U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: DAMAGE TOLERANCE OF HOLE FEATURES IN HIGH-ENERGY TURBINE ENGINE ROTORS

Date: 8/28/09
Initiated by: ANE-111

AC No: 33.70-2

1. Purpose.

a. This advisory circular (AC) provides definitions, guidance, and acceptable methods, but not the only methods, that may be used to demonstrate compliance with requirements in § 33.70 of Title 14 of the Code of Federal Regulations related to the integrity of engine life-limited parts. Section 33.70 contains requirements applicable to the design and life management of propulsion system life-limited parts, including high-energy rotating parts.

b. This AC presents a damage tolerance approach which can be used to address manufacturing and operationally-induced anomalies in turbine engine rotating part hole features. This approach can be readily integrated with the existing "safe-life" process for high-energy rotors to produce an enhanced life management process. This approach does not replace existing safe-life methodology but supplements it. In the context of damage tolerance, this AC is not intended to allow operation beyond the component manual life limit set using the existing safe-life approach which limits the useful rotor life to the minimum number of flight cycles required to initiate a crack. Rotor failure modes for which full containment of high-energy debris can be demonstrated are excluded from the procedures outlined in this AC and need not be accounted for in the overall risk assessment.

2. Applicability.

a. The guidance provided in this document is directed to engine manufacturers, modifiers, foreign regulatory authorities, part manufacturers who hold Parts Manufacturer Approval (PMA) authority, and Federal Aviation Administration (FAA) designated engineering representatives. Within this AC the term "engine manufacturer" refers to any person who holds a design approval of an engine life-limited part.

b. This material is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. We ("the FAA") will consider other methods an applicant may present to demonstrate compliance. Terms such as "should," "shall," "may," and "must" are used only in the sense of ensuring applicability of this particular method of compliance when the method in this document is used. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. If we find that following this AC would not result in compliance with the applicable regulations, we will not be bound by this AC, and we may require additional substantiation as the basis for finding compliance.

c. This material does not change, create any additional, authorize changes in, or permit deviations from existing regulatory requirements.

3. Related Regulations.

a. Section 33.4, Instructions for Continued Airworthiness.

b. Section 33.15, Materials.

c. Section 33.19, Durability.

d. Section 33.27, Turbine, compressor, fan, and turbo-supercharger rotors.

e. Section 33.63, Vibration.

f. Section 33.70, Engine life-limited parts.

g. Section 33.75, Safety analysis.

4. References and Related Reading.

a. FAA Documents.

(1) AC 33-3, "Turbine and Compressor Rotor Type Certification Substantiation Procedures," September 9, 1968.

(2) AC 33.14-1, "Damage Tolerance for High Energy Turbine Engine Rotors," January 8, 2001. Note: AC 33.14-1 will be replaced by AC 33.70-3 since the final rule on Aircraft Engine Standards for Engine Life-limited Parts (72 FR 50856), which published on September 4, 2007, removed § 33.14 from part 33.

(3) AC 33.70-1, "Guidance Material for Aircraft Engine Life-Limited Parts Requirements," July 31, 2009.

(4) FAA Report number DOT/FAA/AR-06/3 "Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts" (available at www.tc.faa.gov/its/worldpac/techrpt/ar06-3.pdf).

b. Industry Documents.

(1) "Development of Anomaly Distributions for Aircraft Engine Titanium Disk Alloys." Technical paper presented by the AIA Rotor Integrity Sub-Committee at the American Institute of Aeronautics and Astronautics Conference in April 1997.

(2) "Development of Anomaly Distributions for Machined Holes in Aircraft Engine Rotors." Technical paper presented at ASME Turbo Expo in Barcelona, Spain in May 2006.

(3) SAE/FAA Committee On Uncontained Turbine Engine Rotor Events, Report No. AIR 1537, Data Period 1962-1975.

(4) SAE/FAA Committee On Uncontained Turbine Engine Rotor Events, Report No. AIR 4003, Data Period 1976-1983.

(5) SAE/FAA Committee On Uncontained Turbine Engine Rotor Events, Report No. SP-1270, Data Period 1984-1989.

5. Definitions. The following definitions apply within this AC:

a. Component Feature. A unique location, structural shape, or surface of a component or part. For a disk, component features are blade slots, bore or web locations. Other examples are grooves, slots, or holes. Usually different machining processes and practices are required to produce each unique feature.

b. Component Event Rate. The number of events for a given rotor component stage for each engine cycle, averaged over the projected life of the component.

c. Damage Tolerance. An element of the life management process that recognizes the potential existence of component imperfections that are the result of inherent material structure, material processing, component design, manufacturing, or usage. Damage tolerance addresses this situation through the incorporation of fracture resistant design, fracture-mechanics, process control, or nondestructive inspection.

d. Default Probability of Detection (POD) Values. Values representing mean probabilities of detecting anomalies of various types and sizes. These values are accepted as valid provided the inspection is conducted consistent with good industry practice.

e. Design Target Risk (DTR). The relative risk of failure caused by material, manufacturing, and service induced anomalies and the standard against which probabilistic assessment results (stated in terms of feature, component, and engine level event rates) are compared.

f. Engine Event Rate. The cumulative number of events predicted for a given anomaly type for each engine cycle, for all rotor life-limited parts in a given engine, calculated over the projected life of those components.

g. Event. A rotor structural part separation, failure, or burst, with no assessment of consequence.

h. Focused Inspection. A component inspection in which the inspector has been instructed to pay special attention to specific component feature(s) or location(s) and the necessary specialized processing instructions have been provided.

i. Full Field Inspection. A component inspection without special attention to any specific component feature(s) or location(s).

j. Hard Time Inspection Interval. The number of engine cycles since new or since the most recent inspection after which a rotor part must be made available and must receive the inspection specified in the Airworthiness Limitations Section (ALS) of the Instructions for Continued Airworthiness (ICA).

k. Hazardous Engine Effects. Any of the effects listed in § 33.75(g)(2). Failure of rotating parts usually results in the non-containment of high-energy debris, which is the primary hazardous engine effect addressed by this AC. Disks, hubs, impellers, large rotating seals, and other similar large rotating components represent potential sources of high-energy debris.

l. Hole Feature. A set of one or more circular holes at the same axial and radial location where any given hole falls at least partially within the circumferential (diametral) shadow of the largest hole and its size is greater than 75 percent of the diameter of the largest hole. (See Appendix 5).

m. Inspection Opportunity. An occasion when an engine is disassembled to at least the modular level and the hardware in question is accessible for inspection, whether or not the hardware has been reduced to the piece part level.

n. Low Cycle Fatigue (LCF). The process of progressive and permanent local structural deterioration occurring in a material subject to cyclic variations, in stress and strain, of sufficient magnitude and number of repetitions. The process will culminate in detectable crack initiation typically within 10^5 cycles. A detectable crack initiation is defined as 0.030 inches in length by 0.015 inches in depth.

o. Manufacturing Anomaly. A surface-related imperfection introduced during the manufacturing process (subsequent to melting) that is considered potentially detrimental to the structural integrity of a life-limited rotating part during its service life.

p. Maintenance Exposure Interval. A statistical distribution which defines the number of flight cycles between engine shop visits. This interval provides an opportunity to inspect the engine internal parts because the module or parts have been disassembled as a result of normal maintenance activity.

q. Mean POD. The 50-percent confidence level POD versus anomaly size curve.

r. Module Available. An individual module removed from the engine.

s. Module. A combination of assemblies, subassemblies, and parts contained in one package, or arranged to be installed in one maintenance action.

t. Operationally-Induced Anomaly. A surface imperfection introduced during service operations (includes flight operations and maintenance) that is potentially detrimental to the structural integrity of the life-limited rotating part.

u. Part Available. A part that can be inspected, as required by the ALS of the ICA, without any further disassembly. Depending on the inspection requirements, some parts may require a fully disassembled "piece part" condition, while other parts may be available for inspection while still in the assembled module.

v. Probabilistic Risk Assessment. A fracture-mechanics based simulation procedure that uses statistical techniques to mathematically model and combine the influence of two or more variables to estimate the likelihood of various outcomes for a product. Since not all variables may be considered or may not be capable of being accurately quantified, the numerical predictions are used on a comparative basis to evaluate various options. Results from these analyses are typically used for design optimization to meet a predefined target or to conduct parametric studies. This type of procedure differs from an absolute risk analysis, which attempts to consider all significant variables and is used to quantify, on an absolute basis, the predicted number of future events with safety and reliability consequences.

w. Probability of Detection. A quantitative statistical measure for detecting a particular type of anomaly (flaw) over a range of sizes using a specific nondestructive inspection technique under specific conditions. Typically, the mean POD curve is used.

x. Rotor Life-Limited Parts. Engine rotor parts whose primary failure is likely to result in a hazardous engine effect, which is any of the conditions listed in § 33.75.

y. Safe Life. A low cycle fatigue-based process in which life-limited components are designed, manufactured, and substantiated to have a specified service life or life limit, which is stated in operating flight cycles, operating hours, or both. The "safe life approach" requires that parts be removed from service prior to the development of an unsafe condition (i.e., crack initiation). When a component reaches its published life limit, it is retired from service. The safe life approach only applies to parts which define crack initiation as the limit of the useful life such as rotating parts.

z. Soft Time Inspection Interval. The number of engine cycles since new, or the most recent inspection, after which a rotor part in an available module must receive the inspection specified in the ALS of the ICA.

aa. Stage. The rotor structure that supports and is attached to a single aerodynamic blade row.

6. Background.

a. As required by § 33.70(a), applicants must perform appropriate damage tolerance assessments to address the potential for failure from material, manufacturing, and service induced anomalies within the approved life of the part. This is necessary because service experience with gas turbine engines has demonstrated that material, manufacturing and service-induced anomalies do occur, and they can potentially degrade the structural integrity of rotor life-limited parts. Several approaches are currently available to address this requirement and have been introduced by AC 33.70-1 and AC 33.14-1. The methodology described in Chapter 2 of this AC was first introduced in AC 33.14-1 to address the potential presence of hard alpha anomalies in titanium rotors.

b. The complex and time-consuming nature of the effort required to develop the technical elements associated with this method—for example, data collection, analysis, methodology development, acceptable design targets, and validation—has led to a decision to introduce the surface damage tolerance assessment methodology for manufacturing and in-service anomalies in phases. Phase 1 of this methodology, introduced in this AC, presents a damage tolerance approach which can be used to address manufacturing and operationally-induced anomalies in circular hole features (see Appendix 5) in rotor parts. We will introduce other phases in future ACs that will address the remaining surface features.

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CHAPTER 1. ENHANCED LIFE MANAGEMENT PROCESS

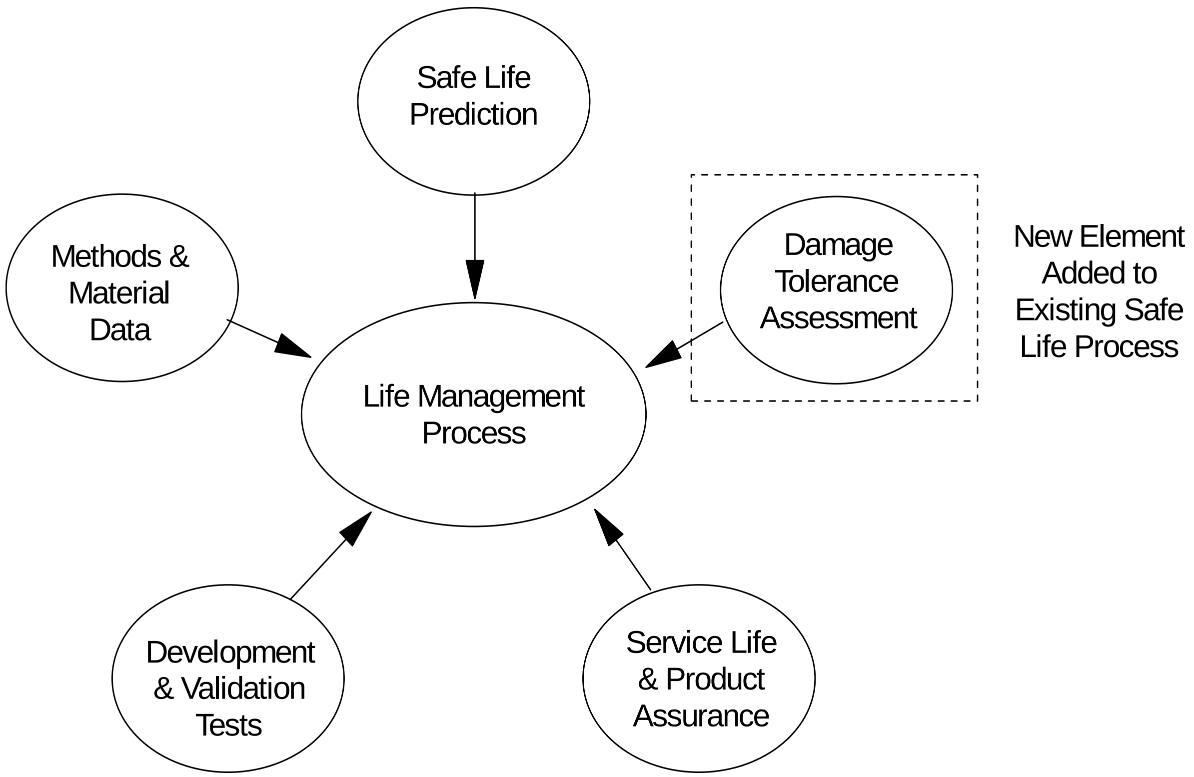
1. Based on historical experience, the safe-life philosophy has worked well and provides a solid base for further enhancement. Modifications to the industry standard life management procedures should augment, not replace, current approaches, which are based on the safe-life philosophy.

a. A new element, damage tolerance, has been added to the existing conventional life management process to define the enhanced life management process. We expect enhanced life management to further minimize the occurrence of uncontained rotor failures and thus improve flight safety (see figure 1-1).

b. Use of the enhanced life management process, shown in figure 1-1, will result in damage tolerance assessments being conducted on critical rotating part designs. These will be in the form of fracture-mechanics-based probabilistic risk assessments, the results of which will be compared to specified design target risk values. Designs that satisfy these DTR values will be considered in compliance with the damage tolerance requirements of § 33.70. Engine manufacturers will have a variety of options available to achieve the DTR. These options include, but are not limited to:

- component redesign,
- material changes,
- material process improvements,
- manufacturing process improvements,
- manufacturing inspection improvements,
- enhanced in-service inspections, and
- life limit reductions.

Figure 1-1: Enhanced Life Management Process



CHAPTER 2. DAMAGE TOLERANCE ASSESSMENTS

1. Approach.

a. As described in AC 33.70-1, Probabilistic Damage Tolerance Risk Assessments (PDTRA) is an acceptable method to assess the ability of a part to tolerate anomalies. The results of these assessments will provide the basis for evaluating the relative damage tolerance capabilities of candidate part designs and will also allow the engine manufacturer to balance its designs for both enhanced reliability and customer impact. The results will be compared against design target risk values (see paragraph 6, "Design Target Risk," in this chapter).

b. The need for further risk reducing actions on the part of the engine manufacturer is based on whether the design under consideration satisfies the desired DTR values. If the targets are met, then the design is in compliance with § 33.70. The manufacturer has a variety of options available to achieve the required DTR and may conduct quantitative parametric studies to determine the influence of key variables such as inspection methods, inspection frequency, hardware geometry, hardware processing, material selection and life limit reduction. The manufacturer may make changes to the design, or field management of the part, or both, to achieve the DTR values.

c. PDTRA will usually be performed during the engine component detail design phase. Paragraph 2 of this chapter defines an assessment methodology applicable to manufacturing and service-induced anomalies and provides a process to refine a design to achieve the desired DTR values.

2. Methodology.

a. Probabilistic risk assessments may be conducted using a variety of methods, such as Monte Carlo simulation or numerical integration techniques. When performing a PDTRA, use of the standardized inputs and default data presented in this AC will achieve consistent assessment results.

b. A list of standardized inputs is provided under paragraph "c" below. Default input data is described in paragraphs 3 and 4 of this chapter. Use of this default data in probabilistic assessments requires no further demonstration of applicability or accuracy. However, when this data is used, the applicant should follow the guidelines accompanying this data to ensure applicability. Use of inputs other than these default values may require additional validation to verify applicability, adequacy, and accuracy.

c. Probabilistic risk assessments should incorporate the following inputs as part of a basic analysis: component stress, surface area, material properties, crack growth (propagation) life, anomaly distribution, design service life, inspection PODs, and maintenance exposure rate.

(1) Input. The following data sets are defined as basic input elements.

(a) Stress. This variable influences crack propagation life. Data input should encompass the most limiting operational principal stresses. Engine cycle(s) for design LCF certification, or actual usage (if known), should be used to establish the stress distribution.

Surface assessments should incorporate the appropriate surface and near surface stress distributions, including the effects of stress concentrations and vibratory stresses.

> Note: The method described in this AC has been calibrated against industry experience without considering the effect of shot peening and the resulting beneficial residual stresses on the crack propagation lives. As a result, with this method it is inappropriate to include the beneficial effects of shot peening.

(b) Surface Area. This variable influences the probability of having a manufacturing-induced anomaly on the surface of a specific component/component feature. For hole features, this corresponds to the total surface area of one hole in a given feature.

(c) Material Cyclic Crack Growth Rate (CCGR) Data. Use average crack growth rate properties of the base material as the default condition to calculate crack propagation life.

(d) Propagation Life. Number of cycles for a given size anomaly to grow to a critical size. This is based on knowledge of part stresses, including the vibratory stresses, temperature, geometry, stress gradient, anomaly orientation, and material properties. Linear elastic fracture mechanics should be used for the calculation of propagation life. Default conditions should assume anomalies to be in the worst orientation to the stress field.

(e) Anomaly Distribution**.** For manufacturing-induced assessments, use the default anomaly distributions outlined in paragraph 3 of this chapter or FAA-approved company-specific data. Company-specific data should be developed using the same process employed to derive the default anomaly distributions. For manufacturing-induced anomaly assessments, this process is described in a technical paper titled "Development of Anomaly Distributions for Machined Holes in Aircraft Engine Rotors" - see paragraph b.(2) in "References and Related Reading." The paper also describes the process required to establish the potential benefits (e.g., reduced anomaly size/frequency distributions) derived from the imposition of enhanced surface inspections during the manufacturing process. Note: In all assessments, anomalies will be treated as sharp propagating cracks from the first stress cycle.

(f) POD. Default PODs and instructions on use of individual company values are contained in paragraph 5 of this chapter. For surface assessments, consider the effects of fluorescent penetrant inspection (FPI) and eddy current inspection (ECI) as appropriate.

(g) Maintenance Exposure Interval. For the purpose of assessing inspection benefits, model exposure interval curves for the engine, module, or component in question in the analysis.

(2) Calibration.

(a) Each engine manufacturer should calibrate its analytical prediction tools by conducting the industry test case detailed in Appendix 1.

(b) The manufacturing-induced anomaly test case in Appendix 1 consists of a probabilistic analysis of a simulated titanium ring disk with a row of ½" diameter holes, using specified inputs and scenarios. Test case results in the ranges from 2.58E-04 to 3.22E-04 events within the service life of the part (for the “no inspection” case) and from 7.29E-05 to 2.25E-04 (for the “with in-service inspection” case) are considered acceptable. Test case results outside of these ranges may indicate deficiencies with either the probabilistic assessment technique or the assumptions made.

(3) Output: Manufacturing-Induced Anomaly Assessments. Holes.

(a) Applicability. This procedure applies to circular holes in rotor life-limited parts with the exception of the bore hole. The bore hole is specifically exempted because the machining anomalies observed in field events originating at the bore hole do not resemble the anomaly types observed in drilled hole features, which suggests different damage mechanisms.

(b) Hole Feature Assessments. The probabilistic assessments and prediction of event potential for a given hole feature should be calculated over the entire anticipated service life of the part. This result should be expressed as the number of predicted events for each cycle and should be designated as the predicted “hole feature event rate.” The predicted hole feature event rate should then be compared to the hole feature level DTR value to assess design acceptability.

(4) General Comments.

(a) The FAA encourages engine manufacturers to incorporate fracture resistant design concepts where possible. Credit may be given for fracture resistant or burst resistant engine design features, which clearly demonstrate, through both analysis and test, a reduction in the potential for rotor failure due to the presence of unanticipated anomalies. Credit may be determined using the probabilistic risk assessment methods contained with this AC and by data which supports the fracture resistant features of the design.

(b) Because the design of an aircraft turbine engine rotor is a lengthy process involving numerous iterations, each of which can substantially alter the initial design risk value, it is important that the design feature satisfy the appropriate DTR value at the time of engine certification. Some risk assessments will be conducted several years after the engine enters service due to in-service problems, changes in engine service usage, improvements in analytical predictive tools, or changes in engine component materials. In these instances, it is important to note that the DTR values should be satisfied throughout the life of the hardware.

(c) Etch inspection is widely used in the industry to evaluate material quality on rotor part surfaces. While etch inspections are not yet included in the damage tolerance assessment, they have been identified as the foremost means of detecting non-geometric anomalies (worked layers) in holes by the FAA Report number DOT/FAA/AR-06/3 “Guidelines to Minimize Manufacturing Induced Anomalies in rotor life limited parts” – see paragraph a.(3) in “References and Related Reading.” As such, etch inspections currently in-place perform a vital role and should not be discontinued because of any damage tolerance analysis set forth in this AC.

(d) Crack propagation assessment guidelines for consistent treatment of out of phase stress vs. temperature history are included below. These guidelines apply only to the probabilistic damage tolerance analysis.

1 Crack propagation under out-of-phase stress vs. temperature transient loadings is a complex phenomenon. Compared to isothermal tests, non-isothermal experimental results suggest that the crack propagation rate can be higher than predicted at the temperature of the maximum stress when the maximum temperature during the flight is greater than the temperature at the maximum stress (see figure 2-1).

2 While some OEMs have developed models to predict this phenomenon, no industry standard is yet available.

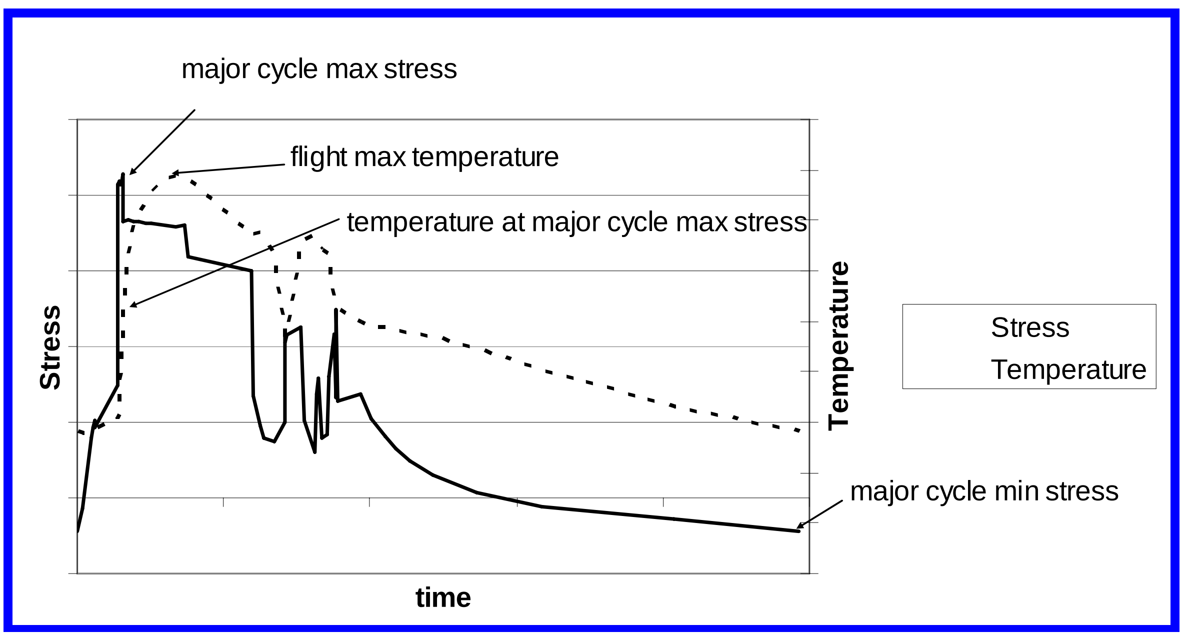
3 The following design guidelines provide a default approach for the probabilistic analysis described in this AC.

4 Design Guidelines (Default Option). These are not intended to become a general industry standard. For the major and minor stress cycles over the full flight, the temperature to consider is the most life limiting between:

- Temperature at maximum stress during the cycle, and
- Maximum temperature during the flight

5 Design Guidelines (Alternative Option). A crack propagation model accounting for out of phase temperature vs. stress history for the full flight can be used if it is validated with the OEM laboratory and field experience on the considered material.

Figure 2-1. Stress and temperature transient loadings over a flight mission



3. Anomaly Distributions.

a. A key input distribution associated with PDTRA assessments is the size and rate of occurrence of the anomalies. This type of information is statistical in nature and can be presented in a form that specifies the number of anomalies that exceed a particular size in a given amount of surface area.

b. Manufacturing-Induced Anomaly Distributions.

(1) Manufacturing-induced anomaly distributions that apply to circular hole features in disks have been developed to characterize the size (depth) distribution and frequency of said anomalies (see Appendix 2). The distributions apply to circular holes machined in titanium, steel, nickel, or powder nickel rotor components.

(2) The anomaly distributions contained in Appendix 2 may be used to determine compliance with paragraph 6 ("Design Target Risk") of this chapter. The background pertaining to the development of these distributions is contained in the technical paper "Development of Anomaly Distributions for Machined Holes in Aircraft Engine Rotors." The distributions were developed by modeling crack sizes detected during component/engine testing or through in-service experience using an EIFS (Effective Initial Flaw Size) approach. The final distributions were validated based on OEM field experience. This process resulted in a probability of exceedance curve (see figure A2-1) that can be used to determine a relative risk reduction but not an absolute level of risk.

(3) Individual engine manufacturers who want to use an alternate anomaly distribution or an improved inspection capability, or extend the PDTRA process to features other than circular holes should use a methodology similar to that contained in the paper "Development of Anomaly Distributions for Machined Holes in Aircraft Engine Rotors." This paper contains instructions on how to develop an alternate distribution, which must be substantiated by the appropriate background data. Alternate manufacturing-induced anomaly distributions should:

(a) include fracture and crack find data,

(b) include inspection POD data, and

(c) be based upon substantial field experience.

4. Manufacturing Credits Applicable to Manufacturing-Induced Anomaly Distributions.

a. To encourage the use of best practices when manufacturing circular holes in rotor life-limited parts, a process has been established to take credit for available manufacturing process validation and controls that reduce the risk of hole damage during manufacture. This process includes:

(1) Process validation to a modern standard as described in FAA Report number DOT/FAA/AR-06/3.

(2) Single point boring as a method of finishing a hole. This is restricted to titanium alloys.

(3) Honing all alloys as a method of finishing a hole.

(4) The provision of a coolant monitor to ensure the flow of coolant towards the cutting edge.

(5) Power monitoring to a standard detailed in the FAA Report number DOT/FAA/AR-06/3.

(6) Other process monitoring, including feed force, vibration, etc., to a standard similar to that for power monitoring above.

(7) Inspection for detection of non-geometric anomalies.

b. The degree of allowable manufacturing credit is a function of which of the above available actions are actually employed during hole making. Calculation of manufacturing credit is outlined in Appendix 6. The manufacturing-induced probabilistic damage tolerance approach has been developed excluding the benefits of enhanced manufacturing validation and process controls. Hence, the credit is applied as a reduction factor to the results of the manufacturing-induced probabilistic assessments prior to comparing with the hole feature DTR.

5. <u>Default Input - Nondestructive Evaluation (NDE) POD</u>.

a. Detection of non-geometric anomalies, such as highly distorted grain structure, white or amorphous layer, and bent grain, which have dominated the experience of cracking in rotors, is quite distinct from detecting cracks and geometric anomalies such as nicks or dents. Cracks that may develop from non-geometric anomalies can be detected by conventional methods, such as eddy current, penetrant or ultrasonic inspection, when the part is inspected at shop visit. These methods, however, may be of very limited benefit at new manufacture. If credit for inspection at new manufacture is claimed, applicants must demonstrate that the capability of the technique on the target anomaly types. The default POD data supplied in this AC in Appendix 4 only refers to the detection of cracks.

b. The capability of individual NDE processes, such as eddy current, penetrant, or ultrasonic inspection, for the detection of local material anomalies (discontinuities or potential anomalies), is a function of numerous parameters, including the size, shape, orientation, location, and chemical or metallurgical character of the anomaly. In addition, the following four parameters should be considered when assessing the capabilities of an NDE process:

(1) The material being inspected (for example, its composition, grain size, conductivity, and surface texture).

(2) The inspection materials or instrumentation (for example, the specific penetrant and developer, the inspection frequency, instrument bandwidth and linearity).

(3) The inspection parameters such as scan index.

(4) The inspector (for example, his or her visual acuity, attention span, and training).

c. The “default” POD data supplied with this AC are characteristic of inspection capability that has been measured under typical, well-controlled conditions. These default POD values are provided primarily to facilitate selection of nondestructive inspection techniques that are best suited to support attainment of damage tolerant inspections. Manufacturers should recognize, however, that although properly applied inspections should result in capability similar to these default values, they are strictly applicable only under the conditions under which they were acquired (see Appendix 3). POD curves are described in Appendix 4, figures A4-1 and A4-2, as listed below:

(1) Appendix 4, Figure A4-1. Mean POD for Fluorescent Penetrant Inspection of Finish-Machined Surfaces.

(2) Appendix 4, Figure A4-2. Mean POD for Eddy Current Inspection of Finish Machined Surfaces.

NOTE: Refer to Appendix 1 for an example of the use of this data and to Appendix 3 for the NDE Applicability of these POD curves.

6. Design Target Risk.

a. The DTR is a benchmark relative risk level selected to enhance the overall safety of high-energy rotating components. Since no machine or device is 100-percent reliable, it is inappropriate to require a level that is technologically unachievable. Nevertheless, the goal is to achieve a significant and distinct improvement over and above current rotor designs.

b. For manufacturing-induced anomaly assessments, designs must meet the specified feature DTR to be considered acceptable. (Note: Only circular hole feature assessments and DTR’s are currently available.)

c. Design Target Risk values are specified in Table 2-1 below:

Table 2-1. Allowable Risk for Circular Holes

Component Feature	**Design Target Risk (feature events per component published service lifetime)**
Circular Holes	2.0 E-05

CHAPTER 3. "SOFT TIME INSPECTION" ROTOR LIFE MANAGEMENT

1. Approach. The overall life management process encompasses a wide spectrum of design, manufacturing, and product support issues. This section addresses only one facet of that process, the assurance of structural integrity using inspection techniques and intervals derived from a damage tolerance (fracture mechanics-based) assessment. The inspection philosophy is intended solely to protect against anomalous conditions. It is not intended to allow operation beyond the safe-life limit specified in the Airworthiness Limitations Section of the Instructions for Continued Airworthiness.

a. When probabilistic assessment indicates risk levels greater than the desired target, many strategies can be used to reduce the predicted risk to the appropriate level. However, only the in-service inspection option is addressed here.

b. The industry data on uncontained fracture experience summarized in SAE reports AIR 1537 (1959 through 1975), AIR 4003 (1976 through 1983), and SP1270 (1984 through 1989) was used to guide the development of the inspection philosophy. These reports indicate that maintenance-induced uncontained failure rates were comparable to the failure rates for anomalous conditions (material and manufacture). This data suggests that additional inspection requirements, if not properly integrated into the normal maintenance scheduled for the engine, would have no net benefit to reduce uncontained failure rates.

c. The inspection philosophy presented here evolved from the desire to easily integrate inspections into the operation of the engine yet still achieve measurable reduction in the uncontained failure rates. The inspection philosophy advocates the use of opportunity inspections rather than forced inspections at 'not to exceed' intervals. These opportunity inspections occur due to the 'on-condition' maintenance practices used by operators today. Although opportunity inspections occur at random intervals, they can be treated statistically and used effectively to lower the calculated risk of an uncontained event.

d. Opportunity inspection refers to those instances when the hardware in question is available in a form such that the specified inspection can be performed. This condition is generally viewed as being reduced to the piece part; however; opportunity inspections can be performed on assembled modules. For example, an ECI of a disk bore may be specified on an assembled module whenever the module is available. This inspection is an opportunity inspection based upon module availability rather than piece part availability.

e. Whenever possible, the designs should use opportunity inspections to meet the DTR levels. However, in some instances, the probabilistic analysis may indicate an unacceptable risk level when using just opportunity inspections and some additional action may be required to meet the DTR. One of the options to mitigate this risk is to force inspection opportunities by specifying disassembly of modules or engines when a cyclic life interval has been exceeded. There are many options on how to implement forced disassembly. Options range from mandatory engine removal and subsequent teardown at not to exceed cyclic limits ("hard-time" limits) to mandatory module teardown when the naturally occurring module availability exceeds the specified cyclic life inspection interval of one of the parts contained within that module ("soft-time" limits). This AC advocates the use of the piece part soft-time inspection option and only suggests that forced disassembly of modules be considered when it is required to meet the DTR levels.

f. The soft-time inspection philosophy retains the “on-condition” maintenance practice and minimizes the impact of additional module disassembly. The inspection requirement exists only after the engine has been removed from the aircraft for a reason other than the inspection itself and is in a sufficient state of disassembly to allow access to the module containing the component in question. An available module containing a part with Cycles Since Last Inspection (CSLI) in excess of the soft-time interval must be disassembled to a condition that allows inspection by the procedure specified by the engine manufacturer. The engine manufacturer must evaluate the risk associated with parts that become available for inspection before the soft-time interval to determine if the CSLI can be reset.

g. The maintenance impact of the soft-time intervals should be considered during the design phase. Use the probabilistic analysis, summarized in Chapter 2, along with the anticipated engine removal rate and the module and piece part availability to develop designs that not only achieve the design target but also result in acceptable soft-time intervals and procedures, if such action is required.

h. When invoked, the soft-time inspection approach establishes interval limits beyond which rotor components must be inspected when the rotors are available in modular form. The soft-time inspection requirement is not intended to affect the current practice of forced inspection programs to address safety of flight concerns that arise in the course of engine operation and maturation. These safety of flight concerns should continue to be addressed through aggressive inspection programs, which are communicated using service bulletins.

i. Applicants should recognize that the inspection assumptions made in the probabilistic risk assessment must be communicated and implemented accurately to the field by using the ALS of the ICA. These assumptions must also be validated by the review of engine removal rates and module and piece part availability data. For example, the ALS must call out an eddy current inspection if that was an assumption in setting the original soft-time interval. Similarly, the amount of inspected material should correspond to the analysis assumptions. Likewise, if field experience suggests that the opportunity inspection intervals are in excess of the assumed rates in the probabilistic risk assessment, then appropriate corrective action, such as a modified inspection plan, is required.

j. The soft-time inspection interval and reference to the corresponding inspection procedures must be specified in the ALS of the ICA. This information must be provided for all rotor parts with specified retirement life limits that require any inspection plans beyond opportunity inspections to meet the DTR levels. The required inspection information should also be included in the individual ALS of the ICA with the other rotor inspection requirements. The manufacturer must also provide necessary information to focus the prescribed inspections to those areas of highest relative risk.

2. Inspection Scenarios. The following scenarios clarify the action that should be taken at a maintenance inspection opportunity. Note that the inspection plans may vary for each part, depending on the outcome of the probabilistic assessments.

a. Maintenance Opportunity - Hardware Available For Opportunity Inspection. Hardware available in the condition to perform the specified opportunity inspection must be inspected by the procedures specified in the ALS of the ICA. This is a mandatory inspection.

b. Maintenance Opportunity - Module Below Soft Time Interval. Hardware accessible in the assembled or partially disassembled module may be nondestructively inspected by the procedures specified in the ALS of the ICA. The CSLI may be reset to zero, provided the engine manufacturer has assessed the risk impact associated with this action. This is a discretionary inspection.

c. Maintenance Opportunity - Module Above Soft Time Interval. Hardware listed in ALS of the ICA must be made available for nondestructive inspection, using the specified procedures. This inspection must be performed whenever the module is available and the CSLI for any contained hardware that exceeds the inspection cycle limit. This is a mandatory inspection.

3. Soft Time Inspection Interval Example. An example of Soft Time Inspection Interval development is provided in Appendix 2 of AC 33.14-1.

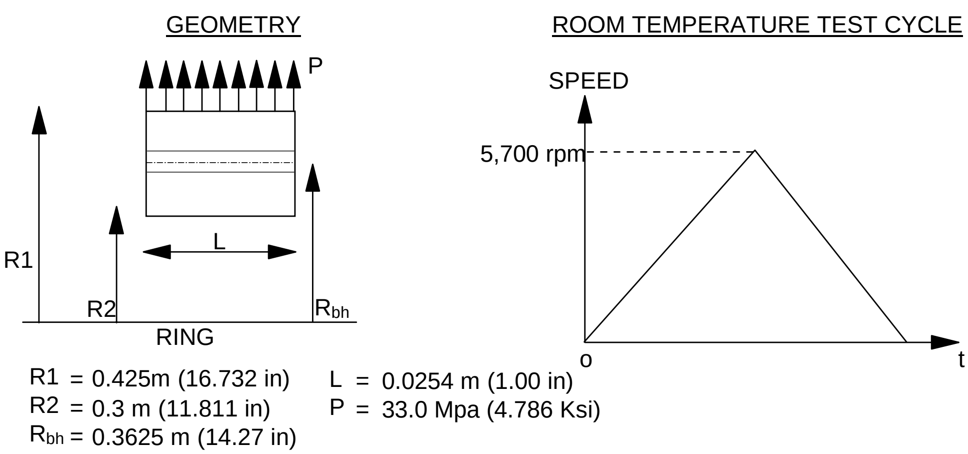
APPENDIX 1. MANUFACTURING-INDUCED ANOMALY CALIBRATION TEST CASE

1. This appendix provides detailed instructions for the calibration of a probabilistic risk assessment methodology for manufacturing-induced anomalies in circular holes. The package includes all required input data for the test case; analysis guidelines; and an analysis section that permits manufacturers to estimate the level of acceptability of their risk calculations and gain insights on intermediate results.

2. Test Case Input Data.

a. Problem Description. The test case geometry (figure A1-1) consists of a titanium ring disk under simple cyclic loading for 20,000 cycles. The maximum speed is 5,700 RPM and an external pressure load of 33 MPa (4.786 ksi) is applied on the outer diameter to simulate blade loading. The disk contains 40 circular holes of ½ inch (1.27 cm) diameter at a radial location of 14.27 inches (36.2458 cm).

Figure A1-1



b. Anomaly distribution curve. The anomaly distribution is provided in Appendix 2. Finished part manufacturing inspections are fully accounted for in this curve. No additional modifications are necessary. The anomaly distribution is defined in terms of depth and is dependent on the Length to Diameter (L/D) ratio for the hole. The anomaly distributions should be linearly extrapolated when anomaly sizes are required outside the range of data provided.

c. POD. The POD curves used to determine the effect of an in-service inspection are contained in Appendix 4. The default curves to be used are the Mean (50 percent Confidence) POD for eddy current inspection of finish-machined surfaces with the reject level set at one-half the calibration notch threshold response. For this test case, we assumed that this curve applies to the whole surface, including the entire hole and the front and aft face of the component.

d. Material Data. Two sets of material data are provided:

(1) Physical properties. Data required:

Density: 4,450 kg/m^3 or 0.161 lb./in^3

Young's modulus: 120,000 MPa or 17.4E3 ksi

Poisson's ratio: 0.361

(2) Crack Growth. Assume the following data represents air crack propagation. Crack propagation rate:

K threshold = 0.0 MPa$\sqrt{m}$ or 0 ksi$\sqrt{in}$

Fracture toughness= 64.5 MPa$\sqrt{m}$ 58.7 ksi$\sqrt{in}$

For K ratio (Min K/Max K) = 0.0

da/dN = 9.25 E-13 $(\Delta K)^{3.87}$ (da/dN in m/cycle and ΔK in MPa$\sqrt{m}$)
- or -
da/dN = 5.248 E-11 $(\Delta K)^{3.87}$ (da/dN in in/cycle and ΔK in ksi$\sqrt{in}$)

For K ratio (Min K/Max K) = -1.0

da/dN = 1.281 E-14 $(\Delta K)^{3.87}$ (da/dN in m/cycle and ΔK in MPa$\sqrt{m}$)
- or -
da/dN = 7.2684 E-12 $(\Delta K)^{3.87}$ (da/dN in in/cycle and ΔK in ksi$\sqrt{in}$)

(a) The above data apply at the test case component temperature.

(b) Crack propagation data are stress ratio dependent.

(c) Crack propagation data for a stress ratio of 0.0 was taken from MCIC-HB-01R, "Damage Tolerant Design Handbook, A Compilation of Fracture and Crack Growth Data for High Stress Alloys," vol. 1, dated December 1983 (page 411.257, figure 4.113.104). It represents generic Ti 6-4 Paris fit data. These data are provided for example purposes only and do not constitute a recommendation for analyzing actual components. The R-ratio effect is idealized to illustrate variations caused by FM analytical techniques and may not represent actual material behavior.

(3) Tensile Properties:

Yield = 834 MPa or 121.0 ksi

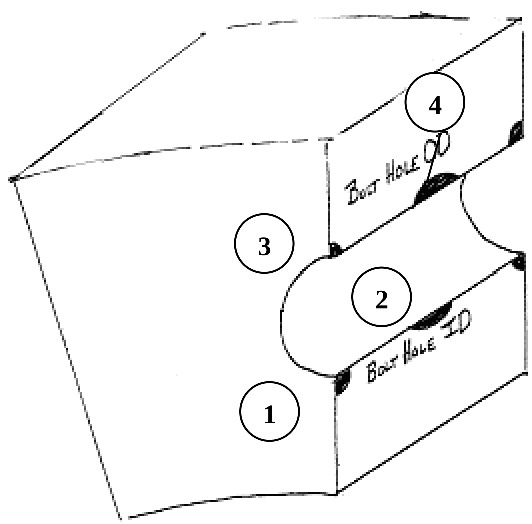
UTS = 910 MPa or 132.0 ksi

3. Test Case Analysis Guidelines. Analytical guidelines for probabilistic assessments are provided with the intent to minimize the variations of the manufacturer's results due to analytical assumptions. The case presented is based on a typical surface anomaly probabilistic fracture-mechanics approach. The hole is subdivided into four locations as identified in figure A1-2; the

relative risk or probability of fracture (POF) is calculated for each location. Results for the highest risk location are multiplied by the number of holes and by the surface area per hole to arrive at the total hole set POF or relative risk. This analytical approach can be broken down into five basic steps (described further in paragraphs “a” through “e” below):

a. Stress analysis,
b. Hole set definition including surface area and number of holes,
c. Crack growth model definition,
d. Crack growth calculations, and
e. Relative risk calculation.

Figure A1-2



a. Stress analysis. The level of mesh refinement of the part model is left up to the individual manufacturer’s discretion. However, the manufacturer should take steps to ensure that the final answer does not change by a significant amount (5-percent on relative risk or POF) if a finer mesh is chosen. The limiting operational principal stress is the hoop stress. Component stresses are determined in order to perform crack growth analysis. The disk is assumed to be at constant temperature. There are no thermal stresses. The stress model must include stress concentration at the hole.

NOTE: Typically a Kt would be applied to the rim stress due to the blade slot or a 3D model would include the blade attachment slot. However, it has not been included in the test case.

b. Hole set definition including surface area and number of holes. Hole sets are defined further in Appendix 5.

c. Crack growth model definition. Construct crack growth models for each of the locations defined in figure A1-2.

(1) Assume a 2:1 crack aspect ratio semi-circular crack for surface cracks, with surface length (2c) equal to twice the depth.

(2) Position one surface crack at the center of the hole at the inner diameter and one at the center of the hole at the outer diameter.

NOTE: In design analysis of engine hardware, position the crack in the life-limiting location of the entire hole.

(3) Assume a 1:1 crack aspect ratio quarter-circle crack for corner cracks, with surface length (c) equal to depth (a).

(4) The effect of surface enhancement, such as shot-peen, is not considered in the test case analysis.

(5) Position one corner crack at the life-limiting corner of the hole at the inner diameter and another crack at the life-limiting corner of the hole at the outer diameter. See Note in paragraph 3.c.(2) above.

d. Crack growth calculations. Perform crack growth calculations using the predicted stresses and crack growth rate data to determine the residual life associated with each location. Conduct the calculations for a range of initial crack sizes to ensure that the component service life is covered. The following guidelines apply to the test case crack growth calculations:

(1) All anomalies act as sharp propagating cracks (no incubation life assumed).

(2) The cracks are orientated normally to the maximum principal stress at the crack origin.

(3) Consider the impact of stress gradients. The stress direction should remain constant along the stress gradient. Use directional stresses normal to the max principal stress plane at the crack origin for the stress gradients.

(4) Use average crack growth data obtained in air (instead of in a vacuum).

(5) No surface enhancement effects.

(6) For surface cracks, consider a surface crack growth correction factor in the stress intensity (K) solution.

(7) For corner cracks, consider a corner crack growth correction factor in the stress intensity (K) solution.

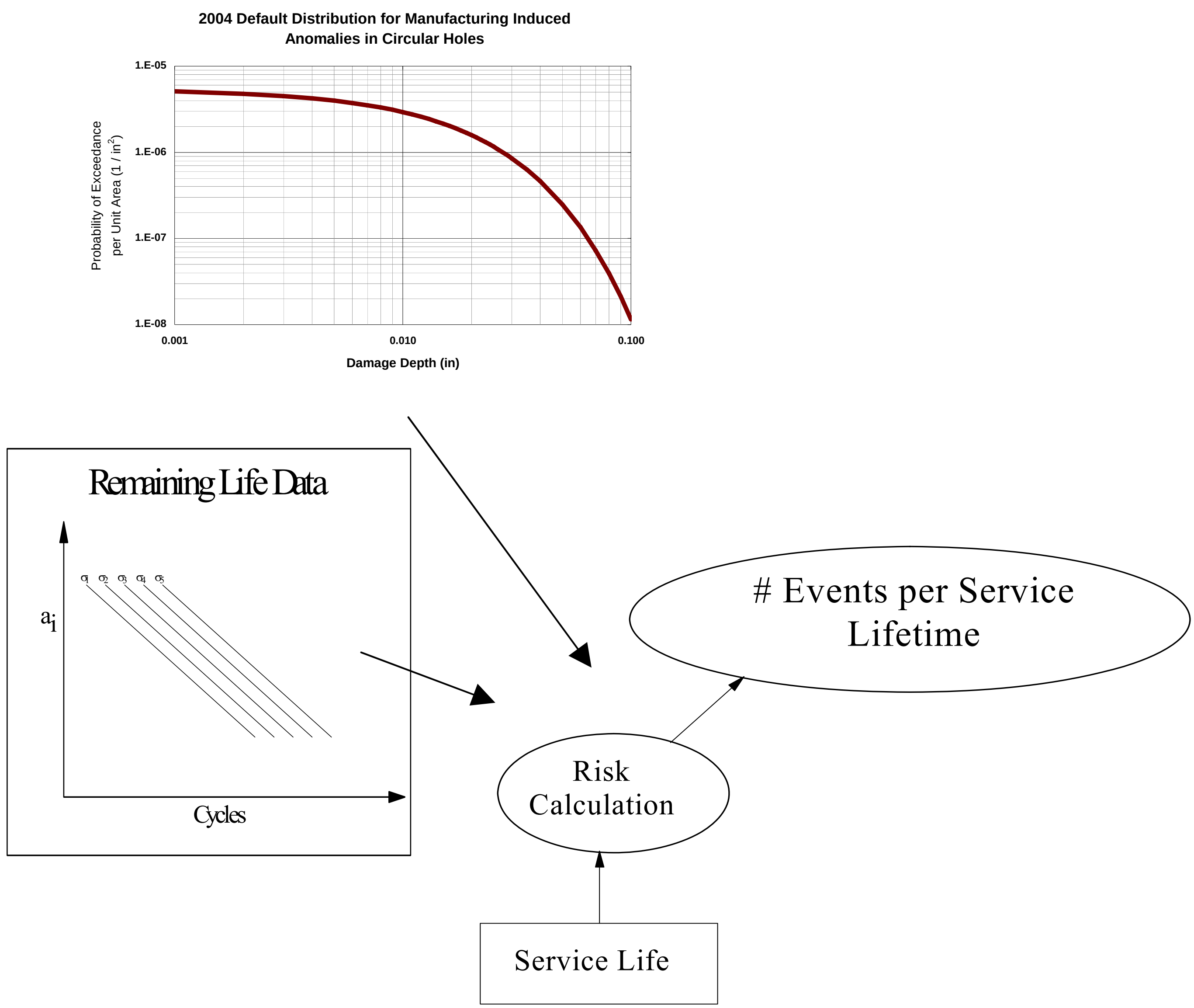
e. Relative risk calculation.

(1) The POF for each location is calculated by integrating the total surface area of all the holes in the feature, anomaly distribution, residual life, and inspection POD (if applicable) from the previous steps (see figure A1-3). The POF of each hole can be calculated by either an

integrated probabilistic method or a “Monte Carlo” method. In the Monte Carlo method, the number of simulations required is related to the computed risk. The general rule is that the number of simulations should be at least 2 orders of magnitude higher than the computed risk. For example, if risk is 1 failure in 10^4 parts, the number of samples required is 10^6. This ensures that about 100 “failed” parts are involved in the assessment. The results for the limiting location are multiplied by the number of holes in the feature to determine the total feature POF.

(2) The disk probability of fracture will be calculated twice assuming: (a) no in-service inspection, and (b) two in-service ECIs; one at 4,000 cycles and another at 8,000 cycles. The “with inspection” POF calculations are performed in the same manner as “without inspection,” except the inspection POD data and cycles to inspection are included in the risk integration (see figure A1-4). The inspection POD curve applies to 100 percent of the hole and the front and back surface area. Assume that 90 percent of the parts are inspected at 4,000 cycles and an independent 90 percent of the parts are inspected at 8,000 cycles. These inspection intervals are provided for example purposes only. Inspection intervals for actual components may vary.

Figure A1-3


2004 Default Distribution for Manufacturing Induced Anomalies in Circular Holes
Probability of Exceedance per Unit Area (1 / in^2)
1.E-05
1.E-06
1.E-07
1.E-08
0.001
0.010
0.100
Damage Depth (in)
Remaining Life Data
a_i
Cycles
Events per Service Lifetime
Risk Calculation
Service Life

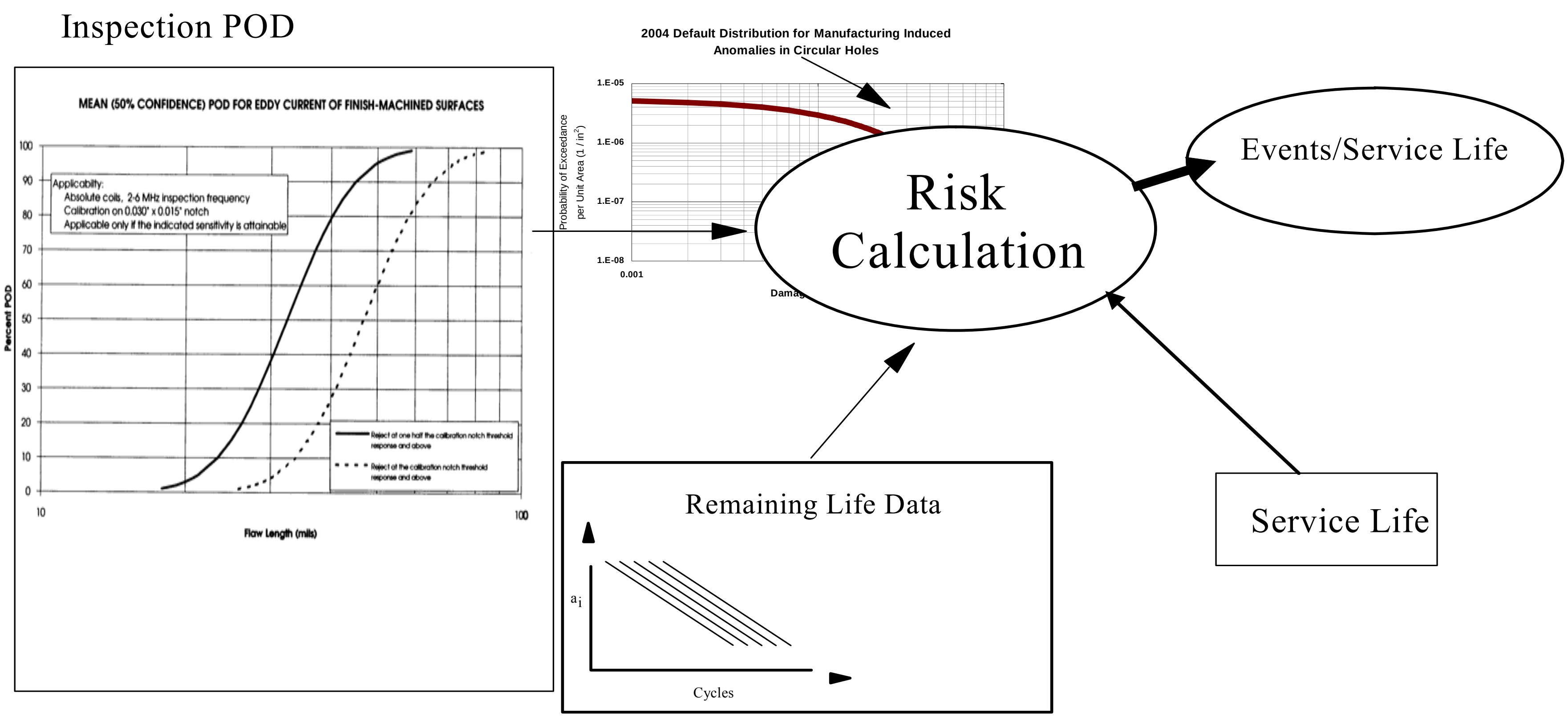

Inspection POD
MEAN (50% CONFIDENCE) POD FOR EDDY CURRENT OF FINISH-MACHINED SURFACES
Applicabilty:
Absolute coils, 2-6 MHz inspection frequency
Calibration on 0.030" x 0.015" notch
Applicable only if the indicated sensitivity is attainable
Percent POD
Flaw Length (mils)
Reject at one half the calibration notch threshold response and above
Reject at the calibration notch threshold response and above
2004 Default Distribution for Manufacturing Induced Anomalies in Circular Holes
Probability of Exceedance per Unit Area (1 / in^2)
1.E-05
1.E-06
1.E-07
1.E-08
0.001
Risk Calculation
Events/Service Life
Remaining Life Data
a_i
Cycles
Service Life

Figure A1-4

4. Results. A number of manufacturers have performed this test case. A statistical analysis of the results, given in events per service life, was performed and demonstrated the statistical values shown in the table below (m = mean value; s = sample standard deviation):

Table A1-1

Failure Risk Events/Service Life	**Mean value: m**	**m – 1.65 s**	**m + 1.65 s**
Without in-service inspection	2.88E-04	2.58E-04	3.22E-04
With an in-service inspection	1.28E-04	7.29E-05	2.25E-04

All results in the range of (m-1.65s, m+1.65s) for both conditions are considered acceptable.

NOTE: This range is defined as the interval, centered on the mean value, covering 90-percent of the result population assuming a log-normal distribution.

APPENDIX 2. DEFAULT ANOMALY DISTRIBUTION CURVES

1. Manufacturing Anomaly Distribution Curves for Circular Holes.

a. This appendix shows the anomaly distribution curve associated with the manufacturing-induced anomalies in circular holes in titanium, steel, nickel, or powder nickel engine rotors.

(1) Figure A2-1 illustrates a probability of exceedance curve for manufacturing-induced anomalies for circular holes. The horizontal axis represents the anomaly depth in inches. The vertical axis represents probability of exceedance per unit surface area ($1/in^2$) of the single hole in a feature (see Appendix 5 for a feature definition).

(2) Table A2-1 shows the tabular data corresponding to the plot in figure A2-1. The distribution reflected in figure A2-1 is defined by the equation (Eq. A2-1).

(3) The exceedance curve in figure A2-1 defines the distribution corresponding to the hole geometry with relatively high L/D ratio (L/D > 1.3). For lower values of L/D, use a frequency reduction factor as a multiplication factor on equation (Eq. A2-1).

(4) The above frequency reduction factor is defined below in a form of a plot (figure A2-2), a table (Table A2-2) and an equation (Eq. A2-2). Use the frequency reduction, ν, as a multiplication coefficient for the right-hand-side of Eq. A2-1 for the cases where 1.0 < L/D < 1.3. Outside of this range, the frequency factor is defined as follows:

$\nu = 1.0$ for any $L/D > 1.3$
$\nu = 0.04$ for any $L/D < 1.0$

Figure A2-1

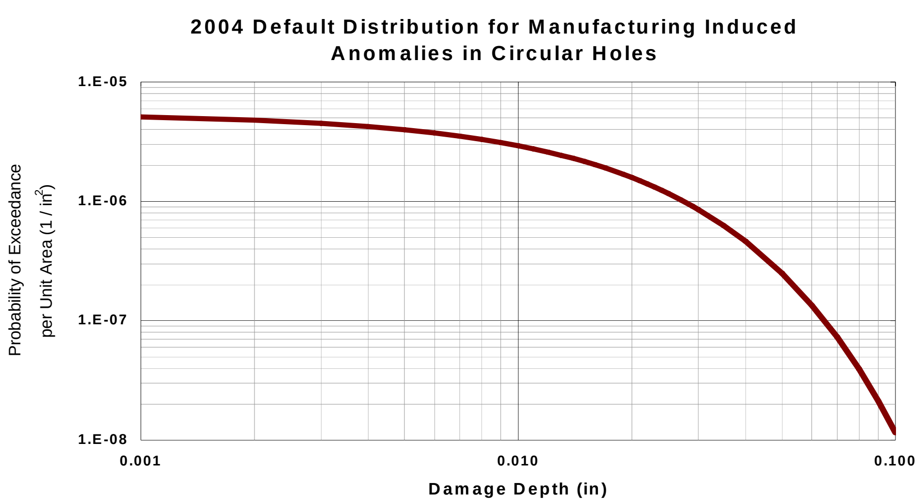


Table A2-1. Tabular Data for Figure A2-1

Depth, in	**Exceedance, $1/in^2$**
0.001	5.10E-06
0.002	4.80E-06
0.003	4.51E-06
0.004	4.24E-06
0.005	3.99E-06
0.006	3.75E-06
0.007	3.53E-06
0.008	3.31E-06
0.009	3.12E-06
0.010	2.93E-06
0.011	2.76E-06
0.012	2.59E-06
0.013	2.44E-06
0.014	2.29E-06
0.015	2.15E-06
0.016	2.03E-06
0.017	1.91E-06
0.018	1.79E-06
0.019	1.68E-06
0.020	1.58E-06
0.021	1.49E-06
0.022	1.40E-06
0.023	1.32E-06
0.024	1.24E-06
0.025	1.16E-06
0.026	1.09E-06
0.027	1.03E-06
0.028	9.68E-07
0.029	9.10E-07
0.030	8.56E-07
0.035	6.29E-07
0.040	4.63E-07
0.050	2.50E-07
0.060	1.35E-07
0.070	7.30E-08
0.080	3.94E-08
0.090	2.13E-08
0.100	1.15E-08

Equation for the default hole anomaly exceedance curve:

Equation A2-1

$F(x) = \nu * 5.42E\text{-}06 * EXP(-61.546*(x))$

where x is anomaly depth in inches, and F(x) is exceedance probability per unit area ($1/in^2$).

Figure A2-2. Frequency Reduction Factor

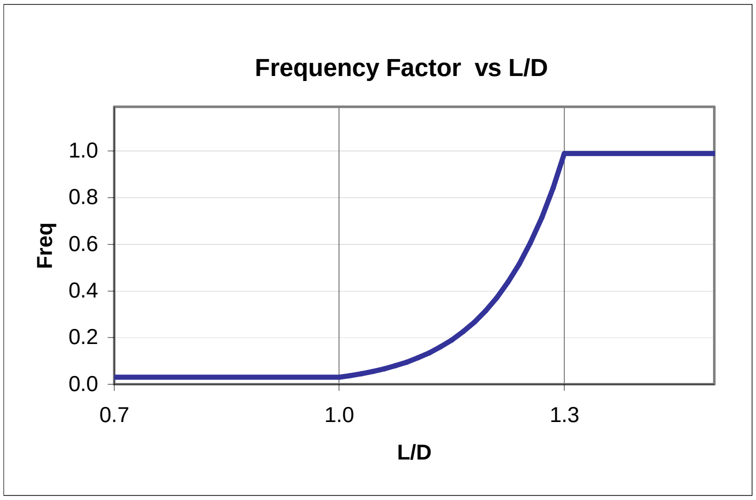


Table A2-2. Frequency Reduction Factor as a Function of Hole L/D

L/D	**L/D freq.**
0.000	0.040
1.000	0.040
1.015	0.047
1.030	0.055
1.045	0.065
1.060	0.076
1.075	0.089
1.090	0.105
1.105	0.123
1.120	0.145
1.135	0.170
1.150	0.200
1.165	0.235
1.180	0.276
1.195	0.324
1.210	0.381
1.225	0.447
1.240	0.525
1.255	0.617
1.270	0.725
1.285	0.851
1.300	1.000
2.000	1.000

Equation for the L/D frequency reduction factor as a function of L/D is:

Equation A2-2

$\nu = 0.04 * EXP[10.7296 * (L/D - 1)]$

where L/D is a ratio of the hole length L over diameter D, and the dimensionless frequency factor ν should be used as a multiplication coefficient for the right-hand-side of the equation Eq. A2-1 for cases where $1 < L/D < 1.3$.

APPENDIX 3. DEFAULT POD APPLICABILITY

1. Use of Default POD Data.

a. This appendix defines conditions relevant to the use of accepted estimates of the probability of detection for specific types of anomalies and specific nondestructive evaluation/inspection techniques, which may be considered as default values when applied under appropriately similar conditions. The conditions defined in this appendix do not necessarily guarantee the validity of these POD values. For example, if inspection parameters, such as penetrant concentration or temperature, are inadequately controlled, the penetrant capability shown in the accompanying figures in Appendix 4 will not be attained, even if the correct penetrant is selected. We recommend use of a written plan for controlling and monitoring inspection processes (see paragraph 3 of this appendix).

b. If the conditions described for each inspection are not satisfied, the resultant inspection capability and reliability will be reduced. Use of the default POD values in Appendix 4 would then be inappropriate and would result in an overly optimistic damage tolerance assessment.

2. Demonstrations of Inspection Capability.

a. For eddy current inspection techniques, a default POD curve is provided in Appendix 4. Use of the default POD curve must be based on demonstration that the stated calibration and reject signal levels are attainable on the component being inspected, and, for example, are not prevented by noise or geometrical features. The demonstration conditions should be appropriate to the properties of the part inspected that may affect the inspectability, such as surface conditions, depth to be inspected, or proximity to edges. No other demonstration of this default capability is necessary as long as the requirements for the specific inspection technique are satisfied (see paragraphs 3-5 of this appendix).

b. For specific inspection techniques applied under well-controlled conditions, it might be possible to achieve POD values that are significantly better than the default POD values. Manufacturers may take advantage of any such improved capability and reliability only if it is supported by a well-documented demonstration program. Similarly, a well-documented demonstration program may be necessary to measure POD values appropriate to specific conditions excluded from those default values supported by explicit, reasonable assumptions.

3. General Restrictions and Applicability.

a. The inspection process must be well controlled and performed in accordance with acceptable procedures, such as those defined by the engine standard practices manual, and consistent with good industrial inspection practices, such as those defined by MIL-STD's or equivalent industry standards.

b. Pertinent inspection process parameters such as coverage, probe indexing, and scanning speeds (see paragraph 5 of chapter 2, and paragraphs 4-5 of this appendix), should be governed by written procedures. Inspection plans and any inspection fixturing should be designed to minimize human and other sources of variability.

c. Inspectors must be fully qualified and trained for at least one of the following: NAS 410/prEN4179, MIL-STD-410, ASNT-TC-1A, ATA-105, or equivalent, and provided with adequate training instructions in the specific inspection method.

d. The specified default ECI and FPI POD data apply to all materials. Geometric conditions, such as radii and edges, can create areas where inspections cannot be accomplished. Limitations also exist relative to depth of penetration and near surface resolution. Conditions under which the default POD data were acquired are outlined in paragraphs 4-5 of this appendix. Seek advice about the equivalence of alternative conditions from those with expertise in NDE. Areas of high compressive residual stress can have negative effects on the capability of various NDE techniques, most notably penetrant inspection.

e. Applicability of the default POD data is limited to components that exhibit no abnormal surface condition and that have been properly cleaned for each shop manual requirements. No other special pre-inspection cleaning or polishing is required.

4. Restrictions and Applicability: ECI.

a. Eddy current inspection is an inspection technique suitable for the detection of surface or near-surface anomalies. For the purposes of this AC, ECI is intended primarily for application to engine-run components. The default POD data were acquired under the following conditions:

- Probes containing absolute coils, with inspection frequency in the range 2-6 MHz.
- Probe fixturing is capable of following surface contours of the component being inspected, with adequate control of attitude, lift-off and scan indexing. Scan direction was parallel with any uniform feature changes.
- Provision was made for automatic recording of the inspection process signals or automated alarm, or both, when the inspection threshold is exceeded.

b. The default POD data apply to surface-connected, low-cycle fatigue cracks. Cracks are assumed to have a 2-to-1 aspect (length:depth) ratio. Crack sizes are expressed in terms of the length at the surface. Cracks must not be obscured by oxide, contaminants, etc. Inspected surfaces should be flat or only moderately curved. Choice of the appropriate POD curve from those provided must be based on component demonstration of the attainable inspection sensitivity (see paragraph 2 of this appendix).

5. Restrictions and Applicability: Penetrant Inspection (PT/FPI).

a. PT is an inspection technique suitable for detection of anomalies that are open to the inspected surface. For the purposes of this AC, PT is intended primarily for application to engine-run components. The default POD data were acquired under the following conditions:

(1) Fluorescent penetrants were qualified as level 4 by MIL-I-25135, or equivalent, and used with dry powder developer (as a minimum).

(2) Application of penetrant and developer was automated, or for each, standard practices were employed. See, for example, MIL-STD-6866 and AMS-2847.

(3) Manipulation of the part was possible to present to the inspector an unimpeded view of the surface to be inspected.

b. The default POD data apply to surface-connected low-cycle fatigue cracks. Cracks are assumed to have a 2-to-1 aspect (length:depth) ratio. Crack sizes are expressed in terms of the length at the surface. Cracks must not be obscured by oxide, contaminants, etc. Inspected surfaces should be readily visible. Choice of the appropriate POD curve from those provided must be based on whether focused or full field inspection conditions apply, as those terms are defined in paragraph 4 ("Definitions") in the body of this AC.

APPENDIX 4. DEFAULT POD CURVES

Figure A4-1

MEAN (50% CONFIDENCE) POD FOR FLUORESCENT PENETRANT INSPECTION OF FINISH-MACHINED SURFACES

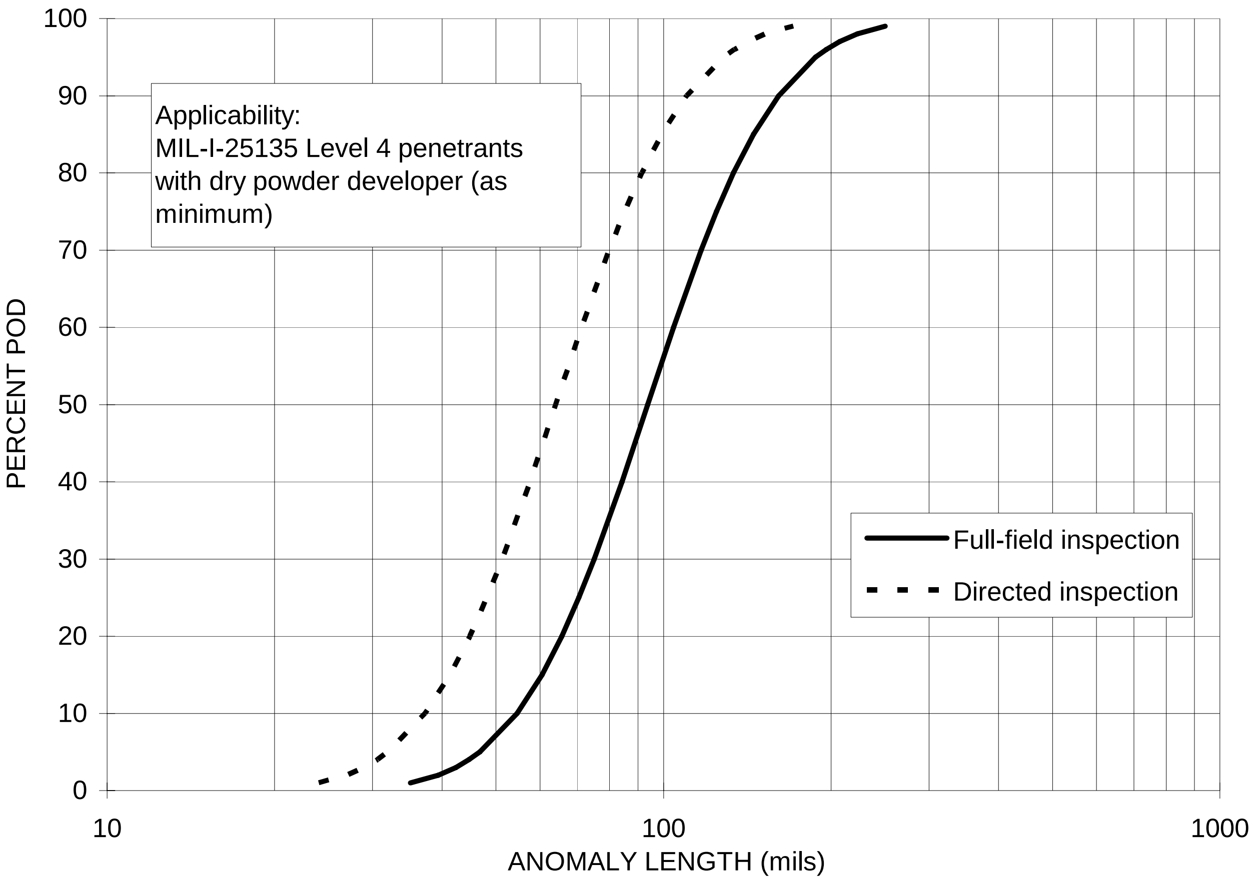
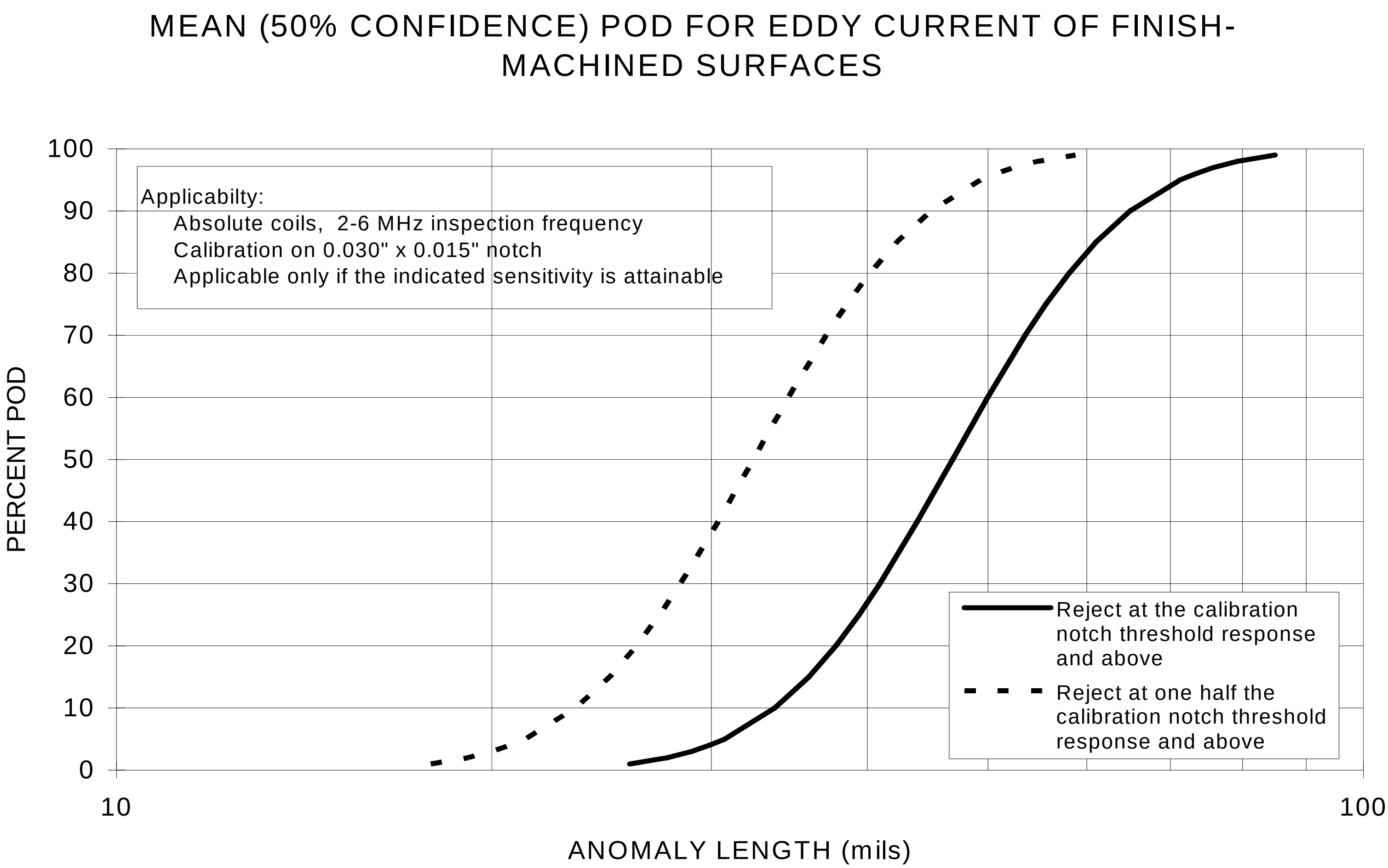


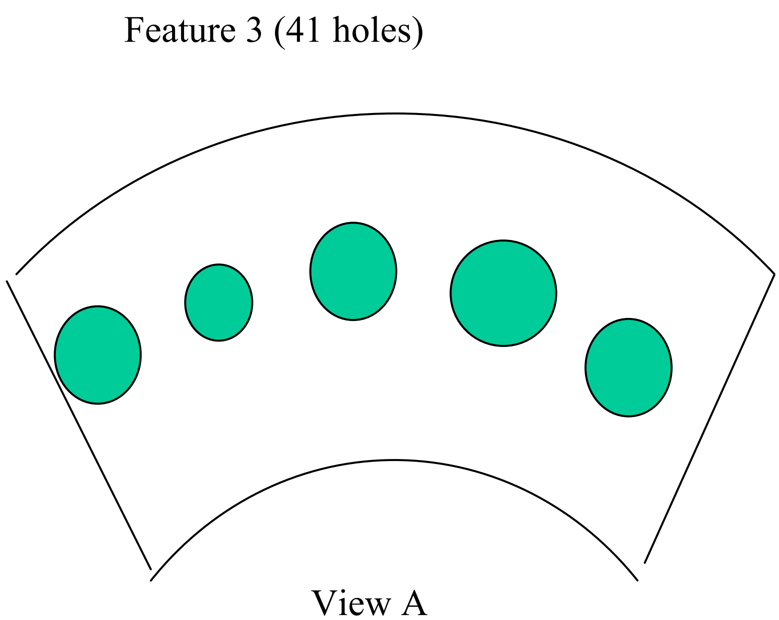
Figure A4-2

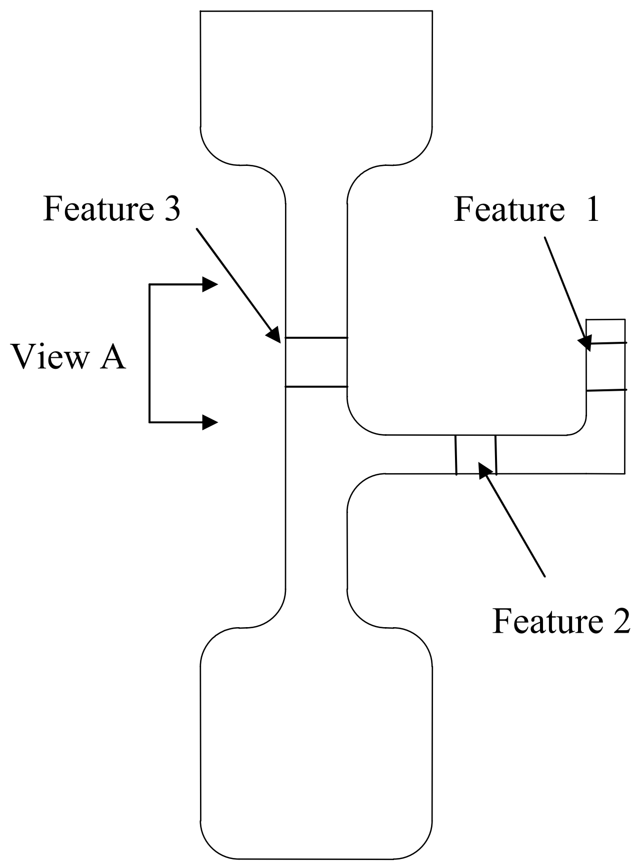

MEAN (50% CONFIDENCE) POD FOR EDDY CURRENT OF FINISH-MACHINED SURFACES
Applicabilty:
Absolute coils, 2-6 MHz inspection frequency
Calibration on 0.030" x 0.015" notch
Applicable only if the indicated sensitivity is attainable
Reject at the calibration notch threshold response and above
Reject at one half the calibration notch threshold response and above
PERCENT POD
0
10
20
30
40
50
60
70
80
90
100
10
100
ANOMALY LENGTH (mils)

APPENDIX 5. DEFINITION OF A HOLE FOR MANUFACTURING ANOMALY ASSESSMENTS

1. Hole Feature. A set of one or more circular holes at the same axial and radial location where any given hole falls at least partially within the circumferential (diametral) shadow of the largest hole, and its size is greater than 75 percent of the diameter of the largest hole. Note that "circular" is relative to the machining axis and not necessarily as viewed by the stress field.

Figure A5-1





APPENDIX 6. MANUFACTURING CREDITS

1. This appendix contains the approach for taking credit for enhanced hole making manufacturing processes in the POF calculations to meet the bolt hole feature DTR. These credits were developed based on experience from a number of engine manufacturers.

Table A6-1. Process Controls, Control Definitions and Credit Factor

Process control	**Definition**	**Credit Factor**
Process validation	A procedure in which it is demonstrated that the Manufacturing Process delivers parts consistent with the Design Intent (see FAA Report number DOT/FAA/AR-06/3). Process validation is understood in this AC to include an inspection of the part for geometric anomalies (cracks, scratches, dents, scores, etc.) after manufacture. Such an inspection may be visual, enhanced visual, or semi-automatic such as ECI. In addition, an implicit consideration in assigning credit to the various processes is that secondary operations such as chamfering, edge breaking and finishing are controlled and subject to process validation as described in FAA Report number DOT/FAA/AR-06/3.	5
Single Point Boring	The removal in a finishing operation of a small depth of material, at least 0.004" deep, in the bore of the hole by use of a single point boring tool. This credit is allowed for titanium alloys only.	5
Honing	The removal of a small depth of material, at least 0.002", by a self-centering grinding operation. This credit is allowed for all materials.	5
Coolant Monitor	A device which ensures that there is a continuous flow of coolant with periodic checks on the pressure and the concentration of the coolant supplemented with the training of operators to ensure the direction of the flow towards the cutting edge (see FAA Report number DOT/FAA/AR-06/3). This credit is allowed for all materials.	5
Power Monitor	A device that continuously monitors the power consumed by the machine tool and which must be shown to be sensitive to conditions such as worn tools, loss of coolant, etc., which give rise to anomalies (see FAA Report number DOT/FAA/AR-06/3). This credit is allowed for all materials.	For the use of either a power monitor or a feed force monitor, 20. For the use of both a power monitor and a feed force monitor, 30.
Feed Force Monitor	A device that continuously monitors the feed force used by the machine tool and which must be shown to be sensitive to conditions such as worn tools, loss of coolant, etc., which give rise to anomalies (see FAA Report number DOT/FAA/AR-06/3). This credit is allowed for all materials.	

Process control	**Definition**	**Credit Factor**
Inspection	In this context, inspection is confined to the use of inspection techniques specifically aimed at detecting non-geometric anomalies, such as highly distorted material, smeared material, white or amorphous layer (see FAA Report number DOT/FAA/AR-06/3). Generally, this would be an etch inspection specifically targeted at the hole and which must be shown to detect such anomalies. This credit is allowed for all materials.	5

2. Rules for Applying Credits.

a. Process validation is assumed to be mandatory on machining processes on all future products.

b. Use of manufacturing credits including process validation should be part of the certification data submittal.

c. Coolant monitoring, power monitoring, and feed force monitoring should be used in both roughing and finishing operations.

d. Credit for process monitoring (power or feed force) cannot be claimed unless coolant monitoring is also in use.

e. Credit for either single point bore or honing can be claimed, as appropriate, but not for both together.

3. Credit Application Process.

a. Decide which controls are to be applied.

b. Total the credit factors for the combination of controls.

c. Calculate the probability of burst for the hole feature in the disc.

d. Divide the probability of burst by the total of the credit factors.

e. This reduced probability of burst should be compared to the DTR.

4. Credit Examples. For feature of 32 holes where the initial design POF is calculated to be 5 X 10^{-4} events per service life:

a. Datum
Process validation and inspection for geometric anomalies
Process Validation 5
Total Credit 5
POF with controls is now 1 X 10^{-4} events per service life
This is not adequate against HOLE FEATURE DTR.

b. First selection

Selected combination of controls is:

Process validation	5
Honing	5
Coolant Monitor	5
Etch Inspection	5
Total credit	**20**

POF with controls is now 2.5 X 10^{-5} events per service life.
This is not adequate against HOLE FEATURE DTR

c. Improved Selection

Improve the combination of controls to:

Process validation	5
Honing	5
Coolant Monitor	5
Power Monitor	20
Etch Inspection	5
Total credit	**40**

New POF with controls is now 1.25 X 10^{-5} events per service life.
This is acceptable to HOLE FEATURE DTR.

d. Other possible selections

Note that the following combinations of controls would also give an acceptable HOLE FEATURE DTR:

(1)

Process validation	5
Coolant Monitor	5
Power Monitor	20
Total credit	**30**

(2)

Process validation	5
Honing	5
Coolant Monitor	5
Power Monitor	20
Total credit	**35**

APPENDIX 7. SURFACE (MANUFACTURING INDUCED ANOMALY) DAMAGE TOLERANCE ASSESSMENT FLOWCHARTS

Note: For more details on the steps described in the following figures, refer to Chapter 3 and to the appendices.

Fig. A7-1 : Surface Damage Risk Assessment Workflow

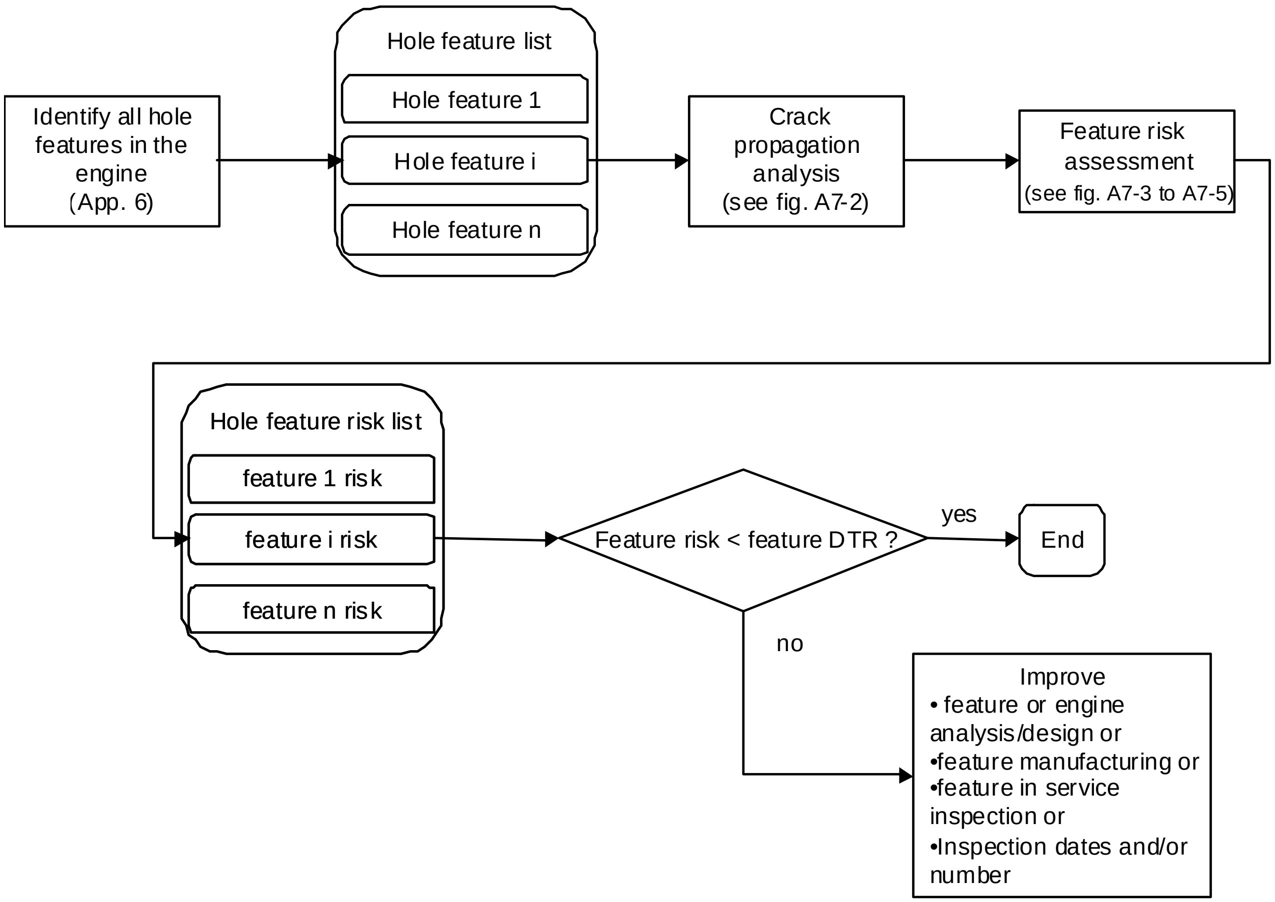


Figure A7-2: Crack Propagation Analysis

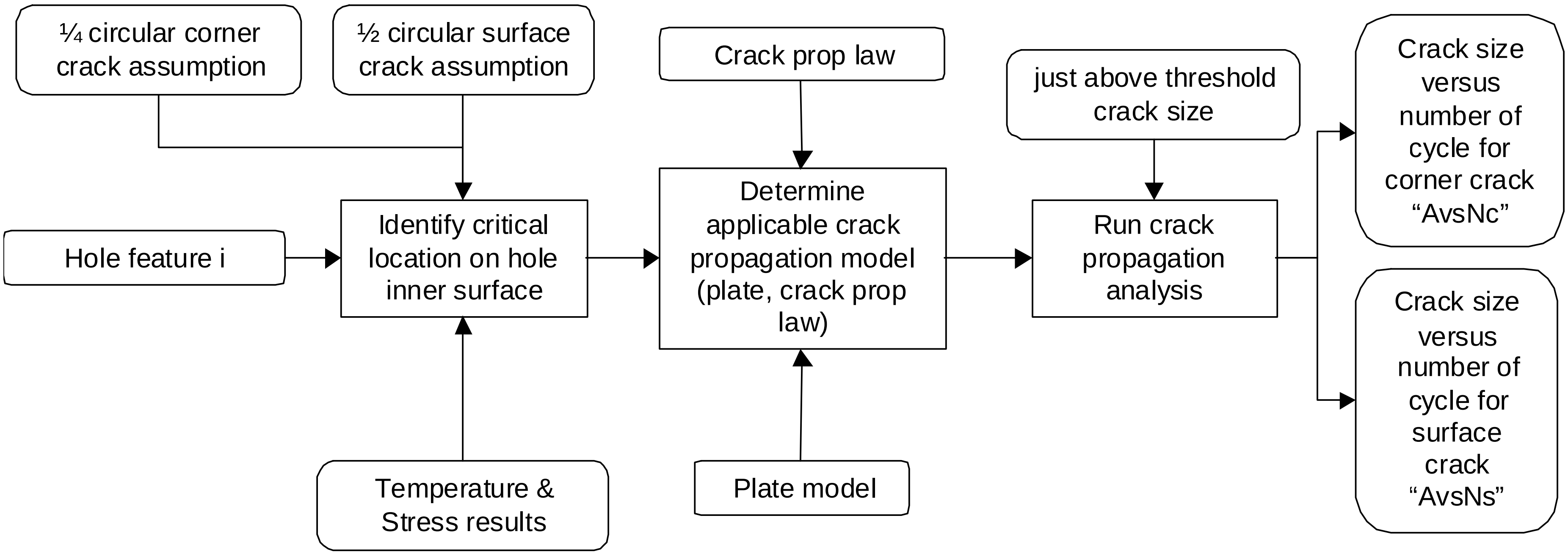
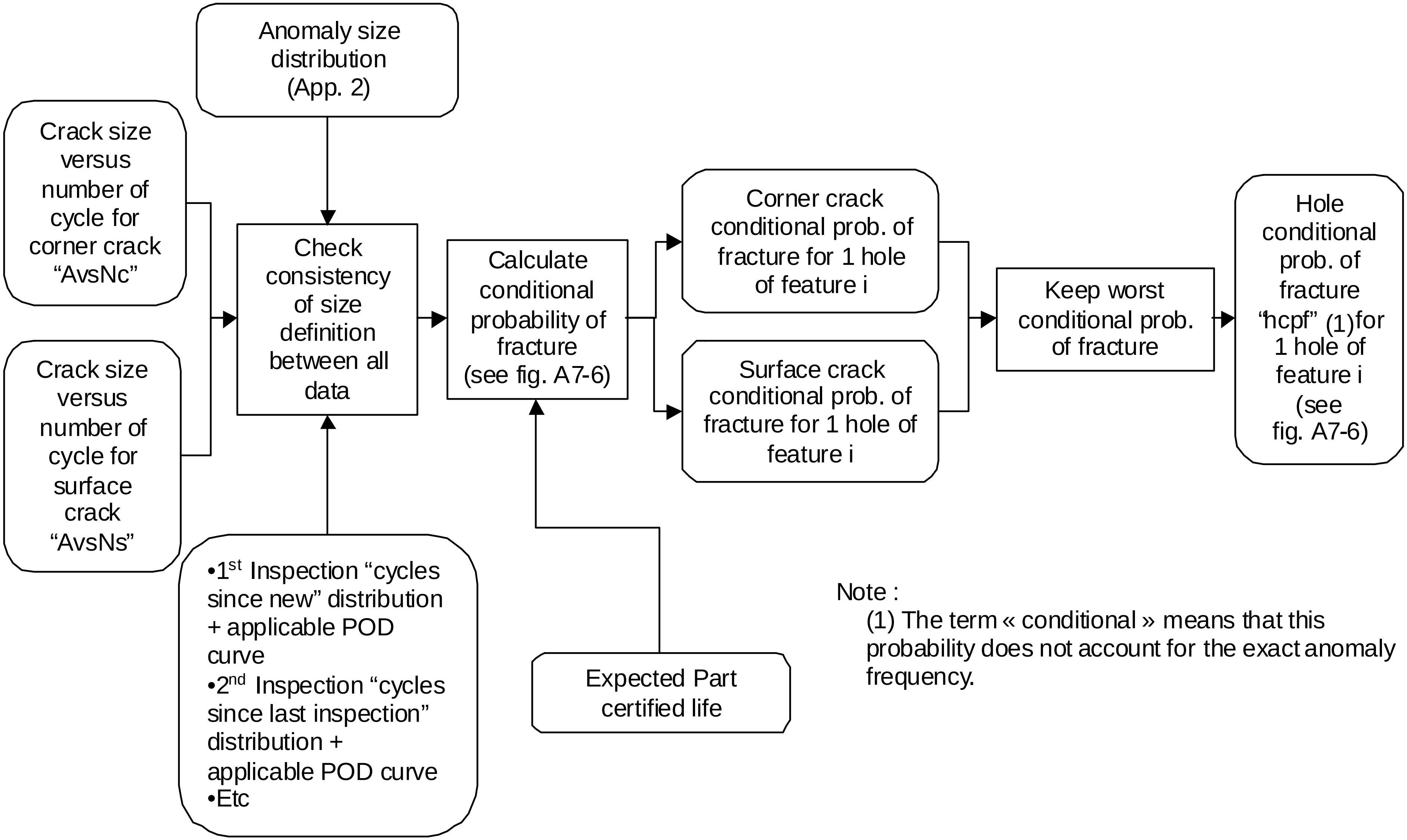


Figure A7-3 : Feature Risk Assessment (1/3)

1st step : consider only one hole of the hole feature i and calculate the conditional probability of fracture for this hole.



Note :
(1) The term « conditional » means that this probability does not account for the exact anomaly frequency.

Figure A7-4: Feature Risk Assessment (2/3)

2nd step : Calculate the probability of fracture for one hole by combining the conditional probability of fracture for one hole with the hole actual inner surface area, the applicable manufacturing credits and anomaly frequency correction factor.

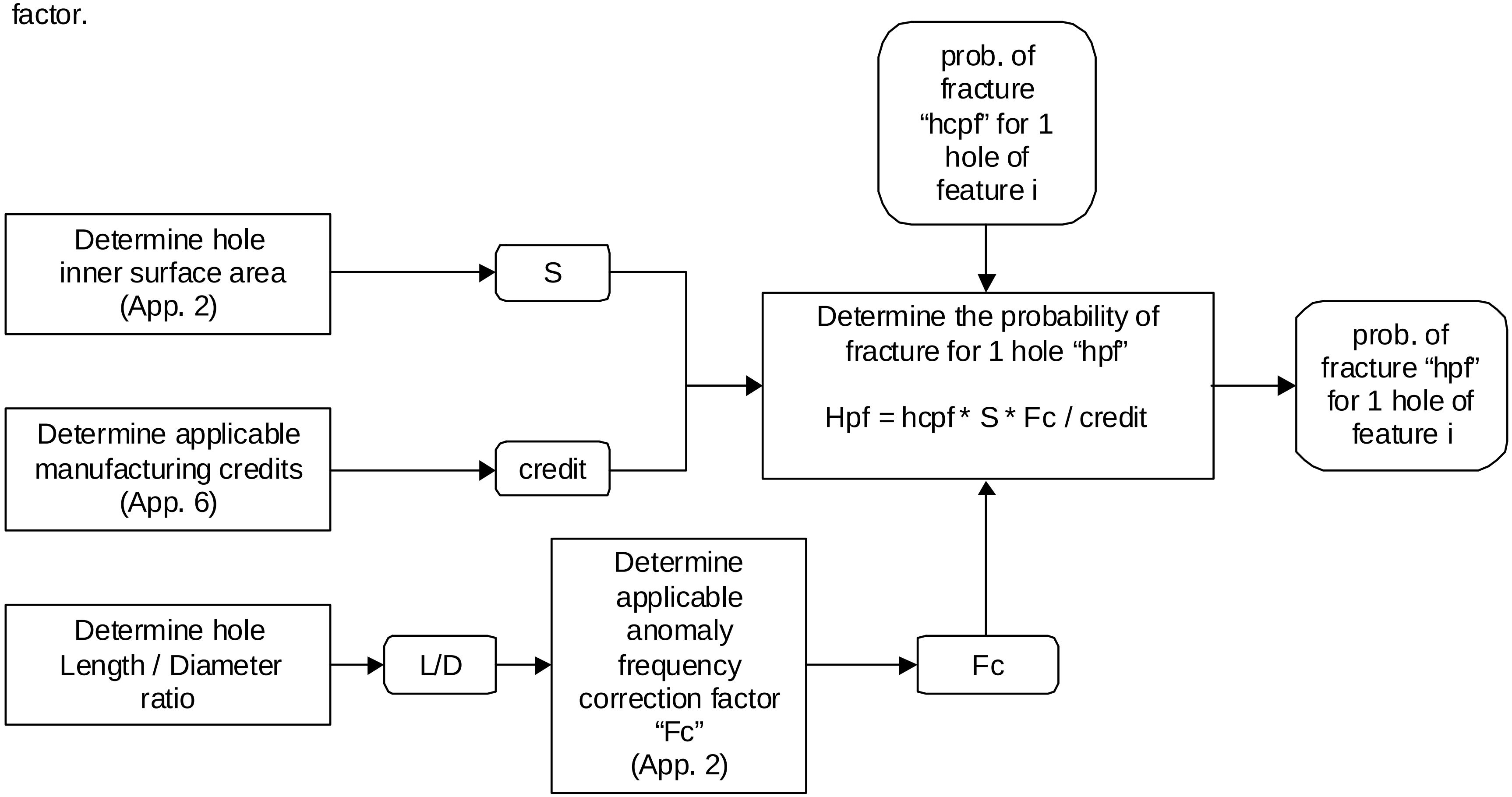


Figure A7-5: Feature Risk Assessment (3/3)

3rd step : Calculate the risk of fracture for the feature i from the probability of fracture for one hole.

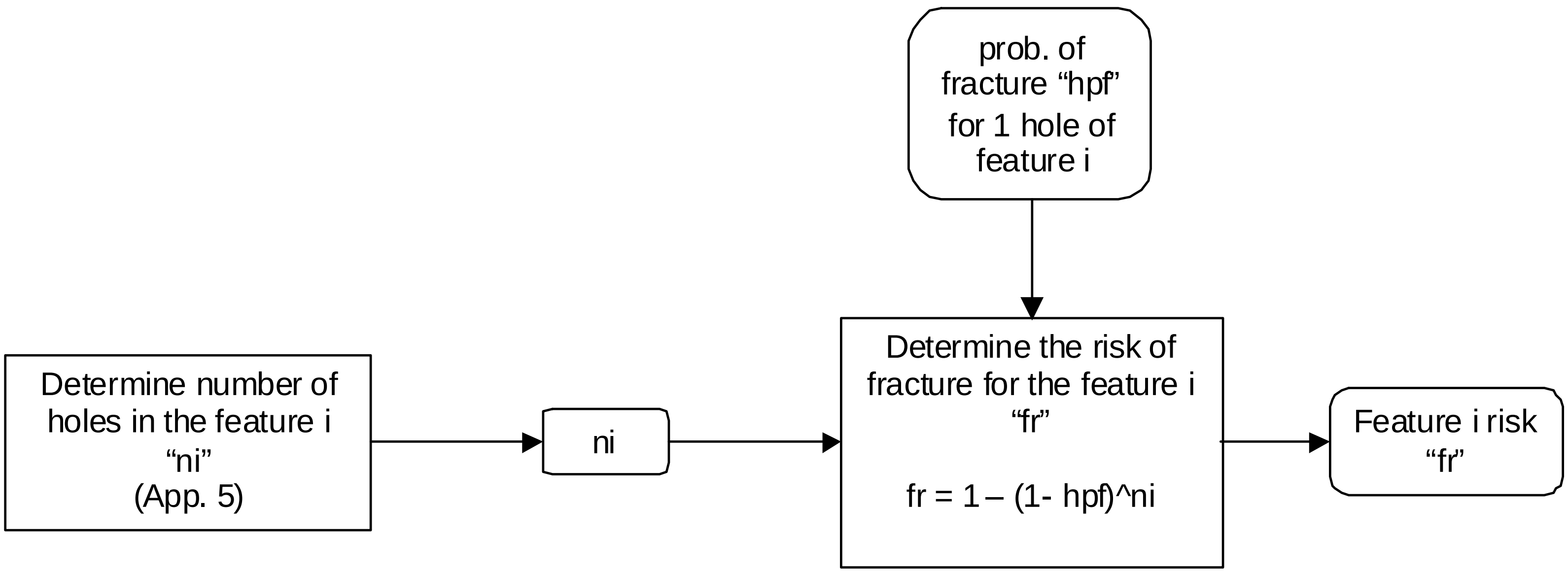
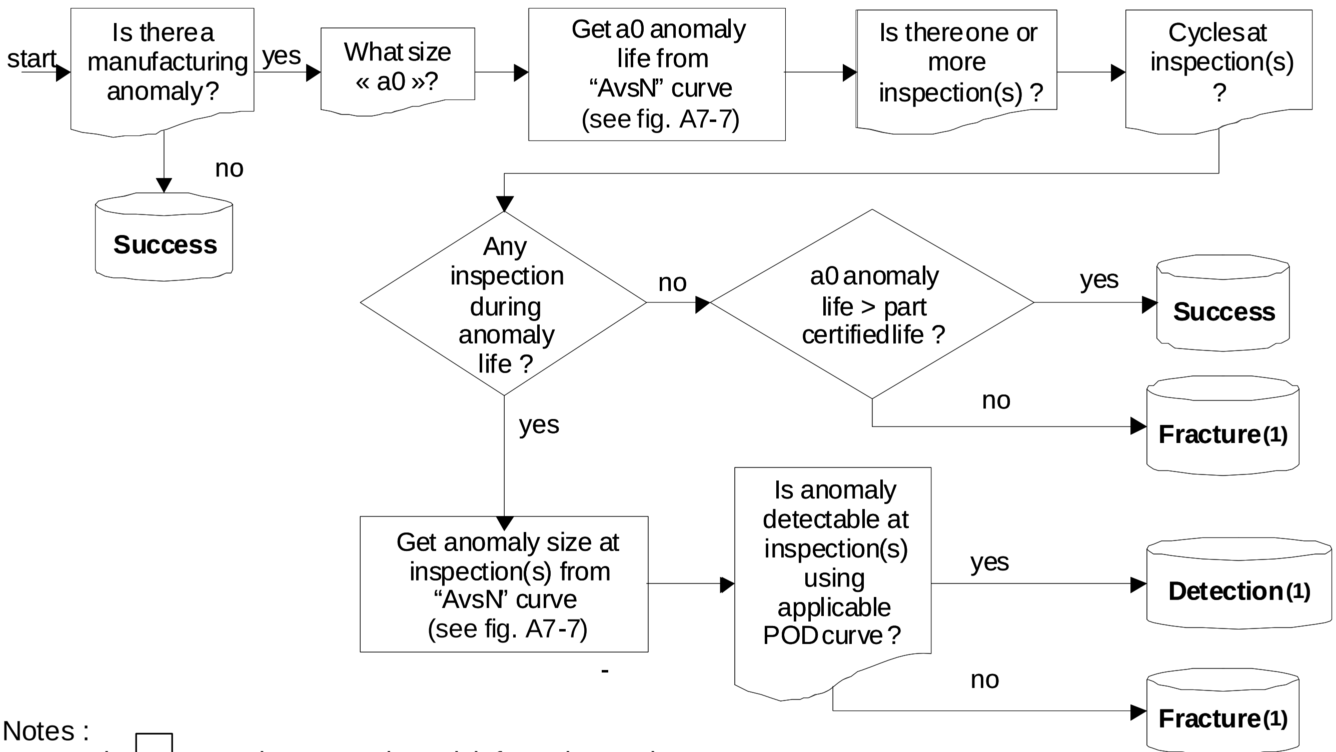


Figure A7-6: Conditional Probability of Fracture Calculation

The POF calculation is described here following a Monte Carlo simulation process. A large sample of holes should be simulated (see App. 1, 3 (e)). Each hole simulation in the sample follows the flowchart below to determine if it : fractures before part certified life / succeeds to reach part certified life / is detected with a crack.



Notes :

- each requires a random pick from the pertinent random variable distribution
- (1) record the number of cycles at fracture or detection for each hole

$$\text{Conditional prob. of fracture before N cycles} = \frac{\text{number of fractured holes before N cycles}}{\text{total sample size}}$$

Figure A7-7: a0 Anomaly Life & Anomaly Size at Inspection(s) Calculations

from "AvsN"Curve