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Significant Issues in Proof Testing: A Critical Appraisal

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DEFINITION OF SYMBOLS

a	crack depth
a'	effective crack depth
a_1, a_2, etc.	initial crack depths in remaining life calculation
a_l	critical crack depth calculated using LEFM
a_o	depth of crack which would just survive the proof test
a_p	critical crack depth calculated using EPFM
a_s	maximum tolerable crack depth under service loading
c	half surface crack length
c_o	critical half surface length under proof test conditions
c_s	critical half surface length under service conditions
da/dN	crack growth rate per cycle
$(da/dN)_f$	fatigue crack growth rate
da/dt	crack velocity
m	exponent in crack growth law
m'	exponent in combined static and fatigue crack growth law
t_1, t_2, etc.	calculated remaining lifes corresponding to a_1, a_2, etc.
C	crack growth law constant
E	Young's modulus
E'	$E/(1-v^2)$
F	geometric term in expression for K_1
J	J-integral
J_e	elastic component of J
J_p	plastic component of J
J_{Ic}	J at crack initiation, measure of toughness
J_{max}	J at maximum load in fatigue cycle
J_o	applied J under proof test conditions
J_R	ductile tear resistance measured by J, measure of toughness
K_I	stress intensity factor
K_{Ic}	fracture toughness
K_{Ith}	stress intensity factor at the onset of SCC
K_{max}	K_I at maximum load in fatigue cycle
K_{min}	K_I at minimum load in fatigue cycle
N	number of load cycles
P	applied load
P_c	plastic collapse load
P_{min}	minimum proof load level
P_o	proof test load
P_s	most onerous service load
P_y	general yield load
Q	hydrostatic crack tip stress parameter
R	ratio of minimum to maximum load in fatigue cycle
ΔJ	cyclic change in J
ΔJ_{eff}	effective ΔJ
Δa	increment of ductile tear
ΔK	cyclic change in stress intensity factor
ΔK_{eff}	effective value of ΔK

DEFINITION OF SYMBOLS (CONT)

$\Delta\sigma$	cyclic change in stress
ν	Poisson's ratio
π	usual meaning
σ	applied nominal stress
σ_{max}	σ at maximum load in cycle
σ_{min}	σ at minimum load in cycle
σ_r	residual stress
σ_y	yield stress

ABBREVIATIONS

ABAQUS	commercial finite element computer program
AE	acoustic emission
ANSYS	commercial finite element computer program
ASTM	American Society for Testing and Materials
CCG	creep crack growth
CEGB	Central Electricity Generating Board
CT	compact tension specimen
CTOA	crack tip opening angle
CTOD	crack tip opening displacement
EPFM	elastic-plastic fracture mechanics
EPRI	Electric Power Research Institute
FCG	fatigue crack growth
FLAGRO	NASA fatigue crack growth computer program
FPI	fast probability integration
HAZ	heat affected zone
LEFM	linear elastic fracture mechanics
MCPT	multiple cycle proof testing
NASA	National Aeronautics and Space Administration
NASCRAC	NASA Crack Analysis Code
NDE	non-destructive evaluation
NESSUS	Numerical Evaluation of Stochastic Structures Under Stress
PSAM	Probabilistic Structural Analysis Methods
SwRI	Southwest Research Institute

EXECUTIVE SUMMARY

Proof testing a component by applying a load greater than it would experience during service is a well established method of screening out manufacturing and material defects before the product is delivered. The quality assurance conferred by proof testing hardware and its use as a method of establishing fitness-for-service have been discussed many times in the open literature.

Fracture mechanics has often been employed to justify proof test procedures and to quantify claimed benefits arising from increased structural reliability and remaining safe life. In recent years there have been a number of developments in the field of fracture mechanics that impact on the theory underpinning proof test philosophy. With fracture mechanics and proof testing playing a major role in NASA fracture control requirements, and with the severe structural demands made on aerospace propulsion systems, such as the space shuttle's main engine, there is an important need to re-establish the principles on which the proof test philosophy is based, in the light of state-of-the-art technology.

This report is the first stage in the process of specifying a state-of-the-art proof test methodology. In it some of the issues which impact the interpretation and quantification of proof test benefits are identified and discussed. The intent is not to identify all those issues which are related to proof testing, but to concentrate on those which play a significant role in determining the ramifications of the proof test, and which can be addressed and resolved within the current knowledge base, or on a short timescale. Examples of some of the fracture mechanics issues addressed within this context are:

- application of elastic-plastic fracture mechanics to proof test analyses;
- effect of material's fracture behavior, whether it is brittle or ductile, on proof test procedures;
- sensitivity of a proof test analysis to assumed defect shape;
- influence of ductile tearing and instability on analysis of single and multiple cycle proof tests;
- relative merits of deterministic and probabilistic analyses;
- relationship of proof test load level to the margin of safety conferred by proof testing;
- effect of proof loading on subsequent structural integrity under service conditions;
- effect of proof loading on subsequent material fracture behavior;
- optimization of periods between proof tests to maximize the lifetime of re-certifiable components;
- relationship of proof loading to non-destructive examination;
- effects of proof loading in a service environment.

Other issues which are not related to the technical aspects of proof test analysis are also discussed for completeness. These non-technical subjects influence how, and how frequently, a proof test should be carried out, but do not directly affect the technical justification for the testing. Examples of these kinds of issues are:

- the economics of proof testing
- personnel training and certification
- proof test procedures, documentation and safety plans
- role of test fixtures, seals and fasteners

Some important technical issues which directly relate to proof testing methodology are presently being addressed in two other NASA sponsored projects being performed at Southwest Research Institute and under subcontract at Rocketdyne: "Elastic-Plastic and Fully Plastic Fatigue Crack Growth" (NASA Contract Number NAS8-37828) and "Comparison of Single Versus Multiple Cycle Proof Testing" (Contract Number NAS8-37451). The results of these two projects have been used to complement the investigations in the current project.

The technical issues raised are critically reviewed using the following criteria:

- their importance in a proof test methodology;
- their status and general acceptance;
- the availability of implementing technology;
- further technological requirements;
- the data required to implement the technology;

The conclusion of this review of significant issues affecting proof testing is a list of parameters and phenomena that are deemed not only essential to formulating a proof test methodology, but also well enough understood and validated, or probably could be within the time and resources of the project, to be used as a technical basis for underpinning the methodology. Inclusion of the list items in a proof test methodology would: promote this to a state-of-the-art technology; identify those aspects which would aid optimization of proof test design with respect to maximizing its effectiveness; and increase awareness and understanding of outstanding issues, like the relative merits of single and multiple cycle proof loading.

Items included on this list are:

Related to analysis:

- guidance on how to determine proof test margins and safe remaining life
- guidance on determining proof test intervals for re-certifiable components
- guidance on which applications, materials, and structures are most conducive to the benefits of proof testing
- elastic-plastic fracture mechanics (EPFM)
- discussion of different fracture regimes and the fracture mechanics parameters applicable to each
- ductile instability analyses
- simple approximate methods of estimating the EPFM parameter J
- recommended treatment of secondary stresses in EPFM
- comment on the use of EPFM parameters for characterizing proof test loads with respect to service loading
- elements of probabilistic analyses
- relationship of proof test probabilistic methodology to existing NASA probabilistic methodologies
- suggested methods of deriving probabilistic distributions from existing but limited data
- indications of the probability of detecting flaws in aerospace hardware
- analysis treatment of multiple cycle loading
- guidance on residual stress distributions in typical aerospace hardware
- indications of defect distributions in aerospace components

- discussion on the impact of defect shape on proof test margins
- comments of the significance flaw characterization in proof test analyses
- synergistic relationship of proof testing and NDE

Related to material behavior

- recommendations for obtaining material data for proof test usage
- description of different types of material fracture behavior and their impact on proof test analysis
- rules for assessing the interaction of static and cyclic crack extension mechanisms
- rules for assessing the effect of load history on subsequent fracture behavior
- rules for assessing the effects of environment on material behavior

Related to test conditions

- guidance on proof test temperature
- guidance on when to perform multiple cycle or single cycle proof tests
- recommendations on the need to simulate service environments
- recommendations on loading rates and hold times
- suggested test media
- use of real-time NDE to enhance flaw screening capability

It is concluded in this report that a proof test methodology based on probabilistic analysis will be far more effective than one based solely on a deterministic philosophy. The probabilistic approach removes many of the technical problems and logical inconsistencies which beset a deterministic methodology. The value of the proof test is greatly enhanced as a flaw screening method when combined with non-destructive examinations of the component.

It should be recognized that the proof test is not universally applicable as a pre-service method of guaranteeing structural reliability during service, especially if more reliable and effective NDE methods are available. This is because its range of application may be limited by both non-technical and technical factors. Furthermore, the process of guaranteeing the structural reliability of a component during service is usually not based solely on the results of a proof test. These observations lead to the conclusion that a proof test methodology should be pragmatically based on a series of levels with guidance on which level is most appropriate for a given application: the higher the level, the greater the technological sophistication.

It is also concluded that proof test analysis capabilities would be greatly increased by developing:

- a probabilistic data base consisting of source data, and/or distribution functions and their respective constants, for all key assessment parameters
- computer software for calculating elastic-plastic fracture mechanics parameters and performing a proof test analysis
- a methodology for determining the cost benefits of proof testing

1. INTRODUCTION

Proof or overstress testing a component consists of applying a load greater than it would experience during service. This practice is well established as a means of detecting, possibly destructively, gross manufacturing and material defects before the product is delivered. The quality assurance conferred by the proof testing of hardware and its use as a method of establishing fitness-for-service, have been discussed in a number of published articles [1-10].

There are still major outstanding issues concerning the advisability of performing proof tests in some situations, its effectiveness as a flaw screening method, and whether the potential benefits outweigh the costs and effectiveness of establishing quality assurance using alternative non-destructive (NDE) methods. However, it is not acceptable to dismiss the proof test because of cost, because of difficulties in performing the test, or because of the damage it might inflict, without having a reliable NDE alternative of assuring the quality of the delivered article.

Examples of some areas where uncertainties still linger are the efficacy of proof testing ductile materials and the advantages and disadvantages of single cycle versus multiple cycling proof tests. On technical grounds, for example, components made of ductile materials should be poor candidates for proof testing because of their high toughness, low yield stress, and ability to tolerate crack extension under a rising load. This high tolerance to cracking implies that large defects will survive the proof loading and reduce its flaw screening capability. The effectiveness of the proof test for ductile materials may be so reduced that relatively simple and cheap NDE procedures will be able to provide a more effective means of ensuring acceptable quality. It has also been argued that multiple cycling will introduce more damage into the component than single cycling, because of the additional increase in crack size this will produce. This factor would appear to eliminate any benefits that may accrue from multiple cycle proof testing of ductile materials. However, the Rocketdyne Division of Rockwell International has pioneered the application of multiple cycling proof testing to propulsion systems and demonstrated the benefits on actual hardware in terms of increased survivability during service. This contradiction between the preconceived expectation of poor performance of proof testing, and the actual results, illustrates but one of the many conflicting issues which help confound and confuse questions as to whether and how to proof test.

The proof test cannot be treated in isolation from its effects on subsequent structural reliability. It is not sufficient to argue that a component is fit-for-service because it has survived the proof loading. This assurance can only be made if the damage introduced by the proof test can be quantified in some form and judged against the benefits, which themselves have been similarly quantified based on the extra knowledge gained from the test. It is only through this quantification of damage and benefits that the test conditions that maximize the effectiveness of the proof test can be identified. Before this procedure can be carried out the mechanics and mechanisms of the proof test process have to be understood in terms of structural and material behavior.

The discipline of fracture mechanics provides the analytical tool that links the mechanics and mechanisms of proof testing and relates their effects to fracture behavior, and hence to a means of quantifying damage and benefits. Fracture mechanics plays a key role in analyzing proof test procedures that are used to screen for unacceptable defects. It provides the means of quantifying benefits arising from increased structural reliability and

remaining safe life. Over the past 20 years there have been major developments in fracture mechanics which may have important ramifications on the way a proof test is analyzed. For example, there have been significant developments in elastic-plastic fracture mechanics, the assessment of crack instability after ductile tearing, and failure analysis due to plastic collapse mechanisms. Since fracture mechanics plays a major role in NASA fracture control requirements [2,11-15], there is an important need to re-visit the principles under-pinning the proof test procedures which form part of those requirements, in the light of current state-of-the-art technology. This is particularly the case for aerospace propulsion systems, such as the space shuttle main engine, which have severe structural demands placed on them.

A previous NASA review of proof test technology [7] suggested that increased knowledge in four areas would produce greater understanding of proof testing, and hence a consequent improvement in its effectiveness. These areas are related to the effects of multiple cycling on proof testing; probabilistic modelling of proof testing; innovative testing techniques; and the relationship of proof testing to non-destructive testing. To these topics could be added the effect of proof loading on subsequent fracture behavior; optimization procedures for determining proof test intervals; and the effectiveness of testing in service environments.

Two major technical issues which directly relate to proof testing methodology are presently being addressed in parallel NASA sponsored projects being performed at Southwest Research Institute and under subcontract to Rocketdyne Division of Rockwell International. These are NASA Contract Number NAS8-37828, "Elastic-Plastic and Fully Plastic Fatigue Crack Growth", and Contract Number NAS8-37451, "Comparison of Single Versus Multiple Cycle Proof Testing". The results of these two projects have provided, and continue to provide, valuable state-of-the-art technology with direct application to proof testing.

In this report the available information on these and other proof test related topics is reviewed with the intent of defining the current state-of-the-art in proof test logic and practice. This information is then used to identify those technical issues which are important in understanding the ramifications of proof testing and in the formulation of a methodology for assessing its effectiveness. To further this end, each technical issue is judged against criteria related to its perceived importance in proof testing; its status and general usage; the availability of enabling technology; further technological requirements; and the data required to implement the technology.

Each section of the Report addresses a particular aspect of proof testing practice and analysis. Section 2 reviews the many uses of proof testing and discusses its perceived advantages and disadvantages. This discussion highlights the difficulties in proof test decision making. Proof test methodologies are addressed in Section 3, where deterministic and probabilistic approaches are discussed. Section 4 is concerned with the factors that influence the choice of proof test conditions, such as the test environment and the type of loading. Section 5 describes technical aspects of the analyses used to support the proof test, and Section 6 addresses how the proof test loading impacts on the assessment of subsequent structural integrity of the tested component under service conditions. Issues which are not related to a proof test analysis but which play an important role in the quality and safety of the test, such as personnel training, test procedures and safety plans, are discussed in Section 7. In Section 8, the results of the investigations reported in the previous sections are discussed in general terms, and in Section 9 conclusions are drawn regarding those parameters and phenomena which are deemed important in the formulation of a proof test methodology.

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2. APPLICATIONS AND PERCEIVED BENEFITS AND CONCERNS OF PROOF TESTING

There are many kinds of structures that are proof tested. Ultimately, the decision as to whether to proof test a component rests on the perceived benefits and concerns. These are driven by, among other things, the safety, quality assurance, and economic considerations of proof testing relative to other in-process and final NDE inspection techniques. This section briefly reviews some of the reported applications of the proof test method and highlights some of its potential benefits and detriments.

2.1 Review of Proof Test Applications

Prior to 1959 proof testing was performed to expose material and/or manufacturing deficiences, but there was no quantitaive interpretation as to what a successful proof test meant in terms of subsequent operational usage. A quantitative interpretation based on linear elastic fracture mechanics was first introduced in that year and reported some years later by Tiffany and Masters [1] along with other applications of fracture mechanics to pressure vessels.

Nichols [3,4] in his major review of overstressing techniques in 1968 quotes many examples where proof testing has been applied, including structures as diverse as bridges, storage tanks, pressure vessels, pipelines, penstocks and spiral casings for hydraulic turbines. Tiffany [2] has discussed the role of proof testing in the fracture control of metallic pressure vessels in the aerospace industry. His developed proof test methodology addresses such components as high pressure gas bottles, solid propellant motor cases and storable and cryogenic liquid propellant tanks. Certification procedures used for pressure vessels at deactivated ATLAS missile sites have been described by Luttrell and Henderson [16] and re-validation of air storage vessels by Smith and Cameron [17].

There are other reported applications of proof testing to pressure vessels in a variety of industries. Notable amongst these are the proof testing of nuclear reactor pressure vessels in the power generation industry [5,8,9,18,19]. The significance of the proof overload on the fracture resistance in ferritic steel pressure vessel materials has been reviewed by Smith and Garwood [20]. Novotny [21] has reported on the increase in pressure vessel service life due to the mechanical stress relieving effects of overstressing. Other pressure vessel applications have included the optimization of proof testing and non-destructive examination (NDE) for aluminum pressure vessels [22]; structural integrity verification by acoustic emission (AE) during proof testing of welded steel and aluminum vessels [23]; applications to reactor components [25]; and an assessment of the influence of pre/in-service inspections and tests on reactor pressure vessel reliability [24].

Many other uses have also been found for proof testing in the aerospace and aircraft industries. Buntin [26] describes the theory and practice behind proof testing of F-111 production aircraft. Carlyle [27] has shown how the effectiveness of the proof test can be enhanced by NDE monitoring using real time AE. Au and Speare [28] detail the calculation of proof test safety factors in relation to reusable solid fuel motor cases. Corle and Schliessmann [29] have demonstrated improved flaw detection in rocket motor casings by AE when used in conjunction with proof testing. Broek [10] has argued for the use of proof testing to determine safe inspection intervals for aircraft subject to multiple site damage. Collipriest and Kizer [30] have investigated proof test logic when applied to construction materials used

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for the structural tankage of Saturn V second stage rockets. Dawicke, *et al.* [31] evaluated the pressure proof test concept for fuselage structures. Hsieh, *et al.* [32] have proposed a methodology for utilizing the flaw screening capabilities of the proof test in order to establish the integrity of fracture critical fasteners. Also, in the aerospace industry, NASA, through its fracture control documents, has specified proof testing for pressure systems, rotating machinery, and fracture critical fasteners [2,11-14].

The foregoing applications are based on a single cycle proof test. The benefits of multiple cycle proof testing of ductile aerospace hardware have been addressed by Mendoza and Vroman [6], Besuner, *et al.* [7], Hudak and Russell [33], and Hudak, *et al.* [34]. These authors investigated the role of ductile tearing and probabilistic analyses in proof test assessments.

Proof testing has been employed to assess the defect tolerance of pipelines [35]; to assess the implications of hydrotesting on line pipe serviceability [36-41]; to investigate the defect tolerance of high toughness pipe steels [42]; to develop a proof test logic for hydrogen embrittlement control [43]; and to monitor the proof testing of a repaired steam locomotive boiler using AE [44].

There have been many proof test applications of reliability and probability analysis techniques. Yang [45,46] has presented reliability analyses for fatigue critical structures in aircraft based on periodic proof testing. Shinozuka and Yang [47] have addressed the problem of optimum structural design based on cost constraints and Barnett and Hermann [48] have performed a similar exercise with respect to the role of proof testing in design with brittle materials. Statistical and reliability treatments based on proof test results have also been developed for pressure vessels [49,50] and gas duct pressure welds [51]. The combined effects of proof testing and NDE on the reliability of cyclically loaded structures has been explored by Harris [52].

These multivarious applications of the proof test demonstrate the versatility and widespread usage of the method as a tool to establish the integrity and reliability of structures for service. However, the clearly perceived benefits of the approach are not always realized, and Nichols [3,4] reports a number of cases where failures occurred after overstressing that were attributed to its deleterious effects. Certainly, if failure occurs during a test on a full scale structure then massive damage and economic penalties can result, as demonstrated by the catastrophic failure of a shrunk on disc during overspeed testing at Hinkley Point A power station [53].

2.2 Potential Benefits of Proof Testing

The effectiveness of a proof test may differ from location to location within a given component due to variations in stress amplitude, constraint, material properties, and the efficacy of complementary NDE techniques. Based upon the review of proof testing, the following benefits arising from proof testing are often given: increased structural reliability; fabrication and quality assurance; enhancement of non-destructive examination (NDE); defect sizing and flaw screening in situations where NDE is not useable; mechanical stress relief; and verification of stress analysis.

2.2.1 Structural Reliability

Probably, the most commonly understood reason for proof testing is its use as a demonstration of structural integrity. The practice of proof or overstress testing prior to operational usage has been an accepted form of "good design practice" for many years. The rationale behind this belief is that proof test survival provides increased assurance of survival of a component at a lower stress during operation. It is argued that the improved structural reliability occurs because, during the proof test, weaker components are removed from the in-service population without impairing the reliability of the surviving components. Testing in an embrittling environment such as pressurized hydrogen may be required in some aerospace applications in order to prove survivability under these conditions.

2.2.2 Fabrication and Quality Assurance

Many standard structural guidelines exist that call for overstress proof testing as an integral part of the fabrication and quality assurance procedures. Proof testing can be performed prior to operation as a post-process or in-process fabrication test, or periodically to re-certify components after operational usage. The purpose of the proof test in these cases is to expose deficiencies, poor material, and poor workmanship, which may manifest themselves through cracking, leakage or rupture during the proof test. In the past, proof testing has also proved valuable in detecting poor design features, and in checking the functional sealing capability of the basic design.

2.2.3 Flaw Screening

The value of proof testing is increased when it is combined with fracture mechanics principles and used as a quantitative flaw screening method. The screening enables the component to be entered for service with a high degree of confidence that no flaw is present greater than a size which is determined from fracture mechanics. The significance of this is twofold: first, confidence is gained in assessing the component during subsequent service since an area of uncertainty related to the existence of large defects and poor material is reduced; second, an initial safety margin may be identified based on the ratio of the largest flaw size surviving the proof test to the critical flaw size calculated at operating conditions. There is also a related benefit: the severity of the notch or crack may be reduced by blunting due to the proof loading.

2.2.4 Other Benefits

Proof testing may not only be used as an alternative means of detecting unacceptable defects (for example, if geometric complexities compromise the effectiveness of non-destructive examination (NDE)), but also as a complementary method to NDE. Component reliability may be increased through a strategy of combined inspection using both proof testing and NDE. In addition, it is also argued that the detectability of defects by NDE is improved by proof testing as this increases the separation between flaw surfaces due to crack tip blunting.

Mechanical stress relief as a consequence of proof testing may reduce or remove detrimental residual tensile stresses introduced by fabrication or handling. Furthermore, beneficial compressive residual stresses can be introduced during this process when localized yielding occurs. In the case of autofrettage, compression is introduced on the inside diameter of a

pressure vessel. For notches or pre-existing defects, plasticity that occurs at the tip or notch root produces beneficial compression and crack closure that can retard subsequent fatigue crack growth.

Finally, proof testing may give the opportunity for strain gauging the component during proof loading in order to provide verification of structural stress analysis. This is an important consideration because accurate stress analysis results are essential for the accurate determination of fracture mechanics parameters and demonstration of structural adequacy.

2.3 Concerns Related to Proof Testing

For each specific application, the usefulness of the proof test in verifying the quality of each article has to be evaluated in the light of possible detrimental effects and cost impacts, compared with the reliability and cost of alternative NDE methods. Detrimental or negative effects of proof testing are related to the introduction of damage; cost of testing and failures that happen during testing; practical difficulties in performing and designing useful proof tests; and incidental effects resulting from the testing. However, if there is not a reliable alternative NDE method available, and in-service failures cannot be tolerated, then the cost of proof testing, and other practical problems and difficulties associated with it, become of less concern in deciding whether to proof test or not.

2.3.1 Damage

The most common concern in proof testing is how to avoid the introduction of unnecessary damage in the component. Damage can be introduced into the component during proof testing from a number of causes. For example, if the test is performed under conditions where the material is significantly lower in ductility than it would be at operation, there is the possibility of initiating cracking due to the overload that would not otherwise have occurred. In addition, even in cases of comparable ductility, severe proof conditions can accelerate subsequent fatigue crack initiation and growth due to the overload.

The size of existing defects may be increased by subcritical flaw growth occurring by monotonic, cyclic and time dependent mechanisms which weakens surviving components relative to the pre-test condition. This flaw growth can be extremely detrimental if allowed to occur during proof unloading or subsequent storage prior to operational usage.

Potential degradation of future component performance or material capability due to proof testing can also occur due to the introduction of detrimental yielding; a reduction in ductility due to prestraining and strain ageing; and the creation of local tensile residual stresses.

2.3.2 Cost

Issues such as complexity of the component design, operational usage and class of material will contribute significantly to defining test conditions and the relative cost of proof testing compared with alternative NDE methods. The costs associated with proof testing include the expense of performing the test and the risk of component failure. The latter expenses include possible damage to the tooling and test facilities, as well as the component replacement cost. These have to be weighed against the ramifications of service failure which oftentimes can be extremely severe.

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The cost and possible advantages of proof testing should be compared to those of non-destructive testing, to determine its relative value as an effective flaw screener for ensuring component reliability. An obvious criterion for choosing a flaw screening procedure is that it minimizes the total expected cost while meeting a particular structural reliability level during operation.

A high incidence of proof failure can occur if the flaw size screened by the proof test is small compared to likely defect sizes introduced by the fabrication process. Therefore, while increasing the severity and/or number of proof tests can lead to greater structural reliability in service for surviving components, it may needlessly increase the number of component failures during proof testing which arise from flaw sizes that are smaller than the size that would have grown during subsequent service to have caused failure. As the cost of proof testing and proof failures decreases it is anticipated that the optimum number of proof tests and the proof load level will increase. In addition, if the primary quality assurance measure is through nondestructive inspection procedures, unnecessary risk of proof failure can occur if the flaw size screened by the proof test is smaller than that which is readily detectable by NDE.

Besides the cost of the proof test per se, there are costs incurred in performing a proof test analysis in order to assess the effectiveness of the test. These additional expenses arise from stress analysis and acquisition of material property data that pertains to the test conditions.

2.3.3 Practical Difficulties

The feasibility of performing proof tests is intimately related to practical issues related to difficulties in performing the test. For example, difficulties in full-scale proof testing of large structural systems may preclude any possibility of doing so; cryogenic proof testing may be desirable, but impractical due to effective sealing concerns; simulation of operational stresses is very desirable, but may not be possible due to the existence of thermal stresses or external loading during operation. Proof testing in potentially explosive media such as high pressure hydrogen, may be impractical due to safety concerns.

2.3.4 Incidental Effects

The conditions under which a key component is proof tested may be qualified by the incidental effects that this has on other components which are intimately associated with the testing. For example, a sub-component may be overstressed because it forms part of the load path to the main component. Similarly, some parts may experience multiple cycle proof testing because they are sub-assemblies of larger structures, each of which is proof tested in the course of assembling a key component. The proof load level, and hence, the effectiveness of the proof test, may have to be reduced in order to avoid the consequences of inadvertent failure of these sub-assembled items.

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3. PROOF TEST METHODOLOGIES

There are two approaches to developing a proof test methodology: the deterministic and the probabilistic. A deterministic methodology for proof test analysis is an essential precursor to a probabilistic treatment. Indeed, where the available data is not sufficient to support a probabilistic approach, a deterministic analysis is the only alternative. Thus, the two approaches have much that is in common.

The general logic behind proof test methodologies is discussed in Section 3.1. The technical significance of deterministic and probabilistic approaches to proof test analyses are summarized in Tables 1 and 2, respectively, and discussed in more detail in Sections 3.2 and 3.3.

3.1 Proof Test Logic

The major purpose of a proof test is to ensure the safety of the tested component during normal operating conditions. Fracture mechanics concepts have been employed for many years to provide a methodology to support the proof testing of components [1-4].

3.1.1 The Principle

The principle behind the method is illustrated in Figure 1 for the case of a single cycle proof load application to a cracked brittle material. In Figure 1 the maximum defect size, a_o, that could just survive the proof test overload, P_o, is calculated using fracture mechanics principles. Limited knowledge of the defect size distribution remaining in the component is obtained if the test is successful, it can be argued that no defect of size greater than a_o exists in the component after the test.

In the context of a proof test, failure does not necessarily imply a catastrophic event, but refers to any indication that the component is not fit for service. For example, leakage between compartments in aerospace propulsion systems during operation could result in the release of volatile liquids with catastrophic results. In this case, penetration of the wall of the component by a defect during proof loading would be classified as a failure, even if the through wall flaw remained stable during the test.

The proof test logic assumes the worst case scenario that a defect of size a_o is present in the component, and this is used as the initial crack size in a remaining life estimation. By adjusting the value of P_o it is hoped to arrive at a calculated value of a_o so that the required remaining life can be realized without incurring an unacceptable risk of failure during the proof loading. The remaining life is determined by sub-critical crack growth during service, due to mechanisms such as fatigue, environmental attack and creep, up to a maximum tolerable size, a_s, which is calculated from fracture mechanics for the most onerous service load, P_s.

In general, the calculation of a_o is simpler than the evaluation of a_s, as the conditions under which the proof test is performed are usually well defined and controlled, and less complex than the conditions which pertain at operation. Similarly, the determination of the amount of crack growth during service can present a formidable task.

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Table 1. Technical Assessment for Issue 3.2: Deterministic Approach

Importance	A deterministic approach defines those elements of a fracture assessment that are essential to a proof test analysis. Furthermore, progress in developing a probabilistic methodology is dependent on understanding these deterministic elements.
Present Status	The deterministic approach has been widely used to support proof test analyses. It has proven successful in the past, although there are reported instances when unanticipated failure occurred during subsequent service. However, there are many theoretical problems and inconsistencies associated with the deterministic approach. Many workers who have critically reviewed the logic of proof testing from the deterministic viewpoint, have concluded that it is not satisfactory. However, it is still employed and considered useful in quality assurance and fitness-for-service applications, especially in simulated service environments. Its effectiveness is increased if it is used in conjunction with other flaw screening technologies, such as NDE. It provides demonstrative benefits related to such issues as mechanical stress relief and empirical validation of stress analysis results.
Availability of Implementing Technology	Some of the deterministic elements, such as stress analysis, linear elastic and elastic-plastic fracture mechanics, are now well established and supported by computer software packages.
Further Technological Requirements	These are related to the application of the deterministic elements of the methodology. Topics such as the treatment of secondary loads, flaw characterization, time dependent fracture, and the interactions between static and cyclic loading, are still not fully understood.
Data Required to Implement the Technology	This is related to the data available to implement the various deterministic elements of the methodology. In the case of recertification for service the effects of prior service history on material behavior are not fully understood.

Table 2. Technical Assessment for Issue 3.3: Probabilistic Approach

Importance	The probabilistic approach is essential to providing a technical understanding, and quantitative justification, for the proof test and its relationship to subsequent structural reliability.
Present Status	It is recognized that a probabilistic analysis helps remove the technical problems and logical inconsistencies which beset the deterministic approach. It is also seen as a way of combining the safety, technical and economic issues within a comprehensive methodology. There are a number of reported instances where elements of a deterministic approach have been replaced by probabilistic elements, and this has greatly strengthened the effectiveness of the proof test argument as a guarantor of component integrity. It is generally accepted that any benefits that accrue from multiple cycle proof testing can only be explained in terms of a probabilistic framework.
Availability of Implementing Technology	The same items as are listed in Table 1 are available. Additionally, a variety of distribution functions, which describe uncertainties in the required parameters, and methods of solving probabilistic problems are available. Probabilistic computer software, such as NESSUS, will need to be modified for use in a proof test analysis.
Further Technological Requirements	The same items as listed in Table 1 for a deterministic approach are applicable. Additionally, there are requirements related explicitly to a probabilistic analysis. Most existing fracture mechanics probabilistic approaches are limited to linear elastic applications. An adaptation of these to incorporate the additional complexities of elastic-plastic fracture and ductile instability will be required.
Data Required to Implement the Technology	Far more data is required to implement a probabilistic methodology than is indicated in Table 1 for a deterministic analysis. The data base has to be sufficient for any uncertainties associated with material scatter, inspection, measurement and calculation to be quantifiable by probability distribution functions. This detail of information is likely to be available only for a limited number of assessment parameters, such as variations in some of the material properties and, possibly, the distribution of defect sizes in a component.

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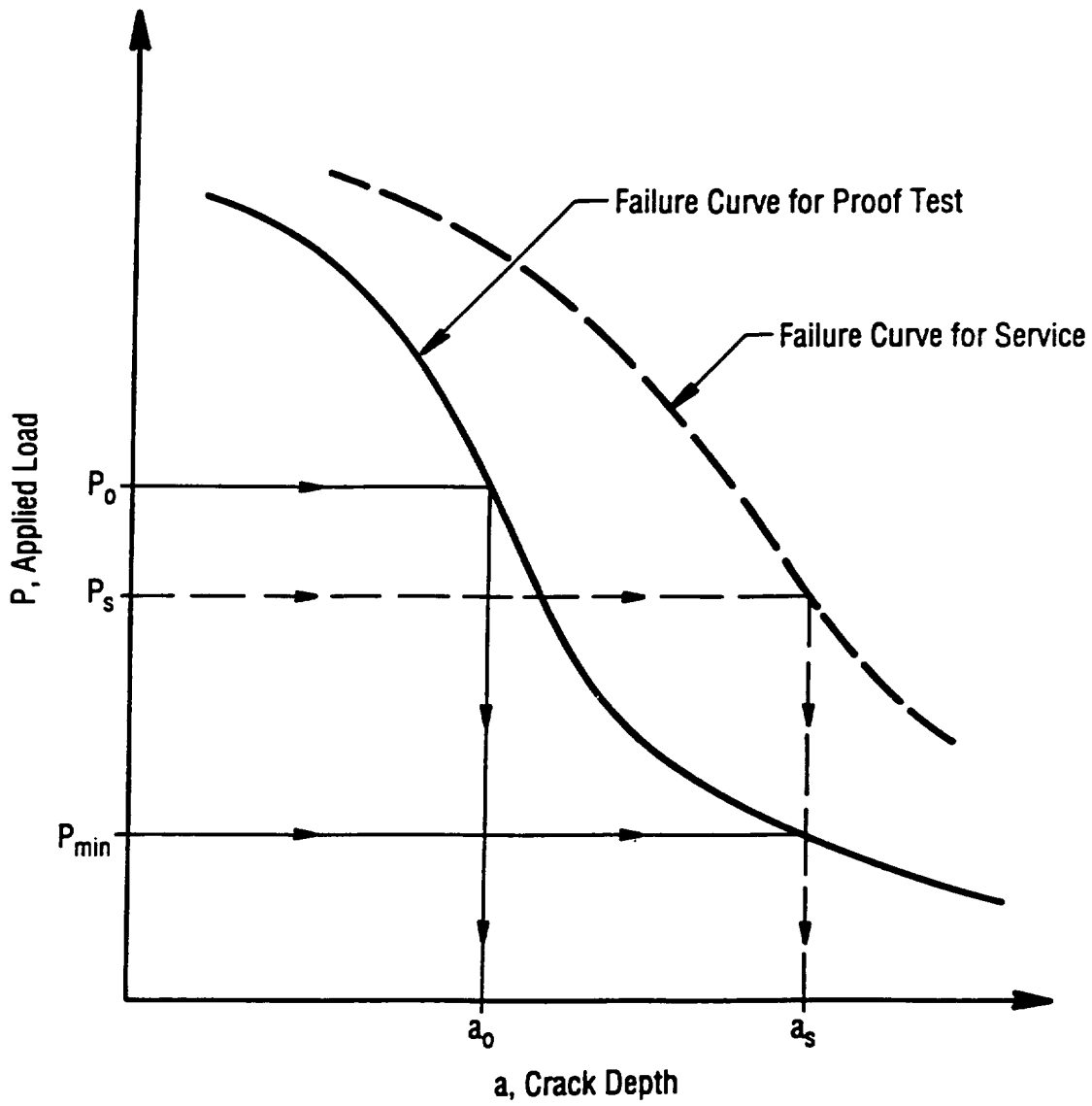
Figure 1. Single cycle proof test logic.

An important aspect of applying the proof test method is recognition that the defect of size a_o is a postulated defect whose size is calculated using a worst case scenario, it may not actually exist in the component. However, a comprehensive proof test methodology should take full account of the effects of proof loading on defects actually present in the component during the test and which survive it. This should include consequent fracture and fatigue behavior, as well as the effects of proof loading on the detectability of defects should a post-test non-destructive examination be performed. This can be accomplished through a probabilistic approach to proof test analysis.

3.1.2 *Influence of Defect Shape*

In practice, naturally occurring defects are idealized as semi-elliptical or elliptical in shape, depending on whether they are surface breaking or embedded. This means that they cannot be characterized by a single crack-size parameter, a_o or a_s. If specific information on typical crack shapes is not available for a given component, then to cater for this situation a range of defect depths and lengths have to be assessed and proper account taken for the potential change in defect shape during proof loading and subsequent service. Typical defect shapes have aspect ratios a/c in the range of 0.1 to 1.

Figure 2 illustrates the application of a proof test analysis to determining the remaining safe life of a defective component when the flaws are assumed to be surface breaking. Initially, a locus of crack depths, a_o, and surface lengths, $2c_o$, of defects which could just survive the proof loading is determined using fracture mechanics principles. A similar exercise is then performed using the most onerous service loading to obtain a locus of crack depths, a_s, and surface lengths, $2c_s$, which would cause failure under these service conditions. The proof load locus is then used to define a set of initial defect depths (a_1, a_2, a_3, etc., in Figure 2) and the growth of these flaws is assessed under service loading conditions, taking full account of the change in shape, to obtain the corresponding times (t_1, t_2, t_3, etc.) or cycles to failure. The minimum of these times or cycles then represents the safe remaining service life of the component.

Uncertainties in the flaw shape are better treated within a probabilistic analysis rather than using a deterministic assessment and following the lengthy procedures implied by Figure 2.

3.1.3 *Application to Brittle Materials*

Fortuitously, the proof test philosophy can most easily be justified for brittle materials, which are the ones most susceptible to fracture during service. This results from the fact that in brittle materials crack extension is coincident with catastrophic failure. There are no complications related to stable crack extension prior to instability. Furthermore, because low toughness materials are not tolerant of cracking, the maximum tolerable defect size tends to be small and inversely proportional to the square of the applied load. This increases the flaw screening capability and produces a greater ratio of a_s/a_o for a given ratio P_o/P_s than is the case for tougher materials, thus giving greater flexibility in the choice of proof load. This advantage can be further increased by performing the proof test at a temperature where the toughness is lower than it would be in service [2,7], although this advantage may be partly or wholly offset by the costs associated with higher probability of component failure during the proof loading.
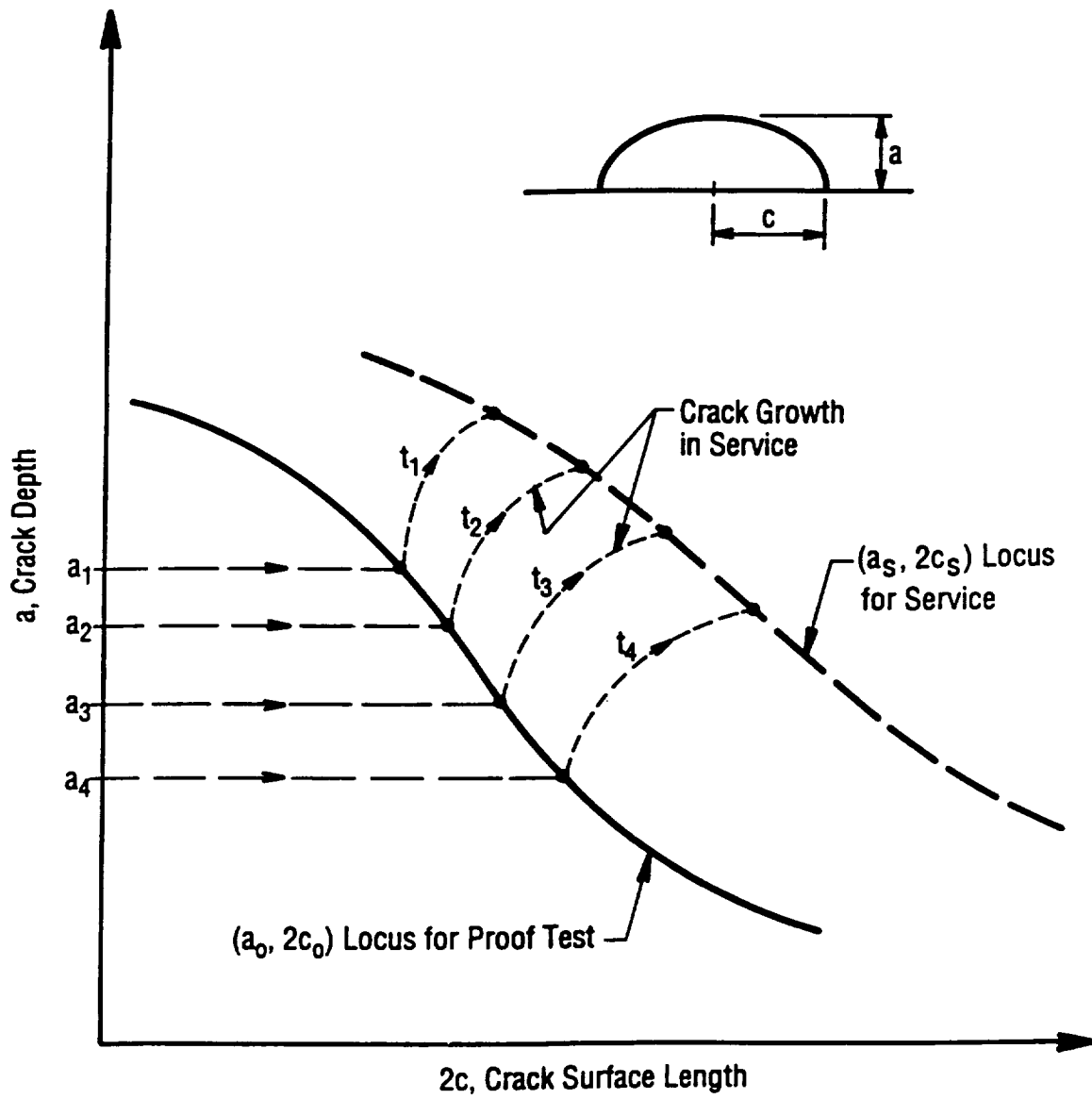
Figure 2. Determining the remaining life for surface breaking defects.

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Complications can arise as a consequence of the proof testing of brittle materials, such as ferritic steels, below their ductile-brittle toughness transition temperature. These problems are relevant to materials that are proof tested at a higher temperature than occurs in service, and relate to load history and material effects modifying the subsequent toughness of the material. More discussion of these topics is given in Section 6.4. These types of material are not widely used in the manufacture of aerospace propulsion systems.

3.1.4 Application to Ductile Materials

Although the illustration in Figure 1 pertains to materials where fracture occurs without any prior crack extension due to static failure mechanisms, the concepts have also been applied to ductile materials where tearing precedes instability. In particular, advantage has been taken of the increase in toughness of ductile materials with increasing tear length in order to move from single cycle proof test loading to multiple cycle loading [6,7,34].

The application of the proof test philosophy to ductile materials is complicated by the more sophisticated analysis required compared with brittle materials. Allowance has to be made for the possibility of ductile tearing from the crack tip during the proof loading, and a ductile instability assessment should be performed.

3.1.5 Other Considerations

Although most proof test analyses reported in the open literature successfully employed linear elastic fracture mechanics, it is now recognized that a proof test analysis should be based on elastic-plastic (EPFM) rather than linear elastic (LEFM) fracture mechanics. Crack tip plasticity reduces the maximum tolerable defect size in a structure with respect to the predictions of linear elasticity theory, because it increases the value of the crack driving force for a given applied load (Figure 3). Thus elastic-plastic fracture mechanics can produce significantly different failure predictions compared with a linear elastic analysis. It is imperative that the fracture analysis of ductile materials be based on EPFM as the level of crack tip plasticity at failure in ductile materials will generally be much greater than in brittle ones.

The temperature at which the proof loading is applied may differ from the actual operating temperature and the environment the test is carried out in may differ from the service environment. Furthermore, the type of the loading used in the proof test may differ from the most onerous loading experienced in service. For example, the highest risk of failure during service may be during start-up when the component is subjected to severe thermal stressing while the proof loading is applied in the form of internal pressurization. Appropriate allowance has to be made for these possibilities when choosing the proof test parameters, such as P_o, and when interpreting the results.

Periodic proof testing is frequently used to re-certify components for further service. Depending on the consequences of failure, the criterion for the component to re-enter service is usually specified in terms of the ratio of the calculated remaining life to the time to the next proof test. In the aerospace industry, this ratio can be as high as 4 for fracture critical components.
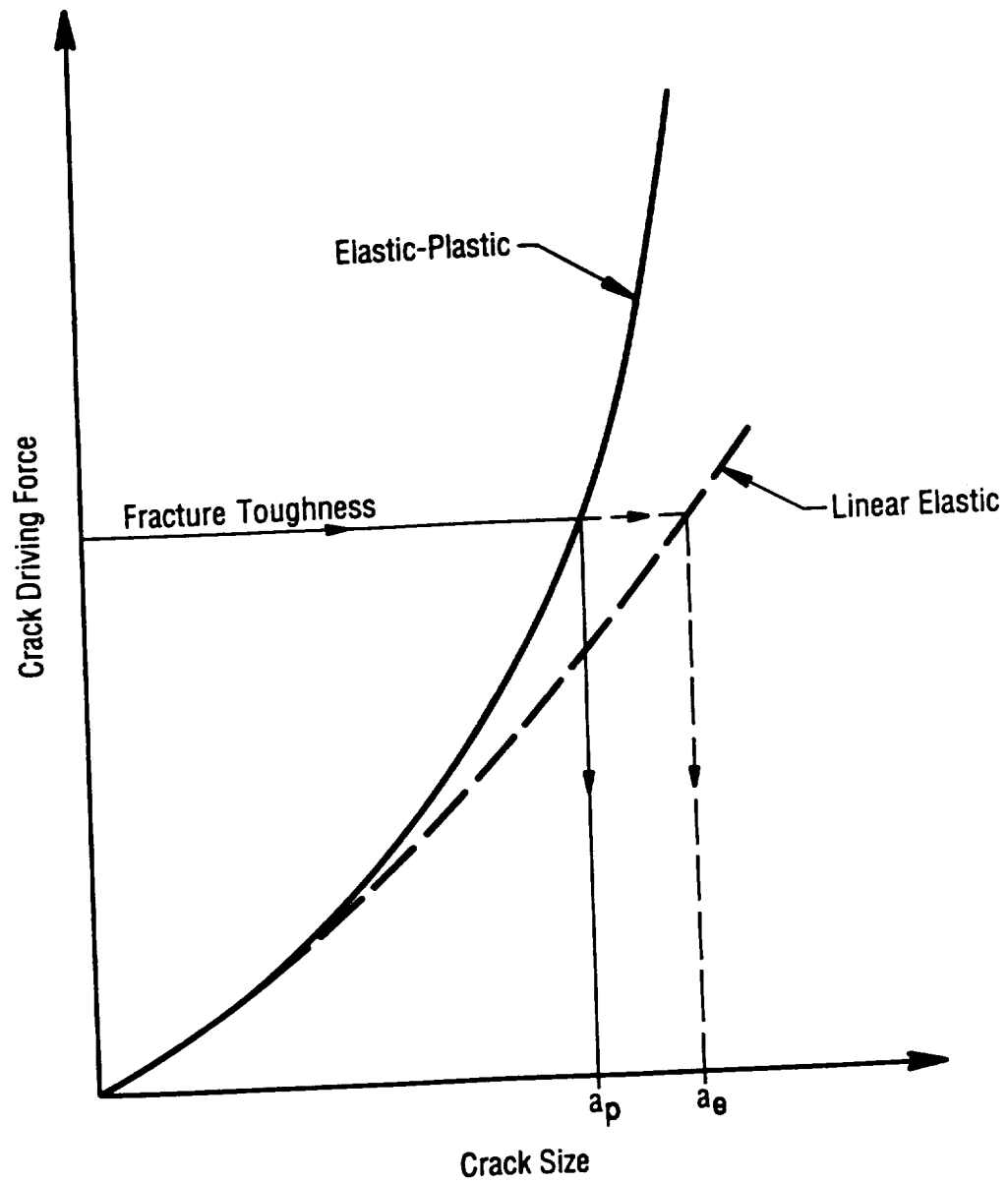
Figure 3.   Crack tip plasticity reduces the critical crack size, a_p, compared to a linear elastic prediction, a_e.

3.2 Deterministic Approach

In a deterministic assessment it is necessary to use specific data in the fracture mechanics calculations. In order to assure safety pessimistic data should be employed. In normal structural integrity assessments this would mean, for example, using lower bound values for the fracture toughness and the yield stress in the analysis. However, this approach will not necessarily assure safety in a proof test methodology.

It is prudent to use upper bound values for the toughness and yield stress in order to maximize the value of a_o because this is postulated to be an upper bound to existing defect sizes. Conversely, lower bound values for the fracture toughness and yield stress should be used in the evaluation of a_s. If the test is carried out in an aggressive environment, then a lower bound value for the stress corrosion cracking threshold stress intensity factor, K_{Ith}, should be used instead of the fracture toughness value [2,43]. This choice allows for the possibility that the crack tip is in an area of good material during the proof test, but propagates into poorer material during service. Although this conservative approach to deterministic analyses results from safety considerations, it can seriously erode proof test factors and reduce the apparent effectiveness of the proof test. To avoid this possibility, proof test analyses often use consistent data for the calculation of a_o and a_s. This approach can be justified if it can be demonstrated that there will be no significant variations in material properties in the region of the postulated defect during its growth in service.

The deterministic proof test concept appears to be a simple and scientific way of assuring component safety during operation. However, a number of recent applications of the single cycle proof test method to defective components have indicated that further developments are required to the original approach [8,9]. This is particularly the case for materials that fracture by ductile mechanisms with a high toughness and fracture resistance.

There is no discernable benefit to applying multiple cycling proof testing techniques to brittle and ductile materials if the test is to be analyzed using a deterministic methodology. To demonstrate that multiple cycle proof testing can have a beneficial effect on ductile materials requires the application of a probabilistic methodology in order to show that the damage introduced by concurrent fatigue and stable tearing is more than compensated for by the removal of detrimental sized defects from the population. Although brittle materials cannot tear, it is know that there is an appreciable acceleration in their fatigue crack growth rates as failure is approached due to propagation by combined cyclic and static mechanisms. It may statistically be possible to demonstrate a beneficial effect of multiple cycles for these materials also, although the calculated change in the defect distribution may be considerably smaller than for ductile materials.

3.3 Probabilistic Approach

The proof testing problem is particularly well-suited for probabilistic analysis. The most common purpose for proof testing is simply to reduce the probability of component failure in service by removing defective hardware from the population. Influencing this process are many uncertainties, which include the flaw population in the component, the properties of the material from which the component is manufactured, the loads which the component will experience in service, and many others.

A "successful" proof test does not, in general, guarantee a zero probability of subsequent failure in service. Interpreting exactly what a successful (or unsuccessful) proof test does imply about component reliability (e.g., how much has the probability of failure in service changed?) requires probabilistic analysis. This same analysis procedure also provides unique opportunities to optimize the initial design of the proof test, and to optimize the intervals between proof tests for re-certifiable components. Some of these powerful connections between proof testing and probabilistic analysis were recognized in the early days of proof testing analysis (e.g., 1960s NASA research reported in [47]).

The results of a probabilistic analysis are useful in helping to rank the relative importance of proof test parameters. This information is extremely useful in determining the sensitivity of the results to specific input items. It is useful to know, for example, that the results of a proof test analysis may be sensibly independent of how the flaws are characterized in terms of shape, or the nature of the test media. Knowledge of the degree of uncertainty in the value of a parameter is important, particularly if the results of the analysis are sensitive to variations in this value. This kind of information is often not readily extracted from a deterministic approach, where time and energy may be expended in calculations and refinements that ultimately do not influence the outcome of the analysis.

Formal proof test optimization requires the simultaneous evaluation of a joint reliability problem: the probability of component failure during the proof test, and then during the subsequent service exposure. These issues are illustrated schematically in Figure 4. As the ratio of proof load to design load increases, the probability of failure during the proof test increases. On the other hand, the probability of failure in service for a component which has previously survived this proof test is likely to decrease with increasing proof factor. Optimum design of a proof test must mathematically optimize these two reliability functions, weighing the consequences of proof failure versus service failure.

3.3.1 Choice of a Basic Probabilistic Method

A probabilistic analysis of proof testing can take several different forms, depending on the specific questions being asked. The setting of these questions is a key part of a probabilistic methodology. Some possibilities include:

(1) If the component survives the proof test, what does this imply about the post-proof population? (e.g., what is the largest remaining flaw?)

(2) What is the probability that a flaw larger than some specified size will survive a given proof test protocol?

(3) What is the probability that a given population of components will all survive a specified proof test protocol?

(4) If the component survives the proof test, what does this imply about the probability of failure in subsequent service?

(5) How much does the probability of failure in subsequent service change because the component survived the proof test?

Questions (1)-(3) are more straightforward because they consider only the proof test itself. Questions (4)-(5) require much more complex analysis because of the additional need to evaluate conditional reliability in service, especially when (as is usually the case for propulsion systems) service loads and proof loads are fundamentally different in character.

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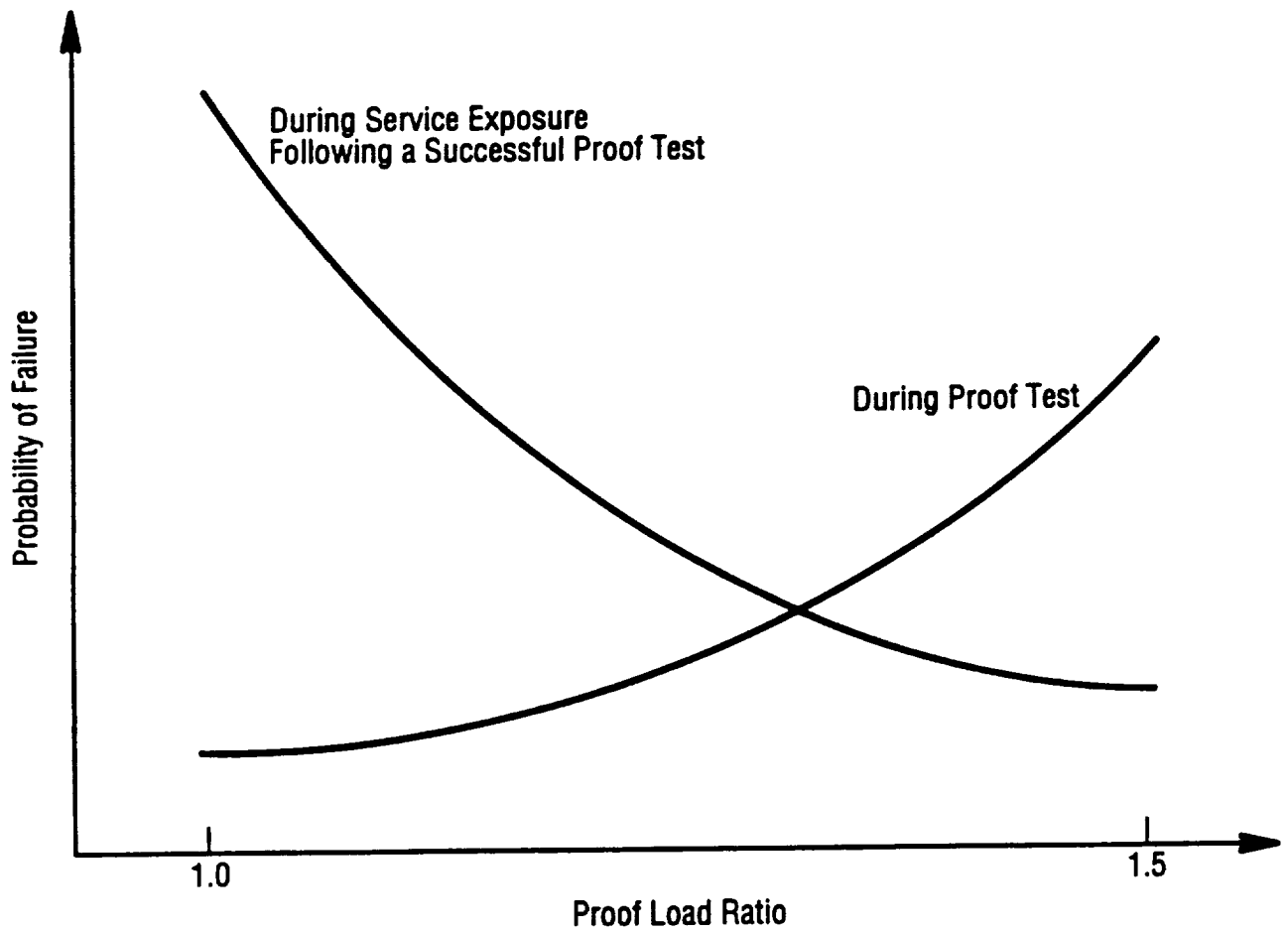
Figure 4.   Schematic representation of interacting reliability issues associated with proof testing and subsequent service exposure.

Selection of a specific computational method to solve a probabilistic problem depends on both the questions posed and the complexity of the analysis involved. A simple brittle fracture formulation will permit a relatively straightforward solution technique. There are many examples of brittle fracture problems being solved probabilistically in the literature [48-50]. On the other hand, very few examples are available of probabilistic elastic-plastic fracture solutions. A proof test analysis presents additional difficulties such as allowing for multiple cycles, ductile tearing and time dependent effects.

Although a comprehensive and rigorous treatment of the probabilistic analysis of proof testing is not feasible at this time, simplifying assumptions can be made to facilitate the computations while still providing meaningful reliability information concerning the efficacy of the proof loading.

The most general technique for solving the above probabilistic problems is based on Monte Carlo simulation. Monte Carlo is a well-known and well-established technique which has often been applied to fracture problems. Approximate techniques based on the Fast Probability Integration (FPI) concept [54], offer similar accuracy to Monte Carlo but much greater speed and some additional output information. These methods can be applied to well-behaved failure functions. Some of the more complicated computations, such as those involving conditional probabilities and NDE inspection, require more advanced system reliability analysis methods that combine an efficient importance sampling method with the FPI method [127].

3.3.2 Random Variables and Required Data Base

Many of the important variables required to analyze a proof test and to determine its ramifications regarding subsequent service reliability are characterized by some uncertainty or randomness. The most obvious random variables are the size, shape, location, and orientation of any cracks or crack-like defects in the component both before and after the proof test. If the influence of nondestructive inspection on reliability is considered, then the probability of flaw detection should also be added to this list.

Scatter or uncertainties in material properties are also significant. The important material properties needed for a proof test analysis are detailed in Section 5.4, and some of the changes that may occur to material behavior because of the proof loading are discussed in Section 6.4. The material properties of concern are: fracture toughness, tensile data, and crack growth rates due to fatigue and other mechanisms. It is clear that the uncertainties associated with materials data will be further compounded by the additional uncertainties in material response resulting from the effects of the proof test.

There are also uncertainties in assessment data resulting from stress analysis and geometrical modelling of a component under both proof tested and service conditions. The loads applied to a component during proof testing are usually well-known, but the translation of those applied loads into local stresses in a complex component will introduce uncertainties. These can be attributed to several different factors, including variations in component geometry (tolerances, weldment geometry and distortion, etc.), specification of boundary conditions associated with proof test fixtures, and the general task of stress analysis itself. Stress analysis of the component under (usually well defined) proof testing conditions should be subject to less uncertainty than analyses performed using simulated service loadings which include, among other things, complex thermal and vibratory phenomena.

The scatter or uncertainty associated with each of these "random variables" must be described by some statistical distribution in order to perform a mathematical computation of reliability. These distributions can typically be represented by standard functional forms such as Weibull, lognormal, normal, or exponential distributions. Most of these distribution functions can be characterized by simple mathematical forms which describe both the central tendency of the data (for example, the average or mean value) and the likely scatter of the data around this central tendency (often described in terms of the standard deviation). A typical distribution function is usually completely described by two or three scalar parameters.

One of the most significant issues limiting the use of probabilistic methods to proof test analysis is the availability of the required probabilistic data base, that is, lack of specific information about the appropriate distribution functions for crack size, fracture toughness, etc. Current material data bases for aerospace propulsion component design or fracture control are typically deterministic. They provide little, if any, information about the statistical nature of the data, although some anecdotal information for a very limited number of materials is scattered throughout the literature [49,50]. In the future, the advent of general probabilistic design and analysis methods for aerospace propulsion systems is likely to lead to some increases in the amount of probabilistic information available.

In some cases, it may be possible to construct the needed statistical distribution from available deterministic information. If historical information is available about appropriate distribution shapes and typical coefficients of variation (i.e., the ratio of the standard deviation to the mean value) for important random variables, then it may be possible to build the probabilistic distribution around a given mean value using simple estimation techniques. For example, Gates [55] has suggested a simple means of estimating distributions for the flow stress and fracture toughness. The validity of this and other approaches requires further verification.

The importance of different random variables and the importance of assumptions about their distributions can be assessed on the basis of probabilistic sensitivity factors. These sensitivity factors, which can be calculated automatically based on the FPI concept [54] or an efficient sampling method [128], indicate the relative contribution of each random variable and its associated uncertainty to the reliability. The sensitivity factor reflects both the assigned scatter in the input variable and its functional influence in the mathematics/physics of the calculation. These factors provide a rational basis for ranking the relative importance of different random variables and can suggest where additional work is most or least needed to improve the data base or analytical theory.

3.3.3 Relationship of Proof Testing to NASA Probabilistic Methodologies

The advent of probabilistic methodologies is proving an important new development for NASA applications in structural integrity and life analysis. The current centerpiece of NASA technology in probabilistic structural analysis for propulsion systems is the NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) software system currently being developed by Southwest Research Institute under contract to NASA [56,57]. This computer code, developed to support the larger project on "Probabilistic Structural Analysis Methods (PSAM) for Select Space Propulsion System Components" is already being used at NASA Centers, by aerospace contractors, and in other industries as well. These developments can provide important analysis tools for a probabilistic based proof test

methodology, and they provide an incentive for the methodology to be consistent with the computational algorithms and data bases which are employed in the structural analysis software. For example, it may be possible to develop a NESSUS application module which supports the design and analysis of proof tests.

Furthermore, the impact of probabilistic technologies in reshaping the philosophy and process by which future aerospace structures will be designed and analyzed will, inevitably, have implications in the development of a proof test protocol for these components. However, the full ramifications of these technological changes on proof testing will not become apparent until some time in the future.

The design or evaluation of a proof test on a probabilistic basis may require the identification of a target reliability level; i.e., a quantitative standard to determine whether the demonstrated or estimated component reliability is "good enough." The definition of this standard will likely need to originate outside the framework of the proof test methodology, perhaps in some overall reliability assessment of the entire engine or subsystem. Again, this indicates the need for substantial links between the probabilistic proof test methodology and the total structural reliability program established by NASA.

4. CHOICE OF PROOF TEST CONDITIONS

Out of necessity, proof test conditions may differ significantly from service conditions. Oftentimes the environmental conditions during proof testing will be less severe than during service. Appropriate allowance has to be made for these differences when performing a proof test analysis.

There are three major issues which need to be addressed when specifying proof test conditions. These are the nature of the test environment; the kind of loading that will be applied; and the role to be played by NDE. The technical issues associated with each of these topics are summarized in Tables 3, 4, and 5 respectively, and discussed in more detail in Sections 4.1 through 4.3.

4.1 Test Environment

The choice of specific environmental conditions for the proof test, (i.e., temperature and media), are dependent upon numerous considerations. These include requirements to conform to standard structural guidelines and the need to directly demonstrate component survival in the operating environment through structural testing.

The environment can impact on the proof test analysis through its effects on material characterization; component damage; flaw screening potential; computational complexity; safety requirements and failure consequences.

4.1.1 Material Property Data

Adequate materials characterization is essential for an accurate proof test analysis: without it crack growth rates and fracture cannot be predicted. Material behavior is dependent on temperature, loading rate and media. Testing at temperatures and in environments where material deformation and damage characteristics are not well understood and quantifiable will reduce the effectiveness of proof testing.

Interpretation of material behavior may become difficult if the proof test temperature is different from the operating temperature. For example, it is known that overstressing brittle materials can change their fracture toughness at lower temperatures due to load history effects. Conditions which maximize knowledge of material response should be chosen within the constraints imposed by other issues.

4.1.2 Component Damage

The possibility of causing unnecessary component damage due to proof testing in an aggressive or embrittling environment, or at severe temperatures, needs to be avoided if at all possible. Conditions that can contribute to this concern are temperatures where strain or strain age embrittlement may occur; environments that cause accelerated rates of crack growth (true corrosion and stress corrosion fatigue and high oxidation rates); embrittlement due to transition temperature and/or material-environment incompatibility; and proof testing in the creep temperature regime.

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Table 3. Technical Assessment for Issue 4.1: Test Environment

Importance	It is essential that the full implications of testing in a specific environment are fully understood if a proof test is to be successful and the introduction of unnecessary component damage is to be avoided.
Present Status	This depends on the purpose of the test. If it is intended to demonstrate that the component can survive service conditions, then it is generally accepted that the test should be carried out in an environment which simulates operational circumstances. However, if the proof test is used only as a flaw screening method, then any complications which make this objective difficult to accomplish should be avoided.
Availability of Implementing Technology	The technology for performing internal pressurization and mechanical load tests should be available. The technology becomes more difficult and costly if testing at cryogenic temperatures, or in aggressive environments, or under thermal transient conditions, is required.
Further Technological Requirements	A greater understanding of the effects of environment on fracture behavior would assist in helping to quantify the detriments and benefits of testing in a given environment.
Data Required to Implement the Technology	Data on the effects of environment on material fracture behavior.

Table 4. Technical Assessment for Issue 4.2: Applied Loadings

Importance	The type and magnitude of the loading applied during the proof test plays an essential role in determining the effectiveness of the test as a flaw screening method.
Present Status	It is generally accepted that the proof load should exceed the maximum service load by at least 10%. However, there is less agreement concerning other factors, such as loading rate, the time over which the proof load should be sustained, and whether single or multiple cycling should be used.
Availability of Implementing Technology	There should be no problems associated with attaining moderate loading rates in the proof test. Fast loading rates, and simulation of service loads, such as thermal transients, is far more difficult. Sustained loading, and cyclic loading, should not pose any insurmountable problems with regard to test implementation.
Further Technological Requirements	These are related more to the analysis of the test rather than the practicality of carrying it out. There are still uncertainties associated with the analysis of time dependent effects, and in taking into account the interaction between static and cyclic failure mechanisms. Resolution of these areas would help to define the load conditions which maximize the effectiveness of the proof test.
Data Required to Implement the Technology	Quantification of the effects of cyclic and time dependent loading on subsequent material fracture behavior.

Table 5. Technical Assessment for Issue 4.3: Role of NDE

Importance	NDE is not an essential part of proof testing, but it can greatly increase its effectiveness when performed in conjunction with it.
Present Status	NDE methods are now widely used throughout a range of industries to detect and size crack-like and naturally occurring defects. It is recognized that proof testing increases the defect detectability of NDE methods. When used in conjunction with each other, the two methods provide a powerful flaw screening capability.
Availability of Implementing Technology	Pre- and post-proof test NDE procedures which utilize ultrasonics, eddy current, radiography and magnetic particle and dye penetration techniques are now well established. Acoustic emission is available for real-time monitoring.
Further Technological Requirements	Developing real-time techniques, such as technologies based on infrared and shearography, may provide possible future alternatives to acoustic emission.
Data Required to Implement the Technology	The probability of detection of defects of different shapes, sizes, and acuity. The increase in detectability due to proof loading and the accuracy of sizing detected defects.

Unnecessary material degradation or crack growth during the on-load or load hold portion of the proof test can needlessly initiate cracks. Of even more critical concern is the potential for subcritical growth during either the unload portion of the proof cycle or during subsequent storage. This should be minimized if at all possible. For example, where it is necessary to proof test in an embrittling environment, such as high pressure hydrogen, extreme care must be taken to ensure that the unload rate is sufficiently rapid to minimize sub-critical flaw growth during unloading. In addition, the proof test temperature, pressure and duration must be such that minimal hydrogen is diffused into the material so that unacceptable levels of internal hydrogen embrittlement will not inhibit subsequent operational usage.

4.1.3 Flaw Screening

The efficacy of the proof test to screen flaws is affected by the environmental conditions in the test in many complex ways. These are related to material properties, the aggressiveness of the media, the loading and unloading rates, and the time the proof load is sustained. For example, proof testing at temperatures below operation could afford better flaw screening potential. This is because the yield stress is typically raised, allowing a higher nominal elastic stress to be applied, and, in brittle materials, there is generally a corresponding drop in toughness. Both of these factors will enable the proof test margin to be increased. However, this increase in flaw screening potential may be countered by unnecessary initiation of cracks or an increase in proof test mortalities. A detailed proof test analysis is required before the optimum environmental conditions for proof testing can be specified.

4.1.4 Computational Complexity

The easiest situation to analyze is a proof test based on linear elastic fracture mechanics, an inert medium, and low loading rates at temperatures where time dependent phenomena are not significant. Any change in circumstances that moves away from this ideal scenario introduces additional complications. Although the computational difficulty of performing an analysis will not usually play a major part in determining proof test conditions, it should be a consideration in choosing the test environmental variables which are not dictated by more important considerations.

4.1.5 Failure Consequences and Safety Considerations

The type of "fluid" used in the proof test and whether pneumatic or hydrostatic pressurization is used has ramifications regarding safety considerations, proof failure and the possibility of performing post mortem failure analysis. Due to the incompressible nature of liquids, hydrotesting will usually result in a leak-before-break situation for ductile materials. In contrast, the compressibility of gases enables them to store up large quantities of energy which can be released suddenly, giving rise to a potentially catastrophic rupture. This possibility requires special precautions to be implemented in the test facility design and operating procedures, as well as additional leak detection equipment and analytical support to assess the likelihood for leak-before-burst. Special precautions are also required when rotational loading is used in the proof test.

Determining the cause of proof failure is much easier when the failure is contained and the fracture region is readily accessible. There have been numerous instances where brittle failures have occurred and produced so much destruction in the component and surrounding structure that diagnostic failure analysis was greatly hampered.

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4.2 Applied Loadings

The selection of a specific proof load history — load factor, hold times, loading and unloading rates, and number of proof cycles — is perhaps the central decision in proof test design. The implications of these choices for a total proof test strategy are, in some cases, straightforward and direct, and in other cases complex and multidimensional. It must be emphasized that these choices should not be made in isolation from other proof test design issues, such as test environment or material properties.

4.2.1 Proof Load Factor

The proof load factor is normally expressed as a multiple of the nominal design load, and is typically in the range 1.1 to 1.5. The larger the factor, the smaller are the defects screened by the proof test. It follows naturally, therefore, that a higher proof load will generally indicate higher reliability during subsequent service exposure. It may also have other beneficial effects, such as enhancing shakedown, creating compressive residual stresses, and blunting sharp crack tips.

There is clearly a limit to the size of the proof load beyond which unacceptable detrimental effects begin to occur. Some of these limits are specified in order to avoid detrimental yielding and plastic failure in uncracked regions of the component. Most importantly, high proof loads increase the chance of expensive hardware failures during the proof test from defects which would have been innocuous under the subsequent service history. The potential for subcritical growth of existing defects under high proof loads also cannot be ruled out.

Selection of a proof load factor is confounded by differences between proof test and actual service conditions, such as load types, local stress profiles, temperatures, and environments. While typical proof loading of pressurized systems involves only an applied internal pressure, service loads may also include thermal stressing, tensile forces and bending moments. Furthermore, proof test fixturing may not exactly simulate boundary conditions experienced in service. The proof load factor may need to be adjusted to simulate or to compensate for these effects. However this is done, it is clear that in complex geometrical components there will always be the likelihood that local stresses occurring during service will exceed the maximum level which can safely be generated in the proof test using simple loading devices.

One possibility of overcoming these generic difficulties would be to modify the standard definition of the proof factor and utilize fracture mechanics concepts to relate the factor directly to the crack driving forces present during proof testing and service. It is the ratio of these driving forces which ultimately determines the ratio a_o/a_s, which in turn controls the remaining safe life under service conditions. This was recognized by Tiffany [2] who used an inverse load factor, namely the ratio K_I/K_{Ic} derived from linear elastic fracture mechanics, to infer the remaining life. Here K_I is the applied stress intensity factor at the proof load, and K_{Ic} is the fracture toughness at operation.

These complications raise a critical question whose answer is fundamental to the formulation of both a proof test methodology and protocol: how important is it to compensate fully for differences between proof and service conditions? Differences between proof and service may be of limited significance if the proof test is used only to evaluate and screen the existing defect population in the component, or to demonstrate general quality of workmanship. If, on

the other hand, the proof test is intended to simulate more onerous loading conditions than those encountered in service in order to provide a direct assessment of remaining life or reliability under service conditions, then these differences can be very significant.

4.2.2 Hold Time

The selected time during which the maximum pressure or maximum load is held constant is influenced by both operational and fracture mechanics concerns. The hold time should be at least long enough to ensure that the maximum load is actually attained and can be maintained stably. Additional time may be required to adequately monitor the component for leaks or other irregularities.

Time-dependent flaw growth at a constant load can be attributed to two major causes: sub-critical growth due to environmental attack or creep deformation at the crack tip, and, in ductile materials, stable tearing (see Section 5.4 for more discussion on the material aspects of these topics). These two causes have different implications on the proof test analysis.

Subcritical growth can reduce the survivability of the component in service if it occurs during the proof test. This arises because relatively small and innocuous defects may be extended in size to give a greater population of larger defects than before, increasing the probability of failure. Alternatively, subcritical growth could promote failure of service life threatening defects during proof loading by propagating them to a critical size. This scenario would beneficially screen out damaging defects. Since both of these effects could occur concurrently, it is not clear without performing a probabilistic analysis whether the end result would be deleterious or advantageous.

Flaw growth due to stable tearing is limited to materials that fail by ductile mechanisms. In principle, time dependent tearing during sustained proof loading is not different from the tearing that occurs as the applied load is increased. The time dependent extension can be viewed as equivalent to further tearing due to an increase in the crack driving force which results, not from an increase in load, but from a reduction in the yield properties of the material due to creep deformation [58,59]. The problem then reduces to the non-trivial one of estimating this increase in crack driving force with time.

Some observers have reported that when proof test failures were attributable to time-dependent growth, failure always occurred during the first minute or so at constant load [15]. They concluded that much longer hold times (which they also explored) produced no significant effects. Other observations, including limited research conducted by SwRI under the related NASA-Marshall contract on multiple cycle proof testing, suggest that time-dependent crack growth rates will gradually decrease (perhaps to zero) during a hold period, unless failure is imminent. In that case, growth rates will either monotonically accelerate or perhaps first decrease, pass through a minimum, and then increase to failure [60]. These observations suggest that an absolute "threshold time" beyond which failure in the proof test is most unlikely may not exist, although it may be practical to define a maximum hold time in order to avoid acceleration in subcritical time dependent growth.

The situation is complicated if the proof test is performed in an aggressive environment which accelerates the time dependent growth. The environment could do this by reducing the toughness of the material (in a hydrogen environment, hydrogen may diffuse into the highly stressed material around the crack tip) or by a synergistic interaction whereby the crack

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extension due to the environment per se (i.e., subcritical crack growth) increases the crack driving force, which in turn promotes more tearing. Although this scenario would manifest itself as enhanced time dependent tearing, the possibility that the environment degrades the fracture toughness could have serious implications with regard to structural reliability during subsequent service operation (see also Section 6.4).

Real-time acoustic emission (AE) monitoring during the proof test may be able to detect time-dependent subcritical crack growth, and this may influence hold time selection. The use of AE or other real-time NDE techniques, discussed in Section 4.3, may also require some additional time at maximum load to permit complete interrogation of the component.

4.2.3 Loading and Unloading Rate

The effects of loading and unloading rate follow closely the arguments for hold times. Some concerns are operational: practical limits exist on how fast a complex engineering component can be pressurized or depressurized while maintaining adequate control on total pressure and adequate monitoring of component response. Slow loading or unloading rates also raise the possibility of time-dependent crack growth due to environmental attack or creep deformation, if the temperature of the test is high enough. Tiffany [2] makes the pertinent point that the damage resulting from subcritical growth during sustained loading could be dangerously enhanced by a slow deloading rate which still permitted subcritical growth to occur while suppressing the possibility of the larger defects initiating failure. Since analysis of time-dependent growth during load cycling is likely to be even more difficult than analysis during constant load, a reasonable engineering response is probably to minimize time spent during the load increasing or load decreasing portions of the proof test. This is especially true for the unloading half of the cycle.

Extremely fast loading rates may induce changes in the material properties of rate sensitivity materials: the values of yield stress and fracture toughness could significantly differ from the values measured in a conventional static test if strain rates are high enough. Fortunately, typical pressurization rates may be too low to generate these effects in aerospace materials.

4.2.4 Number of Cycles

Tiffany [2] argues that there is nothing to be gained from MCPT and, indeed, multiple cycling could do some needless damage to the component because of cyclic crack growth. This position is generally accepted for brittle materials, and there are good reasons for taking this view if the proof test is performed in an aggressive environment. However, the experiences of Rocketdyne in successfully using MCPT methods on ductile materials provides practical evidence that there are exceptions to Tiffany's view. In practice, some components may be subjected to cyclic loadings similar to a planned MCPT for other reasons. These include the requirement for additional proof tests of components which have been repaired or modified following the initial proof test; complex component systems which must be proof tested at different times during their assembly; and repeat proof testing for component recertification.

It has been proposed that the damage introduced into the component by multiple cycle proof loading can be reduced because lower proof loads can be employed in this case compared with a single cycle proof load [7]. The logic of this conjecture is not apparent to the present authors

since a reduction in the proof load will result in an increase in size of defect that could just survive the proof test. This would reduce the flaw screening capability of the test and erode proof test margins.

MCPT of components fabricated from ductile materials has been performed at Rocketdyne for many years, and was originally motivated by failures of components which had survived an initial single-cycle test and were subsequently retested. Later Rocketdyne experience with MCPT has shown that component failures can occur on the second, third, fourth, or fifth cycles at significantly lower pressures than applied on the first cycle [61]. These failures generally initiated from undetected flaws in the component, typically in thin sections where the defects were large compared to the thickness. In several cases these hardware deficiencies, revealed only after having passed the first proof pressure cycle, were judged to have presented a significant risk of component failure or malfunction in service.

This direct hardware experience illustrates the potential deficiency in the conventional single cycle test, demonstrates the potential benefit arising from MCPT, and poses a challenge to determine optimum strategies for proof testing. The challenge arises because the potential benefits of MCPT must be weighed against the possibility of inflicting additional undetected damage on the component through further subcritical crack growth during multiple loading cycles.

The successful record of performance of Rocketdyne engines whenever MCPT has been implemented, along with occasional failures of defective hardware during MCPT, have served as engineering justification for the practice, at least on components and under conditions where verification has been obtained. But while MCPT logic is generally consistent with the concept of subcritical crack growth in ductile materials, a rigorous, comprehensive theory of crack behavior during MCPT is not yet available as a formal scientific justification for the relative merits of MCPT versus conventional single-cycle proof testing. The early work of Mendoza and Vroman [6], and the follow-up work of Besuner, Harris and Thomas [7] were admirable attempts to develop this theory, but the elastic-plastic fracture mechanics tools available at that time were insufficient to build a technically adequate explanation. However, the basic concept that these works utilized appears to be sound. Increased service reliability is conferred by MCPT because the calculated defect size distribution remaining in the component after cycling is less onerous than the distribution before the proof test, or, indeed, after a single cycle has been applied.

Extensive studies of MCPT are currently ongoing at SwRI under the sponsorship of NASA-Marshall. These studies have prompted the development and evaluation of several different analytical approaches to crack response during MCPT, including interactions between resistance curves and elastic-plastic fatigue crack growth when ductile tearing and fatigue crack extension are concurrent, and probabilistic analysis [33,34]. More recent work in the MCPT program has shown the models of Kaiser [62] and Chell [63] for including the interactions between monotonic and cyclic modes of crack growth to be generally true, although experimental investigations have identified some conditions under which alternative crack growth phenomena may come into play. These phenomena include time-dependent growth near instability and the effects of locally reversed deformation prompted by geometric constraint or displacement control modes.

It appears that the optimum design of MCPT may depend, at least in part, on the specific geometry, material properties, and probable flaw distributions for each component, although more general engineering conclusions may be admissible and appropriate. Further experimental and analytical research into MCPT is actively in progress at SwRI under the NASA contract, and this research is expected to provide more conclusive answers about the optimum number of proof cycles required to maximize the effectiveness of the proof test.

4.3 Role of NDE

The interaction between proof testing and NDE should be considered when designing an optimum proof test strategy. Although proof testing is sometimes conducted as an alternative to NDE, more frequently proof testing is conducted in coordination with NDE inspections, particularly when the effectiveness of NDE is compromised by geometric complexities of the component. The challenge is to optimize simultaneously the design of both proof test and related NDE procedures, with particular attention to the unique contributions of each technology and their mutual interaction. NDE is most often conducted before and/or after the proof test, but useful NDE techniques for real-time proof test monitoring are available and should also be considered.

Coordination between NDE and the proof test is expected to be especially important for components fabricated from tough, ductile materials, where stable growth of pre-existing flaws and leak-before-break is more likely before instability. The need for NDE is influenced by the extent and nature of the expected post-proof service history. If a primary motivation for the proof test is to facilitate improved NDE inspections, then it should be possible to decrease the proof load factor and hence reduce the potential for unnecessary damage to the component.

NDE also interacts with other proof testing issues which are discussed elsewhere in this report. These include economic and management factors, and the influence of NDE on a probabilistic treatment of structural reliability (e.g., probability-of-detection information).

4.3.1 NDE Before and After the Proof Test

NDE is often performed on a routine basis with normal inspection techniques either prior to the proof test, following the proof test, or both. Special attention should be given to the types of defects which are most or least likely to be detected by NDE or by proof testing, with a view towards maximizing the total probability of detection by coordinating the two inspection protocols. Ideally, proof testing should not be performed without the benefit of coordinated NDE, especially for critical components fabricated from highly ductile materials.

Post-proof NDE is especially useful for two reasons: deformation caused by the proof loading may increase the detectability of pre-existing flaws, and the proof loading may also cause additional damage in the form of subcritical crack growth which needs to be detected. Enhanced flaw detectability due to proof loading is a well-documented phenomenon. Local plastic deformation can permanently "open up" cracks such as tight weld fissures in compressive residual stress fields, so that standard post-test NDE inspection can find flaws which might have been missed by pre-test NDE. For example, following the application of multiple proof test cycles to engine combustor cases for the C-5 aircraft in 1969, conventional dye penetrant inspections found cracks in 6 cases which were undetectable prior to proof [64].

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Similar experiences were reported by Martin Marietta during ultrasonic inspections of 2219 aluminum weldments for the Space Shuttle External Tank [22]. This phenomenon does not appear to require a large proof factor.

The requirement for post-test NDE is increased if the proof loading causes a significant increase in damage (e.g., crack size) during the test. In these cases there may be special value in coordinating or comparing NDE information from different inspections, perhaps employing post-test NDE to focus on regions where there were indications from pre-test or real-time test monitoring, or comparing pre-test with post-test signals to note significant differences.

The techniques available for pre- and post-test NDE are long established and the principles behind them are well understood. The main techniques—ultrasonics, eddy current, radiography, magnetic particle and dye penetrant—have established protocols for use by certified technicians.

4.3.2 Real-time NDE Monitoring During the Proof Test

Several NDE techniques can be employed to detect the real-time response of a crack or flaw to the proof test loading itself. Of special interest are acoustic emission (AE), infrared, and shearography techniques. These techniques typically have a large field of view and, hence, do not require either prior knowledge of the flaw location or exhaustive scanning of the component. This does require some substantial initial investment in equipment and trained technicians, but actual monitoring is relatively simple and fast, probably necessitating no delays in the usual proof test procedures.

The most mature NDE technology for real-time monitoring is AE, which detects the elastic energy spontaneously released by nearly all materials when they undergo deformation. The primary target of AE monitoring during proof testing is the emissions from localized deformation associated with flaws and flaw growth. Acoustic emissions can be generated from cracks by several different mechanisms, including plastic deformation at the tip of stationary or growing cracks, creation of new surfaces during crack growth, and the contact and rubbing of opposing crack faces during loading or unloading. The relative amplitude of emissions from these different sources may vary from application to application, and this may have implications for the optimum selection of hold times or loading/unloading rates. Emissions activated by crack propagation may be predominant only during periods of appreciable growth, such as near failure, when an increasing AE event rate is a likely predictor of flaw criticality [23].

AE was first employed to monitor proof testing around 1965, and AE applications to proof testing and related structural reliability problems are now common in many different industries [65]. Some AE investigations are being conducted at SwRI in conjunction with the current SwRI/Rocketdyne/NASA-Marshall program on multiple-cycle proof testing, and these results will provide additional insight.

AE is typically detected by a piezoelectric transducer temporarily affixed to the surface of the interrogated component. If multiple transducers are employed, the specific location of individual emissions can be located based on the relative time of arrival of the AE signal at each sensor. The number of transducers required depends on the geometry of the component and attenuation in the material. Since AE signals can travel relatively long distances in most

materials without significant attenuation, a small number of transducers can service a single component. Standard commercial instrumentation is designed to manage many channels of information.

Essentially all structural materials will emit AE during deformation, but the AE signal strength, and hence the general feasibility of the AE technique, may depend somewhat on material condition, component configuration, and other proof test parameters [90]. Signal attenuation will be greater in some materials, as well. The effects of all these parameters are not well understood, but it appears that less advantageous conditions can usually be overcome via improved instrumentation and monitoring procedures. Some prior experience with the specific material and general class of geometry is desirable.

The sensitivity of the AE method can be limited by ambient background noise which can obscure emissions from cracks, especially in a production environment. Special precautions and fixturing may be necessary to reduce such background noise to tolerable levels. AE signals can also be generated by general or local plastic yielding in the component, residual stress relief, inclusions, and other material features. At this time, it is difficult to determine the nature of an AE source merely by its signature from a single emission. Locating the source of AE is the best means of identification. A follow-up inspection with another NDE method is often required at the located AE source for further verification. The behavior of an AE source as a function of time and stressing mechanism can provide further clues about its identity. AE methods cannot be used by themselves for measuring flaw size, orientation, or depth.

Other advanced NDE methods are available which have had limited applications to real-time proof test monitoring but which show considerable promise. *Infrared* techniques sense the applied mechanical energy which is disturbed, concentrated, and dissipated at local defects as thermal energy: in effect, the defective region becomes hotter. Extremely sensitive infrared cameras are able to detect minute changes in local temperature (less than 0.1°C). Electronic *shearography* compares successive video images of a component illuminated by coherent laser light during application of an increasing stress. Comparisons of before-and-after video images systematically distorted by a shearing lens permit construction of an interferogram which reveals minute changes (as small as microinches) in out-of-plane surface displacements. Local distortions in the component displacement field caused by cracks, such as crack opening displacements or surface dimpling caused by near-crack plastic deformation, would be important targets in proof testing applications.

Both infrared and shearography are non-contacting techniques with relatively large fields-of-view, although some changes in camera orientation might be required to interrogate all of a complex three-dimensional part. The field of view is, in general, smaller than for AE methods. The sensitivity of these alternative techniques to flaws in actual hardware is not yet well established. Uncertainties remain regarding the effects of different material conditions, flaw sizes and locations, and other proof test parameters. The potential susceptibility of the techniques to false positives from other (non-crack) sources of deformation and displacement also requires further exploration.

5. ASPECTS RELATED TO PROOF TEST ANALYSIS

The information and choice of technology required to perform a proof test analysis is dependent on being able to characterize key elements of the component in terms of material response under load, stress distributions consistent with the applied loading, structural restraints, residual stresses, and local changes in materials due to weldments, etc. The assessment of defects under proof test conditions requires appropriate fracture mechanics parameters and the technology to calculate them. Characterization of the shape, size, orientation and distribution of flaws, and appropriate material property data, are necessary in order to implement the technology. A summary of the technical issues related to component characterization, fracture mechanics, flaw characterization and material property aspects are presented in Tables 6, 7, 8, and 9 respectively, and discussed in more detail in Sections 5.1 to 5.4.

5.1 Component Characterization

Understanding the characteristics and mechanical responses of components during proof and operation is crucial for development of successful proof testing procedures. Fracture mechanics based proof assessments depend on accurate component modelling, material characterization, and analysis, to provide realistic stress analysis, crack growth and failure estimations.

5.1.1 Constitutive Modeling

Constitutive models that accurately describe material deformation responses are essential for stress analysis and determination of fracture assessment parameters during proof and operation [66-68]. Ideally the models should simulate monotonic, cyclic and time dependent material behavior, particularly if service history effects are considered important. Although the changes in material properties due to service and proof test conditions (due to cyclic hardening and softening, strain ageing embrittlement, etc.) may be important, in practice it is unlikely that constitutive equations are available for adequately describing these, and resort to direct material property measurements is recommended.

Most finite element analyses used in analyzing proof tested hardware use linear elastic theory, conventional plasticity approaches, or combined plastic/creep models. These are sufficient for most stress analysis and fracture mechanics applications. For components tested or operated at high temperature where creep and rate effects are significant, unified constitutive models may be necessary to adequately capture the deformation response. Unified models combine creep and plasticity into one inelastic strain contribution rather than treating them separately. At present, usage of unified models is not sufficiently mature for them to be efficiently utilized in practice. Therefore, conventional models will have to be used for component analysis in most cases, and proof test conditions should be chosen wherever possible so that these apply.

5.1.2 Stress Analysis

Stress analysis provides the magnitude and distributions of stresses and strains in component critical sections. These quantities are required for fracture mechanics analyses. The accuracy of the stress analysis will be determined by how accurately service and proof test loading conditions are known. Special considerations are also required in order to

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Table 6. Technical Assessment for Issue 5.1: Component Characterization

Importance	An accurate characterization of the component for stress analysis and fracture mechanics purposes is necessary for a proof test analysis based on flaw screening capability.
Present Status	Stress analysis methods, geometrical modelling of structural components, and characterization of material deformation by constitutive laws are the three key tasks of component characterization. Techniques for performing these tasks have been available for many years and are widely accepted and used. In practice, simplifying assumptions regarding component characterization are frequently made in order to expedite a cost-effective solution.
Availability of Implementing Technology	Modern finite element stress analysis computer codes, such as ABAQUS and ANSYS, allow detailed three-dimensional modelling of complex structural components, they also usually contain routines for evaluating fracture mechanics parameters. Constitutive equations describing material behavior in the linear elastic, plastic and time dependent regimes are normally available within the software.
Further Technological Requirements	Simple, but relatively accurate, technology is required that can be readily integrated into deterministic and probabilistic proof test methodologies. Characterization of residual and other fabrication stresses is an outstanding problem.
Data Required to Implement the Technology	Constitutive laws governing material deformation are required. Reviews of welding residual stresses should provide some guidance on the magnitudes and distributions of stresses at various weldments.

Table 7. Technical Assessment for Issue 5.2: Fracture Mechanics

Importance	Aspects of linear elastic (LEFM) and elastic-plastic (EPFM) fracture mechanics are essential for the analysis of proof tested components.
Present Status	The concepts behind LEFM have long been established as a means of assessing the integrity of defective structures subjected to static and cyclic loads. In LEFM the crack driving force is characterized by the stress intensity factor, K_I. The limitations of LEFM are also recognized: if significant crack tip plasticity occurs then LEFM over-predicts failure conditions. EPFM extends LEFM into the plastic regime through the J-integral parameter, which has been widely used to assess the fracture behavior of ductile materials. However, J also has limitations on its use, and a universal EPFM parameter is currently not available. There have been several approximate methods proposed for estimating J in the presence of secondary loads, but none of these are generally accepted.
Availability of Implementing Technology	There are now a number of published compendia of K_I solutions which cover a great variety of defective structures and applied loadings. The computer codes FLAGRO and NASCRAC can generate K_I solutions which are relevant to aerospace propulsion systems, and also perform cyclic crack growth analyses. Finite element computer codes such as ABAQUS and ANSYS contain routines for evaluating LEFM and EPFM parameters. A limited number of J solutions have been tabulated in EPRI elastic-plastic engineering handbooks. Approximate and versatile methods of evaluating J based on a reference stress approach are available and can be relatively easily applied. These depend on knowing K_I and the plastic collapse load of the structure. Methods of determining J for secondary loads have been proposed within the EPRI J estimation scheme, and within the reference stress approach. Fracture criteria, and equations describing material resistance to crack extension under static , cyclic and time dependent deformation conditions are available expressed in terms of calculable fracture mechanics parameters.
Further Technological Requirements	Work for NASA at SwRI and Rocketdyne is continuing and will lead to recommendations of EPFM parameters for use in the static and cyclic assessments of aerospace propulsion systems. This project should help resolve some of the outstanding issues associated with the treatment of secondary loads. The development of computer software for implementing these recommendations would provide a valuable tool for proof test analyses. There is presently no accepted procedure for accurately assessing defects at welds. Since welds are a major source of flaws, this problem requires resolution. Experimental validation of the existing material crack growth resistance equations describing the interactions between static and cyclic failure modes is required for materials used in the aerospace industry. Consideration should be given to resolving the problems of employing EPFM parameters to explicitly characterize proof test margins.
Data Required to Implement the Technology	Stress analysis results, tensile data, fracture toughness and sub-critical crack growth constants are required. Characterization of flaws in terms of crack-like defects which can be treated by fracture mechanics is also necessary.

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Table 8. Technical Assessment for Issue 5.3: Flaw Characterization

Importance	It is necessary to simplify the characteristics of naturally occurring defects so that they are amenable to fracture mechanics analysis
Present Status	Rules currently exist for characterizing flaws of irregular shape, arbitrary orientation, and that appear in clusters. These rules are intended to produce a pessimistic representation of the flaw, and are based on LEFM concepts. The rules were not explicitly intended for proof test or EPFM applications.
Availability of Implementing Technology	Rules for characterizing flaws are given in ASME Boiler and Pressure Vessel Code, Section XI.
Further Technological Requirements	Flaw characterization rules applicable to EPFM and proof test applications are required.
Data Required to Implement the Technology	Knowledge of fatigue and fracture behavior of naturally occurring defects under elastic-plastic conditions.

Table 9. Technical Assessment for Issue 5.4: Material Property Aspects

Importance	Material property data that are representative of the material condition during the proof test and under service conditions are essential for proof test analyses
Present Status	Presently ASTM standards specify the procedures to be followed in the measurement of tensile data, fracture toughness and fatigue crack growth data. The special problems associated with proof testing, namely, use of "upper bound" data in some circumstances, and specification of the statistical significance of the data, are not directly addressed.
Availability of Implementing Technology	Standard material property testing is relatively straightforward. However, application of a proof test methodology requires material property measurements under conditions which are outside of the scope of normal testing procedures. For example, J-resistance (toughness) values at large tear lengths and the fracture behavior of materials undergoing crack extension by concurrent static and cyclic mechanisms may be required for ductile materials. Knowledge of the effects of proof test environment on material behavior may also be necessary.
Further Technological Requirements	Recommendations for obtaining and analyzing material property data which have to be measured in conditions which violate the standard testing procedures are required.
Data Required to Implement the Technology	Not applicable.

analyze complicated structural geometries and other features, such as welds. These considerations are made more difficult if fracture mechanics parameters are to be calculated from numerical analyses based on finite element computer codes.

Finite element methods provide the most versatile approach for performing numerical stress analyses, and are generally the preferred method in the analyses of complicated three-dimensional structures. Computer codes such as ABAQUS [69] and ANSYS [70] are widely available and used. In practice, detailed finite element stress analyses are often avoided due to time constraints and cost. Factors which impact on the accuracy and realism of stress analyses are: use of simplified methods; simulation of plastic constraints and geometric restraints; determination of residual stresses; and problems associated with welds.

Simplified analyses

Finite element or other numerical stress analysis methods are often simplified by reducing the geometrical complexity of a component to a form which is more readily addressed by coarsening finite element meshes and modifying and simplifying boundary conditions. The sophistication of numerical calculations is frequently reduced by using approximate methods to predict elastic-plastic stress redistributions from linear elastic stress analysis results, direct geometric simplification to take advantage of handbook stress and stress intensity factor solutions, and simplifying the applied loads (including residual stresses).

Simplification of stress analyses should be performed with care to ensure that realistic analysis conditions exist. If proof test condition simulations are overly conservative, the flaw screening potential of the proof test may be grossly overestimated, resulting in an underestimate of the size of flaws that may survive the proof test, an overestimate of service life, and an unrealistically high component mortality rate prediction during the proof test. If the proof test conditions are optimistically simulated (the stresses are underestimated), the apparent effectiveness of the test is reduced as margins conferred by the proof test are eroded, as is its flaw screening capability.

Constraints and restraints

It is important to simulate the level of plastic constraint and geometric restraints that exist in the structure, as these affect deformation in the vicinity of a defect. This is particularly the case when numerical methods are being used to evaluate fracture mechanics parameters. Factors which may significantly influence constraints and restraints include local geometry (e.g., thickness, geometric discontinuities); far field state of stress (plane stress versus plane strain); far field applied loading type (tensile forces or bending moments); degree of crack tip plasticity (small scale or large scale yielding); whether the defect is submerged in a plastic enclave (crack tip yielding to free surface, potential load shedding or stress redistribution); and boundary conditions (restraints against rotation, imposed displacements).

The calculated values of fracture mechanics parameters can be very sensitive to the form of loading and geometric restraints: there can be significant differences between values evaluated under load and displacement control for similar values of the local stresses in the defect free component. In the latter case, there can be a strong interaction between the effective loading on the defect and the change in structural stiffness due to its presence. Analysis simplifications should incorporate these important effects.

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Residual/preload stresses

Residual/preload stresses are developed during fabrication, installation, or surface treatment processes. The residual/preload stresses of a component are oftentimes difficult to estimate but can be significant relative to determination of component defect tolerance. In addition, the limitations of mechanical stress relief of residual stresses (shakedown) imposed by triaxial states of stress should be fully recognized.

Weld issues

Welded sections are particularly important as sites for pre-existing or initiating defects: there is an increased likelihood of generating processing and fabrication flaws in the weldment compared to the parent metal. Complications arise in the stress analysis of welds due to inhomogeneous material properties resulting from uneven heating and cooling, discontinuities caused by weld mismatch and unflushed weld beads, remaining residual cool down stresses when no stress relief operation is performed and strength variations that may exist between welds and the adjacent parent metal (soft or hard welds).

5.2 Fracture Mechanics Aspects

Fracture mechanics concepts underpin proof test analysis methodologies: the calculation of a crack driving force for actual or postulated defects and the comparison of this driving force with an appropriate representation of the material resistance to crack growth. The general role played by fracture mechanics in a proof test analysis has already been described in Section 3.1. Here discussion will center on the definition and computation of appropriate crack driving forces for sub-critical growth and fracture, and their relationship to material resistance to propagation. Consideration is given to both linear elastic (LEFM) and elastic-plastic (EPFM) fracture mechanics.

5.2.1 Linear Elastic Fracture Mechanics

As noted in Section 3.1, proof test analyses should be based on EPFM rather than LEFM. Nevertheless, a LEFM characterization of the problem is the first step in performing the full elastic-plastic analysis, and some aspects of the full elastic-plastic analysis will occasionally reduce to a LEFM computation.

The most widely used and validated LEFM parameter is the stress intensity factor, K_I. For a broad range of configurations, the applied K_I can be expressed as a function of applied (nominal) stress, crack size, and component geometry according to

$$K_I = F\sigma\sqrt{\pi a} \tag{1}$$

Here σ characterizes the applied stress, a is a characteristic crack dimension, and F is a nondimensional term typically of order 1 which describes the functional dependence of K_I on geometrical attributes (such as the crack shape, size, and orientation) in comparison to the nominal dimensions of the component.

Methods of determining K_I are now well established. As can be seen from Equation (1), this is largely a matter of obtaining an expression or value for the parameter F. These days, F solutions are available for many common cracked geometries in analytical or tabular form in handbooks [71-74]. Algebraic expressions for F for some of the most commonly occurring defects in aerospace structures subjected to simple loads (e.g., pure tension, pure bending) have been derived and many of these are conveniently summarized in the FLAGRO manual [75]. Several computer codes are available to perform these K_I calculations directly, including the two NASA codes FLAGRO [75] and NASCRAC [76], and these codes typically accommodate complex applied stress distributions. In the event that a LEFM problem of interest is not addressed by an existing handbook or computer code, several techniques are available to compute K_I using numerical procedures, including the finite element and boundary element methods. These LEFM technologies are all quite mature and readily available for the use in engineering applications.

5.2.2 Elastic-Plastic Fracture Mechanics

Several different parameters have been proposed and used for EPFM analyses, including crack-tip opening displacement (CTOD) and crack-tip opening angle (CTOA), but the most widely accepted and extensively developed and applied parameter is the J-integral. Therefore, the J-integral is the natural choice as the primary characterizing parameter for the proof test methodology. J describes the intensity of the elastic-plastic crack-tip stress-strain fields under many conditions, and when nonlinear deformation near the crack tip occurs on a sufficiently small scale, J is directly related to the LEFM parameter K_I according to

$$J = \frac{K_I^2}{E'} \qquad (2)$$

where $E'=E$ in plane stress, and $E'=E/(1-v^2)$ in plane strain, E is Young's modulus and v is Poisson's ratio.

A convenient approach to estimating an elastic-plastic J value is to represent it as the sum of independently derived elastic, J_e, and plastic, J_p, components:

$$J = J_e + J_p \qquad (3)$$

The elastic J is computed from K_I as described earlier, but it is usual to evaluate it with respect to an effective crack depth, a'. This modification generally, but not always, increases the computed value of K_I slightly, and is introduced to allow for crack-tip plasticity under small-scale yielding (SSY) conditions. The effective crack depth a' is usually larger than a by roughly half of a computed crack tip plastic zone size. This correction is usually significant only for a narrow range of J values falling between the early onset of plasticity and the development of EPFM conditions.

J_p is more difficult to evaluate than J_e, but several engineering approaches are available. EPRI has published several handbooks [77,78] which tabulate finite element J_p solutions for various cracked geometries based on a power-law constitutive relationship, but the total number of geometries thus addressed is much smaller than for LEFM K_I values. Ainsworth

[79] has developed the so-called reference stress methodology which may be used to calculate J from the LEFM stress intensity factor, an estimate of the plastic limit load for the cracked body, and an expression for the material constitutive relationship. This approach lies at the heart of the R6 structural reliability methodology developed by the former Central Electricity Generating Board (CEGB) in the UK and now widely used throughout the UK and other countries.

The SwRI/Rocketdyne team is currently investigating the use of the reference stress approach to compute J for cracked geometries of particular relevance to aerospace propulsion systems under another NASA-Marshall contract on elastic-plastic fatigue crack growth, and this technology is expected to mature significantly during the next few years. This work is expected to generate a compilation of tabular and analytical (reference stress) J solutions, along with insights on how the reference stress method can be used to extend this data base.

However, there are still likely to be outstanding problems in obtaining relatively accurate, but simple, expressions for J which can be used to assess complicated three-dimensional defective structures subjected to complex loading conditions and geometrical restraints. This is particularly true if the loading includes secondary stresses, and there are additional uncertainties associated with crack shapes and plastic constraint (i.e., whether the deformation is plane stress or plane strain, or a mixture of the two).

The accurate computation of the applied J is more complicated when the crack is located in or near the interface between dissimilar materials, such as weldments, which may have different stress-strain relationships (e.g., different strengths). Recent studies [119] have suggested that under some conditions, simple bounding techniques can provide sufficient accuracy, although these methods do not work under all conditions. The application of estimation schemes such as the reference stress method to this class of problems has not yet been explored in depth.

5.2.3 Criteria for Fracture

Brittle materials

EPFM should be applied when assessing the structural integrity of cracked brittle (as well as ductile) materials, unless it can be demonstrated that failure will occur under linear elastic conditions. This is because materials that fail by brittle mechanisms can still possess a high toughness. Furthermore, materials with low toughness can still fail with significant crack tip plasticity if the defect is present in a thin section where the absolute crack depth is small.

The failure criterion for brittle materials is:

$$J \geq J_{Ic} \tag{4}$$

where $J_{Ic} = K_{Ic}^2 / E'$.

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Ductile materials

The fracture toughness of ductile materials increases as ductile tearing increases so that further load must be applied to cause failure after crack extension has initiated. The simple failure criterion of Equation (4) needs to be modified to take this into account and the piont of ductile instability is predicted when 2 criteria are simultaneously satisfied. These are:

$$J = J_R(\Delta a) \tag{5}$$

and

$$dJ/da = d(J_R)/d(\Delta a) \tag{6}$$

where a is the crack depth, Δa the amount of ductile tearing, and $J_R(\Delta a)$ the toughness, measured in terms of J, corresponding to the tear length Δa. A graphical representation of the instability criteria represented by Equations (5) and (6) is shown in Figure 5.

5.2.4 Plastic Collapse

Plastic limit analysis plays an important role in the reference stress approach to calculating J. The plastic collapse load also determines fracture behavior of very ductile materials: theoretically it is the parameter that governs failure for materials which have infinite ductility and toughness. Therefore, under conditions of widespread plasticity, predicted failure results based on J or the plastic collapse load will be very similar, as shown in Figure 6. Cracked ductile materials will typically initiate tearing at loads near to the general yield load, continue to tear as the applied load is increased, and become unstable at or near the plastic collapse load (see Figure 6). In very thin sections containing part-penetrating defects (which is the situation for some aerospace propulsion components), initiation of tearing will be coincident with plastic collapse because the absolute depth of the defect will be too small to produce a significant crack driving force.

In materials that do not possess any strain hardening capability, plastic collapse occurs when the stress in the cracked section is everywhere at yield and a mechanism (for example, a plastic hinge) exists to accommodate the displacements required for collapse. Under these conditions, and in its simplest form, the cracked section behaves like a tensile specimen undergoing yielding, although this analogy cannot be taken too far. For example, in complex structural geometries, such as a nozzle attached to a pressure vessel, the mechanism of collapse may require the formation of plastic hinges at several locations in order for unlimited deformation to occur. A flow stress rather than the yield stress is used to calculate the plastic collapse loads of materials which strain harden. In general, the flow stress is evaluated as the average of the yield stress and the ultimate strength of the material.

Expressions for plastic collapse loads for structures subjected to tensile forces, bending moments and internal pressure, may be obtained from the compendium of solutions published by Miller [80]. Unfortunately, the range of solutions is not so great as for the equivalent compendia which detail K_I solutions. This is because of difficulties in deriving accurate and meaningful plastic limit solutions for complex structural geometries and loadings. It is usually possible to estimate a lower bound value for the plastic collapse load,
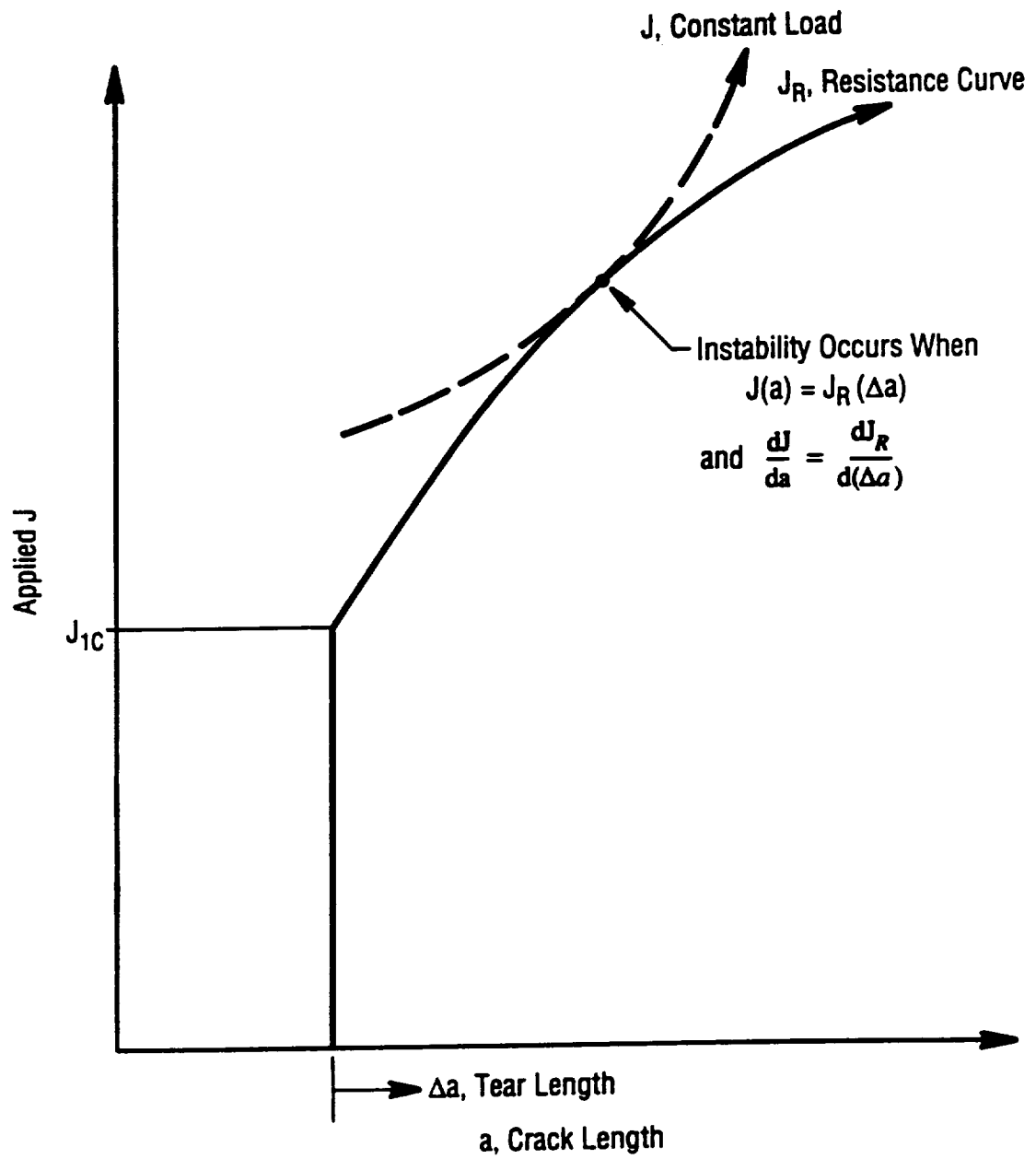
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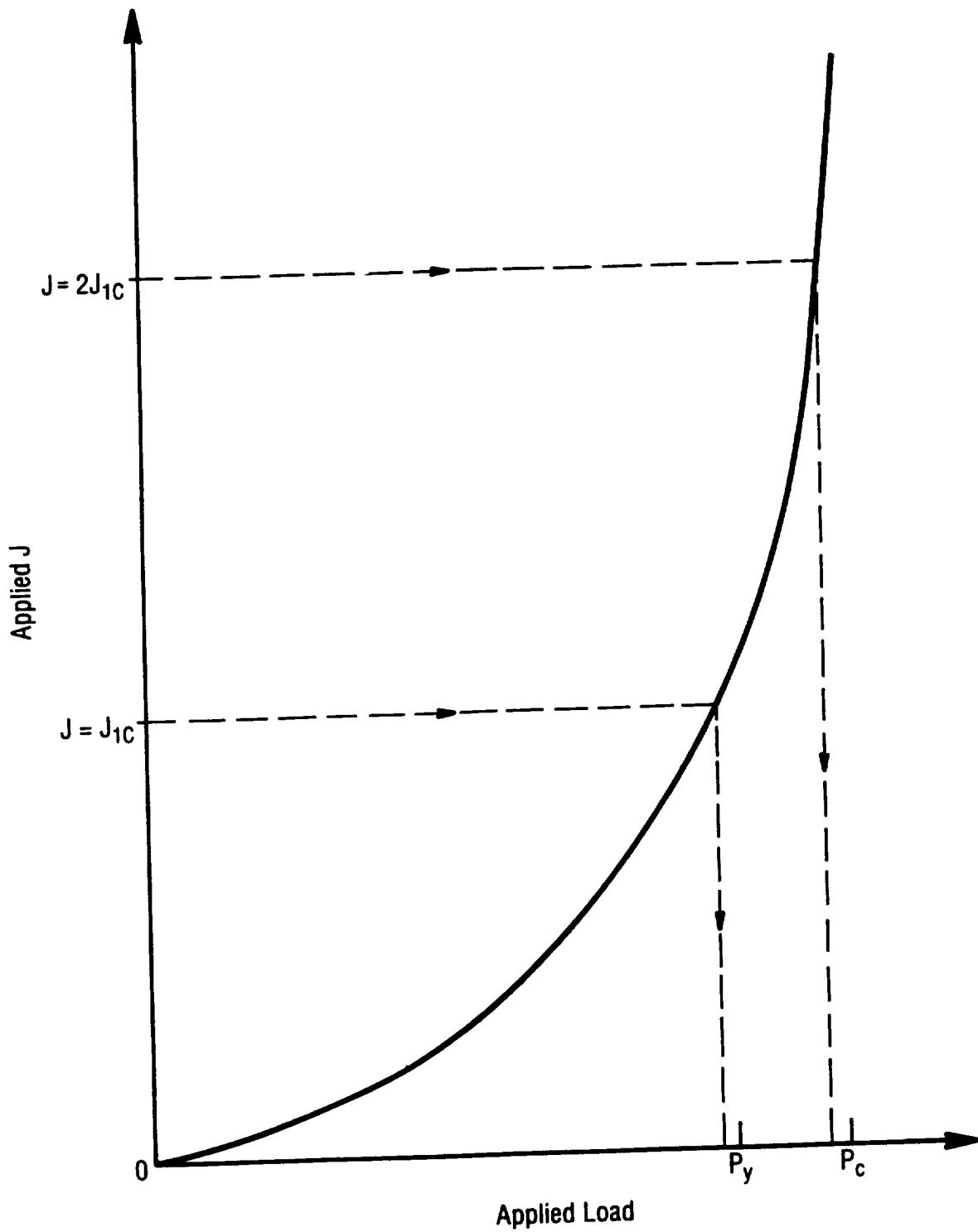Figure 5. Schematic showing instability criterion for ductile materials.

Figure 6. Tough ductile materials typically initiate tearing near the general yield load (P_y) and become unstable near to the plastic collapse load (P_c).

but not always possible to determine how pessimistic the resulting solution is. Presently, the most accurate method of establishing plastic collapse loads is to perform fracture tests on scaled-down models of the structure.

5.2.5 Treatment of Secondary Stresses

Although it is unlikely that proof testing procedures will involve thermal transient stresses, secondary stresses due to welding residual stresses may be present. A fracture mechanics treatment for thermal stressing will almost certainly be required as part of an assessment under service conditions.

J-integral formulations have been developed for two-dimensional geometries subjected to combined primary and secondary loads [81,82], and also for axisymmetric and other three-dimensional structures [83]. However, the situation with regard to existing J solutions for secondary (i.e., thermal, residual, displacement imposed) loads is far less advanced than for the primary loading cases, due, to a large extent, to the variety of such loads, which makes a general characterization of them difficult, if not impossible.

These complexities obviate the possibility of developing a compendium of J solutions for secondary loads as has been done for primary loads in the elastic-plastic handbooks sponsored by EPRI [77,78]. There is thus a need to develop and validate alternative approaches which make use of existing elastic-plastic J based methodologies, but which have the flexibility to cope with the wide variety of secondary loads encountered in practical situations. In the case of displacement loading there may be a strong interaction between the effective loading on the crack and the size of the defect due to changes in structural stiffness arising from the presence of the defect [84]. These effects should properly be taken into account in determining J.

In LEFM, the stress intensity factors due to secondary and primary loads may be calculated independently and linearly added to give the total value [85]. Thus primary and secondary loads that give rise to the same value of stress intensity factor will contribute equally to the possibility of fracture. This is not the case in the fully plastic regime where the cracked section has undergone general yielding. In this regime, the effects of secondary loads on fracture are greatly reduced as they cannot influence the conditions at plastic collapse, which are determined solely by primary loads.

There are a number of methods which have been proposed for evaluating J for combined primary and secondary loads which avoid having to resort to elastic-plastic finite element computations [86-89]. Under EPRI sponsorship, Kumar, German, Wilkening, Andrews, deLorenzi and Mowbray [86] have suggested a method for extending the EPRI J estimation scheme to thermal stresses. The method was developed taking account of the different effects that secondary loads have on fracture behavior in the elastic and plastic regimes. It was proposed that these effects could be adequately simulated by including secondary loads together with primary loads in the elastic contribution to J.

Other approximate J estimation schemes for primary and secondary loads have been developed as part of the R6 defect assessment procedures [87,88] or are related to them [89]. Although these methods are more complicated to use than the EPRI estimation scheme, under some circumstances they have advantages over it. For example, because they are related to the reference stress approach of Ainsworth [79], they can be applied to a wider

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range of structures and loadings than is contained in the EPRI elastic-plastic handbooks. The methodologies of Chell [89] and Budden [88] also allow the effects of plastic relaxation and redistribution of stress to be taken into account should the local peak value of stress exceed yield magnitude.

In the event that a J solution is not already available or easily derivable for some specific cracked component of interest, J can be computed directly from elastic-plastic finite element analysis. While the technology to perform this computation is relatively well-established, the cost and time required to perform the analysis can be substantial, and so this is not currently a viable option for many practical engineering situations.

5.2.6 Characterization of Proof Loading

One of the problems which may limit the effectiveness of the proof test is the difference between the proof load and actual service loads. As discussed in Section 4.2.1, fracture mechanics provides one possible way of resolving this problem, as illustrated in by early work of Tiffany [2] who utilized LEFM concepts. A similar approach to this but based on EPFM offers a way of reconciling the effects of the diverse forms of loading which can occur between proof testing and service. For example, the effects of severe thermal stressing on the value of the crack driving force, J, is limited because these stresses are self-equilibrated. This offers the possibility of producing a similar J level during the proof test through the application of a lower local stress generated by internal pressure. The lower pressure stresses could in theory produce greater crack tip plasticity and a similar applied J value to that induced by thermal loading, because pressure stresses contribute to the plastic collapse load, and the thermal stresses do not (for example, [89]).

Although the foregoing approach offers a solution for some situations, at this time it is not clear how, in general, to best define a proof load factor in terms of crack driving forces. Indeed, it would be difficult to characterize a complicated component by a single proof factor based on J when different parts may experience different local stress levels and be made of different materials.

5.2.7 Limitations on J Theory

Besides the problems of obtaining simple, but relatively accurate, expressions for J which are applicable to complex hardware and service conditions, the application of J to structural assessments is also limited by two other factors. These are its limitations as a crack tip field characterizing parameter; and the lack of an accepted approach to treating time dependent crack tip deformation.

Characterization of crack-tip stress fields

The J-integral is known to have some theoretical limitations as a one-parameter characterization of elastic-plastic fracture, although the practical implications of these limitations for engineering problems are not always fully understood. The most fundamental shortcoming is that J does not fully characterize the near-tip stress fields in conditions where plastic constraint at the crack tip is reduced with respect to the constraint under small scale yielding (e.g., above general yield and in some structural geometries). This effect can manifest itself as an apparent dependence of toughness or tear resistance on the size or configuration of the specimen. One of the best-known examples of this effect is that the

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resistance curve for a compact tension (CT) geometry is often significantly lower than for a center-cracked or surface-cracked geometry [33]. Since archival J-resistance data are usually based on CT experiments and actual flaws in propulsion system hardware are usually tension-loaded surface cracks, this disagreement could lead to potentially serious errors in interpreting proof test results if not recognized and addressed.

Extensive research is ongoing in the international fracture mechanics community to address the problem of plastic constraint and the characterization of crack tip fields. Currently most attention is focused on a two-parameter approach to elastic-plastic fracture in which the crack-tip stress fields are described by J and Q. Q is a hydrostatic stress parameter which describes the variation in the near-tip stress fields from the small scale yielding solution [91]. In reference [91] it is shown that a J-Q approach does satisfactorily describe the crack-tip fields for a variety of specimen geometries (mostly 2-D, although some investigators have begun to explore J-Q approaches to semi-elliptical surface cracks [92]) and have used the analytical framework to rationalize experimental results for cleavage fracture. The applicability of the J-Q approach to ductile tearing has been postulated but not yet demonstrated.

Other current limitations on the general usage of J-Q are the lack of a complete description of three-dimensional plasticity effects (including plane stress versus plane strain deformation) and an absence of engineering methods to estimate Q for practical component geometries. In short, two-parameter approaches to elastic-plastic fracture show considerable promise but are still immature research concepts, not practical engineering tools.

Time-dependent effects

As mentioned in Section 4.2.2, time-dependent crack growth can become significant when hold times are employed. It is known that cracked materials can fail when subjected to a constant sustained load, the time taken to failure depending on the level of crack tip plastic deformation and whether ductile tearing resulted from the initial loading [97]. The time to failure is shorter the greater the plasticity, and becomes particularly significant after general yielding has occurred. Since tearing of ductile materials is postulated as part of the proof test analysis when calculating a_o, then the potential for time dependent deformation increases in this case.

Time dependent fracture behavior is attributed to creep relaxation, even though the temperature is below that at which creep deformation is usually significant. It is currently not clear whether this behavior can be attributed to an increase in J with time due to a reduction in the effective yield stress of the material, or to a reduction in toughness due to time dependent changes in the mechanism of fracture. Recent work by Brust and Leis [58,59] supports the proposition that changes in the mechanics, rather than the mechanism, dominate time dependent fracture behavior. Unfortunately, fracture mechanics technology for time-dependent growth at ambient temperatures and in non-aggressive environments is rather immature and no validated methods are currently available.

5.2.8 Cyclic Loading

Except for the initial load application, most cyclic loading tends to occur under linear elastic conditions. This is because the cyclic yield stress of materials is approximately equal to twice the yield stress under monotonic loading. However, short cracks in plastic enclaves produced

by severe thermal loading or geometric discontinuities, and deep cracks subject to high nominal primary loads, can undergo cyclic yielding and should be treated using EPFM concepts.

Linear elastic cycling

During service, or while proof testing (if multiple proof cycles are applied), crack extension by cyclic growth mechanisms may be significant. Cyclic crack growth in the LEFM regime is characterized by the stress intensity factor range, ΔK, which is calculated from the expressions

$$\Delta K = K_{max} - K_{min} \tag{7}$$

where K_{max} is determined using the maximum stress in the cycle, σ_{max} and K_{min} using the minimum stress, σ_{min}. Under proof test conditions the cyclic loading is usually characterized by changes in a single load parameter (e.g., internal pressure). In these cases, Equation (7) simplifies to Equation (1) with σ replaced by $\Delta\sigma = \sigma_{max} - \sigma_{min}$.

Calculations of cyclic crack growth are typically performed using a fatigue crack growth (FCG) law which relates the driving force ΔK to an empirical description of the material resistance. The most common description of cyclic resistance is a simple power law form,

$$\frac{da}{dN} = C(\Delta K)^m \tag{8}$$

where C and m are derived from least-squares regression of experimental FCG data.

Elastic-plastic cycling

The driving force for cyclic crack growth under elastic-plastic conditions is satisfactorily described by ΔJ, the cyclic change in the J-integral. The EPFM equivalence to Equation (8) is obtained by using the same material constants and replacing ΔK by $(E'\Delta J)^{1/2}$. This is an important point, because it enables the extensive FCG data obtained from ΔK characterized tests to be used to evaluate crack growth under conditions of cyclic plasticity. Engineering expressions for ΔJ based on the EPRI handbook and reference stress approaches to J are available [77-79]. More solutions are being generated at SwRI as part of a NASA contract on elastic-plastic fatigue crack growth. When the total stress range $\Delta\sigma$ is small compared to twice the yield stress, the plastic component of ΔJ will be negligible, and the cyclic driving force sensibly reduces to Equation (2) with K_I replaced by ΔK.

The crack driving force may be significantly changed if crack closure occurs during cyclic loading [120]. Although crack closure is clearly promoted when part of the cycle is in compression, it can also occur during the tensile part. Changes in closure are more likely to occur when significant plastic deformation occurs at maximum load in a cycle since crack opening stresses can be considerably lower at large maximum stresses or in the presence of net section yielding [121]. In these cases, the crack driving force is related to the part of the cycle where the crack remains open and is characterized by an effective driving force

expressed in terms of ΔK_{eff} or ΔJ_{eff}. The evaluation of ΔJ with closure is more difficult then when it is not present. Closure phenomena can lead to nonconservative predictions of crack growth if not properly accounted for.

5.2.9 Subcritical Crack Growth Under Steady Loading

Under steady loading conditions crack extension can occur by other mechanisms, such as stress corrosion cracking (SCC) and creep crack growth, (CCG) depending on the environment and temperature. In these cases the crack resistance is usually expressed in a form similar to Equation (8) with da/dN replaced by the crack velocity, da/dt, and ΔK by K_{max} for SCC, and by the creep parameter C_t for CCG, with a corresponding change in the value of the material constants C and m.

5.2.10 Crack Growth due to Static and Cyclic Loading

Multiple cycle proof testing and cyclic loading under service conditions may induce crack growth by static and cyclic mechanisms. The static mechanisms may consist of local cleavage of grains in brittle materials, and coalescence of adjacent voids in ductile materials. This combination of static and fatigue crack growth mechanisms is especially likely as failure is approached.

Brittle materials

The cyclic crack growth rate will be enhanced for materials failing by a brittle mechanism as the conditions at the maximum load in the cycle approach those required to cause fracture. Several different forms for the material resistance have been proposed to account for this situation, but only two will be mentioned here.

Forman, Kearney and Engle [93] have proposed the following growth law for LEFM situations:

$$da/dN = (da/dN)_f \; / \; [(1-R)K_{Ic} - \Delta K] \tag{9}$$

and Chell [63] has derived an elastic-plastic version of a form originally proposed by Heald, Lindley and Richards [94]. This is:

$$da/dN = (da/dN)_f \; / \; [1 - J_{max}/J_{Ic}]^{m'} \tag{10}$$

where $(da/dN)_f$ is the normal fatigue law (see Equation (8)), m' is a material constant and J_{max} the value of the applied J at the maximum load in the cycle. Both of these laws predicted infinite growth rates (instability) when the brittle failure criterion defined in Equation (4) is attained.

The form of the material resistance governing combined static ductile and fatigue mechanisms (so-called tear-fatigue) is not currently known if part of the load cycle is compressive. However, for cycles typical of proof testing, where only tensile loads are applied, the following law appears to describe the enhancement in the crack propagation rate due to tear-fatigue [63,95,96]

$$da/dN = (da/dN)_f \; / \; \{1 - (dJ_{max}/da)/[dJ_R(\Delta a)/d(\Delta a)]\} \tag{11}$$

where dJ_{max}/da is the gradient of the applied J, J_{max} at the maximum load in the cycle, $J_R(\Delta a)$ is the crack growth resistance at tear length Δa.

This equation is applicable when $J_{max} > J_{Ic}$. Note that Equation (11) predicts an infinite growth rate (ductile instability) when $dJ_{max}/da = dJ_R/d(\Delta a)$ as required (compare Equation (6)).

5.2.11 Mixed Mode Loading

The most onerous loading experienced by defects is usually that due to the component of stress which acts perpendicularly to the plane containing the crack. This form of loading, called Mode 1, is the most common. However, situations do arise where cracks can experience shearing (Mode 2) and/or torsional (Mode 3) forces. The number of K solutions for these forms of loadings are very limited, and the available elastic-plastic J solutions are even rarer. Furthermore, the failure criteria which govern these loading modes are only poorly understood and quantified in terms of toughness values. This is particularly the case where loading involves combinations of Mode 1, Mode 2, and Mode 3. Given these difficulties, it is not possible at the present time to include the effects of mixed mode loading in a proof test analysis.

5.3 Flaw Characterization

Most existing J solutions, like the K_I solutions, are based on standardized, mathematically regular crack shapes (e.g., planar through cracks with straight crack fronts, planar elliptical embedded and semi-elliptical surface defects, and quarter-elliptical corner cracks). Actual crack shapes may deviate significantly from these idealized representations. The use of available J or K_I solutions will generally require recharacterization of the actual size and shape of the defect into some equivalent idealized form. This process is an art rather than a science, and depends more on engineering judgement than on validated fracture mechanics analysis.

The process of modelling defects by geometrically simpler ones which are easier to analyze is called flaw characterization. The distributions of size and shape of pre-existing and service induced flaws, as well as the characteristics or peculiarities of naturally occurring defects, are important issues in assessing component reliability: the initial crack size and shape are two of the most important variables in any fracture mechanics assessment. Flaw characterization should be performed so as to produce a conservative assessment result. In a deterministic proof test analysis this can lead to contradictions in the assumptions made with respect to assessing critical defect sizes in the component under proof and service conditions (see Section 3.2).

Guidelines for flaw characterization are contained in ASME Boiler and Pressure Vessel Code, Section XI. Unfortunately, for the reason stated above, these may not be suitable for direct application to a proof test analysis. Furthermore, the guidelines were developed using engineering judgement based on linear elastic fracture mechanics. Their application to defects which are predicted to fail in the elastic-plastic regime should be treated with extreme caution.

Some defect characteristic issues of direct concern to proof testing are irregular shapes, blunted as opposed to sharp defects, interactions between multiple defects in close proximity, and the orientation of the defect with respect to a free surface or the maximum principal stress.

5.3.1 *Irregular Shapes*

Naturally occurring defects are normally irregular in shape, and pose difficult engineering problems because they do not always conform to conventional defect types addressed by fracture mechanics handbooks. Paris and Sih [122] provided guidelines on how to estimate K_I around the crack front of an irregular defect. These can be used to approximately calculate the local rates of crack advance or the possibility for local instability. However, the task of estimating the nominal rate of crack advance or instability for the crack as a whole is expected to be more desirable for practical purposes. There are presently no J solutions or guidelines available for irregularly shaped defects.

5.3.2 *Blunted Tip Radius*

Naturally occurring defects are frequently blunt: they have a finite notch root radius. Rice [98] has given an estimate of the maximum tangential strain directly ahead of the notch. Assuming the onset of rapid crack extension is controlled by a particular value of maximum strain, an apparent toughness can be derived which is predicted to increase in proportion to the square root of root radius. Experimental data by Mulherin [99] illustrating the influence of a finite root radius shows excellent agreement with prediction down to a critical minimum root radius. An engineering approach to assessing failure by brittle mechanisms from blunt notches has been proposed by Milne, Chell and Worthington [100]. This approach showed good agreement with experimentally measured apparent toughness values for steels over a range of notch sizes. Similar approaches applied to fatigue crack growth initiation from the root of a sharp notch have shown that the number of cycles to initiation are approximately proportional to the stress range and the square root of the root radius [101].

Given the potential for a substantial increase in apparent toughness above the toughness measured for a sharp defect, assurance needs to be made that crack initiation does not occur in a component during operation after it has survived the proof test. In these situations, a substantial drop in apparent toughness could occur after the crack tip has been sharpened by fatigue, or some other mechanism, and a potentially catastrophic failure might result.

5.3.3 *Interacting Multiple Cracks*

Interacting multiple cracks can seriously impact residual life or stress at failure. If the defects are sufficiently close, a magnification of the crack driving force can occur due to the interaction of the adjacent defect. In linear elastic fracture mechanics, the interaction is small, and produces a less than 10% increase in K_I values, if the land separating the defects exceeds the maximum dimension of the larger defect [73,102]. However, if the defects are

close, a significant reduction in load carrying capability or remaining life is to be anticipated. It is not clear at the current time how these predictions would change if elastic-plastic, rather than linear elastic, conditions prevailed.

5.3.4 Defect Orientation

Cracks may be inclined to free surfaces or be in a plane which is not normal to the applied maximum principal stress. In such situations, it is usual to recharacterize the defect for assessment purposes in order to avoid problems associated with shear loading, and to overcome the possible unavailability of an appropriate fracture mechanics solution. There are a number of ways that the recharacterization can be done. A common method used in LEFM is to project the defect onto planes which are perpendicular to the three applied principal stresses and to assess the most onerous of these situations. Whichever approach is adopted it should be demonstrably conservative with respect to a proof test analysis.

5.4 Material Property Aspects

Material property data are needed to perform the fracture mechanics calculations required in the proof test methodology. Some aspects concerning the choice of upper and lower bound materials data in a deterministic approach to a proof test philosophy have been discussed in Section 3.2. Aspects related to a probabilistic approach have been addressed in Section 3.3. The type of materials data required to support fracture mechanics analyses have been indicated in Section 5.2.

Ideally the material property data should be measured on materials which are in the same condition as the proof tested component during its proof test and during service. If proof testing is being used to re-certify a component for further service, then account should be taken of the effects of service exposure on material behavior. Another important consideration is to assess the effects of the proof test loading on consequent material fracture behavior. A fundamental part of the proof test methodology involves demonstrating that components surviving the proof loading will have their integrity enhanced rather than impaired by the proof test. The effects of proof loading on subsequent material response, and the implications regarding the methodology, are discussed in Section 6.4.

The material properties that are important in assessing the possibility for fracture are tensile data, fracture toughness and crack growth constants.

5.4.1 Tensile Data

Yield stress, ultimate strength and the constitutive equations relating stress to strain are required for elastic-plastic computations of the stress field and fracture mechanics parameters, and in the use of alternative J methods, such as the reference stress approach [79]. Although actual stress-strain data can be used in evaluating J via the reference stress approach, the data has to be represented by a power law before the EPRI J estimation scheme can be employed. Yield properties are also necessary for evaluating the plastic collapse load of the structure.

5.4.2 Fracture Toughness

Plastic constraint is a key parameter in determining the fracture toughness value which is appropriate for the structure, which in turn governs the calculated critical flaw size. Factors

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local to the crack which may significantly influence fracture toughness are: geometry (e.g., thickness); material variability, particularly at the microstructural level (local embrittled zones); state of stress (plane stress versus plane strain); local loading (tensile or bending); and degree of crack tip plasticity (small scale or large scale yielding).

Special consideration will need to be given to cracks which are located at welds. In these cases, the variation of microstructure and material properties between the weld, heat affected zone (HAZ) and base metal can produce difficulties regarding the measurement and selection of the most appropriate fracture toughness to use. A pessimistic deterministic proof test analysis can always be performed by using a combination of the highest values of fracture toughness and yield stress obtained from the weld and base metal properties when calculating a_o, and the lowest combination when determining a_s, but this approach may seriously erode proof test margins.

Consideration should also be given to the possible detrimental influence of environment, should the proof loading occur in an aggressive atmosphere, such as hydrogen. The environment may significantly reduce load carrying capacity especially where the proof load is held steady for any length of time, allowing sub-critical crack extension to occur.

It is generally accepted that the fracture toughness value used in normal defect assessments should have been measured on a valid sized test specimen according to fracture toughness testing standards [103]. Alternatively, toughness values measured on specimens of the same section size as the component may be acceptable in some circumstances although even this approach cannot be readily applied to very thin sections. These requirements are intended to facilitate transference of toughness data measured on laboratory sized specimens to use in structural assessments. Provided the so-called J-validity requirements [103] are met in measuring toughness, then these values will produce a conservative assessment.

The J-validity requirements introduce a complication into the proof test methodology: a deterministic proof test analysis may require "upper bound" toughness values (see Section 3.2) and there are presently no guidelines regarding the measurement of these. This problem may be overcome by measuring toughness data on actual components, which would be very expensive, or on specimens that reproduce as near as is possible the situation in the component regarding typical dimensions and plastic constraint. This type of data is likely, however, to have the stigma of being classified as invalid. A procedure for obtaining data for use in proof test analyses, that recognizes the special problems associated with this, is required.

There are particular problems associated with ductile materials. Materials failing by ductile mechanisms will generally tear before they become unstable. A resistance curve expressed in terms of fracture toughness as a function of tear length is required to assess for this. This curve will contain information regarding the toughness value at the onset of tearing, and the gradient of the resistance curve, which is needed to assess instability (compare Equation (6)).

A proof test analysis of a ductile material requires the full toughness against tear length curve to be determined. This is a difficult exercise, not only due to the complications in measuring toughness on very large specimens to allow enough ductile tearing, but also with regard to the J-validity specimen size requirements: it is well known that at large levels of ductile crack extension, the toughness curve becomes dependent on the dimensions of the specimen used for the measurement [104,105].

The inverse of this situation is encountered when assessing very thin structures, where the section size may be of the order of a fraction of a millimeter. In these cases the so-called stretch zone, which characterizes the dimension of the crack tip opening displacement in ductile materials, may be comparable to the section thickness. It is unlikely that toughness data obtained from tests on standard sized laboratory specimens, which are usually tens of millimeters in size, will be relevant to these applications as the "initiation" value in these specimens is usually around 0.2 millimeter. Indeed, in very thin components ductile failure will occur by a plastic collapse mechanism which is insensitive to the material's toughness.

Analysis of multiple cycle proof loading of ductile materials requires postulated fatigue growth beyond the initiation of tearing (so-called tear-fatigue, where fatigue crack growth occurs concurrently with stable ductile tearing, see Section 5.2.10). There is evidence that no significant mechanistic interactions occur between fatigue crack growth and ductile tearing provided the R ratio (minimum load in the cycle divided by the maximum load) is equal to or greater than zero [95,96]. The interactions appear to be mechanical and result from physical crack extension.

Some measurements of J_{max}, the value of J at the maximum load point in the cycle, during tear-fatigue at negative R ratios on pipeline steels have been interpreted as indicating a reduction in the fracture toughness with respect to a monotonically measured resistance curve [106]. This effect is not properly understood at the moment, although it is known that crack closure occurs during fatigue crack propagation at negative R values. Rather than an actual reduction in the toughness resistance of the material due to tear-fatigue the possibility strongly exists that the problem is related to how J_{max} is measured in a tear-fatigue test where crack closure occurs. Tear-fatigue tests on the same material at R values greater than or equal to zero did not indicate any deleterious effects on the material's toughness.

Provided multiple cycle proof testing are carried out at zero or positive values of R, the current evidence suggests that no significant reduction in toughness will occur during the proof test because of cycling. This may not be the situation under service conditions, and appropriate allowance should be made in service-based assessments for cyclic loading at negative R if this occurs in the tear-fatigue regime. Note that negative R values are also possible during the proof test if localized yielding occurs at geometric discontinuities.

If the proof test load is sustained for any appreciable time, especially at temperatures where creep deformation is significant, then consideration should be given to the possibility of time dependent deformation and its influence on fracture toughness. Unfortunately, relatively little is known about time-dependent crack growth in common aerospace alloys at ambient temperatures. A few research programs addressed this topic in the late 1960s and early 1970s [124], but these efforts all predated the development of formal elastic-plastic fracture mechanics. Apparently only Ingham and Moreland [97] have attempted to characterize time-dependent EPFM effects in the formal framework of J-resistance curves. Further basic studies are currently planned under the MCPT contract which may elucidate the relevance of time dependent fracture to aerospace propulsion systems. This effect can be minimized by reducing the time that the proof test load is applied.

5.4.3 Crack Growth Propagation Rates

Crack propagation data are needed to assess the remaining service life and sub-critical crack growth during the proof test. This is the case if multiple cycling is used as part of the proof

testing procedure for ductile materials. Techniques for measuring and analyzing fatigue crack growth data are documented in ASTM Standards [103]. Data which is relevant to the temperature and environment of the component should be obtained.

Crack growth laws need to be suitably expressed in terms of fracture mechanics parameters, taking into account the environment during the proof test and service. The sub-critical growth mechanisms that could cause crack extension are fatigue, possibly environmentally enhanced, stress corrosion cracking and creep crack growth. Stress corrosion cracking would be of concern under steady loading conditions for any significant amount of time, and creep crack growth if the loading was sustained at temperatures where creep deformation was significant. It is clear that some test fluids and environments can greatly promote time dependent propagation under a steady load, and some aerospace materials, such as titanium alloys, are susceptible to environmentally assisted crack extension even under nominally ambient test conditions [123].

The importance of sub-critical crack extension involving multiple cycling will increase if cracks undergo ductile tearing during the proof test. Ductile tearing may be postulated to occur as part of the proof test analysis, or it could be real and occur at existing defects. In either case, the combination of ductile tearing and fatigue crack extension (tear-fatigue) is known to enhance the total crack extension per cycle [62,95,96].

6. EFFECTS OF PROOF TESTING ON SUBSEQUENT COMPONENT INTEGRITY

On occasion analysis will indicate that the proof test should not be carried out because it will be prove ineffective in guaranteeing reliability of the component in service. Some of the reasons why a proof test may be ineffective are discussed in Section 6.1.

If a proof test is performed, then the ramifications of proof loading on the subsequent assessment of component integrity need to be fully recognized. The proof loading can influence the residual stress distributions which were present in the component prior to the test; change flaw size distributions; and change subsequent material behavior. The technical issues associated these topics are summarized in Tables 10 through 12 respectively, and discussed in more detail in Sections 6.2 through 6.4.

6.1 Reasons Why a Proof Test Analysis May Fail to Provide Assurance of Safety

The concept of providing an assurance of safety is a deterministic one. In situations where a proof test does not provide assurance of subsequent safe operation, a probabilistic analysis may still be able to demonstrate an improvement in reliability due to proof loading. The successful application of MCPT by Rocketdyne to aerospace components is an example of an apparent increase in reliability in a situation where an assurance of safety was difficult to establish only through proof testing.

The margin of safety provided during service by proof testing a component is related to the ratio a_s/a_o, and this ratio increases as the size of the proof test load P_o is increased. However, there is a maximum value of proof load that can be applied above which the threat of failure during the proof test exceeds the anticipated benefits that may accrue from it. Similarly there is a minimum proof load P_{min} below which the safety of the component cannot be assured from a proof test analysis (see Figure 1). If the difference between P_o and P_{min} is unacceptably small, or negative, then the proof test cannot be used to establish the integrity of the component for service. In these cases alternative NDE methods should be investigated for detection capabilities, which may be considerably below that predicted from a proof test analysis. Fracture mechanics concepts can then be applied to establish that the undetected defects do not impair the safety of the component. However, if the NDE detection size is larger than a_o, there may be no alternative but to redesign the proof test to allow a larger proof test factor, and/or to introduce a schedule of very frequent re-proof tests.

There are a number of reasons why a proof test analysis may fail to provide sufficient assurance of safety during subsequent service. These are related to: pessimistic assumptions made in the analysis; the tolerance of the structure to cracking; degradation of material properties resulting from the proof loading; and anticipated severe service loads which cannot be simulated in the proof test.

6.1.1 Pessimistic Assumptions

A prudent deterministic approach to proof test analysis combines the results of two pessimistic fracture analyses, one related to maximizing a_o, the other to minimizing a_s. Although this is intended to guarantee subsequent component integrity, it often imposes a

Table 10. Technical Assessment for Issue 6.2: Redistribution of Stresses

Importance	The proof load may result in either compressive or tensile residual stresses. The latter may be a threat to the future integrity of the component.
Present Status	The use of the proof load as a means of mechanical stress relief is well known. There are a number of cases where welding residual stresses have been measured before and after an overload, and a reduction in the peak tensile stresses has been demonstrated as a result of the overload. In contrast, there has been at least one reported case of a notched bar that was loaded in compression and failed during the unloading due to the generation of tensile residual stresses at the notch root.
Availability of Implementing Technology	This is a stress analysis problem which can be addressed using the finite element computer codes ABAQUS or ANSYS, or alternative more simpler but less accurate methods.
Further Technological Requirements	To improve prediction and measurement of residual stresses.
Data Required to Implement the Technology	Knowledge of the residual stresses in the component prior to proof testing, and the loads applied during the test.

Table 11. Technical Assessment for Issue 6.3: Post-test Flaw Characterization

Importance	It is necessary to know the change in flaw size and shape distributions produced by proof testing in order to be able to accurately assess the integrity of the component during subsequent service.
Present Status	Flaw characterization rules, such as those contained in ASME Boiler and Pressure vessel Code, Section XI, do not explicitly address the possible re-characterization problem related to proof loading.
Availability of Implementing Technology	In principle, fracture mechanics concepts can be used to assess the changes in size and shape of defects as a result of proof loading.
Further Technological Requirements	Flaw characterization rules relevant to the post proof test situation are required.
Data Required to Implement the Technology	Knowledge of defect size distribution and the behavior of natural defects under elastic-plastic proof test conditions.

Table 12. Technical Assessment for Issue 6.4: Post-test Material Response

Importance	It is essential that any degradation in material fracture properties due to proof testing are recognized and quantified in order for a reliable assessment of subsequent service life to be made.
Present Status	Although it is widely recognized that materials data relevant to the condition of the material at the time should be used in an assessment of structural integrity, there are few, if any, guidelines regarding how this data is to be obtained. It is known that preloading a cracked component prior to service may have beneficial as well as detrimental effects on subsequent fracture behavior. (For example, beneficial effects occur on warm prestressing ferritic steels, and fatigue crack growth retardation can result from an overload. In contrast, preloading a cracked ductile component so that the defect tears and undergoes extensive plastic deformation will induce observable damage, in the form of the enlargement and possible coalescence of voids, in the material ahead of the crack tip.)
Availability of Implementing Technology	The technology to characterize load history effects on material fracture behavior is still in its infancy.
Further Technological Requirements	The development of measuring procedures and technologies that enable the effects of load history on material fracture behavior to be quantified are required.
Data Required to Implement the Technology	Test data showing the effects, if any, of previous load history on current fracture behavior.

high penalty in the reduction of proof test margins, if not their total erosion. A probabilistic analysis could profitably be used to reduce the level of pessimism contained in this approach, or, if it could be justified, the use of consistent assessment data should be considered.

To employ fracture mechanics it is necessary to idealize naturally occurring defects as sharp planar cracks with shapes that are compatible with existing fracture mechanics solutions. On occasion, it may be necessary to re-characterize clusters of natural defects by a single crack whose size bounds the cluster. These approximations introduce potential inconsistencies, as well as pessimisms, into the analysis. For example, it may be necessary to treat natural defects as non-planar defects when calculating a_o, but to assume they are planar when evaluating a_s.

6.1.2 Defect Tolerance

Structures made from very tough, ductile materials, are usually extremely tolerant of cracking, and will fail at, or very near to, the plastic collapse load. Similarly, thin section components are tolerant to deep part-penetrating defects because the absolute size of the crack is limited and the crack driving force insufficient to cause instability before the onset of plastic collapse. In both these cases, the ratio of defect depth to section size at failure will generally be large, and the difference between a_o and a_s will be small. These factors can contribute to a major erosion of proof test margins derived using a deterministic approach. This conclusion is consistent with the accepted view that structures which are intolerant to cracking provide the best candidates for proof testing.

6.1.3 Material Property Degradation

There are two possible ways that material properties may deteriorate: due to the proof testing conditions, and due to the effects of service exposure. The latter is clearly relevant to components which need to be re-certified in order to re-enter service. The former represents damage which is unavoidably introduced as a consequence of the proof testing procedure. The possible types of material degradation are discussed in more detail in Section 6.4. It should be noted that the effects on material response resulting from the proof loading may not all be detrimental. For example, it is known that under some circumstances the proof loading may retard fatigue crack propagation rates during service.

6.1.4 Unreproducible Service Loads

It is normally only practicable to apply relatively simple types of loads during the proof testing, such as internal pressure or tensile loads. More complicated loads, especially those that do not have a mechanical source, such as thermal stresses, are either too difficult or too expensive to apply, or both. Thus there may be parts of a component that can experience local stressing during service operation that is more onerous than that which can be applied at the proof test stage. In these cases alternative screening methods, such as NDE, should be employed to determine the defect sizes required for an integrity assessment. In a sense these cases do not constitute a failure of the proof test methodology, they are more an indication of the practical limitations of applying proof testing concepts to all components.

6.2 Redistribution of Stresses

There is a potential during the proof loading for redistribution of stresses to occur in those regions of the component where the local stress is at or near yield point magnitude. These

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regions are normally associated with geometric discontinuities, such as sharp corners and holes, and residual welding stresses. If the component is being re-certified after being subjected to service loadings, then there is the possibility that further residual stresses are present, the consequence of local plasticity generated by severe thermal loading during operation, or local geometric discontinuities.

The effect of the proof loading on the stresses in these local regions of high stress may be either beneficial or detrimental. Benefits may arise from shakedown when the stresses are tensile. This is illustrated in Figure 7(a), where yielding produces a non-linear relationship between the local stress and the applied load, so that the change in the local stress as the load is increased is far less than if the material behaved linear elastically. The benefits of shakedown arise because when the applied load is reduced the material unloads linear elastically so that the stress after unloading is less than it was before the proof load (Figure 7(a)).

The detrimental aspects arise from the inverse behavior to this, as shown in Figure 7(b). Here the proof loading results in a local compressive stress which reinforces an existing compressive stress to produce yielding. When the proof load is removed, a tensile stress remains which could now reinforce any tensile loading experienced by the region during service. One of the authors is aware of one instance where a notched bar loaded by a compressive force fractured during unloading due to the generation of tensile residual stresses at the root of the notch resulting from the compressive yielding that had occurred during loading.

It is pessimistic to ignore the benefits from shakedown resulting from local tensile stressing, but the detrimental effects of generating tensile residual stresses by proof testing in regions where there were previously compressive stresses needs to be addressed in developing a proof test methodology. Regions where this is likely to occur should be identified and appropriate stress analysis performed to establish whether the region is fracture sensitive.

The proof test will also affect the stress distribution in the crack tip plastic zone. After the proof loading the crack tip will be in compression, but a tensile stress zone will emanate from the tip during reloading under service conditions. Sub-critical crack growth at operation will also reduce the size of any remaining compressive zone. The effects of this complex load history are not easily quantifiable. In terms of assessment, the effects will manifest themselves in apparent changes in material deformation behavior, which is discussed in Section 6.4.

6.3 Flaw Characterization

The most fundamental effect of proof testing on the subsequent component reliability in service - in fact, the direct effect most often intended by the proof test - is increased knowledge regarding the distribution of flaw sizes in the component. Fracture mechanics assessments of remaining operational life should be based on some presumption about the size and shape of the crack-like defects already present in the component. A properly designed proof test will eliminate the possibility of large flaws being part of the defect population that enters service by failing hardware which contains these flaws. However, the change in defect distribution due to the possibility that some flaws have grown in size during the proof test should also be considered when evaluating the effects of proof on in-service reliability.
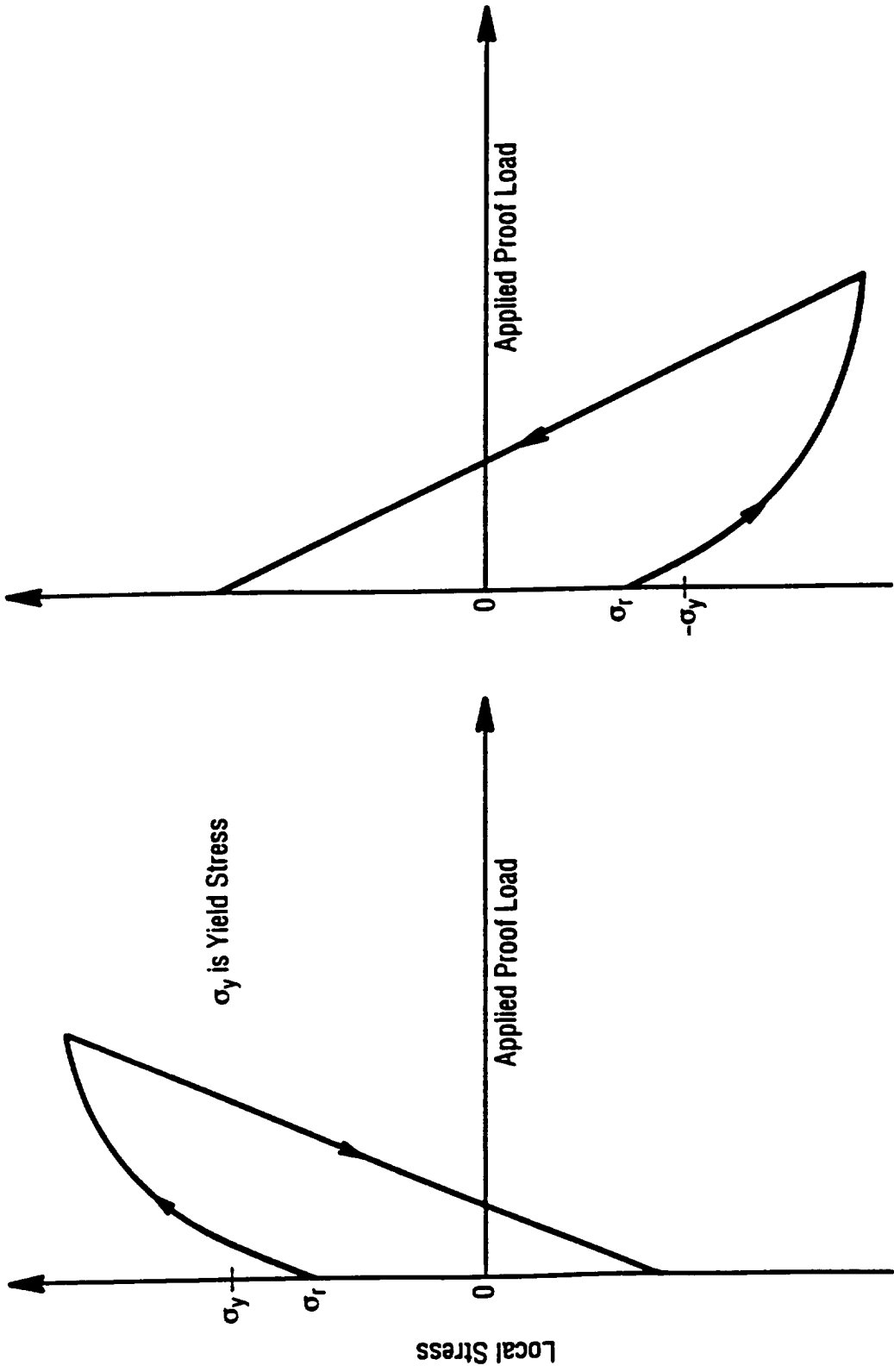
Figure 7.   (a) Beneficial effects of proof loading on local tensile stress σ_r.   (b) Detrimental effects occur when the proof load produces local compressive stresses that add to the existing compressive residual stress σ_r.

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For brittle materials, the largest calculated flaw that could just survive the proof test can be used in a deterministic analysis of the remaining service life. In a probabilistic analysis the flaw distribution can be truncated at the largest survivable defect size, and the distribution renormalized with respect to the remaining population.

However, determining the post-proof flaw size distribution for ductile materials is more complicated. The pre-proof distribution can be changed by the proof test in three ways, as shown in schematically in Figure 8. Some flaws are sufficiently small (Region 1) that ductile crack growth is not initiated, and so they do not change in size. More accurately, flaws in this region can be treated as having experienced a single cycle of fatigue crack growth, although in many cases the amount of crack growth so calculated will be negligible. At the other extreme (Region 3), some flaws are sufficiently large that they cause component failure during the proof test, and so they are removed from the population. In the intermediate case (Region 2), the flaws experience some stable growth but do not cause failure. Computation of the boundaries between these three regions and the extent of crack growth in region 2 requires application of the fracture mechanics technology described in Section 5.2. Depending on the nature of the proof test history, these computations may include elements of resistance curve, fatigue crack growth, and time-dependent crack growth analyses.

As noted above in Section 5.3 on flaw characterization, many naturally occurring flaws will be highly irregular in shape, rather than mathematically straight or semi-elliptical as frequently assumed in fracture mechanics analyses. Proof loading of these defects can cause a variety of other changes in flaw geometry besides self-similar growth. The flaw can extend or change shape locally by separation of small ligaments or "fingers" along the crack front, and closely adjacent defects can link up to form a single larger flaw. These effects are essentially impossible to quantify or to predict from a formal fracture mechanics standpoint. Instead, appropriately conservative assumptions should be made about the simplified initial and final shapes and sizes of the crack-like defects.

Proof loading can also cause the formation of sharp, crack-like flaws from previously blunt or non-planar defects, especially in weldments and perhaps near stress concentrations. This phenomenon may be more likely when proof loading is especially severe or when multiple cycles are applied. Multiple cycles can potentially cause localized low cycle fatigue deformation which can enhance flaw initiation or sharpening in locally susceptible regions. Again, characterizing or predicting these effects is not practical in an engineering methodology, but it should be recognized that they introduce a possible nonconservatism into the proof test logic.

Another potential change in defect geometry due to proof loading is crack tip blunting, which can cause retardation of subsequent crack growth in service. This phenomenon is discussed further in Section 6.4.

6.4 Material Response After Proof Loading

The application of a proof test load which exceeds the normal service loading can have important implications on the fracture behavior of the material during subsequent operation. The material properties of most significance that are liable to change as a result of proof loading are tensile data, fracture toughness, and crack propagation rates.
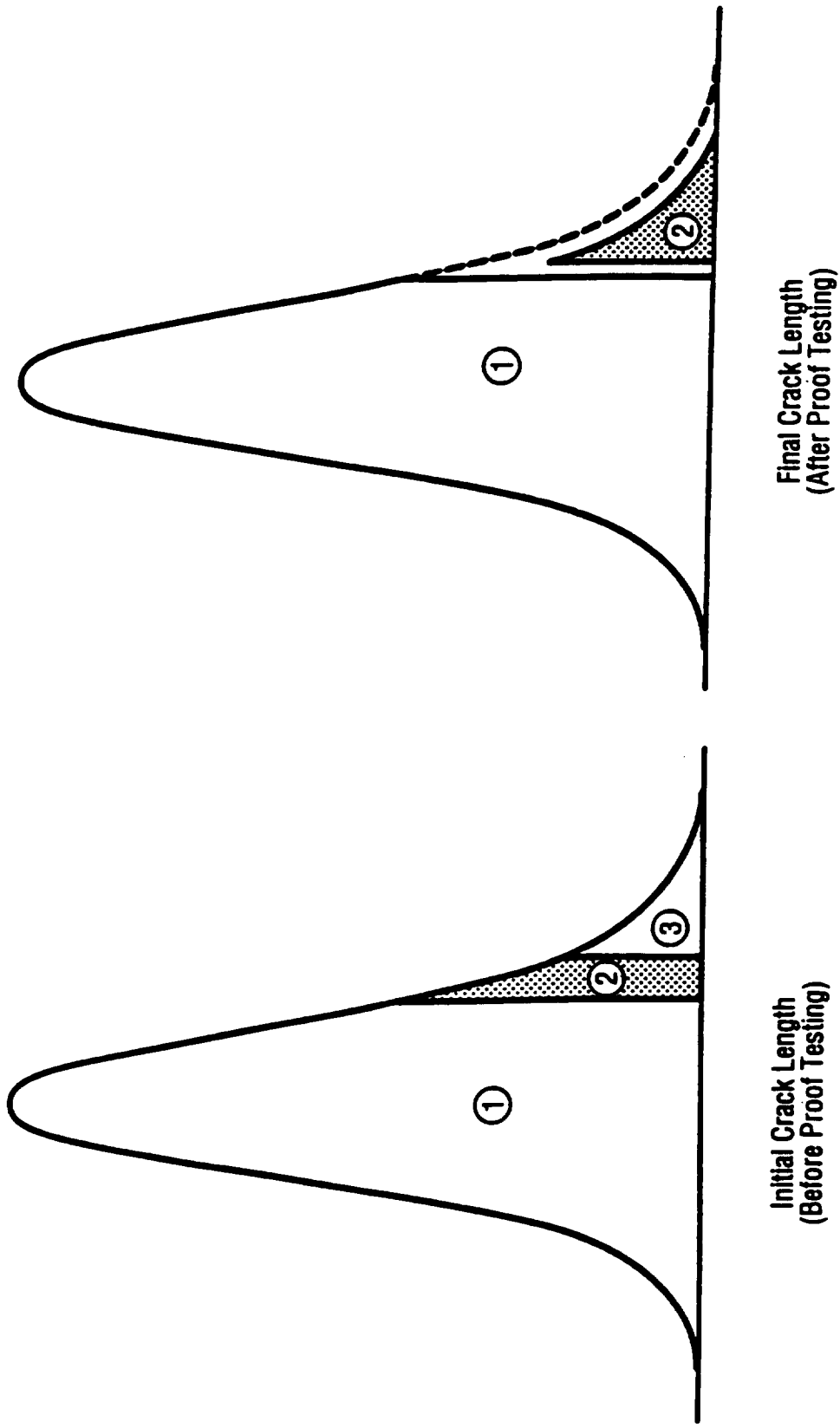
Figure 8. Schematic representation of initial and final crack length distributions for MCPT.

Initial Crack Length
(Before Proof Testing)

Final Crack Length
(After Proof Testing)

6.4.1 Tensile Data

Materials are known to be susceptible to cyclic hardening or softening. This phenomenon can occur in regions of the component undergoing cyclic plastic deformation. It should not be a problem in a single cycle proof test, but needs to be considered in a multiple cycle application. It may be possible to show that cyclic changes to the yield properties are negligible for the strain ranges and the number of cycles that arise in the proof test. If this is not the case then allowance should be made for any changes that occur in the tensile data used to calculate the maximum tolerable defect size, a_s.

Cyclic changes could occur in the crack tip plastic zone during proof testing, especially if the cracked section is loaded to beyond general yield and crack tip plasticity is extensive. However, this is only possible if the crack does not extend during the multiple cycling. Proof test methodologies pessimistically assume in the calculation of a_o that crack extension has occurred. Hence cyclic changes to the tensile properties in the plastic zone of the defect need not be considered because, by extending, the crack will increase its stress field and new plastic deformation will remove any cyclic effects arising from the previous load cycle. However, during multiple cycling, defects below a given size will not propagate and cyclic prestraining in their plastic zones cannot be ruled out.

6.4.2 Fracture Toughness

The effects of proof loading on toughness is dependent on whether the material is brittle or ductile.

Brittle materials

It is now widely recognized that loading a material that fails by cleavage to a load which exceeds its operating load, and at a temperature above the operating temperature, changes the fracture toughness at the operating temperature [3,107-111] (Figure 9). This effect is called warm prestressing and is observed in metals, such as ferritic steels, that fracture at temperatures below their ductile-brittle toughness transition temperature. The reasons why this occurs are understood and theoretical models based on the mechanisms of cleavage, and the mechanics of plastic flow [112] have been proposed to explain warm prestressing, and appear to do so with reasonable accuracy. The enhancement in toughness is observed even if ductile tearing occurs during the proof loading [113].

Toughness enhancement is not predicted to occur if the proof loading occurs at the same temperature as the operating temperature, or at a temperature below it. It also appears to be dependent on the failure mechanisms being stress controlled: there is no evidence that warm prestressing will affect the toughness of materials failing by strain controlled mechanisms, even if fracture occurs with little or no crack tip plasticity, and without any significant stable crack extension preceding the event. This is not intended to imply that the toughness of such materials will not be affected by the proof loading due to other causes.

It is reasonable not to invoke the benefits from warm prestressing in a proof test analysis because of the possibility of sub-critical crack growth during service. Although there is some theoretical evidence that the warm prestressing effect persists even after some sub-critical
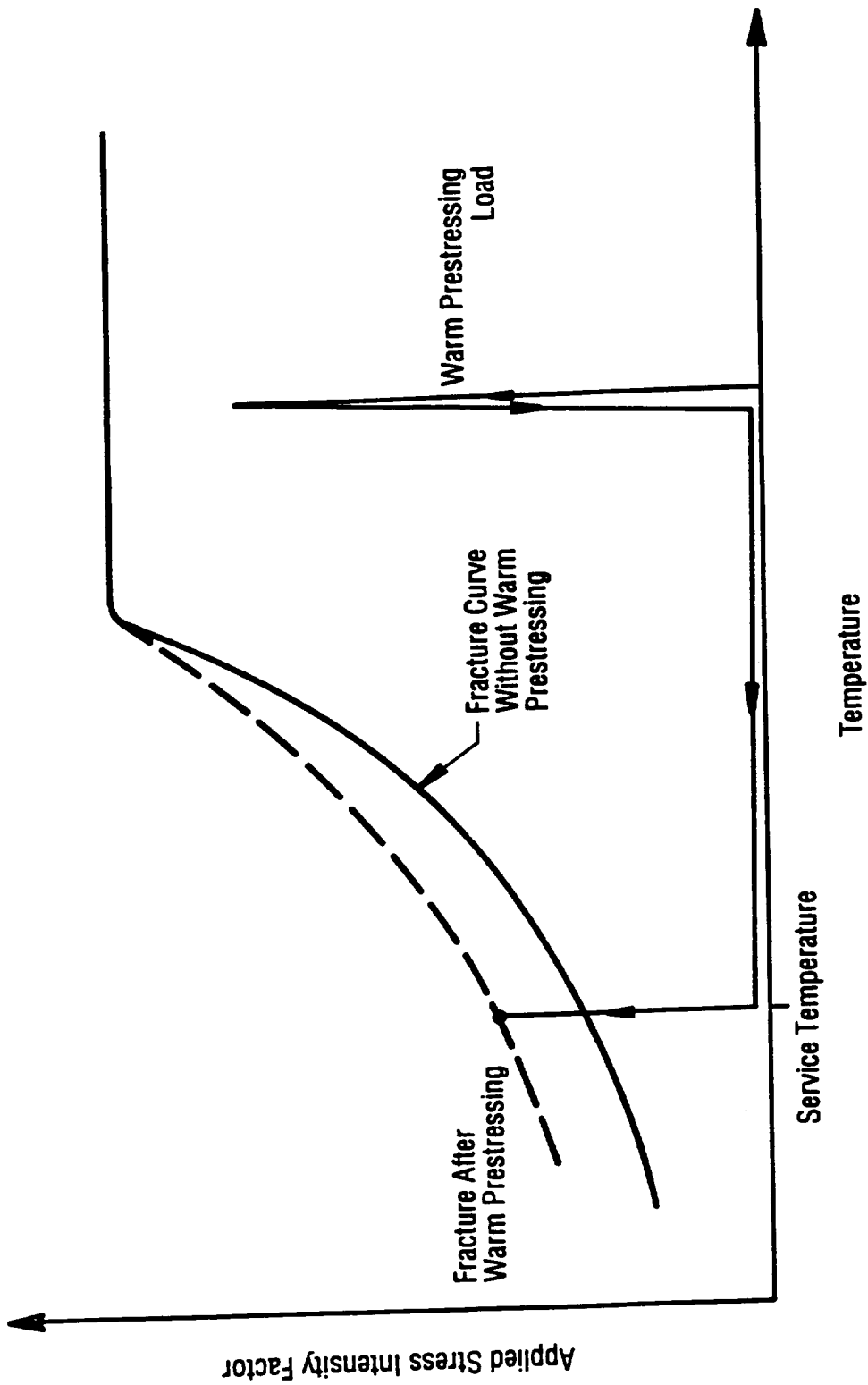
Figure 9. Schematic showing enhancement in fracture toughness for brittle materials after warm prestressing.

crack extension, the amount of crack growth required before the effects are removed is small, and, under some circumstances, the threat of catastrophic failure occurring at an apparent enhanced toughness level during growth cannot be ruled out [114].

Under some conditions material embrittlement could occur during the proof test from strain ageing, dynamic ageing or other causes [113,115]. The time over which the proof load is sustained, and the temperature of the test, will be important parameters in determining the degree of embrittlement, if any is anticipated to occur.

Ductile materials

The effect of ductile tearing at the proof load level on the ductile toughness under service conditions is little understood, particularly if the two occur at different temperatures. This observation applies whether the proof test consists of a single cycle or multiple cycles. Two situations should be considered when assessing the effect of the proof loading on the subsequent toughness of the material.

First, the methodology of proof testing requires that a postulated defect remains on the point of incipient instability after the last proof test load cycle. This implies that the defect grew by tear or tear-fatigue during the proof testing, as shown schematically in Figure 10. Models of tear-fatigue have now advanced to the stage where the situation shown in Figure 10 can be predicted (see Section 5.4). These models also enable the effect on subsequent crack growth at a lower cyclic load (service load) than the proof load to be predicted provided there is no change in temperature between the two loading sequences. However, the models do not provide predictions regarding the influence of the proof loading on the subsequent fracture toughness under service conditions, even if these correspond to the same temperature as the proof temperature. The problem is illustrated schematically in Figure 10 which shows the situation under service loading after the proof loading.

It is essential for assessing the integrity of the component at operation that at least a lower bound initiation toughness is known. At the current time there is no simple way of quantifying the damage introduced by the proof test without resorting to experimental measurement. Theoretical predictions of the effects of the damage, based upon the local damage approach [116], are not practical at the present time: they are expensive as they rely on three-dimensional elastic-plastic stress analysis of the cracked structure, and they are not sufficiently validated to be used with confidence on aerospace components.

Second, the effects of proof loading on defects that were too small to grow by tearing during the test need to be considered. It has been shown that cyclic prestraining may either enhance or reduce the ductile fracture toughness depending on whether the material cyclically softens or hardens [117,118]. Significant cyclic plastic prestraining could occur in the crack tip plastic zone during multiple cycle loading.

6.4.3 Crack Propagation Rates

The proof test could result in retardation of fatigue crack growth during service conditions [31]. However, this effect is likely to be significant only if the proof load cycles are
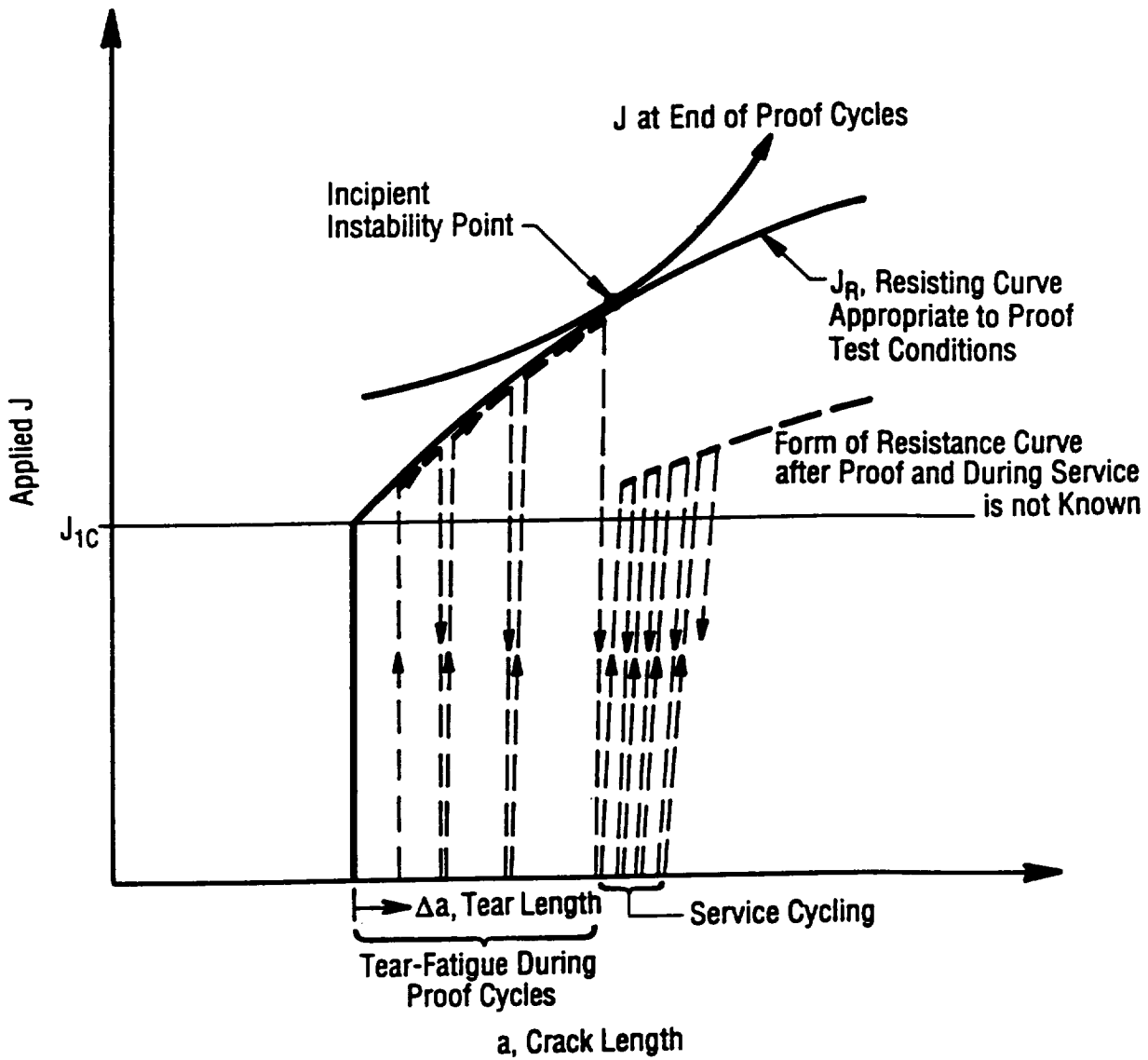
Figure 10.   Tear-fatigue during proof load cycling: effects on subsequent toughness is not known.

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substantially higher than the service cycles [119]. The effect of retardation will be to increase the calculated remaining life of the component with respect to the life determined with no retardation.

The situation with regard to tough materials is not so clear. In these cases the calculated value of the applied J_o during the proof loading may be very large. In fact, as discussed in Section 5.2, the assessment of failure under the proof test conditions may predict that ductile instability will occur very near to the plastic collapse load of the component. In this regime, the applied value of J is very sensitive to the value of the load and the proof loading could constitute a large overload with respect to service conditions when characterized by the ratio $(J_o/J_{max})^{1/2}$ (see Figure 11).

A more important consideration is the possibility of an enhancement in the growth rate during service due to combined static and fatigue crack growth mechanisms, as was discussed for ductile materials undergoing tear-fatigue. In a normal remaining life assessment the reduction in the total fatigue life due to the interaction of static brittle and fatigue crack growth mechanisms is not significant, since the predominant part of the life is spent in propagating small defects with low applied values of J_{max}. However, the value of the largest defect a_o that could just survive the proof test loading may be large enough to produce a significant interaction between static and cyclic failure modes during subsequent operation.

It is known from work on ferritic steels that brittle as well as ductile materials show an acceleration in the crack propagation rate as the load at the maximum part of the cycle approaches the load required to cause fracture under monotonic loading conditions. For brittle materials that do not display any significant resistance to stable crack extension under a rising load, and where fracture is coincident with crack growth initiation, this effect becomes significant when J_{max} exceeds about 0.6 J_{Ic}, where J_{max} is the value of the applied J at maximum load in the cycle. Theoretical modelling of this acceleration indicates that the enhancement in the growth rate is inversely proportional to the term $J_{Ic}-J_{max}$ [63,94].

For ductile materials, there is evidence from tear-fatigue tests on ductile ferritic steels that, provided J_{max} is less than J_o, then although $J_{max} > J_{Ic}$, the growth rate will return to its value calculated from the normal growth rate laws in the absence of tearing [95]. This effect is illustrated in Figure 12. Although this has only been demonstrated for crack propagation at a constant J_{max} equal to J_o the effect could be anticipated to occur at J_{max} levels less than J_o. However, it still has to be proven that this is the case. Alternatively, it could be argued that the fatigue cycling propagates the crack through the ductile fracture process zone corresponding to J_o, developing a new process zone which corresponds to the instantaneous value of J_{max} and consequently re-initiating tear-fatigue and an acceleration in the growth rate.

$$\left(\frac{J_o}{J_{max}}\right)^{1/2} > \left(\frac{J_o'}{J_{max}'}\right)^{1/2} = \frac{P_o'}{P_{max}'} = \frac{P_o}{P_{max}}$$

$(EJ_o)^{1/2}$

$(EJ_{max})^{1/2}$

$(EJ_o')^{1/2}$

$(EJ_{max}')^{1/2}$

$(E'J)^{1/2}$

P_{max}' P_o' P_{max} P_o
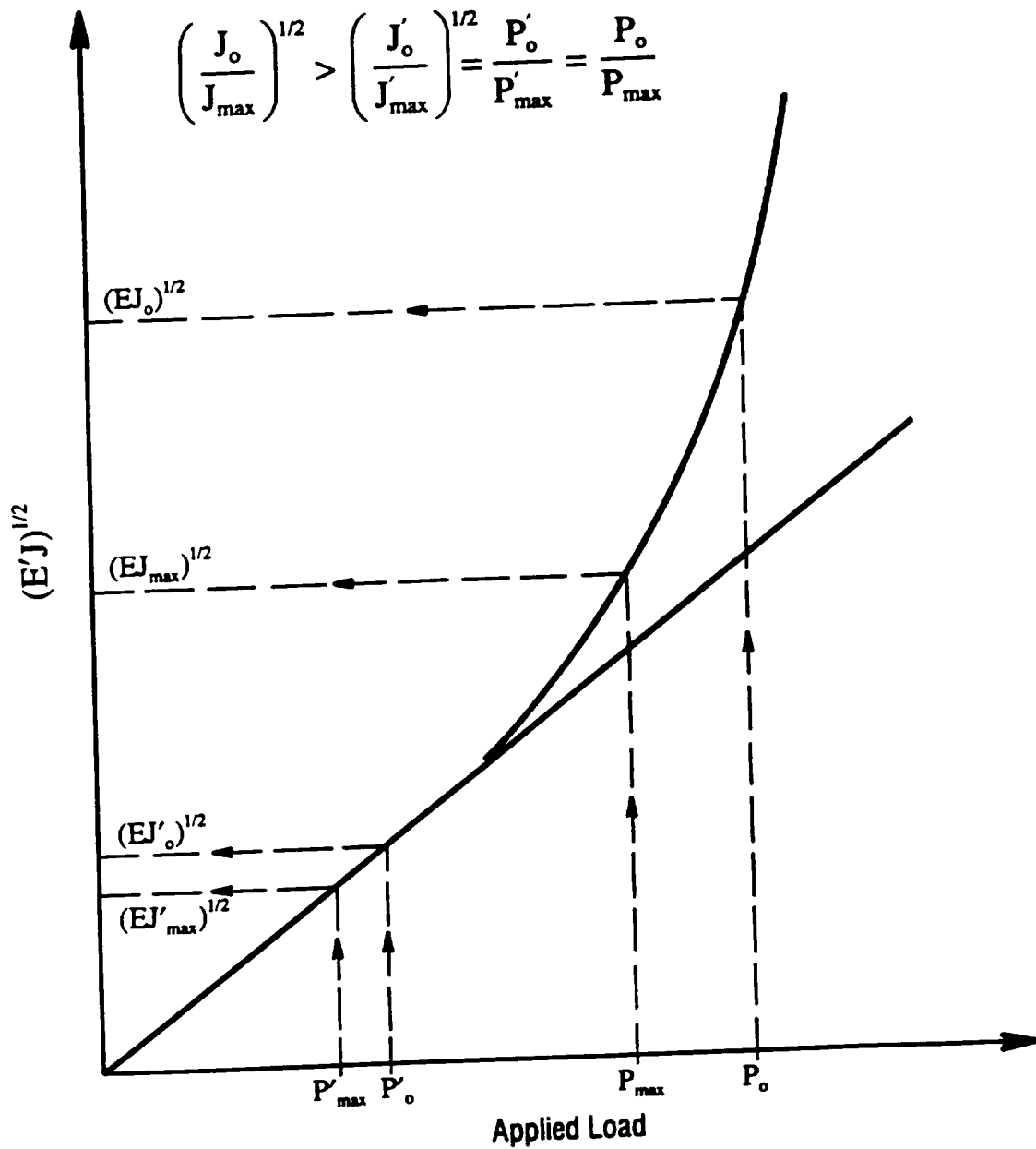
Applied Load

Figure 11.   Schematic showing that overloading, when characterized by $(J_o/J_{max})^{1/2}$, is more significant in the plastic regime for the same ratio of overload (P_o) to maximum cyclic load (P_{max}).
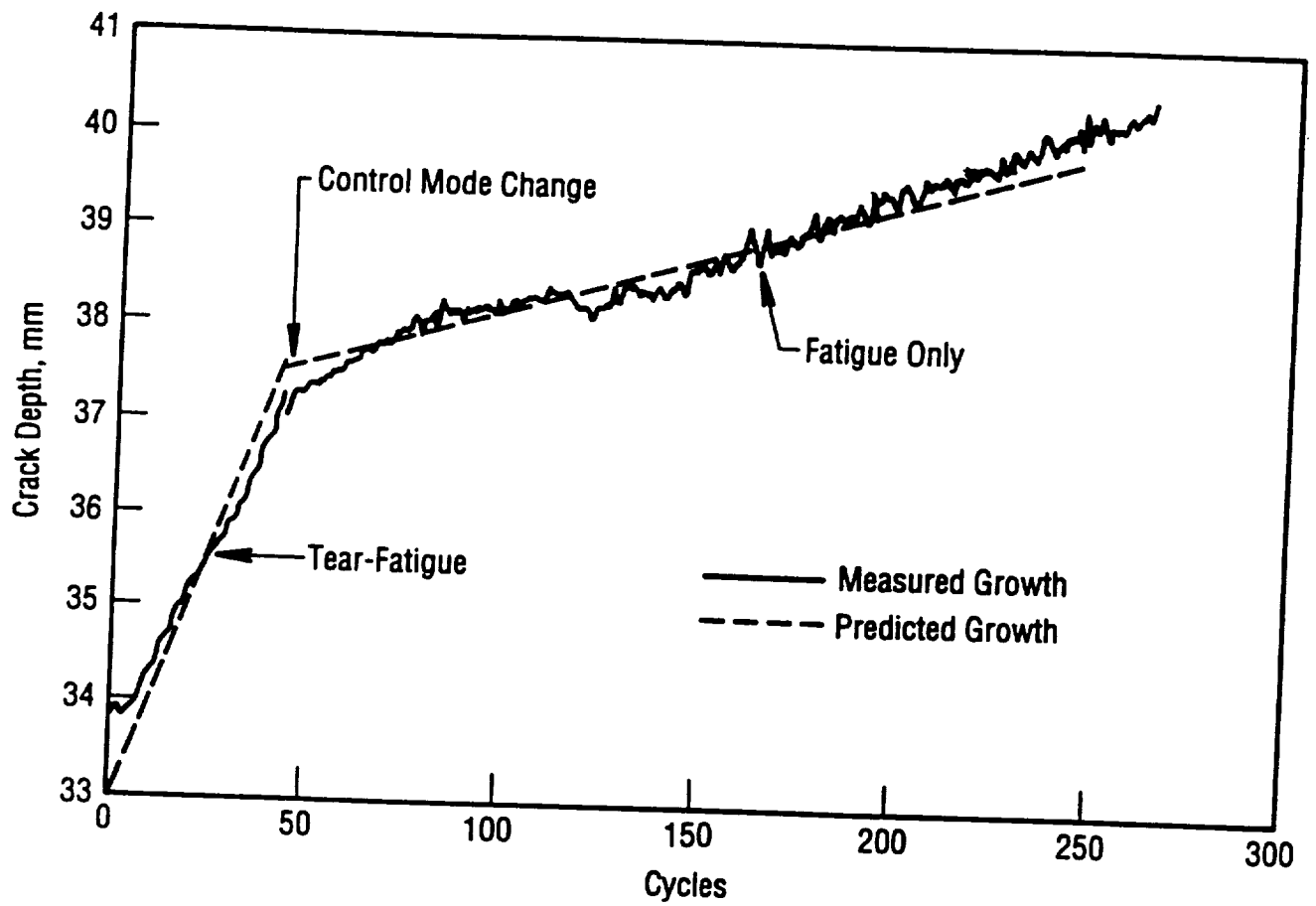
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Figure 12. Plot of measured and predicted crack growth for tear-fatigue under rising J_{max} and following mode change to constant J_{max}.

7. OTHER ISSUES ASSOCIATED WITH PROOF TESTING

There are other issues associated with proof testing that are not directly related to technical assessment and analysis. These issues concern how the proof test is carried out and include personnel training and certification; test fixtures, seals, and fasteners; and test procedure documentation and safety plans.

7.1 Personnel Training and Certification

It is imperative that a program for personnel training be required for those involved in pressure test operations. This should consist of an apprenticeship program in which the mechanic learns basic skills and safety procedures from an experienced technician, relating to the setup of pressure systems and test conduct. This should be followed by training on hydraulic and pneumatic pressure systems covering pressure system terminology, applicable principles of physics, pressure system pretest safety checklists, typical system components and their theory of operation, metallic pressure tubing and flexible hose, pressure test fittings, seals and gaskets, calculation of system energy levels and use of blast shields and/or test cells, codes applicable to pressure testing, and required tools and their proper use.

This initial training should be followed by on-the-job training with a strong emphasis on system and test safety, including pressure system schematic requirements, pressure system design, preparation of pressure system safety checkout cards, pressure relieving devices, use of flexible hose, and ground rules for setting up tests involving pressure. Development of personal skills relating to pressure testing should be documented on a task familiarization checklist which tracks the progress of each mechanic and technician in attaining various on-the-job training skills and class completion.

Personnel training for test engineers should consist of similar course work to that undergone by mechanics and technicians as well as receiving on-the-job-training from a senior test engineer. The emphasis in the course work and during on-the-job-training should be placed on system safety, test data accuracy, and proper documentation for test set up and conduct of tests.

7.2 Test Fixtures, Seals, and Fasteners

Test fixtures, seals, and fasteners are an integral part of any pressure test because without their presence on the test item it would be impossible to create the pressure load conditions necessary for its evaluation. Some of the more important fixture design considerations are as follows: compartmentization of a test item based on various pressure zones present during test; simulation of internal pressure loads; application of external mechanical loads; structural simulation of the actual component or assembly attached to the test item during service; pressure port size, type, and location; ability of the pressure test assembly to be bled of air for hydrostatic tests; internal volume reduction by test fixture to limit energy levels; incorporation of pressure control devices such as burst diaphragms and/or relief valves into the test fixture to allow control of adverse absolute and/or differential pressures caused by pressure system input and/or internal seal leakage; corrosion resistance and/or plating of non-corrosion resistant materials to allow optimum fixture sealing surface conditions and minimum contamination of test item during test; material handling provisions such as sling attach points for massive tool details; internal and/or external mechanical restraints to limit test item and/or fixture displacement; pressure seal-to-test item interface clearance changes due to differential growth rates experienced during test assembly temperature changes and

pressure loadings; material property changes of seals and/or test fixtures due to temperature; high strength material availability for very large fixtures; and high strength fastener availability.

7.3 Test Procedures, Documentation, And Safety Plans

Test procedures are a critical element of the pressure test since they contain the necessary system setup information and the test parameters needed for successful test completion. The type of test procedure is usually dictated by the degree of control required during test conduct. The level of control should be very high for production-type hardware which requires a precise set of instructions to be followed in a consistent manner from test to test. In this instance, test procedures should be reviewed and approved by the user department, test item manufacturing engineer, system safety engineer, and quality engineer. In addition the project engineer and/or the structural analysis group should approve the test procedure in certain special cases involving critical and/or first article hardware program test items. The procedure should then be formally archived. These archived procedures should be referenced by a manufacturing operation record that travels with the test item throughout the manufacturing cycle.

For tests involving development, scrap, and/or incident hardware, a less rigorous approval cycle should be employed with a similar test procedure format to allow more flexibility during test operations.

A good pressure test procedure must contain the following elements to insure safety, test data quality, and overall high efficiency: test system mechanical and electrical/instrumentation schematics, including detailed component description lists; all test parameters such as final absolute and/or differential pressure(s), test item temperature, number of pressure cycles, dwell times at various pressure levels, and pressurization/depressurization rates; reference to resident facility operating procedures describing facility setup, operation, and troubleshooting and contingency plans needed in the event the test item and/or facility experiences an anomalous condition; data collection instrumentation and critical system component redundancy; and test item/facility cleanliness control. In addition, each procedure must receive a hazard analysis to assure that all scenarios involving adverse pressure and/or external load conditions have been addressed by the test procedure and compensated for in the test system.

8. DISCUSSION

The main technical issues highlighted by this appraisal of state-of-the-art technology and its application to proof testing are summarized in Tables 1 through 12. Some topics which are related to emerging technologies are also included in the appraisal (for example, quantification of the effects of proof test loading on subsequent material behavior). In these cases it is considered that there is a reasonable chance these will have matured to have become state-of-the-art technology within the timescales of the proof test project, or that it will be possible to make useful recommendations as to how they should be approximately incorporated in a proof test methodology. In any event, these issues are considered sufficiently important that they should be discussed, and their ramifications made apparent, within the context of proof testing.

It is clear from the appraisal that a probability based proof test methodology offers many advantages over a deterministic one. Its use will remove many of the aspects of the deterministic approach that erode proof test margins and produce inconsistencies in the treatment of the component during the proof loading and while it is undergoing service. The disadvantage of the probabilistic approach is the increase in analysis complexity and the need for additional data compared to a deterministic analysis. However, since the technical issues associated with the steps in a deterministic analysis require resolution before a probabilistic approach can be implemented, the evolution from a deterministic to a probabilistic methodology can be accomplished in stages, with parts of the deterministic analysis being replaced by probabilistic routines as, and when, these become available.

It is worth re-emphasizing that failure within the context of proof testing does not necessarily imply catastrophic failure of the component. There can be many different criteria governing whether a component can be judged to have survived the proof test. Similarly, there are many reasons why it could fail it. This includes the loss of the integrity of seals and leakages caused by through wall crack propagation. In the latter case, although the defect may not have propagated unstably, this would be classified as a failure of the component if, for example, the leak would have resulted in the release of volatile substances had it occurred in service.

One of the greatest advantages of a proof analysis based on the proof load is its capability of providing a one-parameter characterization of the integrity of the structure as it enters service with respect to the service loads it will experience. Unfortunately, this simplicity does not carry over to an assessment based on EPFM. EPFM requires that the proof load be characterized by an elastic-plastic parameter, such as J, and this could prove both economically and analytically demanding. There may be many locations in a component where defects could occur, and each one would need to be characterized by J. Furthermore, the limitations on the application of J theory, and the problems still outstanding regarding its determination by simple methods for complex structures, crack shapes and loadings, would not always warrant such an approach. These problems could be partly overcome by performing a proof test analysis for the most critical region only, or by using bounding data which encompass, in some generic sense, all the parts of the component at risk from cracking.

A reliability for service assessment based on the proof test requires the calculation of a_o, a_s, and the time for the crack to grow from a_s to a_o. The easiest of these quantities to determine is a_o, because this is evaluated under proof test conditions which are usually well defined and controlled. In many cases, the calculation of the other two quantities presents a formidable

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task. A proof test methodology should recognize and describe the close relationships between all three of these quantities, but its primary purpose at this time should be detailing the estimation of a_0. This approach is consistent with the fact that the calculation of a_s and the remaining life is an exercise which is usually performed independently of the proof test.

There will be cases where it can be argued that the proof test is not justified on either non-technical or technical grounds. However, if a service failure cannot be tolerated, and reliable NDE methods are not available, then there appears to be no alternative but to proof test, irrespective of the cost and the practical difficulties involved.

Some practical circumstances which obviate the possibility of proof testing have already been mentioned in this report. These include situations where alternative flaw screening and detection methods are available, and would prove more effective and less expensive to apply, and where the consequences of failure in service does not pose a significant safety or financial risk, and where the component could be replaced or repaired at relatively low cost.

Possible technical reasons why a proof test may not be effective include situations where the component material is very tough; where the walls of the component are very thin; and where the proof load would be so different from the service loads that a proof test would not exercise the critical regions of the component. In addition, test conditions may introduce so many uncertainties that an assessment becomes unreliable. However, this should not exclude the use of the proof test as a quality assurance method for detecting manufacturing errors and poor workmanship.

Given these limitations on the use of proof testing, it would be judicious to adopt a pragmatic approach to the formulation of a proof test methodology, and to accept that although it includes state-of-the-art technology, the application of these sophisticated analysis tools may not always be justified. A methodology based on various levels of sophistication suggests itself as a compromise between not having the technology available when it is needed, and, alternatively, having the technology but not having the justification or the resource to apply it to most problems because of its sophistication. The development of this kind of methodology would allow other factors, besides those previously discussed, to be included in the proof testing decision making process. One of these is the fact that guaranteeing the reliability of a structure for service is not always made solely on a proof test argument. The strengths of these additional factors should be allowed to influence the level of resource expended on proof testing, and hence the level of sophistication required from a proof test analysis.

Given the increase in input data and analysis complexity that a state-of-the-art proof test methodology requires, serious consideration should be given to the development of enabling technology which allows the methodology to be implemented, and the technology to be transferred, to the non-expert user. Steps which could be taken to facilitate these aspects are the extension of material data bases to include EPFM information; probabilistic data, such as distribution functions and their corresponding constants, as these become available; and the development of computer software for calculating elastic-plastic fracture mechanics parameters and performing the proof test analysis. It should be possible to carry out these developments in a manner that utilizes existing NASA data bases, (e.g., the NASA fracture mechanics database [126]) and structural integrity computer software, and that is consistent with the overall NASA approach to probabilistic methodologies.

It may sometimes not be clear whether it is more cost effective to replace a piece of equipment or to re-certify it for further service using the proof test as a method of guaranteeing remaining life. Such decisions are non-trivial and frequently depend on many factors and are accompanied by many uncertainties. The probabilistic method allows these issues to be combined with the probability of a beneficial outcome from proof testing in order to assess the cost benefits of the proof test. Indeed, probabilistic theory has been proposed as an aid in the assessment of economic decisions of this nature [47,48]. In the longer term, the development of a cost benefit analysis which is interfaced with a probability based proof test computer software package would provide a powerful tool for quantifying the benefits of performing a proof test and in helping to maximize its effectiveness. This type of technology would also enable the optimization of proof test intervals for re-certifiable components to be performed.

9. CONCLUSIONS

The technical issues raised in this report have been critically appraised in order to assess their importance in a proof test analysis to determine the fitness-for-service and remaining life of aerospace components. Recent technological advances in the field of fracture mechanics have been included in the appraisal with a view to defining those issues which are mature enough to be incorporated in a proof test methodology. The following criteria were used to assess each issue with respect to inclusion in a proof test methodology:

- its importance in a proof test methodology;
- its status and general acceptance;
- the availability of implementing technology;
- further technological requirements;
- the data required to implement the technology;

These criteria were used to select from the issues reviewed a list of parameters and phenomena that are deemed not only essential to formulating a proof test methodology, but also well enough understood and validated, or probably could be within the time and resources of the present project, to be used as a technical basis for underpinning the methodology. It is concluded that inclusion of the list items in a proof test methodology would:

- promote proof test practice to a state-of-the-art technology;
- identify those aspects which would aid optimization of proof test design with respect to maximizing its effectiveness;
- increase awareness and understanding of outstanding issues, like the relative merits of single and multiple cycle proof loading.

Items included on this list are:

Those related to analysis:

- guidance on how to determine proof test margins and safe remaining life
- guidance on determining proof test intervals for re-certifiable components
- guidance on which applications, materials, and structures are most conducive to the benefits of proof testing
- elastic-plastic fracture mechanics (EPFM)
- discussion of different fracture regimes and the fracture mechanics parameters applicable to each
- ductile instability analyses
- simple approximate methods of estimating the EPFM parameter J
- recommended treatment of secondary stresses in EPFM
- comment on the use of EPFM parameters for characterizing proof test loads with respect to service loading
- elements of probabilistic analyses
- relationship of proof test probabilistic methodology to existing NASA probabilistic methodologies
- suggested methods of deriving probabilistic distributions from existing but limited data
- indications of the probability of detecting flaws in aerospace hardware

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- analysis treatment of multiple cycle loading
- guidance on residual stress distributions in typical aerospace hardware
- indications of defect distributions in aerospace components
- discussion on the impact of defect shape on proof test margins
- comments of the significance flaw characterization in proof test analyses
- synergistic relationship of proof testing to NDE

Those related to material behavior

- recommendations for obtaining material data for proof test usage
- description of different types of material fracture behavior and their impact on proof test analysis
- rules for assessing the interaction of static and cyclic crack extension mechanisms
- rules for assessing the effect of load history on subsequent fracture behavior
- rules for assessing the effects of environment on material behavior

Those related to test conditions

- guidance on proof test temperature
- guidance on when to perform multiple cycle or single cycle proof tests
- recommendations on the need to simulate service environments
- recommendations on loading rates and hold times
- suggested test media
- use of real-time NDE to enhance flaw screening capability

It is further concluded that:

- a proof test methodology based on probabilistic analysis will be far more effective than one based solely on a deterministic philosophy.
- the probabilistic approach removes many of the technical problems and logical inconsistencies which beset deterministic methodology.
- the value of the proof test is greatly enhanced as a flaw screening method when combined with non-destructive examinations of the component.

It should be recognized that the proof test is not universally applicable as a pre-service method of guaranteeing structural reliability during service, especially, if reliable and more effective NDE methods are available. This is because its range of application is limited by both non-technical and technical factors. Furthermore, the process of guaranteeing the structural reliability of a component during service is usually not based solely on the results of a proof test. The strength of these other factors should be allowed to determine the sophistication of proof test requirements and procedures. These observations lead to the conclusion that a proof test methodology should be pragmatically based on a series of levels, the higher the level the greater the technological sophistication. Such a methodology should include guidance for the users to enable them to select the level most appropriate to their circumstances.

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In terms of longer term developments, it is concluded that proof test analysis capabilities would be greatly increased by:

- a probabilistic data base consisting of source data, and/or distribution functions and their respective constants, for all key assessment parameters
- computer software for calculating elastic-plastic fracture mechanics parameters and performing a proof test analysis
- a methodology for determining the cost benefits of proof testing.

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13. ABSTRACT (Maximum 200 words)

Issues which impact on the interpretation and quantification of proof test benefits are reviewed. The importance of each issue in contributing to the extra quality assurance conferred by proof testing components is discussed, particularly with respect to the application of advanced fracture mechanics concepts to enhance the flaw screening capability of a proof test analysis. Items covered include the role in proof testing of elastic-plastic fracture mechanics, ductile instability analysis, deterministic versus probabilistic analysis, single versus multiple cycle proof testing, and non-destructive examination (NDE). The effects of proof testing on subsequent service life are reviewed, particularly with regard to stress redistribution and changes in fracture behavior resulting from the overload. The importance of proof test conditions are also addressed, covering aspects related to test temperature, simulation of service environments, test media and the application of real-time NDE. The role of each issue in a proof test methodology is assessed with respect to its ability to: promote proof test practice to a state-of-the-art; aid optimization of proof test design; and increase awareness and understanding of outstanding issues.

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