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Bibliography for Lecture Series 190

A Recommended Methodology for Quantifying NDE/NDI Based on Aircraft Engine Experience

This Bibliography with abstracts has been prepared to support AGARD Lecture Series 190 by the Scientific and Technical Information Program of the US National Aeronautics and Space Administration, Washington, D.C., in consultation with the Lecture Series Director, Mr Clovis L. Petrin, Jr, U.S. Department of the Air Force.

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88A18156 87/00/00
UTTL: **Application of QNDE to retirement-for-cause analysis**
AUTH: A/YANG, JANN N.
PAA: A/(George Washington University, Washington, DC)
IN: Solid mechanics research for quantitative non-destructive evaluation (A88-18151 05-38). Dordrecht, Martinus Nijhoff Publishers, 1987, p. 101-119.,
ABS: The retirement-for-cause (RFC) is a procedure under which structural components are inspected periodically. The component is retired from service only when it has incurred quantifiable damage detected by the NDE system. The application of NDE results to RFC analysis is described in detail, in particular the importance of dealing with the NDE uncertainty. The RFC analysis methodology is summarized, and the sensitivity of structural reliability and life-cycle-cost with respect to the capability of NDE systems is examined. Numerical examples are given to demonstrate the importance of RFC life management.

87A10727 86/00/00
UTTL: **Manufacturing technology for nondestructive evaluation (NDE) system to implement retirement for cause (RFC) procedures for gas turbine engine components**
AUTH: A/BIRX, D. L.; B/DOOLIN, D. G.
PAA: B/(Systems Research Laboratories, Inc., Dayton, OH)
IN: Review of progress in quantitative nondestructive evaluation. Volume 5A - Proceedings of the Twelfth Annual Review, Williamsburg, VA, June 23-28, 1985 (A87-10676 01-38). New York, Plenum Press, 1986, p. 877-884.,

85A47469 84/00/00
UTTL: **Manufacturing technology for nondestructive evaluation (NDE) system to implement retirement for cause (RFC) procedures for gas turbine engine components**
AUTH: A/TAYLOR, F. M.; B/BIRX, D. L.; C/DOOLIN, D. G.
PAA: C/(Systems Research Laboratories, Inc., Dayton, OH)
IN: Review of progress in quantitative nondestructive evaluation. Volume 3B - Proceedings of the Tenth Annual Review, Santa Cruz, CA, August 7-12, 1983 (A85-47376 23-38). New York, Plenum Press, 1984, p. 1331-1335; Discussion, p. 1335-1337.,
ABS: An automated NDE inspection system capable of detecting 5 x 10 mil surface flaws and 15 mil inclusions in engine rotor components is being developed. This system represents an aid for the implementation of the 'Retirement for Cause' (RFC) philosophy according to which the large percentage of good, used engine rotor components are returned to service, and the small percentage of flawed components are retired for cause. Particular attention is given to the detection and characterization of critical flaws through a utilization of computer algorithms. It is pointed out that the Inspection Module's NDE Instrumentation represents the most advanced computer-controlled ultrasonic and eddy current instrumentation available.

85A47402 84/00/00
UTTL: **Development of a quantitative flaw characterization module - A status report**
AUTH: A/GRUBER, G. J.; B/HENDRIX, G. J.; C/MUELLER, T. A.
PAA: C/(Southwest Research Institute, San Antonio, TX)
IN: Review of progress in quantitative nondestructive evaluation. Volume 3A - Proceedings of the Tenth Annual Review, Santa Cruz, CA, August 7-12, 1983 (A85-47376 23-38). New York, Plenum Press, 1984, p. 309-320; Discussion, p. 320, 321.,
ABS: It is pointed out that life-management technology now being developed for the Air Force under the name 'retirement for cause' requires reliable and accurate ultrasonic techniques for characterizing internal bulk flaws in titanium and nickel-based alloy disk materials. The present paper is

concerned with the utilization of quantitative nondestructive evaluation techniques based on the interaction of ultrasound with internal bulk flaws. A flow diagram of the program established to qualify the Born inversion technique for sizing voids and inclusions in typical aircraft turbine-engine parts is considered. Ultrasound-flaw interaction models are discussed, taking into account the Born model for spherical inclusions, and the Franz-Gruber model for spherical voids. An algorithm performance evaluation is also conducted, giving attention to shear-wave measurements, and longitudinal-wave measurements.

85A47396 84/00/00
UTTL: **Crack characterisation in turbine disks**
AUTH: A/BOND, L. J.; B/SAFFARI, N.
PAA: B/(University College, London, England)
IN: Review of progress in quantitative nondestructive evaluation. Volume 3A - Proceedings of the Tenth Annual Review, Santa Cruz, CA, August 7-12, 1983 (A85-47376 23-38). New York, Plenum Press, 1984, p. 251-260; Discussion, p. 261, 262. Research supported by the Ministry of Defence (Procurement Executive).,
ABS: Nondestructive testing techniques which provide reliable quantitative defect characterization are of considerable importance for a full utilization of fracture mechanics approaches and the application of Retirement-for-Cause (RFC) concepts to critical aerospace components. In the present paper, ultrasonic techniques are presented which have been developed for the detection and characterization of small surface defects in aircraft engine turbine disks. These techniques are based on a utilization of the reflection of surface waves and the phenomena of body-to-surface mode-conversion found at surface breaking and near surface defects for features in the range from 0.05 to 1.0 mm. Possibilities concerning a crack characterization on the basis of the results obtained with the considered techniques are examined, taking into account the midfrequency regime where the defect depth is comparable to or just smaller than the wavelengths involved.

85A47377 84/00/00
UTTL: **Use of field-flaw interaction theories to quantify and improve inspection reliability**
AUTH: A/THOMPSON, R. B.; B/THOMPSON, D. O.; C/BURTE, H. M.; D/CHIMENTI, D. E.
PAA: B/(DOE, Ames Laboratory, Ames, IA); D/(USAF, Wright Aeronautical Laboratories, Wright-Patterson AFB, OH)
IN: Review of progress in quantitative nondestructive evaluation. Volume 3A - Proceedings of the Tenth Annual Review, Santa Cruz, CA, August 7-12, 1983 (A85-47376 23-38). New York, Plenum Press, 1984, p. 13-24.,
ABS: The present status of NDE techniques is examined, and different ways in which they have been, or might be, used to quantify and improve inspection reliability are discussed. Strategies for applying detection models are addressed, including a 'worst case' analysis, a probabilistic approach based on empirically observed variability, and a first-principles probabilistic calculation. The assumptions and advantages of these approaches are mentioned. A scenario is presented for applying detection models to retirement for cause.

83A32649 81/00/00
UTTL: **Nondestructive evaluation - Microstructural characterization and reliability strategies**
AUTH: A/BUCK, O.; B/WOLF, S. M.
PAA: A/(Iowa State University of Science and Technology, Ames, IA); B/(U.S. Department of Energy, Div. of Materials Sciences, Washington, DC)
Warrendale, PA, Metallurgical Society of AIME, 1981, 413 p.,
ABS: Topics in nondestructive evaluation (NDE) in the areas of reliability strategies and NDE characterization of microstrucure and of deformation

and fracture processes are discussed. Individual subjects addressed include: reduction of unscheduled utility outages; new techniques for quantitative NDE; engine component retirement for cause; reliability strategies for advanced coal conversion systems in flawed evaluation, and for nominally brittle materials; nondestructive failure prediction for brittle solids; effect of metallic microstructure on ultrasonic attenuation; acoustic properties as microstructure-dependent materials properties; identification of microstructural changes in metals and alloys; defect characterization. Also considered are: ultrasonic characterization; boundaries between isotropic and anisotropic solids; quantitative models for eddy current analysis of metal solidification; process variables, microstructure, and NDE of a precipitation-hardened aluminum alloy; acoustic microscopy of ceramics and hybrid microelectronic joints; characterization of crack tip plastic zone parameters; acoustic emission; materials stress mapping; early detection of metal fatigue; remaining fatigue lifetime prediction.

83A15160 82/00/00

UTTL: **An enhancement for the ultrasonic test bed to inspect engine disk bolt holes**

AUTH: A/ADDISON, R. C.

PAA: A/(Rockwell International Science Center, Thousand Oaks, CA)
In: Review of progress in quantitative nondestructive evaluation. Volume 1 - Proceedings of the Eighth U.S. Air Force/Defense Advanced Research Projects Agency Symposium on Quantitative Nondestructive Evaluation, Boulder, CO, August 2-7, 1981. (A83-15151 04-38) New York, Plenum Press, 1982, p. 97-105.,

ABS: The quantitative flaw definition program described has demonstrated novel techniques for the sizing of flaws. These techniques have been extended from the idealized geometries, transducer bandwidths, and SNRs used in an earlier research program to situations involving parameters which are more representative of real parts. A hybrid technique consisting of optical and ultrasonic inspection is proposed in pursuit of a 'retirement for cause' strategy in aircraft gas turbine engine disks. The initial, optical approach uses magnifications up to 50X, providing the detection sensitivity needed for small cracks. The microscope output will then be coupled to an image analyzer which automatically scans each frame for crack-like features and retains their number, length and location. These features are then inspected ultrasonically, providing detailed quantitative data.

83A15159 82/00/00

UTTL: **Retirement for cause inspection system design**

AUTH: A/CARGILL, J. S.

PAA: A/(United Technologies Corp., Government Products Div., West Palm Beach, FL)
In: Review of progress in quantitative nondestructive evaluation. Volume 1 - Proceedings of the Eighth U.S. Air Force/Defense Advanced Research Projects Agency Symposium on Quantitative Nondestructive Evaluation, Boulder, CO, August 2-7, 1981. (A83-15151 04-38) New York, Plenum Press, 1982, p. 83-96.,

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

83A15155 82/00/00
UTTL: **Overview of probabilistic failure prediction and accept-reject decisions**
AUTH: A/RICHARDSON, J. M.; B/BUCKLEY, M. J.
PAA: B/(Rockwell International Science Center, Thousand Oaks, CA)
In: Review of progress in quantitative nondestructive evaluation. Volume 1 - Proceedings of the Eighth U.S. Air Force/Defense Advanced Research Projects Agency Symposium on Quantitative Nondestructive Evaluation, Boulder, CO, August 2-7, 1981. (A83-15151 04-38) New York, Plenum Press, 1982, p. 43-58.,
ABS: An assessment is given of the development status of NDE decision formalisms, with emphasis on the degree to which the requirements of structural accept-or-reject decisions and managerial decisions such as total costs, liability risks, etc., are successfully addressed. Attention is given to the relative merits of inspection before or after service, the role of physical models of failure, measurement, and a priori defect statistics, the dependence of the nature of the formalism upon the general material category, and the use of the dominant-defect approximation rather than many-defect models. The formulation of optimization criteria and the relative costs of false rejections and acceptances are also considered.

82A15292 81/11/00
UTTL: **Statistical approach to the solution of multiparameter measurement problems in nondestructive inspection**
AUTH: A/DREIZIN, V. E.
PAA: A/(Kurskii Politekhnicheskii Institut, Kursk, USSR)
(Defektoskopiia, Mar. 1981, p. 5-14.) Soviet Journal of Nondestructive Testing, vol. 17, no. 3, Nov. 1981, p. 161-167. Translation.,
ABS: Various approaches to the solution of multiparameter measurement problems in structuroscopy are treated with the advantages offered by the statistical approach shown. An analysis is carried out of possible statistical methods by which mathematical models of multiparameteric inspection can be coostructed. An efficient new algorithm is proposed, along with a criterion for constructing the optimum model.

90N28073 90/05/00
UTTL: **Critical inspection of high performance turbine engine components: The RFC concept**
AUTH: A/RASMUSSEN, BRUCE A.; B/POHLENZ, ERIC L.; C/HOEFFEL, JAMES D.; D/WILLIAMS, DENA G.
PAA: A/(Wright Research Development Center, Wright-Patterson AFB, OH.); B/(Wright Research Development Center, Wright-Patterson AFB, OH.); C/(Systems Research Labs., Inc., Dayton, OH.); D/(Systems Research Labs., Inc., Dayton, OH.)
ABS: The U.S. Air Force has implemented a new maintenance philosophy, known as Retirement for Cause (RFC), to extend the usefulness of gas turbine engine disks and spacers beyond their original design life. Essential to the successful implementation of this philosophy was the development of a generic, totally-automated engine part inspection system that could reliably detect 5 mil flaws and determine a part's accept/reject status using critical flaw size criteria. Initial implementation of the RFC Inspection System on the Pratt and Whitney F100 engine has significantly reduced the U.S. Air Force engine spare parts inventory requirement and has resulted in a large savings in reprocurement costs.

90N28071 90/05/00
UTTL: ***Assessment and demonstration of the capabilities of NDI processes, equipment, and personnel***
AUTH: A/RUMMEL, WARD D.
ABS: The application of modern materials and structural analysis methods and the use of fatigue and fracture analysis in life prediction and life cycle modeling has focused attention on the need for quantitative nondestructive

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ST/60/4 23 June 1993

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<u>Bibliography for Lecture Series 190</u>

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G.W.Hart

inspection (NDI) methods to quantify materials integrity and life limited component integrity. Advances in both life prediction methods and in quantitative NDI technology have enabled implementation of retirement for cause/life cycle management methods. The combined application of life prediction methods and the application of advanced NDI methods have resulted in improvements in engineering system reliability predictions and in quantification of both systems operating levels and systems life cycle operating margins. The principles of quantitative NDI process characterization, the development of analytical tools for NDI process characterization, and some typical results achieved by quantitative NDI process analysis and characterization are discussed.

90N26814 88/06/00

UTTL: **A general discussion of the retirement for cause inspection system**

AUTH: A/HOPPE, WALLY C.

ABS: The retirement for cause (RFC) system was developed to inspect the F100 engine at the engine overhaul facility of Kelly AFB, San Antonio, TX. This completely automated system, which utilizes both eddy current and ultrasonic inspection technologies, has been thoroughly tested before implementation at Kelly AFB. As of September 1, 1987, after ten and one half months in production, the system has inspected approximately 1900 parts. An overview of the RFC system and a presentation of the results of the reliability tests will be given. Some of the highlights of the inspection techniques and algorithms will also be outlined, in order to show how this automated, computer controlled system can achieve the reliable and sensitive inspections that were demonstrated.

90N26813 88/06/00

UTTL: **Retirement for cause of the F100 engine**

AUTH: A/HARRIS, JOHN A., JR.; B/VANWANDERHAM, M. C.

ABS: Retirement for cause (RFC) is a life cycle management procedure for gas turbine engine components, such as fan, compressor and turbine disks. The procedure enables full use of the safe life inherent in each component, as opposed to arbitrary retirement from service of all components at a calculated low cycle fatigue life. Historically, these components have been retired at the accumulated time (or cycles) where the first fatigue craft in 1000 identical components, all used in an identical manner, could be expected to occur. By definition then, 99.9 percent of these components were being retired prematurely, while they still may have had useful life remaining. The retirement for cause approach is based on fracture mechanics and nondestructive evaluation, and is evaluated economically. The U.S. Air Force recognized the potential of this approach for maintenance life cycle cost savings and began development programs in the late 1970s and early 1980s to reduce the RFC concept to practice. Those programs have been successfully completed. The development and integration of the methodology, its implementation for 23 USAF F100 engine components by the San Antonio Air Logistics Center, and its economic and other benefits are discussed.

89N17256 88/11/00

UTTL: **Relationships of nondestructive evaluation needs and component design**

AUTH: A/HARRIS, JOHN A., JR.; B/VANWANDERHAM, M. C.

ABS: Several well publicized engine and airframe failures which occurred in the late 1960 to mid 1970's time frame resulted in emphasis on development, application and quantification of nondestructive evaluation (NDE) as opposed to reliance on a Zero Defects design philosophy. As the use of fracture mechanics as a basis for damage tolerance and retirement analysis of components became established, additional emphasis was placed on screened flaw sizes, NDE and quantification of reliability. In the late 1970's a structural assessment was conducted on the design of the F100 engine which resulted in a series of relatively sophisticated safety inspections for selected critical components. The Retirement for Cause philosophy also coupled NDE and component lifing analyses to enable return to service decisions for engine components. These activities were (and are) performed usually after the component designs have been finalized. The establishment of Engine Structural Integrity Programs (ENSIP) for new U.S. military engine systems has now made NDE considerations an integral part of the design process. Classification of components, fracture mechanics analyses, critical flaw sizes, material quality, NDE and quantification of inspection reliability are now incorporated in the initial design process and directly influence the resultant component designs. Statistically based probabilistic approaches are supplementing the deterministic methods previously used. The relationships of NDE needs and component design in light of the evolution of the ENSIP approach for gas turbine engine component designs are discussed.

89N13568 RPT#: NASA-CR-183539 NAS 1.26:183539 MCR-88-1044 88/09/00
UTTL: **NDE detectability of fatigue-type cracks in high-strength alloys: NDI reliability assessments**
AUTH: A/CHRISTNER, BRENT K.; B/LONG, DONALD L.; C/RUMMEL, WARD D.
ABS: This program was conducted to generate quantitative flaw detection capability data for the nondestructive evaluation (NDE) techniques typically practiced by aerospace contractors. Inconel 718 and Haynes 188 alloy test specimens containing fatigue flaws with a wide distribution of sizes were used to assess the flaw detection capabilities at a number of contractor and government facilities. During this program 85 inspection sequences were completed presenting a total of 20,994 fatigue cracks to 53 different inspectors. The inspection sequences completed included 78 liquid penetrant, 4 eddy current, and 3 ultrasonic evaluations. The results of the assessment inspections are presented and discussed. In generating the flaw detection capability data base, procedures for data collection, data analysis, and specimen care and maintenance were developed, demonstrated, and validated. The data collection procedures and methods that evolved during this program for the measurement of flaw detection capabilities and the effects of inspection variables on performance are discussed. The Inconel 718 and Haynes 188 test specimens that were used in conducting this program and the NDE assessment procedures that were demonstrated, provide NASA with the capability to accurately assess the flaw detection capabilities of specific inspection procedures being applied or proposed for use on current and future fracture control hardware program.

88N26371 RPT#: AD-A192730 PWA-FR-18301-VOL-1 AFWAL-TR-87-4069-VOL-1 87/08/00
UTTL: **Engine component retirement for cause. Volume 1: Executive summary**
AUTH: A/HARRIS, JOHN A., JR.
ABS: This program developed and integrated materials behavior characteristics, component life analysis, nondestructive evaluation and cost-risk technology to establish and demonstrate the retirement for cause maintenance concept as it applies to rotating components of military gas turbine engines. As such it provides the basis for elimination of classical time or cyclic limits currently imposed for retirement of gas turbine rotor components by substituting a life management system in which each individual component is retired from service when the unique, economical safe life of that component is exhausted. The methodology was demonstrated on and validated for the U.S. Air Force F100 engine's rotor components and has been implemented on that engine system by the USAF Air Logistics Command. Use of Retirement for Cause is projected to result in life cycle cost savings in excess of $1 billion for that engine system. The Retirement for Cause methodology developed is generic, and may be applied to not only other gas turbine engines, but to components of any life limited system.

86N25386 RPT#: AD-A164394 WES-TR-GL-81-12 REPT-2 85/10/00
UTTL: **Bomb crater repair techniques for permanent airfields, series 2 and 3 tests**
AUTH: A/ALFORD, S. J.; B/HAMMITT, G. M., II
ABS: This study is a continuation of Report 1 of this series that described Series 1 tests which were performed using different field methods of repair and restoration of bomb craters. Results from Series 1 tests showed problem areas that needed correction when the crater repairs were trafficked with full-scale loading. Two series, Series 2 and 3, of tests were run to determine if: (1) the loose stone problem at the surface could be eliminated from the well-graded crushed limestone, (2) materials could be used that would neither be affected by the weather nor require any compaction equipment, (3) a crushed aggregate that engineering troops in Germany were trying to use could be stabilized under traffic, (4) a way could be found to place grout with a minimum of equipment, (5) it was possible to cut down on portland cement concrete curing time, and (6) an unconventional pavement repair could be used. Testing consisted of accelerated traffic using either single- and/or multiple-wheel gear assemblies.

86N25376 85/10/00
UTTL: **Advanced quantitative methods for nondestructive evaluation**
AUTH: A/CHIMENTI, D. E.; B/MORAN, T. J.
ABS: Over the past decade and a half progress in nondestructive evaluation (NDE) methods which yield quantitative flaw information has been considerable and has sparked a revolution in the way industry and government view the capabilities and benefits of quality assurance or component integrity. Almost no NDE technique, new or established, is selected for research and development without examining its potential for providing accurate, quantitative defect information. Concurrent with this trend has been the increasing use of fracture mechanics in the design and life management of aircraft systems, placing in turn stringent requirements on quantitative nondestructive evaluation (QNDE). Nowhere are these demands heavier than in the case of advanced aircraft engine alloys where critical flaw sizes are measured in hundredths of an inch. Research in NDE, therefore, has concentrated on improving defect sensitivity and reliability and providing the quantitative information essential to the new system maintenance philosphies, such as Retirement-for-Cause. In addition to the well known quantitative capabilities of standard techniques like radiography, dye penetrant, and in some cases, eddy current, developments in quantitative ultrasonics, eddy current, thermal wave techniques and exploitation of new medicial X-ray imaging methods offer alternatives with enhanced capabilities and possibly reduced cost. The state of the art in QNDE is discussed, as well as advanced methods currently in development.

84N12509 RPT#: AD-A131762 AFWAL-TR-82-4111 83/06/00
UTTL: **Improving NDE (Non-destructive evaluation) capability through multiple inspection with application to gas turbine engine disks**
AUTH: A/YANG, J. N.; B/DONATH, R. C.
PAA: A/(George Washington Univ., Washington, D.C.)
ABS: Techniques are not capable of repeatedly producing correct indications when applied to flaws of the same length. As a result, the probability of detection (POD) for all cracks of a given length has been used to define the capability of a particular NDE system in a given environment. Thus the NDE reliability consists of two types of errors. For safety-critical components in airframe structures, Type I error is of major concern. According to the damage tolerant requirement, the inspection limit or the reset crack size should be the crack length associated with a 90% detection probability and 95% confidence level. On the other hand the main criterion used for analysis of the retirement-for-cause of gas turbine engine components is the minimization of the life cycle cost. The

objectives of this report are to: (1) formulate and derive mathematically the resulting POD curve for multiple inspection systems; (2) investigate quantitatively the benefit and advantage of multiple inspection procedures; (3) establish the direction in which the NDE capability should be improved under certain mission requirements; (4) establish the strategy and sequence for multiple inspection procedures to reduce either Type I or Type II errors or both; (5) determine the POD curve for a disk from the POD curve of an NDE system; (6)determine the inspection reliability of engine disks; and (7) evaluate the benefit of multiple inspections for engine disks.

82N29616 RPT#: AD-A114467 UDR-TR-81-113 AFWAL-TR-81-4160-VOL-1 81/12/00

UTTL: **Evaluation of NDE reliability characterization, volume 1**

AUTH: A/BERENS, A. P.; B/HOVEY, P. W.

ABS: To characterize the uncertainty in non-destructive evaluation (NDE), a probability of crack detection (POD) as a function of crack length is postulated where POD is defined as the proportion of cracks of a given length that would be detected by the NDE technique when applied by inspectors to structural elements in a defined environment. This report; (1) presents a statistical framework for describing the uncertainty in the NDE determinations; and (2) evaluated various characterizations of NDE reliability. The data from a recent Air Force study on NDE reliability estimate the parameters of the NDE model. For these representative capabilities NDE reliability experiments are simulated. Different NDE capability characterizations are computed for each simulated experiment and are statistically compared.

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