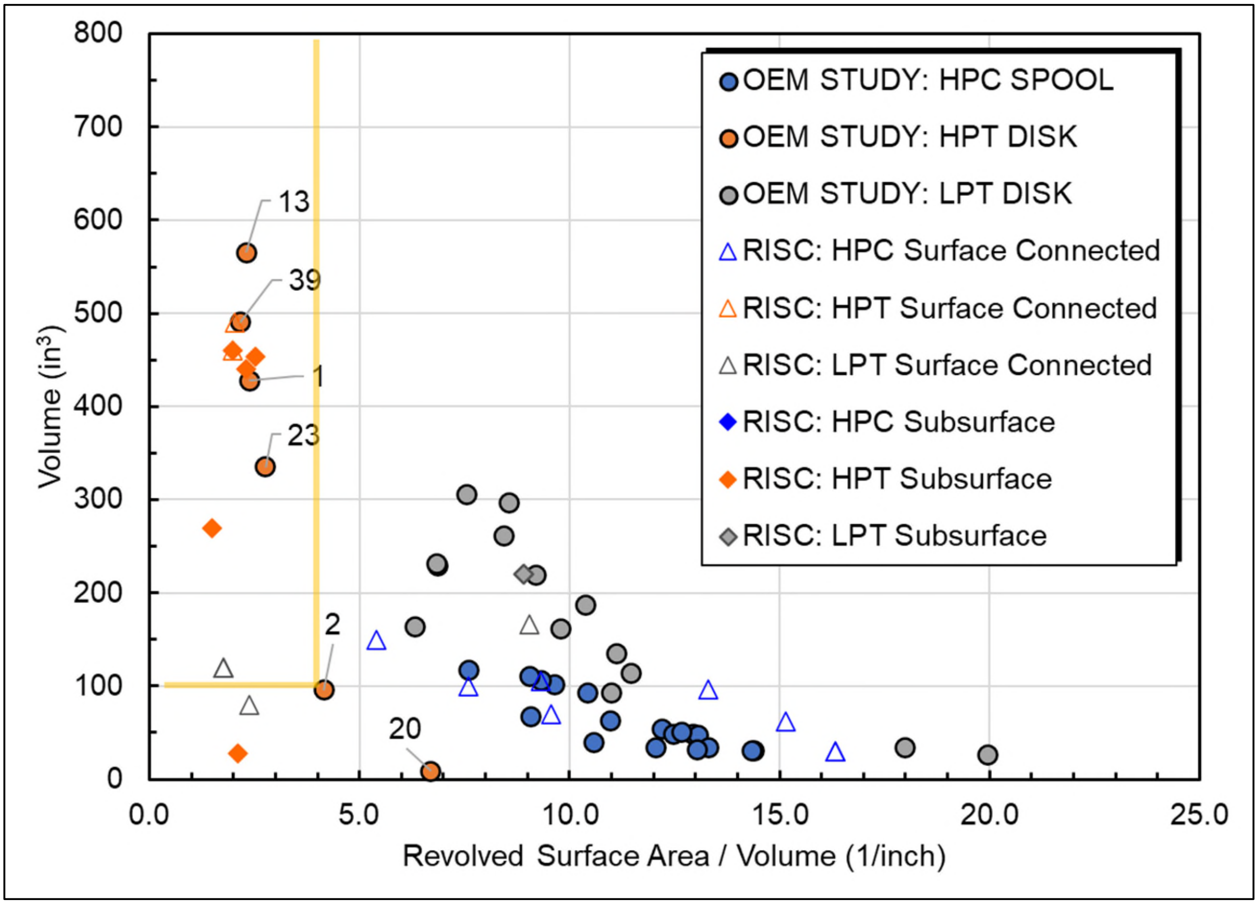


Figure 8. OEM Simulated Parts (From Figure 7) Overlaid Against RISC Find & Fracture Points

3.2 Recommendations Regarding In-Service Inspection of Rotating parts

As previously mentioned, the team tasking identified three objectives:

1. Evaluate whether in-service ultrasonic inspections should be recommended for critical high-energy, life-limited rotating parts. (Section 3.2.1 - Section 3.2.2)
2. Review current techniques, best practices, and practical challenges for sub-surface inspection implementation on finished machined hardware. (Section 3.3)
3. Provide guidance for how to evaluate an in-service UT implementation strategy and its benefits. (Section 3.4)

With part field experience established, the remainder of this report will focus on addressing these objectives.

This team has determined the focus of in-service, subsurface inspections should be directed towards finding cracks or voids within the evaluated parts. Current inspection technologies and approaches are well suited at finding cracks and voids. However, probabilities of detection (POD) fall precipitously for uncracked and unvoided anomalies. Damage tolerance design philosophies are in place within industry to protect against adverse outcomes from expected anomalies. This team believes in-service UT inspections may be useful for detecting rogue anomalies; those anomalies not known during design and certification. The anomalies likely to cause an issue will be contained in highly stressed volumes of disks with the weakest links cracked and voided first. The data in Table 3-2 indicates these locations are disk hubs.

PODs for rogue anomalies are not easily quantifiable and therefore the team has taken care to maximize the impact of any inspection by having scan overlaps and redundancies from different angles. This is considered an industry best practice.

The following sections provide the team's recommendations on in-service UT inspections.

3.2.1 Part Types for Effective Subsurface Inspections

The UT inspections that will provide the most significant impact to aircraft safety are those that:

1) Are applied to a disk of a particular size and geometry such that surface inspections miss a large portion of the disk volume and associated opportunity for an anomaly
2) Are applied to a disk most likely to cause hazard to the aircraft

Section 3.1 shows that the hub/bore of HPT disks provides the greatest overlap of these two criteria and for that reason are the focus for in-service UT inspection. The "Third CAAM Report" (CAAM3) [4] considers HPT and IPT disks as a single entity for hazard assessments and given the similar disk geometries and sizes, this team also recommends some IPT disks for in-service UT inspection. HPC disks/spools and LPT disks are well inspected using the surface inspection techniques currently employed.

For titanium alloys, monolithic large fan disks have a comparably low SA:V as HPT disks (SA:V < 4/inch). However, titanium fan and compressor disks have been through substantial design, melting, and inspection improvements due to industry efforts for hard alpha [3]. The demonstrated, significant improvement in material cleanliness and reduction in field events in titanium indicate that field UT inspections in titanium disks are less impactful than those in nickel. For example, no titanium part produced from melts since 1990 has caused a crack or fracture event due to a sub-surface melt anomaly. The most recent event in fan hubs was caused by titanium texturing, but an in-service UT inspection would not have prevented the event because it occurred prior to first shop visit opportunity. Additionally, large fan disks of high volume are generally configured with multiple deep bores or thin ligaments which make UT inspection of finished parts practically difficult or of little benefit.

While large blade carrying HPT disks and some IPT disks may benefit from an in-service UT inspection protocol, there may be instances where such inspections may be impractical or of limited value. The team has developed the following questions for evaluating such instances:

- *When does the OEM UT inspection of the raw material occur?* OEM UT inspection prior to completion of all thermal mechanical or thermal processing of the material is less desirable than inspection of the final material form. While UT inspection prior to the material final condition may apply more sensitive inspection requirements it may miss anomalies activated or opened during the final material processing after the UT inspection was performed. In such instances, in-service UT inspection may have higher benefit and should be evaluated further.
- *What are the other characteristics of the new make billet and forging inspections?* For example, some forgings may be designed in such a way as to maximize the inspection detection capability. Additionally, a more sensitive inspection or more limiting rejection threshold will correlate to a lower likelihood of an anomaly making its way into a fielded product.
- *Is an inspection on a particular part deemed feasible to conduct?* The geometric shape and condition of finished part surfaces, with machined features present may make inspections on a particular part or location impractical or even impossible.
- *Do subsurface anomalies drive part risk?* This may be true when:
    - Part SA:V < 4/inch.
    - Part overall volume is large enough that the likelihood of a detrimental anomaly (i.e., an anomaly type which may culminate in a part fracture event) is higher. Studies show that 100 in^3 may be a reasonable threshold.
    - A part has marginal or low damage tolerance to anomaly threats (e.g., rogue anomalies in powder metal). This is consistent with the expectations within AC 33.4-2 [5]. This AC states:

> *The incorporation of damage tolerance design methods acceptable to the Administrator enables a TC holder or applicant to evaluate the vulnerability of a safety critical part to anomaly threats. Therefore, TC holders who have designed or assessed safety critical parts using a damage tolerance design methodology may establish in-service inspections based on the part's damage tolerance characteristics and analyses.*

While the AC says that a TC holder or applicant “may establish in-service inspections based on the part’s damage tolerance characteristics”, it is also true that the TC holder or applicant *need not* establish in-service inspections based on damage tolerance characteristics. Sufficient damage tolerance, shown through deterministic or validated probabilistic models may be useful in demonstrating when an in-service inspection need not be applied.

3.2.2 Locations for Subsurface Inspection

Section 3.1 identified that the disk hub is the primary location that should be prioritized for inspection. Table 3-2 presents the overlap of parts with 1) a subsurface crack 2) a shop visit where an inspection would have been possible and 3) a crack believed to be detectable when in the shop. All the reported locations are within the disk hub.

3.3 Inspection Technique Recommendations

This section addresses the second request of the tasking letter. It will review current techniques, best practices, and practical challenges for sub-surface inspection implementation on in-service hardware.

3.3.1 Inspection Goals

The purpose of an in-service inspection is to find anomalies in engine disks that pose a risk to flight safety. Because new-make inspections are most capable of finding melt-related anomalies, in-service inspections are only expected to find anomalies resulting from field exposure. Therefore, the goal of the in-service inspection is the detection of cracks. Because surface-breaking cracks offer additional opportunities for detection, such as fluorescent penetrant or eddy current inspection, the purpose of in-service ultrasonic inspection techniques described below is further focused on sub-surface cracks.

The orientation of the cracks which the inspection is seeking is predictable. In the hub region, the first principal (crack opening) stress is typically in the hoop direction, so once initiated, the cracks will grow in the radial/axial plane. Other locations, such as a disk web, may have a dominant radial stress orientation, causing cracks to grow in the circumferential/axial plane. This document will focus on the detection of radial/axial cracks, but the same inspection principles could be applied to circumferential/axial cracks with a simple change to the orientation of the sound beam refracted angle used for the inspection.

The goal of recommending an inspection protocol is to describe a set of parameters for inspecting a disk, which have maximum sensitivity for detecting the sub-surface cracks described above. Recognizing that technologies and capabilities continue to evolve, the protocol described should only be viewed as a starting point. There may be elements of this protocol which can be exchanged with other parameters, achieving equivalent or superior sensitivities. In addition, new technology could be developed which offers equivalent or superior sensitivities. Such alternate and new technology should be accepted as a substitute protocol, given a suitable demonstration of equivalent or superior sensitivity, as discussed in Section 3.4.

While the above discussion refers to cracks as the primary target of interest for in-service inspections, the remainder of this section will refer to these more generally as "targets".

3.3.2 Review of Current and Enhanced Inspection techniques

Engine OEM's have experience with in-service ultrasonic inspection on rotating parts which can be used as a starting point for inspection technique recommendations. The goal of these inspections is to receive a maximized signal strength from a target. Two approaches used are pulse-echo and pitch-catch, and for either of those, the signal response can be described as a reflected echo from the target, or an amount of scattered energy from the target. Reflected echoes generally offer greater (more detectable) signal strengths, but that signal can only be detected from a narrow range of viewing angles. Scattered energy is distributed from a target across a wide range of angles, often making it a more reliable means of detection.

3.3.2.1 General Inspection Technique Selection

Pitch-catch uses two ultrasound transducers (also called probes) for inspection, one to transmit a sound beam into the part, and a second to receive signals reflected from a target. One example of this is shown in Figure 9. This example takes advantage of knowing that the crack has a radial/axial orientation, allowing the operator to accurately predict the sound path and place the receiving transducer in the optimum location to receive the detection signal. The robustness of this inspection can be increased by using an array receiver, which is more tolerant of variation in the depth of the target, yielding equally sensitive detections for a range of target depths and crack orientations.

This type of approach is effective for detecting radial/axial cracks in the center of the part thickness, where there are parallel surfaces to accommodate the transducers. More complex geometries can also be inspected by this approach using custom designed probes and inspection protocols. This can be implemented using either contact or immersion techniques.

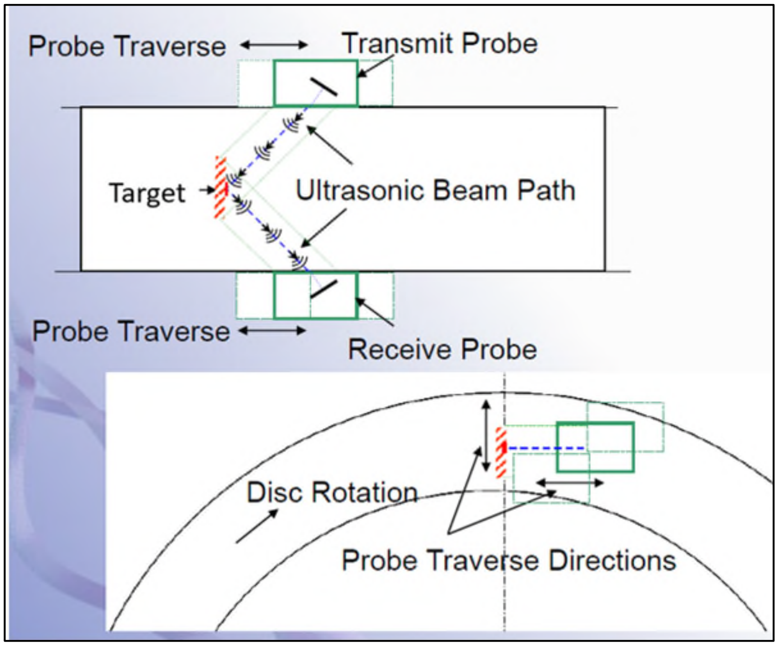


Figure 9. Pitch-catch Inspection Configuration

Pitch-catch approaches can also be designed to detect scattered energy. In this case the transducer does not need precise angular alignment to enable detection. Figure 10 shows one example of this. This can also work with the receiving transducer on the same surface as the transmitting transducer.

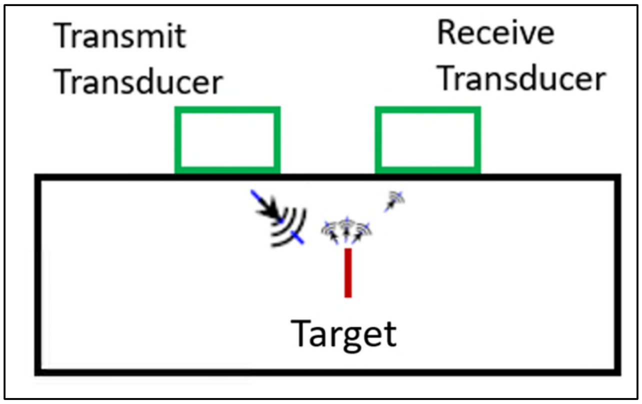


Figure 10. Example Of Pitch-catch Inspection Using Scattered Signal Energy

Immersion pulse-echo is a simplified version of a pitch-catch, where a single transducer is used for both transmitting and receiving the signal, as depicted in Figure 11. The pulse-echo approach has the advantage of being universally applicable to parts of varying geometries, including curvatures and thicknesses. Because of its broad applicability this technique will be the focus of the remaining discussion on inspection technique recommendation, although pitch-catch, array technology or other techniques could be equivalent and acceptable alternatives.

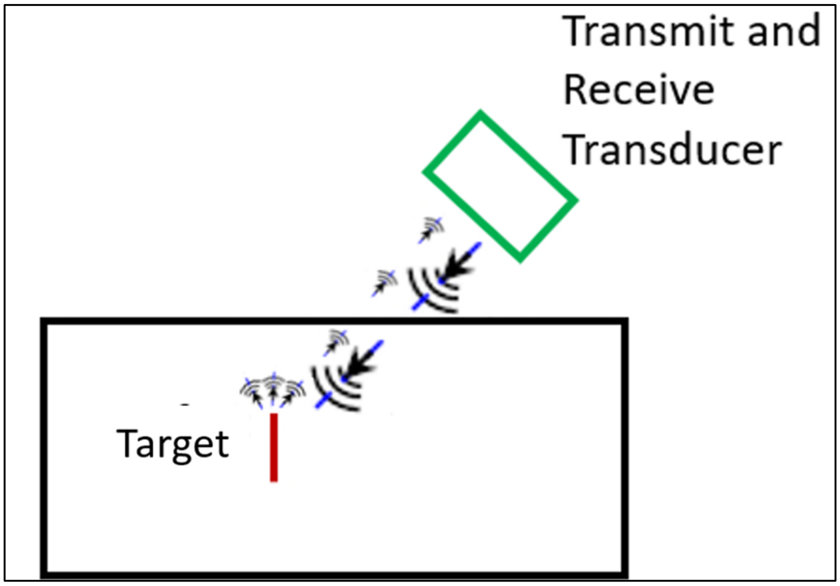


Figure 11. Pulse-echo Inspection Configuration

3.3.2.2 Transducer Selection

The most relevant transducer parameters to be selected for an inspection are frequency, focal length, and element diameter. A common in-service inspection configuration uses a 5 MHz transducer with a 6” (152mm) focal length, and a 0.75” (19 mm) element diameter, shown in Figure 12. For normal incidence inspections, a 10 MHz subsurface focus approach often achieves a higher sensitivity. However, a 10 MHz transducer does have a limitation of lower transmitted energy and a shorter depth range. An additional limitation in coarse grain materials is higher attenuation due to grain scattering, which is problematic when trying to detect the relatively weak scatter signals from crack tips. For angle inspections based on crack-tip-diffraction, a 5 MHz transducer often generates stronger scattered signals than a 10 MHz transducer. Although the scattering energy from small targets is low at any frequency, the lack of “noise” from the grain structure at 5 MHz allows this frequency to return a detectable signal from small (sub-wavelength) targets.

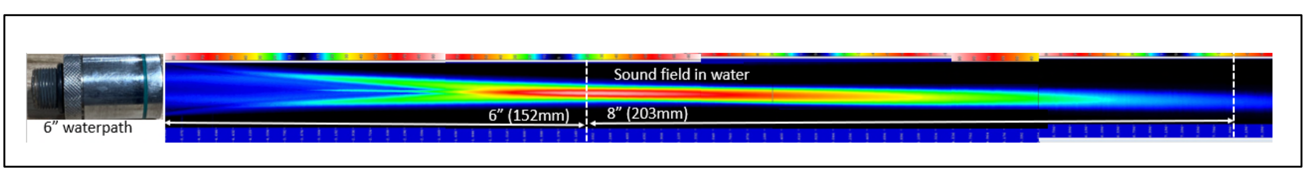


Figure 12. Commonly Used 5 MHz Transducer, Superimposed With Image of Sound Beam In Water

3.3.2.4 Incident Angle Selection

The highest sensitivity is typically observed when the sound beam is oriented perpendicular to the plane of the crack. For a radial/axial crack, the best sound beam orientation would be in the hoop direction, which is impossible for a fully intact part. The preferred sound beam orientation therefore is an angle as close as possible to the hoop direction, which would require the sound beam be inserted into the component with a circumferential incident angle, (See Figure 13). Due to the likelihood of detecting the scatter response rather than reflected response and due to the irregular shape of a crack, more than one angle should be applied to increase the number of opportunities to find the optimal response. The angles to be considered for a radial/axial crack vary only in the circumferential direction. Because a naturally occurring crack is likely to meander to a certain degree, any incident angle selected should be applied in both clockwise and counterclockwise directions. In addition, redundancy of scans from several surfaces of the part, if allowed by geometry and access, could also increase likelihood of detection.

A scan strategy can be devised such that the sound beam will provide a reflection response from a full range of angles. One option is the set of positive and negative angles shown in Figure 14. This set of scans can detect anomalies at any orientation up to 80°. This is demonstrated in Figure 15 and Figure 16 where a set of targets having a range of angles from 0° to 45° are inspected from the first three angles of incidence and overlapping detection sensitivity is observed.

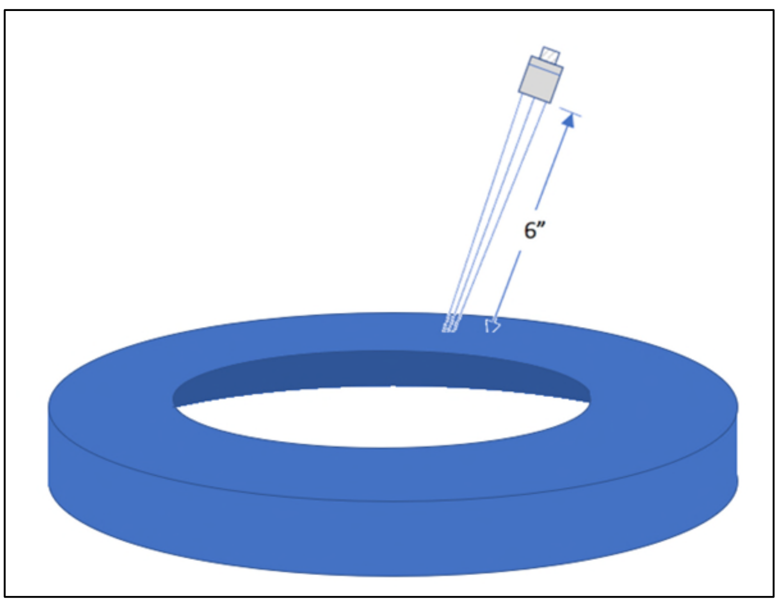


Figure 13. 19° Counterclockwise Circumferential Angle of Incidence Used For 45° Shear Inspection

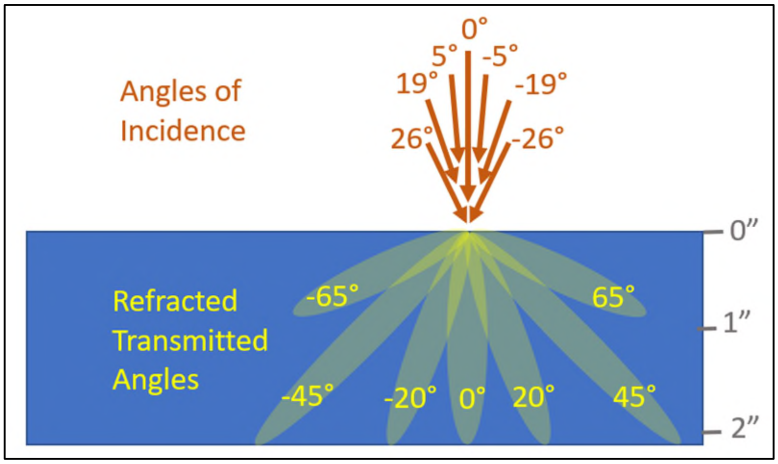


Figure 14. Visual Representation of Sound Beams Covering the Full Range of Angles

Figure 15 shows a diagram of a sensitivity test block, with targets in multiple locations. Each sample contains 4 round bottom holes to act as scattering targets. Angled targets were also included to show sensitivity tradeoffs as a function of sound beam incidence angle. These targets were created at two sizes: #4 (4/64" dia., 1.6mm dia.) to act as a large reflecting surface, and #1 size (1/64" dia., 0.4mm dia.) to demonstrate sub-wavelength response behaviors, potentially as scattering targets. Two samples were made so that the same targets could be tested in a shallow zone (0.25", 6 mm) and a deep zone (1.0", 25mm). These test blocks were fabricated from 303 series steel for rust-resistance, ease of machining, and an acoustic velocity and impedance that are similar to nickel alloys. The drawback of using this material is that the grain structure is coarser than that of most nickel forgings of interest.

Note that the preferred point of comparison between these images is the ability to discern the target signal above the noise background in the material, termed the Signal to noise ratio (SNR). If a signal does not have a high SNR, no amount of signal processing can enable detection. If a target does have a high SNR, the threshold or signal amplification can be adjusted to enable an optimal acceptance criterion. See Section 3.3.3.4 for more information on a common practice for measuring SNR.

Other angles could be selected to fine tune the cutoffs between scans, but it should be noted that incident angles between 8° and 14° offer low penetration energy for both longitudinal and shear scans. Likewise, incidence angles above 22° offer increasingly diminished depth of penetration. Such factors need to be considered when adjusting incident angles.

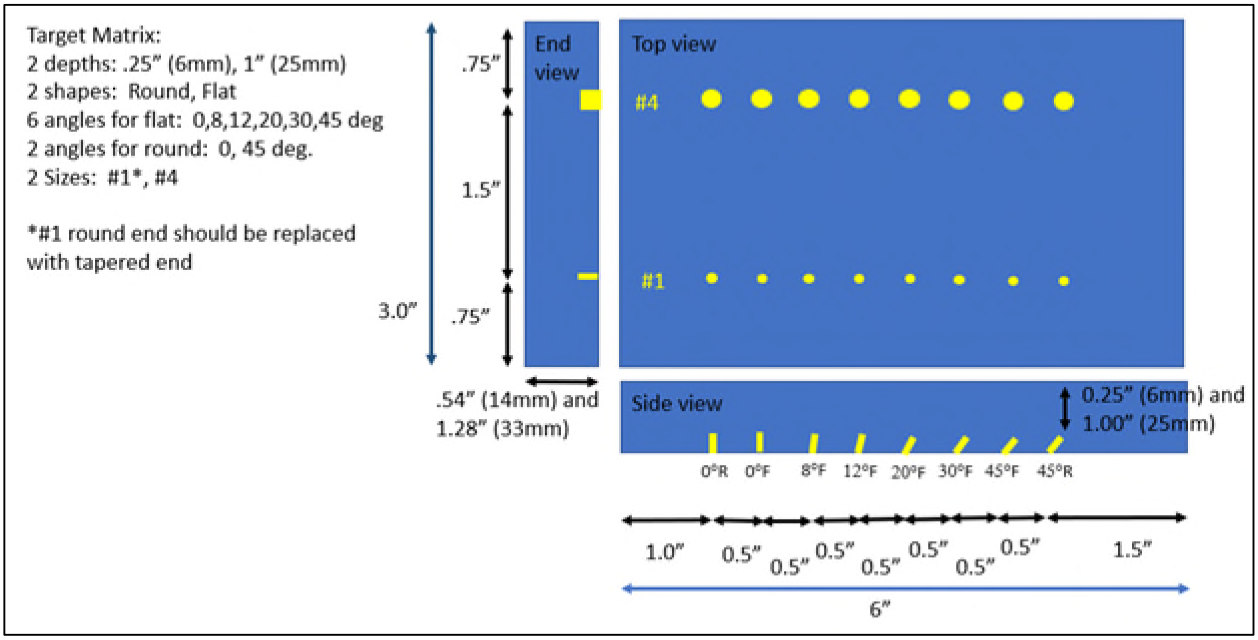


Figure 15. Sketch of Sensitivity Test Block

Transducer:
5 MHz
6" (152 mm) Focal Length
0.75" (19 mm) Diameter
6" (152 mm) Waterpath

	Percent Amplitude			SNR		
Target	0° Long. 6"Wp G=60dB	20° Long. 6"Wp G=60 dB	45° Shear 6"WP G=60dB	0° Long. 6"Wp	20° Long. 6"Wp	45° Shear 6"WP
#4 RBH 0°	33.4	22.2	22.5	7.7	8.1	6.4
#4 FBH 0°	105.0	9.9		25.9	3.2	
#4 FBH 8°	100.0	27.1		24.6	10.1	
#4 FBH 12°	85.0	45.0		20.8	17.3	
#4 FBH 20°	35.0	79.0	10.5	8.1	31.0	2.3
#4 FBH 30°	15.2	85.0	17.5	3.1	33.5	4.7
#4 FBH 45°	12.5	23.4	110.0	2.4	8.6	36.2
#4 RBH 45°	26.3	25.4	22.8	5.9	9.4	6.5

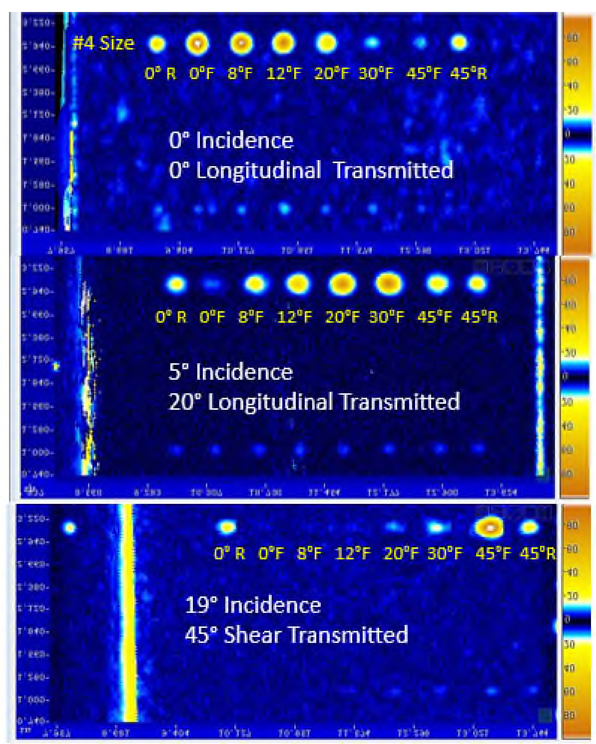


Figure 16. Amplitude and SNR for #4 Size Targets in the Sensitivity Test Block Targets Are Located at a Depth of 1.0” (25mm). Green highlighted values in Table are the highest signal for each target. Amplitudes over 100% are saturated and values shown are likely lower than the true amplitudes.

3.3.2.5 Multi-zone Inspection

Placing the focal spot of the transducer’s sound beam subsurface is an inspection strategy which can boost signal strength for increased sensitivity. Energy is intensified for targets deep below the surface (increases detection) when pushing the focus subsurface. This benefit was demonstrated by the Engine Titanium Consortium (ETC) in the early 1990’s for use in titanium billets [6]. To ensure optimal sensitivity at all depths, multiple depth zones are needed, which corresponds to scanning at multiple water paths.

The depth of field of the 5 MHz, 6 inch (152mm) focal length transducer allows for a single scan to cover a depth range of 1” (25mm). Historic inspection practices have demonstrated that using this transducer at a 6” (152 mm) water path is effective at inspecting the volume from near front surface to 1” (25mm) depth. Figure 17 provides a conceptual view of how such a setup results in the high intensity portion of the sound beam near the surface of the component. Note that this Figure should not be considered authoritative because it uses a beam profile obtained in water, then rotating and reducing beam lengths for subsurface sound fields. This view does not account for aberration due to increasing refracted angles.

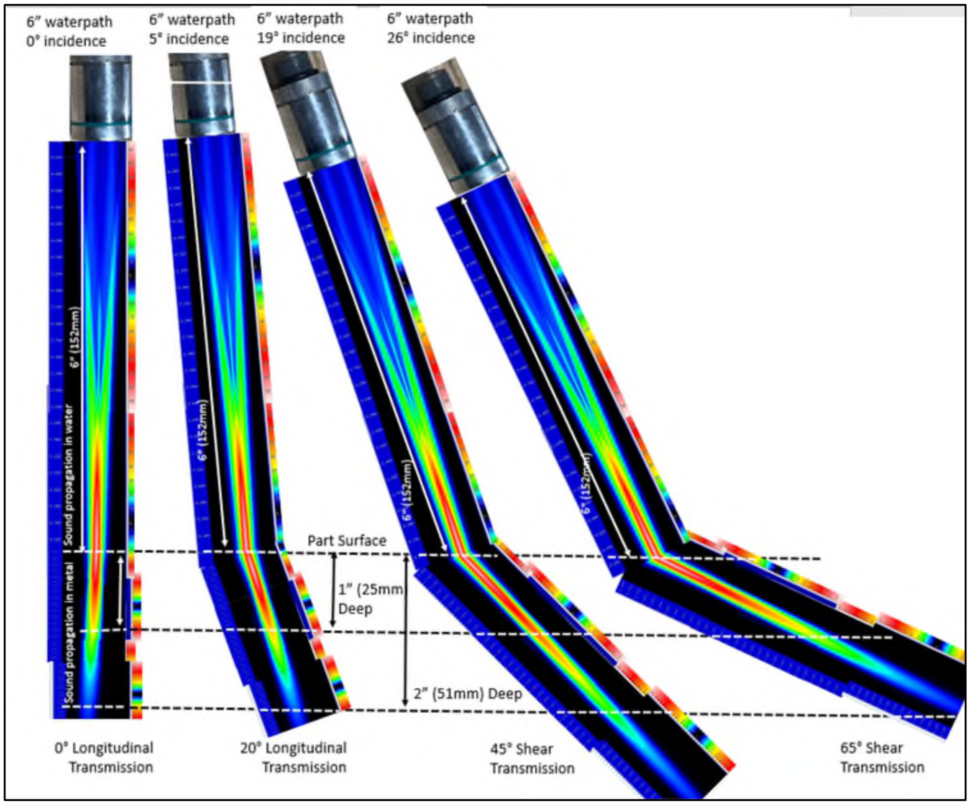


Figure 17. Conceptual View Showing Subsurface Reach of Sound Beam At 6" (152mm) Water Path

The scan performed at the 6" (152mm) water path would be considered effective for delivering sound to shallow targets, thus could be used as the first (shallowest) zone setup. The ability of the sound beam to deliver energy to these shallow targets as a function of incidence angle is shown in Figure 18. In those scans, the targets are the same as those described in Figure 15, except at 0.25" (6mm) depth.

Transducer:
5 MHz
6” (152 mm) Focal Length
0.75” (19 mm) Diameter
6” (152 mm) Waterpath

	Percent Amplitude				SNR			
Target	0° Long. 6"Wp G=52 dB	20° Long. 6"Wp G=52 dB	45° Shear 6"WP G=52 dB	65° Shear 6"WP G=52 dB	0° Long. 6"Wp	20° Long. 6"Wp	45° Shear 6"WP	65° Shear 6"WP
#1 RBH 0°	11.0	7.9		4.0	2.6	3.0		1.6
#1 FBH 0°	10.8	8.9			2.5	3.4		
#1 FBH 8°	9.8	10.4	6.9		2.2	4.1	2.6	
#1 FBH 12°	10.0	10.2	7.2	4.2	2.2	4.0	2.7	1.7
#1 FBH 20°	9.8	9.6		3.8	2.2	3.8		1.4
#1 FBH 30°	8.8	9.5	13.2	5.6	1.8	3.7	6.0	2.7
#1 FBH 45°	7.2	8.4	13.5	10.0	1.3	3.2	6.2	5.9
#1 RBH 45°	0.0	8.0	9.9	6.8	0.0	3.0	4.2	3.6
#4 RBH 0°	24.0	31.0	34.3	12.7	6.8	13.6	17.5	7.8
#4 FBH 0°	100.0	29.0	6.8	5.9	31.9	12.7	2.5	2.9
#4 FBH 8°	94.6	73.5	8.3	4.1	30.1	33.1	3.3	1.6
#4 FBH 12°	70.0	85.8	9.6	5.1	22.0	38.7	4.0	2.4
#4 FBH 20°	25.2	100.0	11.6	5.7	7.2	45.2	5.1	2.8
#4 FBH 30°	13.1	67.8	33.6	5.6	3.2	30.4	17.1	2.7
#4 FBH 45°	11.3	14.6	120.0	21.8	2.7	6.0	64.0	14.4
#4 RBH 45°	25.4	28.7	34.7	20.2	7.3	12.5	17.7	13.2

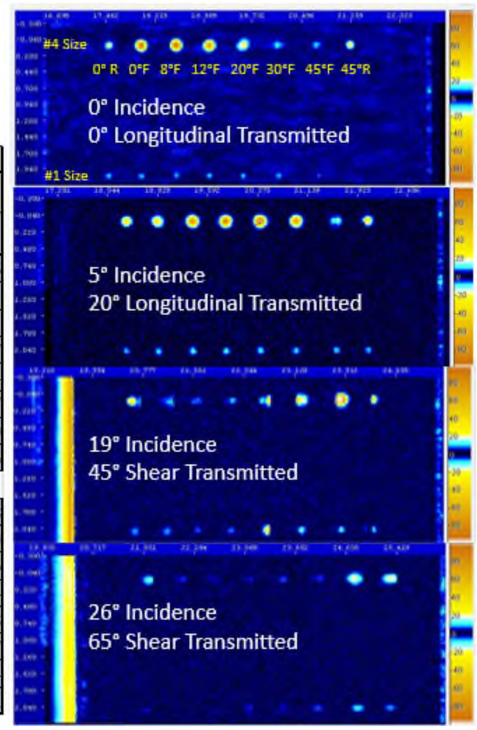


Figure 18. Amplitude And SNR Of Targets 0.25” (6mm) Deep in Sensitivity Test Block
Green highlighted values in table are the highest signal for each target. Amplitudes over 100% are saturated and values shown are likely lower than the true amplitudes.

Adding a scan with a water path less than the transducer’s focal length can enhance sensitivity for deeper targets. An effective setup can be achieved by using the same transducer as above, except with a 2” (51mm) water path. Figure 19 shows a sketch of the transducer setup relative to a component being inspected. Figure 20 provides a conceptual view of how such a setup results in the delivering the high intensity portion of the sound beam to depths between 1” (25mm) and 2” (51mm) below the surface of the component. Again, this figure should not be considered authoritative because it does not fully replicate the effect of refraction. Also note that the 26° incidence (65° refracted shear) is not included in this set because the refraction disrupts the sound beam at such high angles.

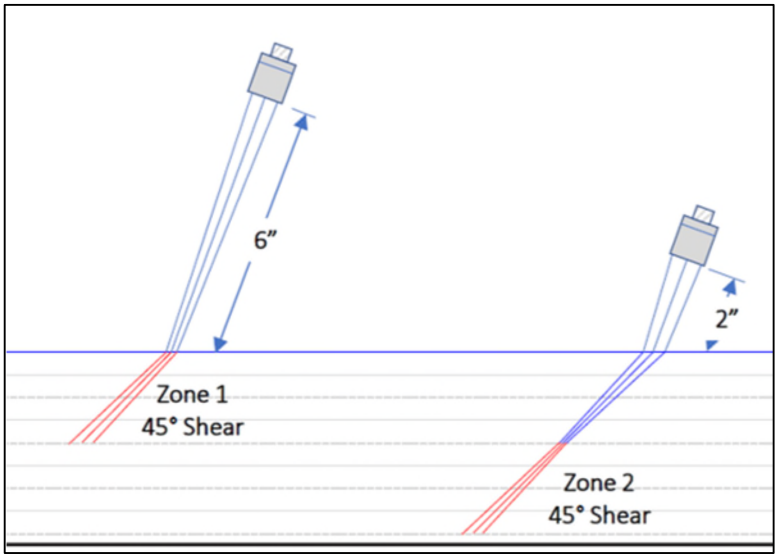


Figure 19. Sketch Of Transducer Arrangement for A Two-Zone Inspection of A Component

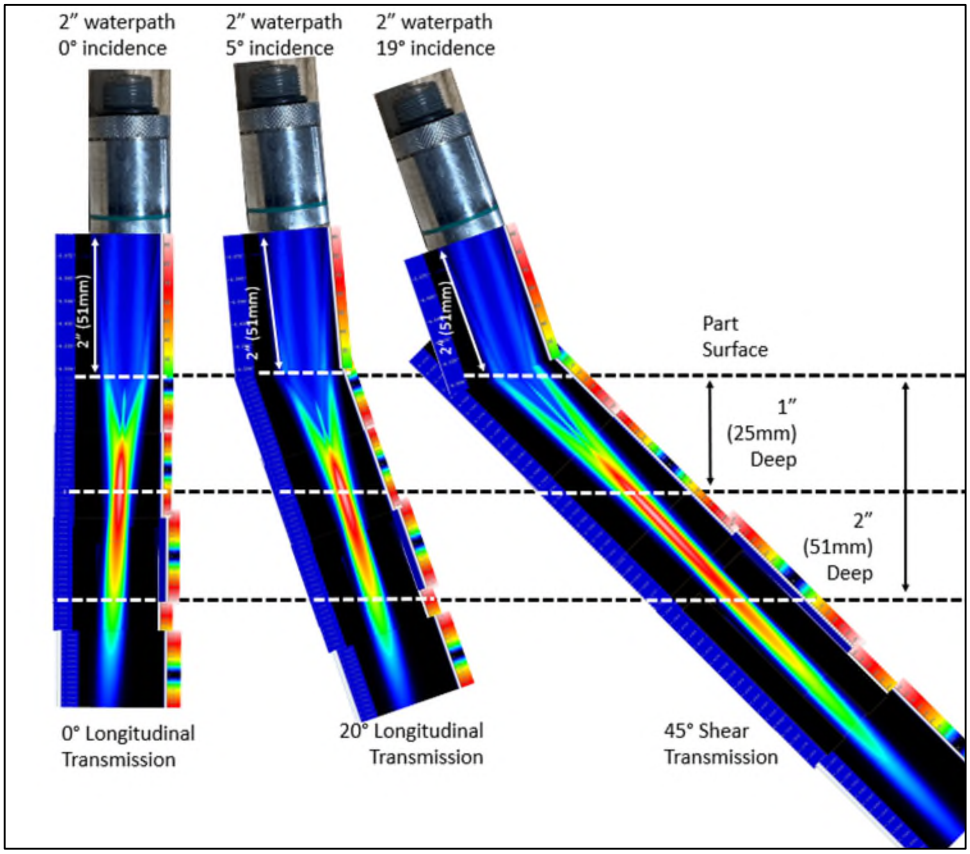
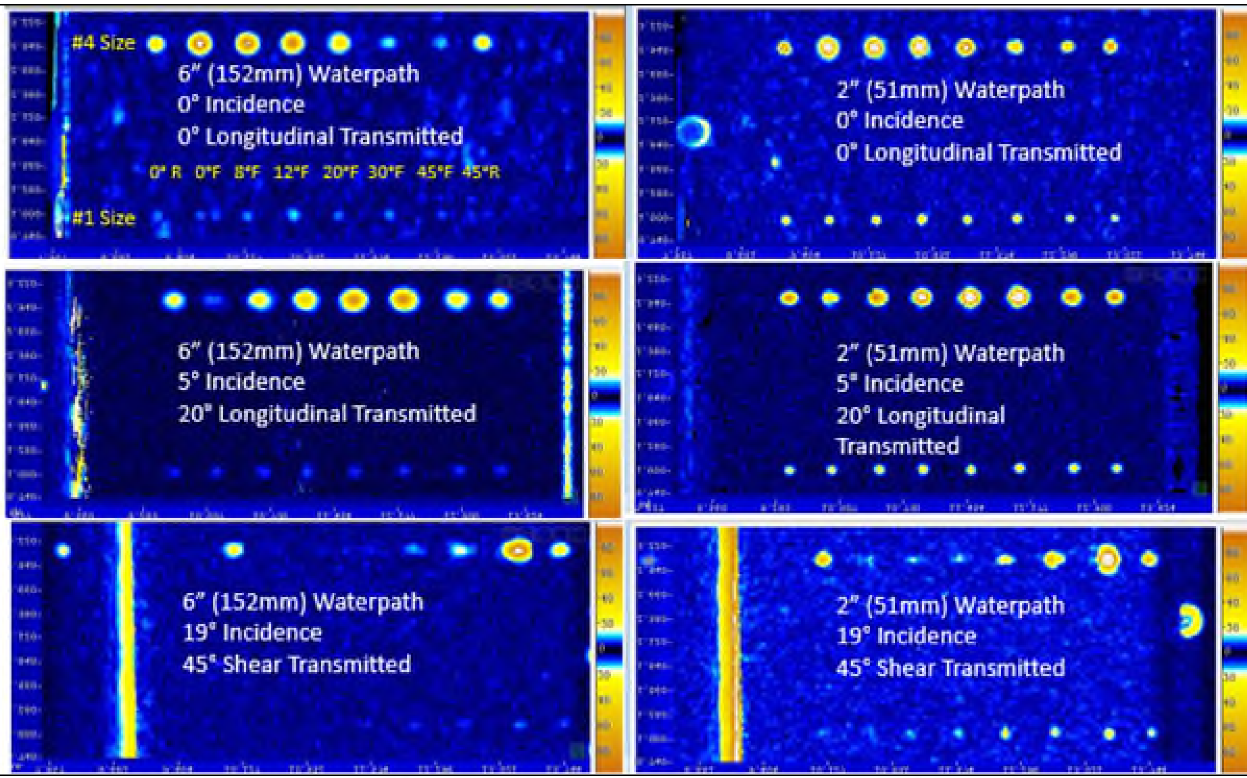


Figure 20. Conceptual View Showing Subsurface Reach of Sound Beam At 2" (51mm) Water Path

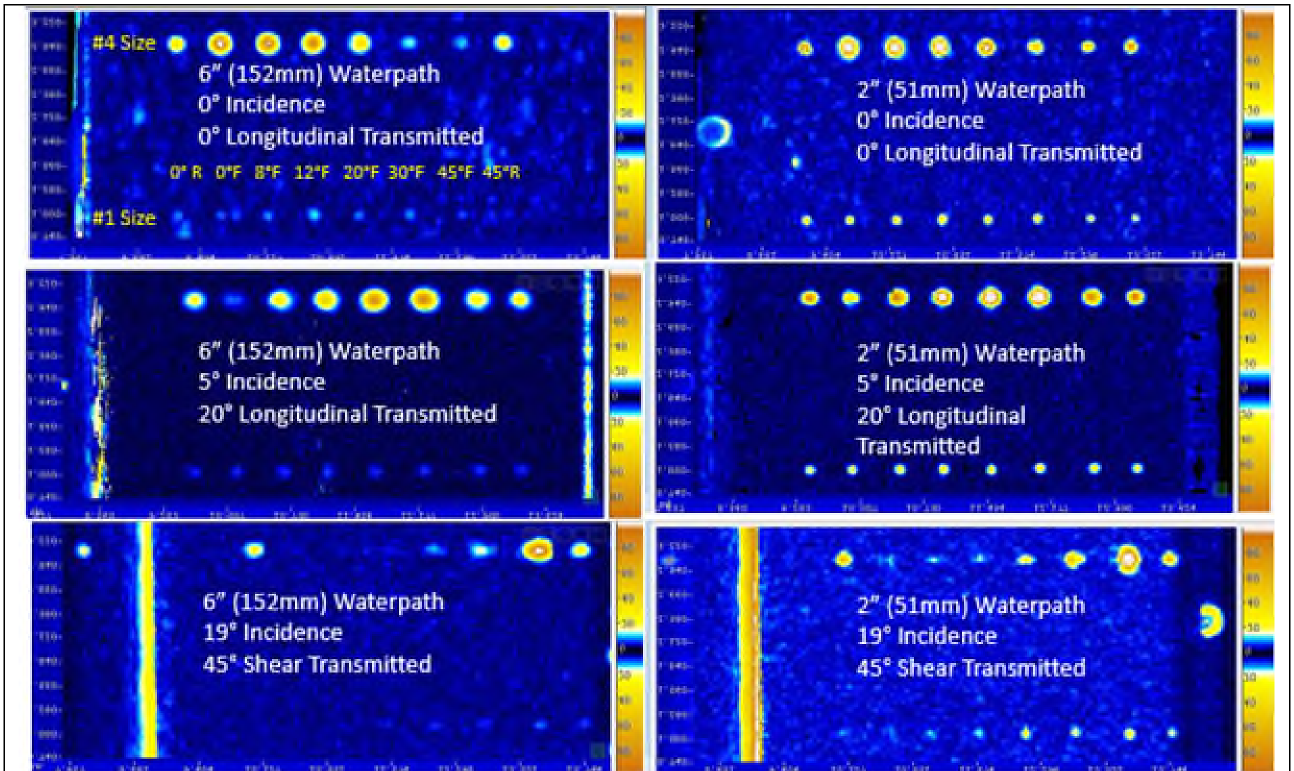


Transducer:
5 MHz
Focal Length:
6″ (152 mm)
Diameter :
0.75″ (19 mm)
Waterpath:
6″ (152 mm) and
2″ (51 mm)

	Percent Amplitude			Percent Amplitude			SNR			SNR		
Target	0° Long. 6″Wp G=60dB	20° Long. 6″Wp G=60 dB	45° Shear 6″WP G=60dB	0° Long. 2″ WP G=60dB	20° Long. 2″ WP G=60dB	45° Shear 2″ WP G=60dB	0° Long. 6″Wp	20° Long. 6″Wp	45° Shear 6″WP	0° Long. 2″Wp	20° Long. 2″Wp	45° Shear 2″WP
#1 RBH 0°	9.6	6.7		31.3	20.6	11.0	1.6	1.9		6.9	5.9	1.0
#1 FBH 0°	9.2	9.8		31.5	24.1	8.2	1.5	3.1		6.9	7.0	0.4
#1 FBH 8°	10.0	6.9		31.7	25.6	14.4	1.7	2.0		7.0	7.5	1.7
#1 FBH 12°	12.0	7.7		34.4	29.4	14.1	2.3	2.3		7.6	8.8	1.6
#1 FBH 20°	9.1	7.0		31.4	27.3	19.1	1.5	2.0		6.9	8.1	2.6
#1 FBH 30°	9.3	7.3		31.6	26.7	21.9	1.6	2.1		6.9	7.9	3.2
#1 FBH 45°	7.3	7.3		23.4	25.3	26.6	1.1	2.1		5.0	7.4	4.1
#1 RBH 45°	6.2	6.6		21.0	23.0	19.7	0.8	1.8		4.4	6.7	2.7
#4 RBH 0°	33.4	22.2	22.5	100.0	84.1	57.9	7.7	8.1	6.4	23.4	26.8	10.4
#4 FBH 0°	105.0	9.9		110.0	38.2	10.7	25.9	3.2		25.8	11.7	0.9
#4 FBH 8°	100.0	27.1		110.0	95.0	14.7	24.6	10.1		25.8	30.3	1.7
#4 FBH 12°	85.0	45.0		110.0	110.0	15.0	20.8	17.3		25.8	35.3	1.8
#4 FBH 20°	35.0	79.0	10.5	100.0	120.0	25.9	8.1	31.0	2.3	23.4	38.6	4.0
#4 FBH 30°	15.2	85.0	17.5	51.0	120.0	55.3	3.1	33.5	4.7	11.6	38.6	9.9
#4 FBH 45°	12.5	23.4	110.0	46.0	88.7	100.0	2.4	8.6	36.2	10.4	28.3	18.8
#4 RBH 45°	26.3	25.4	22.8	86.0	90.6	60.0	5.9	9.4	6.5	20.0	28.9	10.8

Figure 21. Amplitude and SNR of Targets 1.0” (25mm) Deep In Sensitivity Test Block For Scans At Two Water Paths
Green highlighted values in table are the highest signal for each target. Amplitudes over 100% are saturated and values shown are likely lower than the true amplitudes.

The deep zone setup having the 2” (51 mm) water path is demonstrated using the sensitivity test block of Figure 15.



Transducer:
5 MHz
Focal Length:
6” (152 mm)
Diameter :
0.75” (19 mm)
Waterpath:
6” (152 mm) and
2” (51 mm)

	Percent Amplitude			Percent Amplitude			SNR			SNR		
Target	0° Long. 6"Wp G=60dB	20° Long. 6"Wp G=60 dB	45° Shear 6"WP G=60dB	0° Long. 2" WP G=60dB	20° Long. 2" WP G=60dB	45° Shear 2" WP G=60dB	0° Long. 6"Wp	20° Long. 6"Wp	45° Shear 6"WP	0° Long. 2"Wp	20° Long. 2"Wp	45° Shear 2"WP
#1 RBH 0°	9.6	6.7		31.3	20.6	11.0	1.6	1.9		6.9	5.9	1.0
#1 FBH 0°	9.2	9.8		31.5	24.1	8.2	1.5	3.1		6.9	7.0	0.4
#1 FBH 8°	10.0	6.9		31.7	25.6	14.4	1.7	2.0		7.0	7.5	1.7
#1 FBH 12°	12.0	7.7		34.4	29.4	14.1	2.3	2.3		7.6	8.8	1.6
#1 FBH 20°	9.1	7.0		31.4	27.3	19.1	1.5	2.0		6.9	8.1	2.6
#1 FBH 30°	9.3	7.3		31.6	26.7	21.9	1.6	2.1		6.9	7.9	3.2
#1 FBH 45°	7.3	7.3		23.4	25.3	26.6	1.1	2.1		5.0	7.4	4.1
#1 RBH 45°	6.2	6.6		21.0	23.0	19.7	0.8	1.8		4.4	6.7	2.7
#4 RBH 0°	33.4	22.2	22.5	100.0	84.1	57.9	7.7	8.1	6.4	23.4	26.8	10.4
#4 FBH 0°	105.0	9.9		110.0	38.2	10.7	25.9	3.2		25.8	11.7	0.9
#4 FBH 8°	100.0	27.1		110.0	95.0	14.7	24.6	10.1		25.8	30.3	1.7
#4 FBH 12°	85.0	45.0		110.0	110.0	15.0	20.8	17.3		25.8	35.3	1.8
#4 FBH 20°	35.0	79.0	10.5	100.0	120.0	25.9	8.1	31.0	2.3	23.4	38.6	4.0
#4 FBH 30°	15.2	85.0	17.5	51.0	120.0	55.3	3.1	33.5	4.7	11.6	38.6	9.9
#4 FBH 45°	12.5	23.4	110.0	46.0	88.7	100.0	2.4	8.6	36.2	10.4	28.3	18.8
#4 RBH 45°	26.3	25.4	22.8	86.0	90.6	60.0	5.9	9.4	6.5	20.0	28.9	10.8

Figure 21 compares sensitivity for 1” deep targets at two water paths. The shorter water path offers significantly higher SNR than the larger water path at this target depth. It can also be seen that the 0° incidence scan offers larger signal amplitudes, but the 5°

incidence scan offers significantly greater SNR values. Finally, from this comparison, it is evident that the #4 size targets are acting as reflectors, showing improved responses when the sound angle of incidence matches the target angle. The smaller, #1 size targets, on the other hand are acting as scatterers for the longitudinal scans, since the signal strength is similar, regardless of the orientation angle or shape (round vs. flat) of the target. This is not the case for the shear scans, because the shear wavelength is shorter than the longitudinal wavelength.

One more demonstration of detection capability was obtained for a set of 45° flat-bottom holes (FBHs), 2” (51mm) deep in a titanium sample. This sample was chosen because it had targets at the bottom of the deep zone, which had been historically difficult to detect. The inspection results are shown in Figure 22, demonstrating the superior performance of the 5° incidence, deep zone scan.

Tests for inspection depths greater than 2” (51mm) have not been performed. It is recommended to inspect a component using all accessible surfaces to limit inspection depths to 2” (51mm) or less. If not possible, the configuration for 1” to 2” deep zone with an extended data gate could be used to inspect to greater depths.

Curvature of the region also needs consideration when selecting the zones. The reduced water path of the second zone has an interaction with surface geometry which disrupts the focus. Regions with a concave diameter less than 20” (508mm) should be viewed as problematic, Zone 2 scans may offer less sensitivity than using a Zone 1 water path with a Zone 2 data gate.

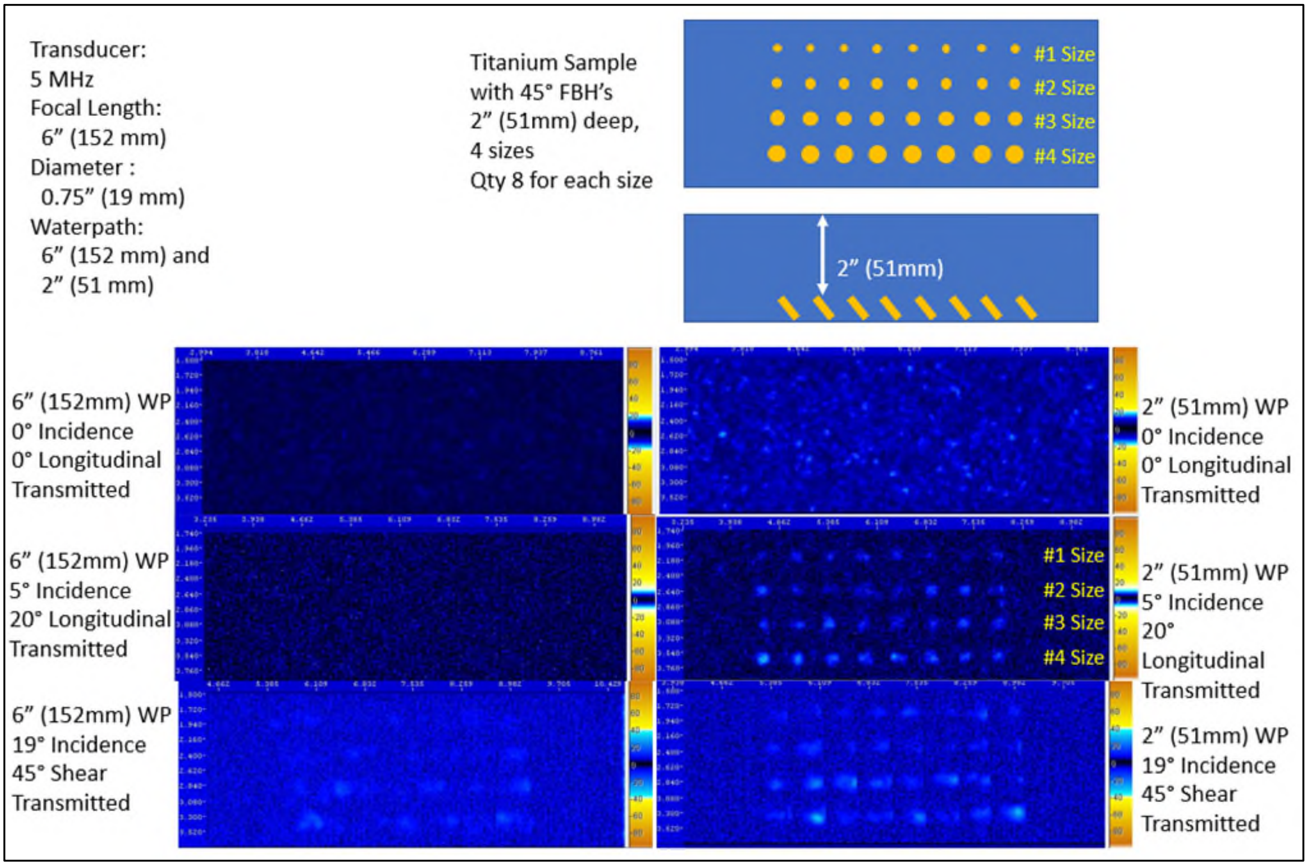


Figure 22. Scan of 45° FBH Targets 2.0" (51mm) Deep in Sensitivity Test Block for Scans at Two Water Paths

Table 3-5. Amplitudes for Figure 22 scan showing 45° FBH targets 2.0” (51mm) deep in sensitivity test block, for scans at two water paths
Green highlighted values in this table are the highest signal for each target.

Amplitudes					SNRs		
Size	Hole Col.	45° Shear 6"WP G=70dB	20° Long. 2" WP G=70dB	45° Shear 2" WP G=70dB	45° Shear 6"WP G=70dB	20° Long 2" WP G=70dB	45° Shear 2" WP G=70dB
	P	14.6	14.6	4.6			
	u	6.32	5.86	2.24			
#1	1	12.4	13.8	5.6	0.7	0.9	1.4
#1	2		14.1	5.3		0.9	1.3
#1	3			4.7			1.0
#1	4		16.7	5.5		1.2	1.4
#1	5		12.9	4.7		0.8	1.0
#1	6		13.5	5.7		0.9	1.5
#1	7		15.5	4.4		1.1	0.9
#1	8	14.4	14	4.4	1.0	0.9	0.9
#2	1		18.5	6.3		1.4	1.7
#2	2	14.6	19.7	5.2	1.0	1.6	1.3
#2	3	14	19.1	4.3	0.9	1.5	0.9
#2	4		18.5	5.4		1.4	1.3
#2	5	14.2	13.8	4	1.0	0.9	0.7
#2	6	13.1	15.2	5.1	0.8	1.1	1.2
#2	7	14.7	19.4	5.5	1.0	1.5	1.4
#2	8	14.8	20	6.2	1.0	1.6	1.7
#3	1	13.8	15.2	5.1	0.9	1.1	1.2
#3	2	21	27.4	5.5	1.8	2.5	1.4
#3	3		17.6	6.2		1.3	1.7
#3	4		16.1	5.1		1.2	1.2
#3	5		17.4	5.1		1.3	1.2
#3	6	13.7		4.5	0.9		1.0
#3	7	12.9	15.3	6.9	0.8	1.1	2.0
#3	8	13	23.4	4.6	0.8	2.0	1.0
#4	1	13.6	16	7.4	0.9	1.2	2.2
#4	2	22.1	13.7	7.4	1.9	0.9	2.2
#4	3		19.4	6		1.5	1.6
#4	4		12.8	5.7		0.8	1.5
#4	5	13.3	14.7	7.3	0.8	1.0	2.1
#4	6	15.5	20.6	6.7	1.1	1.7	1.9
#4	7	17.1	13.8	5.1	1.3	0.9	1.2
#4	8	15.4	20.8	5.8	1.1	1.7	1.5

3.3.2.6 Summary of benefits and drawbacks of refracted angle scans

The results described above are instrumental for selecting an inspection protocol. Although the targets tested thus far are not radial/axial cracks, they do demonstrate that sound energy is being delivered to the depths of interest. If a target offers reflected sound energy, the described angles and zones are effective in picking up that energy.

Furthermore, the demonstration that #1 size targets act as scatterers for 5 MHz longitudinal waves suggests that cracks (which are also expected to scatter sound rather than reflect) will also be effectively detected.

The key strengths of the 20° refracted longitudinal scan are

- It uses the longer longitudinal wavelength (compared to shear wavelength) to produce the scattering response for the small targets
- It pushes the angle slightly towards the radial/axial orientation for favorable response from cracks.
- The angle of incidence is low enough that the refraction of the entire sound beam is well-behaved, meaning the beam retains its focal properties at reduced water paths

Because the 0° longitudinal scan offers degraded SNR responses for scatterers, and because it is oriented furthest from normal to the expected plane of the crack, it is expected to offer no additional detection capability over the 20° refracted longitudinal scan.

The 45° shear scan orients the sound beam closer to normal to the plane of the radial/axial crack, so it is believed to offer capability beyond that of the 20° refracted longitudinal scan in many situations. This capability diminishes with depth, however, because the non-linearity of refraction angle compared to incidence angle distorts the sound beam. For this reason, the 20° refracted longitudinal scan offers complimentary capability for depths over 1.0” (25mm).

The 65° shear scan orients the sound beam closest to normal to the plane of the radial/axial crack, so it is believed to offer superior capability for radial/axial crack detection. Its drawback is that it is only effective for near surface targets due to the aberration from Snell’s Law at such large angles. Cutoff depths for this scan are typically set between 0.25 to 0.5”, depending on the grain structure of the component being tested.

3.3.3 Description of Baseline In-Service Inspection Configuration

3.3.3.1 Setup Parameters

Given the prior discussion, the baseline inspection recommended by the AIA 18-004 team includes the following parameters which are also shown in Figure 23 and Table 3-6. The listed parameters represent the baseline inspection, but alternatives are allowed depending on constraints unique to particular components, and as justified by sensitivity validation tests.

- The baseline transducer is 5 MHz, 6” (152 mm) FL, 0.75” (19mm) dia.

- Inspected volume should be divided into zones: roughly 0” to 1” (0 to 25 mm) deep and 1” to 2” (25 to 51 mm) deep,
    - o shallow zone is inspected using a 6” (152mm) water path (alternatively, set water path to the true focal length of the chosen transducer),
    - o deep zone is inspected with a 2” (51mm) water path.
- Incident angles to be used for the shallow zone are approximately
    - o 19° to generate a 45° shear scan
        - ▪ A special gate is used for this scan: gate should cover both near zone and deep zone depths.
    - o 26° to generate a 65° shear scan
- Incident angles for the deep zone are approximately
    - o 5° to generate a 20° longitudinal scan
    - o 19° to generate a 45° shear scan
- Scan angles are applied in both the clockwise and counterclockwise directions for radial/axial crack detection

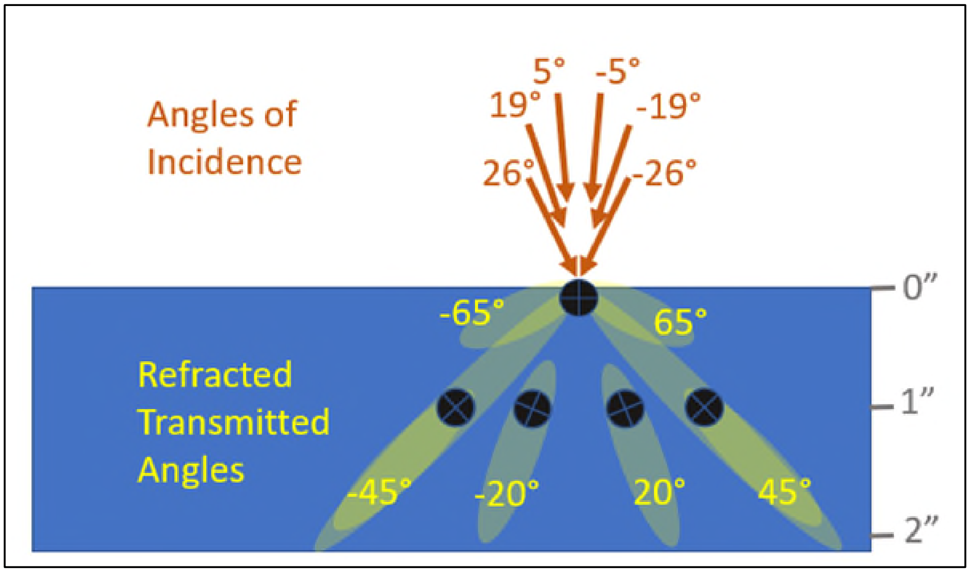


Figure 23. Conceptual Representation of Sound Beams Recommended For In-Service Inspection of Disks
Black circles represent placement of focus (Shallow or deep), yellow ovals represent approximate reach of sound beam.

Table 3-6. Scan Parameters

	Transducer			Position		Gate	
Conceptual Zone and Depth Range	Frequency (MHz)	Focal length [in, (mm)]	Diameter [in, (mm)]	Refracted Angle (deg)	Water path [in, (mm)]	Gate Start [in, (mm)]	Gate End [in, (mm)]
Zone 1 Near Surface to 1.0" (25mm)	5	6 (152)	.75 (19)	45° Shear	6 (152)	Near Surf.	2.1 (53)
	5	6 (152)	.75 (19)	65° Shear	6 (152)	Near Surf.	0.45 (11)
Zone 2 1.0" (25mm) to 2.0" (51mm)	5	6 (152)	.75 (19)	20° Long.	2 (51)	0.75 (19)	2.1 (53)
	5	6 (152)	.75 (19)	45° Shear	2 (51)	0.9 (23)	2.1 (53)

3.3.3.2 Calibration

Baseline calibration can be performed using side-drilled holes (SDH) because a single set of targets can be used for all angles of inspection. A Distance-Amplitude Correction (DAC) curve should be setup so the SDH's at all relevant depths are at 80% Full Scale Height (FSH). Alternatively, DAC can be setup using flat-bottom holes (FBH). This enables an easier protocol for indication sizing but requires a separate calibration set for each angle. An alternative DAC can be used which sets typical noise levels at 15% to 20% FSH. The latter strategy would be most effective if acceptance criteria are based on SNR values, while the former is best if acceptance criteria are based on signal amplitudes. If both amplitude and SNR criteria are applied, careful consideration should be made to select the DAC strategy for data acquisition.

3.3.3.3 Acceptance Criteria

Acceptance criteria is an amplitude threshold or SNR threshold that is as close to the noise floor as is reasonable, to assure maximum sensitivity, while having a low false positive rate.

Historic inspections have used an amplitude threshold for their acceptance criteria. Because materials have differing levels of noise, an amplitude criterion can either lead to excessive false positives or an inspection not at maximum sensitivity. False positives come from a threshold set below common noise amplitudes. A threshold set too high leaves a margin between the noise level and the amplitude threshold, where indications may be observable, but not rejectable. This can be avoided by using an SNR criterion in addition to an amplitude threshold. An SNR threshold of 2.5, for example, can avoid the false positives while keeping the threshold close to the noise level.

Amplitude thresholds still are useful in limiting the noise and thus sensitivity to a known level. Given a gain setting that puts the typical noise at 20% FSH, setting an amplitude threshold of near 80% FSH would provide a balance between false positives and sub-optimal sensitivity.

The selected SNR and/or amplitude thresholds should be pilot tested on parts representative of the population to be inspected prior to implementation to assure that this will not generate an excessive number of false positives.

3.3.3.4 Measuring SNR Values

There is a wide variety of methods used to obtain a SNR measurement for a particular target. The method recommended in AMS2628 [7] is the one used for all the values included in this document. Figure 24 provides an example of SNR for a single target, calculated by the following equation

$$SNR = (S-\mu)/(P-\mu)$$

Equation 1. Signal to Noise Ration for a Single Target

Where S is the maximum amplitude taken from the signal box. The signal box should be drawn around the signal, encompassing the entire signal of interest, but excluding any artifacts or other signal not associated with the target.

μ is the average amplitude of all the pixels in the noise box. The noise box should be drawn to include at least 5000 pixels so that the statistics are robust and descriptive of the sample. The noise box should be drawn to only include noise that appears characteristic of the material surrounding the target (signal box); higher noise regions and lower noise regions should be excluded. The noise box should exclude any artifacts or other stray signals.

P is the maximum amplitude found in the noise box. Because grain noise often has a log-normal distribution, it is often advisable to discard the highest 1 or 2 peak values, and instead use P = 3^{rd} largest peak amplitude.

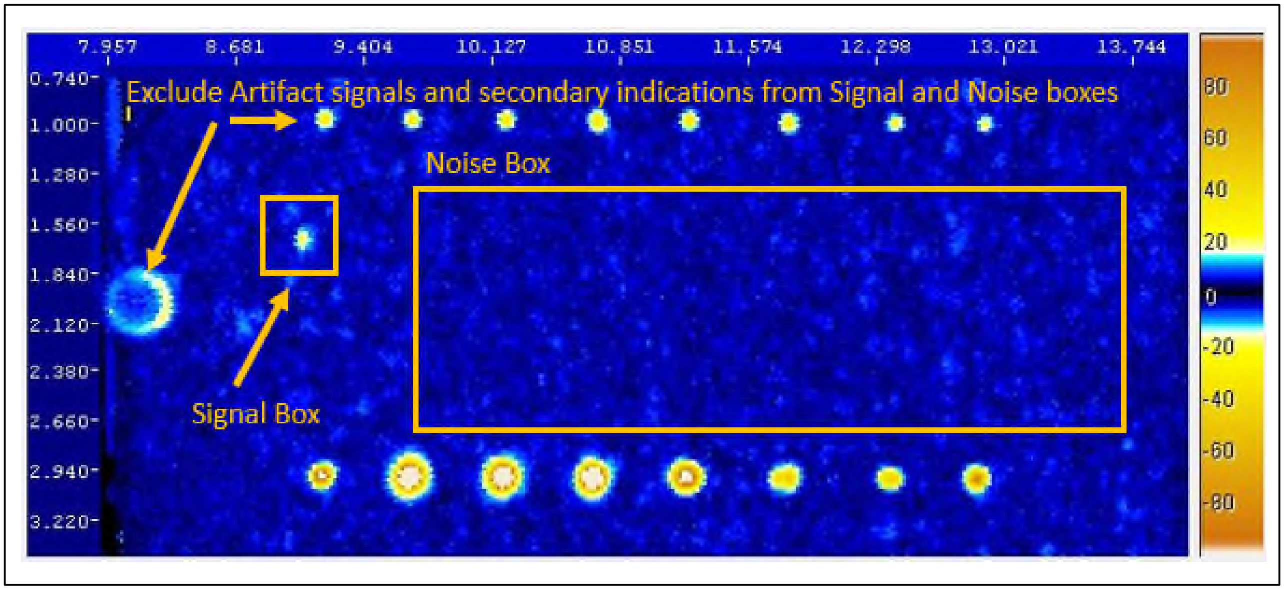


Figure 24. Example Image for Drawing Boxes to Obtain SNR Values

3.4 Validation

This section addresses the third and final request of the tasking letter (See Section 2.1) which focuses on providing guidance for how to evaluate an in-service UT implementation strategy and its benefits.

3.4.1 Confirmation of Selected Protocol Using Naturally Occurring Cracks

The Section 3.3 discussion covers the ability of sound beams to deliver maximum sound energy to various targets, but the targets demonstrating the effects are machined features. Connecting those results to a crack response is more challenging. An opportunity to make this connection presented itself with the four parts having naturally occurring cracks as described in Section 3.1.2. These were obtained as the result of an in-service inspection, and Team A-18-004 requested additional information regarding the inspection results for these parts to understand the characteristics of the anomaly and the inspection more clearly. The OEM provided the response below regarding the field, in-service inspections and subsequent lab inspections:

> *In general, the bore regions where the cracks were found were scanned from four different surfaces (Hub face, hub slopes (2), hub ID). See Figure 25 for example of generic surfaces.*

All field scans were made using a 5 MHz, 45° circumferential shear, clockwise/counterclockwise, surface focus. The hub ID also has a 0° longitudinal scan, but it did not contribute to these findings. Additional lab scans were done using 5 MHz at 20° longitudinal and 0° longitudinal.

Table 3.6 reflects the finds above the inspection threshold.

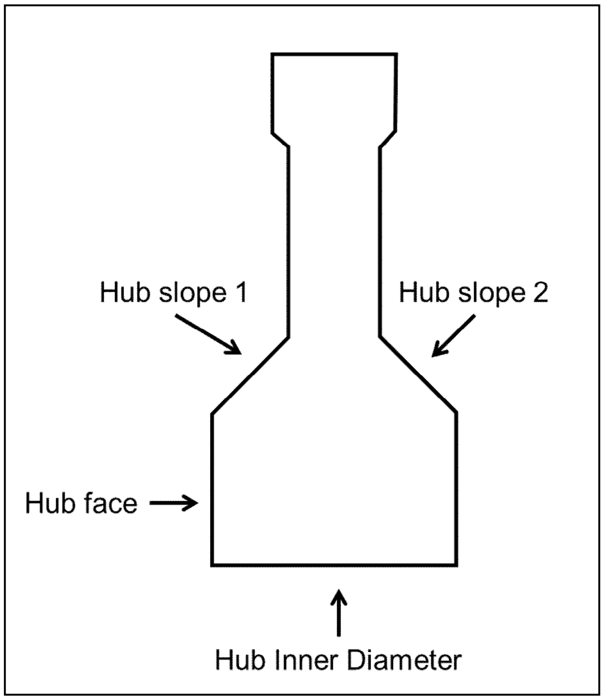


Figure 25. Sample Disk Geometry for Feature Nomenclature

Table 3-7. In-service UT Inspection Rejections Reported By OEM

Part ID #	Anomaly ID	Depth (inch)	Number of Detections by Refracted Angle					Totals	Number of Detections by Surface			
			45 CW (Field)	45 CCW (Field)	20 CW (Lab)	20 CCW (Lab)	0 MZ (Lab)		Hub Face	Hub Slope 1	Hub Slope 2	Hub Inner Diam.
1	A	1.75	3	0	0	0	2	5	2	1	2	0
2	A	1.70	0	2	0	3	1	6	3	2	1	0
2	B	1.70	1	0	2	0	1	4	3	0	1	0
3	B	1.42	2	0	1	2	0	5	1	3	1	0
3	C	1.18	0	0	1	1	0	2	0	2	0	0
3	D	1.70	0	0	0	3	0	3	1	1	1	0
3	E	1.50	0	0	2	1	0	3	1	2	0	0
4	A	1.97	0	2*	1*	2*	0	0	0	2*	3*	0
		Totals	**6**	**2**	**6**	**10**	**4**		**11**	**11**	**6**	**0**
			*** Indications below amplitude threshold but some indication was observable**									

As described in Section 3.1.2, The cracks found in these parts ranged from 22 square mils to 1270 square mils, and Table 3-7 shows that these cracks were all greater than 1" (25mm) deep, so this data directly addresses the sensitivity for the deep zone. Several observations are made:

- 20° refracted longitudinal wave scan (5° incidence) offered the greatest number of detections
- 45° refracted shear scan (19° incidence) offered a significant number of detections, including one target that was not detected with the 20° refracted longitudinal scan.
- 0° longitudinal scan detected few of the targets and did not find any targets which had not already been found at another angle.
- The hub ID did not offer any detections for these deep targets

These observations support an inspection protocol for deep targets which emphasize the 20° refracted longitudinal and 45°refracted shear. For shallow targets, it is expected that the 65° refracted shear offers superior sensitivity for radial/axial cracks. This data, along with prior inspection experience with concave surfaces, also suggests that the ID surface might not benefit from the deep zone scans.

3.4.2 Confirmation of Selected Protocol Using Computer Models

A second means of validation came by exercising a commercially available simulation model which predicts the response of a crack for a variety of inspection configurations. The crack used was oriented in the radial/axial plane, and the inspection modes were consistent with those described in Section 3.3. A parametric study was done, for a

0.030” x 0.015” (0.8mm x 0.4mm) crack at a variety of depths. The results are shown in Figure 26 and show how sensitivity curves overlap.

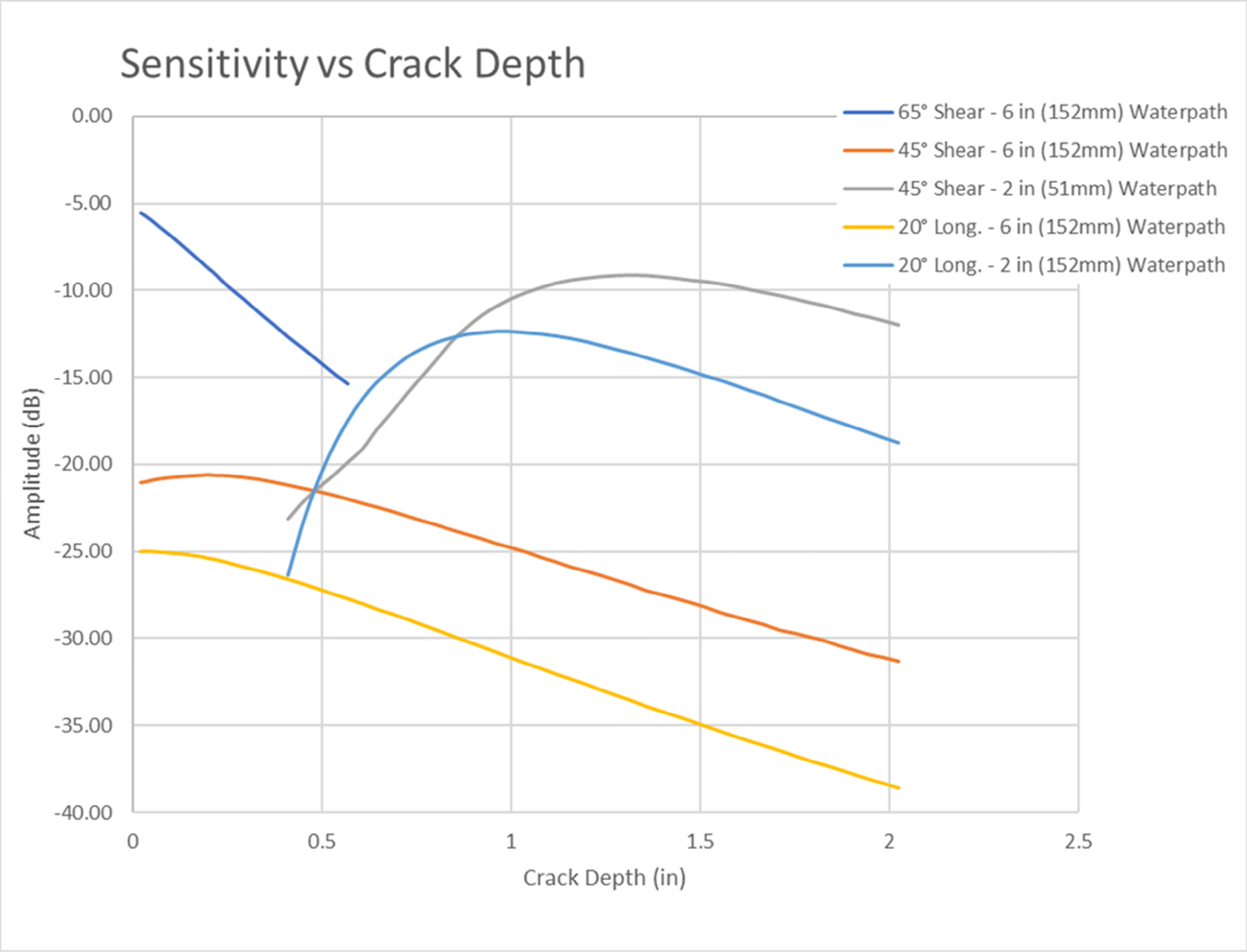


Figure 26. Amplitude Responses of a 0.030” x 0.015” (0.8mm x 0.4 mm) Crack Placed at A Range of Depths According to Parametric Model.
Note that for all shallow zone curves, 0 dB is anchored to the response of a 0.25” (6mm) deep, 0.020” (.5mm) diameter SDH target. For both deep zone curves, 0 dB is anchored to the response of a 1.0” (25mm) deep, 0.020” (0.5mm) diameter SDH target.

3.4.3 Validation of Alternate and New Technology

If an alternate inspection is proposed, validation is best done using cracks. Because the inspection described in this document has a goal of detecting subsurface cracks, those are the best targets for validating inspection capability. Such targets are difficult to obtain because there is no established method for generating subsurface cracks of a known size. Developing this capability should be a follow-on activity for the AIA NDE community. Once such a capability is defined, then a set of subsurface cracks should be created which can show how a given inspection technique's sensitivity compares to the baseline technique.

Until synthetic cracks are available, alternate targets would be synthetic features which have a scattering behavior for ultrasonic energy. Multiple options are available and have differing benefits:

1. SDH's because they are commonly available and clearly demonstrate the ability of a sound beam to penetrate to a given depth.
2. Round Bottom Hole, (RBH's) because it is a better representation of a scattering target.
3. EDM notches cut into a counter-bored hole.
4. #1 FBH's used in conjunction with a 5 MHz longitudinal wavelength, which demonstrated scattering behavior as seen in Section 3.3.2.

Such targets should be selected and justification rational should be generated when validating inspection methods as an alternative to the baseline described in Section 3.3.3.

4.0 Tasking Letter from FAA

U.S. Department
of Transportation
**Federal Aviation
Administration**

800 Independence Ave
Washington, DC 20591

November 9, 2018

Aerospace Industries Association
Attn: David Silver, Vice President, Civil Aviation
1000 Wilson Boulevard, Suite 1700
Arlington, VA 22209-3928

Dear Mr. Silver:

The National Transportation Safety Board (NTSB) recently released a report of the NTSB investigation, NTSB/AAR-18-01, regarding the uncontained engine failure event of American Airlines Flight 383 that occurred on October 28, 2016. This report contains seven safety recommendations issued to the Federal Aviation Administration (FAA). The following two NTSB Safety Recommendations are particularly pertinent to the engine manufacturer community.

1. A-18-003: Establish and lead an industry group that evaluates current and enhanced technologies regarding their appropriateness and effectiveness for applications using nickel alloys, and use the results of this evaluation to issue guidance pertaining to the inspection process for nickel-based alloy for rotating engine components.
2. A-18-004: Require subsurface in-service inspection techniques, such as ultrasonic inspections, for critical high-energy, life-limited rotating parts for all engines.

We would like to collaborate with the Aerospace Industries Association (AIA), Civil Aviation Regulatory & Safety Committee (CARS), Propulsion Sub-Committee (PC) to address these two recommendations.

Safety Recommendation A-18-003 addresses the inspection of nickel rotor products within the supply chain, prior to them being shipped to the airline customer. Specific issues include:

- Benchmarking current practices for the inspection of billet, forgings, and finished parts before shipment to the airline customer.
- Developing information for best practices where the initial, prioritized implementation could begin in 1-2 years. This initiative should include best practices for anomaly evaluation protocols.
- Identifying improvements within a 3-5 year timeframe. This may include suggestions for industry-level development programs.

We estimate this task will take 1 year to provide the information, and 2 years to implement improvements.

Safety Recommendation A-18-004 addresses in-service inspection of these parts; affecting the airline customers and manufacturing repair and overhaul (MRO) networks. Specific issues include:

- Reviewing the current techniques for sub-surface inspection.
- Reviewing current in-service inspection protocols, prior studies, FAA guidance materials, etc., and proposing an approach where initial, prioritized implementation could begin within 1-2 years from proposal submittal.
- Identifying improvements within a 3-5 year timeframe. The proposal may include suggestions for industry-level development programs.

We estimate this task will take 1 year for the initial, prioritized implementation, and 2 years to implement improvements.

After an accident in 1989, teams were established to address a similar melt-related issue in titanium alloys. In 1991, the FAA issued a report titled "Titanium Rotating Component Review Team Report," which described the state of the industry at the time. The report made several suggestions that prompted work in material melting process development, raw material and forging inspection, and development of a probabilistic design methodology to address melt-related anomalies.

Two current and longstanding government/industry teams, the Aerospace Industries Association (AIA) Rotor Integrity Steering Committee (RISC) and Jet Engine Titanium Quality Committee (JETQC) have their genesis in the industry's response to this FAA report. Both have expressed their interest and willingness to support with us in addressing these safety recommendations.

These teams include U.S. and European companies, providing a broad view of the aviation industry, as did the original FAA titanium review team. The FAA would appreciate AIA's consideration of our request to continue working with the Aerospace and Defense Industries Association of Europe (ASD) to ensure we maintain this broad perspective.

We leave it to your discretion whether two working groups would be more convenient and productive than one. In either case, we very much appreciate your assistance and collaboration. Please send any comments or questions to Dr. Tim Mouzakis, AIR-6A1, via email at Timoleon.Mouzakis@faa.gov or by telephone at (781) 238-7114. We look forward to hearing from you soon.

Sincerely,

Dr. Michael C. Romanowski
Aviation Safety
Director, Policy and Innovation Division
Aircraft Certification Service

cc: Robert Ganley (AIR-6A0)

Tim Mouzakis (AIR-6A1)

5.0 Works Cited

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List of Acronyms, Abbreviations, and Symbols

Acronym	Description
AC	Advisory Circular
AIA	Aerospace Industries Association
CCW	Counter-clockwise
CFR	Code of Federal Regulations
CW	Clockwise
DAC	Distance Amplitude Correction
EAR	Export Administration Regulations
EASA	European Aviation Safety Administration
ECI	Eddy Current Inspection
ETC	Engine Titanium Consortium
FAA	Federal Aviation Administration
FBH	Flat Bottom Hole
FPI	Fluorescent Penetrant Inspection
FSH	Full Screen Height
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ID	Inner Diameter
IFSD	In-Flight Shutdown
IPT	Intermediate Pressure Turbine
JENQC	Jet Engine Nickel Quality Committee
LPT	Low Pressure Turbine
MZ	Multi-zone
NTSB	National Transportation Safety Board
OEM	Original Equipment Manufacturer
POD	Probability of Detection
POF	Probability of Fracture
RBH	Round Bottom Hole
RISC	Rotor Integrity Steering Committee
SA:V	Axisymmetric Surface Area to Volume Ratio
SDH	Side Drilled Hole
SNR	Signal to Noise Ratio
TC	Type Certificate
TOF	Time of Flight
UT	Ultrasonic Inspection