SD73-SH-0082A

SPACE SHUTTLE ORBITER

FRACTURE CONTROL PLAN

REVISED SEPTEMBER 1974

Contract NAS9-14000

IRD TM-251TA

WBS 1.3.1.3.3

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TECHNICAL REPORT INDEX/ABSTRACT

ACCESSION NUMBER	DOCUMENT SECURITY CLASSIFICATION
	Unclassified

TITLE OF DOCUMENT	LIBRARY USE ONLY
SPACE SHUTTLE ORBITER FRACTURE CONTROL PLAN	

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CODE	ORIGINATING AGENCY AND OTHER SOURCES	DOCUMENT NUMBER
QN085282	SPACE DIVISION OF ROCKWELL INTERNATIONAL	SD73-SH-0082A

PUBLICATION DATE	CONTRACT NUMBER
September 1974	NAS9-14000

DESCRIPTIVE TERMS

FRACTURE CONTROL, FRACTURE MECHANICS, SPACE SHUTTLE

ABSTRACT

The criteria are presented for preventing Space Shuttle structural failure associated with crack initiation or propagation during fabrication, test, handling, and the operational life of the vehicle. The criteria discussed include: engineering responsibilities, assurance management, production, operation and test, procurement, critical parts selection, design, and structural analysis.

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1.0 GENERAL POLICY

It is the goal of Space Shuttle Orbiter program management to design components which will provide structural integrity even in the presence of undetected flaws. This assurance shall be maintained with minimum impact to weight and cost.

2.0 OBJECTIVE

To establish those criteria, procedures, and controls necessary to prevent Orbiter structural failures due to the presence of defects and flaws, assumed to be present in all fabricated metal products. Additionally, factors contributing to the generation of crack-like flaws shall be controlled so as to minimize the initiation of such flaws.

3.0 SCOPE

All activities that influence the structural integrity of deliverable metallic flight hardware, whether to be used in flight or in test, are subject to the requirements of this document. These activities include, but are not limited to, structural design, analysis, and test; materials selection, purchase, and storage; fabrication process control; quality assurance performance and non-destructive evaluation; and vehicle operations and maintenance.

4.0 PREREQUISITES AND ASSUMPTIONS

4.1 The basic assumption to be employed in a fracture control program is that real structures contain crack-like flaws of the most unfavorable orientation located at the most critical area of the component. Consideration of circumstances other than this basic assumption must be substantiated by evidence resulting from actual experience or test.

4.2 It is assumed that data generated for both critical and non-critical parts as a matter of good engineering practice in the design of flight hardware exist and are available as a basis for the fracture control program. These pre-existing data shall include, but not be limited to:

a. Definition of vehicle loads and environments.
b. Comprehensive structural analysis including fatigue analysis.

4.3 A comprehensive test program will be conducted to verify the basic vehicle design and structural integrity.

4.4 A preflight and preventive maintenance and inspection program meeting all aircraft flight readiness requirements will be developed and enforced for all structure, whether critical or non-critical.

5.0 ORGANIZATION, FUNCTION, AND RESPONSIBILITIES

Effective management of the Orbiter Fracture Control program shall be accomplished by the establishment of a Design Review for Fracture Control. This review shall be functional at Rockwell International and at all levels of subcontractors/suppliers with design responsibility.

Responsibility for implementation of the Fracture Control Plan and associated reviews shall be vested in an individual appointed by the Program Manager. The designated individual shall utilize an advisory board/team consisting of representatives from at least:

1. Engineering Structural Design
2. Engineering Structural Analysis
3. Engineering Materials and Processes
4. Quality Assurance

This board/team shall critique all documentation pertinent to the identification of and control of fracture critical components (see 6.0). All actions taken shall be subject to review by the procuring agency. A NASA observer may attend fracture control board/team meetings to provide full visibility into the fracture control program. The board/team shall participate in all material review actions involving fracture critical components and shall signify concurrence with the disposition action.

5.1 Engineering Structural Design

Each system/subsystem contractor with design responsibility is specifically instructed to implement design practices which will provide components capable of proper function under adverse conditions. Items requiring attention include: (1) stress concentration reduction; (2) elimination of or reduction of residual and assembly stresses; (3) incorporation of features to preclude stress corrosion cracking; (4) compatibility of the design with manufacturing methods; and (5) consideration of inspection requirements for flaw detection.

The board/team representative from Engineering Structural Design shall review all fracture critical designated part designs to ascertain proper application of the aforementioned items and will assure that all parts designated as "fracture critical" bear an identifying legend or general note on the face of the drawing.

5.2 Engineering Structural Analysis

The Engineering Structural Analysis function shall be responsible for performance of the crack growth predictive analysis. This analysis shall be performed in addition to conventional static and fatigue analyses for the component. The analysis procedure to be employed is described in Appendix A of this document. The board/team representative from Engineering Structural Analysis shall review those computations which would result in a component being designated as fracture critical for proper application of assumptions, analysis methods, and initial flaw sizes used in the calculations.

5.3 Engineering Materials and Process

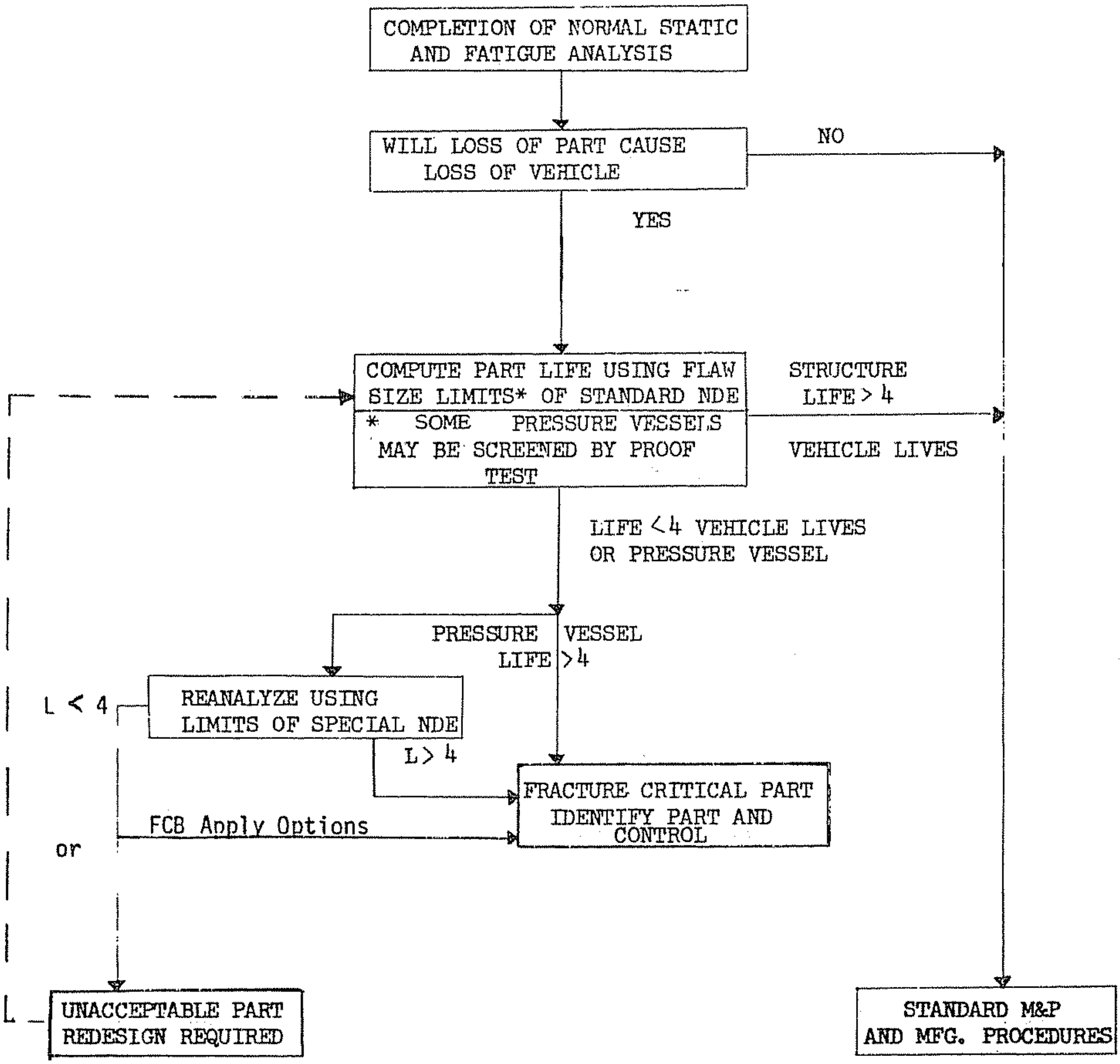
Materials selected for use in Orbiter components shall possess a capability to sustain cyclic loading in the presence of stress concentrations and crack-like flaws. Additionally, Engineering Materials and Process personnel shall be responsible for the implementation of documentation for materials procurement and fabrication process control necessary to achieve and maintain crack growth resistance characteristics while precluding deterimental effects contributory to flaw initiation. Material properties utilized in the crack growth predictive analysis shall be validated for the intended thermal and chemical environment. The normal review of component drawings for adequacy of materials and process callouts will be supplemented on designated fracture critical part drawings by review of the board/team representative from Engineering Material and Process. Compilation of parts designated as fracture critical will be documented and reported in the Material Analysis, Tracking, and Control System (MATCO).

5.4 Quality Assurance

The primary objectives of Quality Assurance are to institute procedures required to ascertain maintenance of materials properties and to provide the non-destructive evaluation (NDE) techniques adequate to detect flaws of the size identified in the predictive analysis. It shall be the responsibility of the representative from Quality Assurance to review engineering documentation pertinent to fracture critical components for adequacy of crack detection methods, accessibility for inspection where required, and methods to ascertain preservation of fracture mechanics related properties.

6.0 PROCEDURES AND REQUIREMENTS

Each of the Orbiter systems/subsystems contractors will utilize the selection logic of Figure 1 to identify standard or fracture critical components. It should be noted that pressure vessels, by definition, are fracture critical components. The following sections address the consideration and basic criteria which must be observed in the application of the fracture control program.



LEGEND: L = LIFE
NDE = NON DESTRUCTIVE EVALUATION

FRACTURE CRITICAL PART SELECTION LOGIC

FIGURE 1

6.1 Materials Properties

Data utilized in the crack growth predictive analysis shall be validated for the anticipated use conditions, including temperature related effects and environmental circumstances. Unless otherwise specified, fracture related materials properties shall be the average of the validated data available. One exception is the requirement to use an environmentally related stress intensity (K_{th}) value, which shall be the lower bound value for the available data. An option to employ materials having optimum fracture mechanics properties is justified provided that substantiation of the achievement of these properties in the component is furnished. The preferred source of materials data related to fracture behavior is the Space Division, Rockwell International Corporation document entitled "Materials Properties Manual" (Publication No. 2543-W). The employment of alternate data shall be fully substantiated to Rockwell International, including identification of the testing source and qualifying data with regard to the material and heat treated temper tested. Users of the fracture mechanics data are cautioned to apply the constants enumerated for a given predictive equation only in that equation, since there are similarities in the nomenclature for the various equations.

6.2 Flaw Sizes (Initial)

Unless otherwise substantiated, the flaw sizes enumerated in the following sections shall be used in analysis and shall be representative of NDE capabilities.

NOTE: Embedded flaws in rolled aluminum plate shall be assumed to be parallel to the rolled surfaces.

6.2.1 Standard Flaws

The analyst shall assume, for the purpose of crack growth analysis using standard NDE (as cited in Figure 1), that standard NDE will detect surface flaws having lengths in excess of 0.150 inch, and depths in excess of 0.075 inch except that the curve for standard NDE in Figure 2 shall be utilized for other length and depth combinations. Also, the analyst shall assume that standard ultrasonics will reveal hidden flaws in excess of 0.100 inch in diameter (or equivalent). The standard capability for radiography shall be the detection of a crack which has a depth in excess of 70 percent of the material thickness. However the crack length on the surface of the part shall be assumed to be 0.150 inches or longer in the analysis and the Quality Assurance Function shall require that a surface flaw detection method is utilized in addition to the radiographic technique employed.

6.2.2 Flaws by Special NDE

Satisfactory accomplishment of a flaw detection demonstration by the Quality Assurance function of each Orbiter system/subsystem will permit the following flaw sizes to be assumed in the analysis. A 0.90 probability of detection at a 95 percent confidence level statistical base is required in the demonstration. Also, a specific inspection procedures document shall be prepared for each fracture critical component to assure this statistical base. When the use of special NDE is required to achieve increased component life (per Figure 1), the analyst may assume that surface flaws will be detected if the surface length is 0.050 inch or greater and the depth into the surface (as applicable) is 0.025 inch or greater. These dimensions are for an aspect ratio equal to 0.5. The crack front area relationships depicted in Figure 2 shall prevail for other aspect ratios of interest to the analysis; e.g., shallower cracks must be longer on the surface. Dye penetrant methods will be the predominant method used for surface flaw detection, however, eddy current and ultrasonic techniques can be applied in the detection of surface flaws.

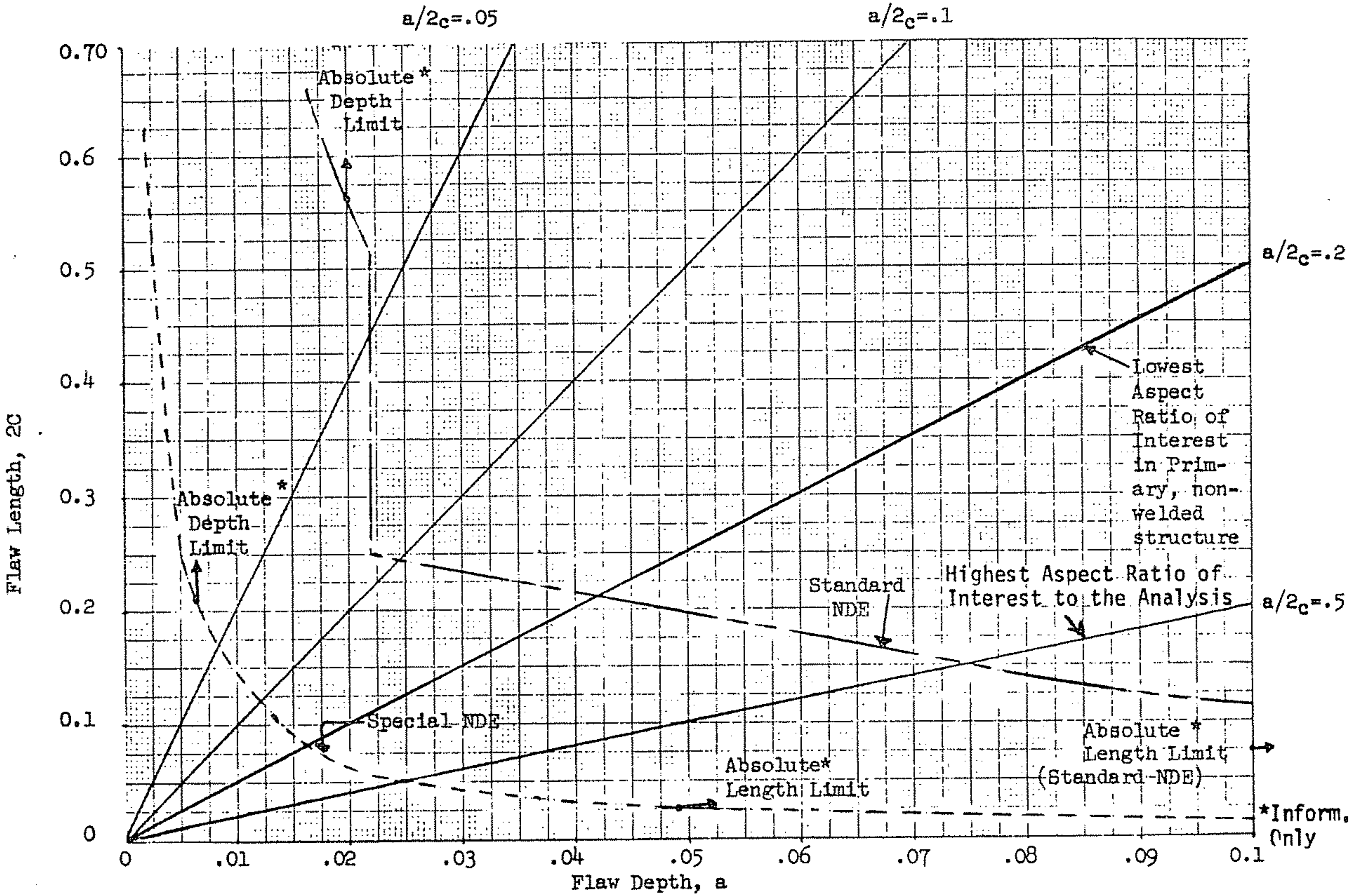
Embedded (sub-surface) flaws may be assumed to be detected by ultrasonics if the area of the crack is equivalent to the area of a 3/64 inch diameter flat surface or larger. The ultrasonic testing proficiency required by Quality Assurance shall be a 2/64 inch diameter flat bottom hole in the materials of concern.

Radiographic inspection is a technique routinely applied to the detection of voids and inclusions. The method has limited applicability in the detection of cracks, however, the analyst may assume that radiographic inspection will detect a material separation (crack) which has penetrated more than 60 percent through the thickness of the material. However, the crack length on the surface of the part shall be assumed to be 0.050 inches or longer in the analysis and the Quality Assurance function shall require that surface flaw detection method is utilized in addition to the radiographic techniques employed.

6.2.3 Flaws Screened by Proof Testing

Proof testing to screen flaws is a viable method for some of the metallic alloys. The utilization of proof testing to determine flaw sizes in primary structure and pressure vessels shall be coordinated with the procuring agency. In the design of pressure vessels to a leak before burst criteria, the analyst is cautioned to use the upper bound of available data on critical stress intensity (K_C - PTC) as the flaw sizing value.

It is the intent of this document to have NDE inspection performed on the interior of pressure vessels following proof testing. It is recognized that accessibility problems can prohibit a reasonable



NDE DETECTION LIMITS - SURFACE FLAWS

FIGURE 2

determination of flaws of the size listed under the special NDE section, Paragraph 6.2.2. However, when demonstrated by fracture mechanics methods that flaws at the detection limit of special NDE techniques will not enlarge during the proof test, those flaws, when screened by inspection of components prior to assembly (i.e., hemispheres, cylinder sections, etc.) will be acceptable as initial flaw sizes for safe crack growth fracture mechanics analysis of those portions of the structure. This does not, however, preclude the requirement that those components be thoroughly inspected following the proof test. Such an inspection is specifically required to ascertain the general quality of the structure in the assembled configuration.

For portions of the structure which cannot be inspected prior to assembly, particularly weld metal and heat affected zones, and where the proof pressure will not screen flaws small enough to meet safe crack growth life requirements, a post-proof inspection of these areas should be performed, when access permits, for the purpose of establishing the initial flaw size limit for the crack growth analysis. Inspection techniques including radiographic, penetrant, ultrasonic methods and augmented visual aids such as rod or fiber optics examination of the weld area may be relied upon for confirmation of the flaw size limit. When access does not permit inspection of these portions of the structure, stringent process control procedures accompanied by a minimum risk inspection rationale may be invoked. Such a rationale must be specifically approved by the Fracture Control Board.

6.2.4 Flaws Out of Holes

The analyst shall assume that drilled holes have 0.100 inch long through cracks (where $t \leq 0.100$) or 0.100 inch corner cracks ($t > 0.100$) emanating from one side of the hole. Establishment of a requirement to ream holes will permit the assumption of initial flaws no greater than 0.050 inch through cracks ($t \leq 0.050$ inch) or 0.050 inch corner cracks ($t > 0.050$ inch). The respective flaw sizes for very thick material when the flaw is assumed to be on the surface of the hole shall be 0.100 inch for drilled holes and 0.050 inch for reamed holes, respectively. The installation of driven rivets in standard structure will permit an assumption of an 0.005 inch corner crack out of the rivet holes.

There is an option available to the board/team to utilize special hole filling fasteners or methods to cold work holes in fracture critical components. This case would preclude the assumption of a crack out of these holes. Election to exercise this option shall be substantiated by empirical data and communicated to the procuring agency on a timely basis. The user is cautioned to account for potentially high residual tensile stresses in the vicinity of these special holes due to the need to avoid stress corrosion cracking.

6.2.5 Precautions on Assumed Flaw Sizes

When the analysis assumes a flaw not to exceed size dictated by the capabilities of a given NDE method, it is the responsibility of the board/team to assure that the method is employed to inspect the part. As an example, weld inspection would require that radiographic and/or ultrasonic methods be used for hidden flaws, since penetrant methods would not detect such flaws. Therefore, a weld analyzed assuming X-ray or ultrasonic method detection limits must be 100 percent radiographically inspected and/or ultrasonic inspected.

6.3 Performance of the Fracture Mechanics Analysis

Appendix A addresses the steps which should be followed to accomplish a safe crack growth life prediction for Shuttle Orbiter components.

6.4 Options Available to the Fracture Control Board/Team

The effective operation of a fracture control program can, in general, be accomplished by following the provisions of this document. However, the complexities and design requirements for all of the components to be used in this vehicle dictate the necessity of reasonable flexibility in applying fracture control to all cases. The following items are options which may be elected by the respective boards/teams. If exercised, the action taken shall be communicated to the procuring agency on a timely basis (nominally, 14 days after the action is taken).

6.4.1 Application of Stress Intensity Reduction Methods

The capability to delay the initiation of flaws and to substantially decrease the rate of growth of an existing flaw is the major reason to employ stress intensity reduction techniques. The use of interference fastener systems or cold worked holes is one example, previously cited in paragraph 6.2.4, of effective stress intensity reduction. Other methods, such as shot peening, have applicability and should be considered where special circumstances exist and weight increases, due to redesign, can be avoided. Techniques which utilize a "crack stopping" build-up, pad, or band on the surface of a highly loaded area in a component are also considered to be applicable to Shuttle Orbiter structure. The utilization of stress intensity reduction methods to achieve safe crack growth life must be supported by analysis and/or test results in the proposal to the procuring agency to use this option.

6.4.2 Application of Proof Test Qualification

There may exist circumstances wherein the results of a fracture mechanics analysis is indeterminate, due to a variety of reasons. It may be necessary to employ a proof test, in this instance, to verify the achievement of operational capability. This proof test will be conducted to produce a stress level substantially in excess (Proof factor = 1.5 minimum) of the maximum operating stress. Proposals to employ this option must be submitted to the procuring agency for approval prior to incorporation.

6.4.3 Modification of Operating Conditions

Operating conditions for the component may, by its very nature, reduce the life of the component below the required analysis life. Every instance encountered which is affected by the presence of a corrosive environment, excessive temperature or other degrading conditions shall be examined to consider alternate means of relieving the adverse condition. Cost/weight trades should be conducted to determine the relative merits of providing improved protection systems (against corrosion, for instance) more insulation (or a heater) in the case of temperature extremes or other alternate means of relieving the particular adverse condition.

Instances may occur where the penalties (weight, oversize parts for the envelope, changed loads input after the design phase, etc.) for achieving full vehicle life are unacceptable to the subsystem performance requirements. The only alternative in this case is to reduce cycles of loading by reducing the life requirement for the component. Election of this option is a very serious step due to impact on Shuttle Orbiter operational capability and full justification for implementation is required to be furnished to the procuring agency. Reduced operating life will be established by determining the safe crack growth life (in missions) of the component using special NDE and dividing the analytical life by four (4). This reduced operating life shall be the "redlined" life of the component. During the Shuttle Orbiter operational phase, this component must be inspected and/or replaced at the end of the life interval. Obviously, the components which are redlined as far as life cycle performance should be capable of being easily inspected and replaced. If an inspected component reveals no flaws when inspected by special NDE at the end of the interval life, it is reasonable to expect the component to survive another full interval before being reinspected. Redlined life components must be designated as fracture critical.

6.4.4 Utilization of Multiple Element (Damage Tolerant) Load Paths

Design considerations often indicate the use of multiple, separate elements sharing the same load path. When this situation occurs, the analysis shall be conducted in the following manner. The most critical element shall be analyzed for safe crack growth life assuming the presence of one flaw. If the total life requirement is not satisfied when the fracture mechanics analytical life is expended, the remaining member (or members) shall be analyzed for residual, undamaged fatigue life when operating at the new, higher stress level. Accomplishment of the required performance life for total Shuttle Orbiter mission requirements when employing this method will signify an acceptable design.

6.4.5 Monitoring of Scheduled Structural Testing

Engineering Structural Analysts shall extract data from scheduled structural tests (conducted for structural development or verification reasons) to: (1) refine loads and stresses on candidate fracture critical components; and (2) monitor crack initiation and growth that may occur during the performance of the test. Information derived from these tests may be used to refine the crack growth analysis of components involved in the tests.

6.4.6 Performance of Fracture Mechanics Oriented Component Tests

When an analysis results in an indeterminate solution and no other alternative is available, the board/team shall elect to have a full size component tested under simulated Shuttle Orbiter conditions with a flaw (or flaws) incorporated into the specimen. Strict adherence to similarity of configuration, loading conditions, and environment shall be observed. If the test achieves the required life for the component (including scatter factor) and the residual static strength is equal to or greater than design limit load, the component shall be considered to be acceptable for use on the Shuttle Orbiter.

7.0 DEFINITIONS

The following terms are commonly used in fracture mechanics analysis and the fracture control program:

Crack or Crack-Like Defects - Defects which behave like cracks that may be initiated during material production, fabrication, or testing or developed during the service life of a component.

Fracture Mechanics - An engineering discipline which describes the behavior of cracks or crack-like flaws in materials under load.

Proof Test - The test load in excess of limit load which a part must sustain to give evidence of satisfactcry workmanship and material quality or to establish the initial crack size.

Fracture Critical Part - As defined in Figure 1 of this component and also in Figures A1 and A2 of the Appendix. Generally, a fracture critical part requires special treatment (e.g., applied special NDE technique to attain a smaller initial flaw size) in order to obtain an acceptable calculated service life (including scatter factor).

8.0 REFERENCES:

NASA Documents

NASA-JSC Specification SE-R-0006A, "NASA-JSC Requirements for Materials and Processes", dated April 1973.

Rockwell International Corporation

Space Division Specification MJ070-0001-1A, "Orbiter Vehicle End Item Specification".

Aerospace Group Directive D-06

Aerospace Group Publication 527-A-16, "Operating Standard for Fracture Control".

Aerospace Group Publication 527-A-12, "Operating Standard for Materials and Processing Control"

Space Division Policy No. C-10, "Fracture Control System"

Space Division Engineering Operations Manual, Shuttle Design Directive 70 2-4.5.3, "Fracture Control Requirements"

Specification MC999-0096, "Materials and Processes Control and Verification System for Space Shuttle Program: Suppliers and Subcontractors"

Specification MF0004-003, "Materials and Processes Control and Verification Systems for Space Shuttle Orbiter: Rockwell International Design"

SD72-SH-0172, "Space Shuttle Orbiter Materials Control and Verification Plan"

Space Division Publication 2543-W, "Materials Properties Manual"

APPENDIX A

CRITERIA FOR FRACTURE MECHANICS ANALYSIS OF SPACE SHUTTLE STRUCTURE

May 1974

1.0 SCOPE

1.1 This document contains the criteria for fracture analysis of space shuttle structural components. The procedures outlined herein are not intended to be directly applicable to advanced composite structures.

2.0 REFERENCES

a. MF0004-003 - Materials and Processes Control and Verification System for Shuttle Orbiter, 15 March 1974.

b. Crack Propagation Predictive Analysis Computer Program "FLAGRO", Rockwell International, Space Division, January 1974

c. Fracture Mechanics Predictive Analysis Program 2003-20, Rockwell International, Space Division, 1 October 1973

d. NASA TM-X-58086 - Computer Analysis of Two-Dimensional Fatigue Flaw-Growth Problems, February 1972

e. TFD-72-729, EFFGRO II Crack Propagation Analysis with Range-Pair Counting, 2 June 1972

f. Materials Properties Manual, Rockwell International, Space Division, Publication No. 2543-W.

3.0 GENERAL ANALYSIS REQUIREMENTS

A fracture mechanics assessment shall be performed for all orbiter primary structural members[1]. The purpose of the assessment is to insure that each structural member has a capacity to resist fracture or intolerable flaw growth under applied mission cyclic loads and environments. A crack growth analysis must be performed for all members whose failure may result in loss of the orbiter. A general logic for selection of components for crack growth analysis and subsequent classification as "fracture critical" is shown in Figure 1.

The crack growth analysis procedure should be based on a logical approach as shown in Figure A1 and A2 for airframe components and pressure vessels, respectively.

1 Primary structural members includes airframe, mechanical systems, and pressure vessels.

3.1 LIFE REQUIREMENT

All primary structural components shall be designed to survive a minimum of four service lifetimes. This requirement shall be demonstrated by a crack growth analysis that assumes an initial flaw placed in the most unfavorable location and orientation with respect to applied stresses and material fracture mechanics properties. The crack growth analysis shall be based on nominal dimensions[1] on the engineering drawing.

In general all orbiter components shall be designed to meet "safe crack growth life"[2] requirements. A service lifetime for a structural member will generally be identical to the design life of the particular orbiter system that the member is a part of. However, if a significant savings in weight or cost can be demonstrated, a shorter service life may be defined for selected components. Such components must be accessible for a thorough inspection and/or replacement at the end of the design lifetime. All parts that require in service inspection or replacement are to be automatically designated "fracture critical."

The use of multiple element "damage tolerant" design features is permissible provided the components meet the following requirements after failure of one of the structural elements.

(1) The remaining structure must withstand limit load and the remaining cyclic life without fatigue failure.

(2) Loss of the part shall not adversely affect any other subsystem or component.

1 If drawing tolerances permit a variation in thickness greater than 20%, a thickness of 1.10 times the minimum dimension shall be used for the fracture mechanics analysis.

2 The term "safe crack growth life" is used herein to describe components designed to insure that initial flaws do not propagate to critical length during their service life.

3.2 ANALYSIS OF PARTS WITHOUT HOLES

The fracture mechanics analysis for parts without holes shall assume the existence of part-through initial flaws in sizes consistent with flaw detection capabilities of standard and special non-destructive evaluation (NDE) techniques. Figure 2 from Reference (a) shows Rockwell International, Space Division, initial flaw size detection capabilities for standard and special NDE.

3.2.1 ANALYSIS OF AIRFRAME COMPONENTS

The crack growth analysis of flaws in airframe structural members without holes must consider, but is not limited to, the geometeries shown in Figure A3. All initial part through crack (PTC) sizes determined by NDE inspection limits (Figure 2) in the aspect ratio (a/2c) range from .2 to .5 shall be considered.

The analysis logic to be used for fracture mechanics analysis of airframe components without holes is shown in the diagram of Figure A1 (left side of page). The figure shows that analysis for part-through cracks is not required for thicknesses less than .075 in. and .025 in. for use of standard and special NDE, respectively. These represent the minimum material thicknesses required for the existence of all flaws defined by the NDE curves. In order to simplify the analysis of parts with thicknesses below the minimums for applicability of the NDE curves, initial through cracks of length (2c) equal to .20 in. and .075 in. are assumed to exist for standard and special NDE, respectively. These initial through cracks are as severe for life analysis as any possible PTC's defined by the appropriate NDE[1] curve (Figure 2).

Components whose computed life is equal to or greater than four times the design life requirement using standard NDE initial flaw sizes are not classified as "fracture critical". However, if it is necessary to use special NDE inspection to obtain four lifetimes, then the structural member is classified as "fracture critical". In some instances, such as parts requiring in-service inspection, the use of special NDE techniques may not be possible. In such instances the use of initial flaw sizes associated with special NDE inspection may not be used in the flaw growth analysis.

1 Extreme caution should be exercised when analyzing parts made from certain materials such as titanium 6Al-4V, STA condition for standard flaw sizes. When the material is worked to the maximum allowable limit stress, flaws on the standard NDE curve are larger than the critical size. In such cases, the stress level must be reduced and/or special NDE used.

3.2.2 ANALYSIS OF PRESSURE VESSELS

The crack growth analysis of flaws in pressure vessels must consider the presence of initial part-through cracks between aspect ratios (a/2c) of .05 and .50 defined by the standard and special NDE curves of Figure 2. The analysis logic diagram to be used for pressure vessels is shown in Figure A2. The diagram shows that pressure wall thicknesses less than .107 in. must be subjected to the appropriate inspection subdivisions of standard NDE. This requirement is based on the assumption that flaws on the standard NDE curve that extend through more than 70% of the pressure wall can be detected by standard radiography techniques (Reference a, Section 3.10.6).

If a particular pressure vessel does not meet the required life based on initial flaw sizes screened by standard NDE then special NDE must be investigated. The use of special NDE includes the assumption that inspection techniques will locate surface flaws that extend through more than 60% of the pressure wall thickness (Reference a, section 3.10.5). Failure to demonstrate the required life for initial flaws dictated by use of special NDE requires redesign (resizing) of the tank pressure wall or the exercising of options in Section 5.0. The use of cryoproof to screen flaws is an acceptable alternative to NDE if flaws screened by its use will not propagate to instability or through the thickness of the vessel wall when subjected to the design cyclic loading spectrum.

All Space Shuttle Orbiter pressure vessels, with the exception of the crew module, are by definition categorized "Fracture Critical". Also, for all pressure vessels, crew module excepted, leak must be assumed to constitute failure.

3.3 ANALYSIS OF PARTS WITH HOLES

The fracture mechanics analysis of structural components with holes shall assume the existence of flaws at the edge of holes consistent with, but not limited to, the geometries shown in Figure A4. Holes with driven rivets shall be assumed to have an initial flaw size of 0.005 inch.[1] Pins and mechanical fasteners may be assumed to be free from flaws.

The flaw growth analysis logic to be used for flaws at holes is shown in Figure A1 (right side of page). To account for the beneficial effects of surface preparation, a smaller initial flaw size is assumed to exist at a reamed hole as compared to a drilled hole. The initial surface length flaw sizes to be assumed for analysis purposes are .10 inch and .05 inch for drilled and reamed holes, respectively. For material thicknesses less than or equal to these values, a through crack of the same

1 This is an interim assumption pending test results.

length is used instead of a PTC. Parts with holes that exhibit at least four lifetimes by analysis using the appropriate initial flaw size are not classified "fracture critical". However, if a component demonstrates a calculated life less than four, a redesign (resizing) must be implemented. If in the redesign to achieve the required life, special crack growth retarding procedures are used, such as interference fasteners or cold working, then the part must be designated "fracture critical". If no special methods are implemented in the redesign cycle, a "fracture critical" designation is not required.

For components where it is necessary to consider the propagation of a crack into a fastener hole or away from a fastener hole toward the edge of a plate, the following analysis assumptions shall be implemented.

(1) When a crack grows to a hole or panel edge, its length increases immediately by an amount equal to the diameter of the hole.
(2) The life prediction analysis is then continued using the new crack length that includes the hole diameter.
(3) The component's total life is obtained by summing the mission cycles prior to and subsequent to reaching the hole or panel edge.

3.4 ANALYSIS METHODOLOGY

The fracture mechanics analysis methodology used to compute flaw growth shall be based on a cycle by cycle or finite incremental length integration of the growth rate equations (da/dN and dc/dN). Also, the methodology used must consider the two dimensional growth characteristics of surface flaws (PTC's). References b, c, and d are examples of computer programs that compute two dimensional growth of surface flaws.

Because of the anticipated temperature and environment excursions for the orbiter, the facility to couple various phases of the mission with varying material properties must be included in the analysis method. References b and c incorporate this feature. Also, all fracture mechanics analysis methodology used for Space Shuttle structures must be consistent with the methodology of References b and c. Any deviations from the methodology of References b and c must have the prior approval of the RI/SD Structural Analysis Group.

The capability to account for complex variable amplitude spectra loadings, excursions between mean stress levels (ground-air-ground effects), and negative stress ratios is an essential requirement for crack propagation analysis of airframe components. Reference b utilizes a range-pair counting routine developed at the Rockwell International's B-1 Division for the Reference e computer program to account for excursions between mean stress levels.

4.0 FRACTURE PROPERTIES DATA

The fracture properties data to be used in the crack growth analysis shall be consistent with the data of Reference f. The data shall be based on test results and characterize the relationship between stress intensity and growth rate for surface flaws and through cracks as a function of material thickness, temperatures, and environments anticipated for the Space Shuttle Orbiter. All data must adequately represent the sigmoidal nature of stress intensity plotted versus growth rate with proper designation of lower (ΔK_o), cutoff (K_{th}), and critical (K_{cr}) stress intensities. All deviations or additions to the data of Reference f must have prior approval of the Rockwell Space Division Materials and Processes Section. All fracture properties used in the crack growth analysis shall be average data, except for the cutoff stress intensity which shall be a minimum property.

5.0 ALTERNATES TO REDESIGN OF PARTS WITH DEFICIENT SERVICE LIFE

For parts whose redesign to obtain four service lifetimes is impractical in that intolerable weight penalties and/or slippage in schedule occur, alternate dispositions such as the following should be considered singly or in combination.

(1) The design life of a component may be reduced from that of the system of which it is a part to a lesser value based on mandatory inspection intervals.

(2) Use of special crack retarding features at fastener holes such as interference fasteners or cold working devices. However, any beneficial crack retardation effects due to such methods must be substantiated by test or reasonable analysis methods.

(3) Structural testing of initially flawed components may be used for analysis refinement where conservatism is inherent to the fracture mechanics analysis.

(4) Proof testing and incremental proof testing (with appropriate post proof inspection) may be used to verify mission life requirements.

(5) Monitoring of scheduled structural tests may result in a redefinition of internal stress distribution in a component. These revised stresses are to then be used in the fracture mechanics analysis.

The implementation of any of the above dispositions for any structural component requires an automatic "fracture critical" classification for the component.

6.0 TERMINOLOGY

The following symbols and terms are commonly used in fracture mechanics analysis and the fracture control program.

Crack or Crack Life Defects - Defects which behave like cracks that may be initiated during material production, fabrication, or testing or developed during the service life of a component.

Fracture Mechanics - An engineering discipline which describes the behavior of cracks or crack like flaws in materials under load.

Proof Test - The test in excess of limit load which a part must sustain to give evidence of satisfactory workmanship and material quality or to establish the maximum possible initial crack size.

Safe Life - Predicted service life of a structural component based on conventional fatigue analysis.

Safe Crack Growth Life - Predicted service life of a structural component based on fracture mechanics analysis which assumes the presence of a crack at the beginning of service.

Scatter Factor - Multiplication factor applies to the required service life of the structure. The product of the scatter factor and required life is used as the target predicted service life to allow for material, manufacturing, loads, service, and analysis methods variables.

Damage Tolerance - As defined in Section 3.1 of this Appendix.

Active Environment - Any liquid or gaseous media and temperature combination which alters static or fatigue crack growth characteristics from "normal" behavior associated with an ambient temperature, dry laboratory air environment.

Fracture Critical Part - As defined in Figure 1 of this document and also in Figures A1 and A2 of this Appendix. Generally, a fracture critical part requires special treatment (e.g., applied special NDE technique to attain a smaller initial flaw size) in order to obtain an acceptable calculated service life (including scatter factor).

Load Block - The entire loads spectrum.

Spectrum Data - A tabulated form of a spectrum defining the maximum and minimum load magnitude and number of cycles for each step in the spectrum.

Load Step - A load level application in the spectrum table.

Limit Load - The maximum load expected on the structure during mission operation including intact abort.

Ultimate Load - The product of the limit load multiplied by the ultimate factor of safety.

Ultimate Factor of Safety - The factor by which the limit load is multiplied to obtain the ultimate load.

K - applied (K) - The stress intensity calculated from an appropriate stress intensity solution and evaluated at a specific applied stress and crack size.

K_{Ic} - Plane strain fracture toughness as measured in accordance with all the requirements of ASTM Specification E399-72.

K_{IE} - The static toughness value of a material containing a part-through-crack.

K_{cr} - The static toughness value of a material and thickness containing a through-crack.

K-cutoff (K_{TH}) - The applied stress intensity value above which sustained load flaw growth is expected to occur as a direct result of environmental activity.

ΔK - Stress intensity range associated with cyclic load application. It is the difference between the maximum and minimum applied stress intensities.

K_{PTC} - For fatigue crack growth analysis, the maximum stress intensity value of the applied stress intensity range which results in an unstable crack propagation for part-through-cracks. This parameter is used in association with the Collipriest crack growth rate equation for the case of part-through-crack.

K_C - For fatigue crack growth analysis, the maximum stress intensity value of the applied stress intensity range which results in an unstable crack propagation for through-cracks. This parameter is used in association with the Collipriest crack growth rate equation for the case of through-crack.

ΔK_o - The stress intensity range below which fatigue crack growth will not occur.

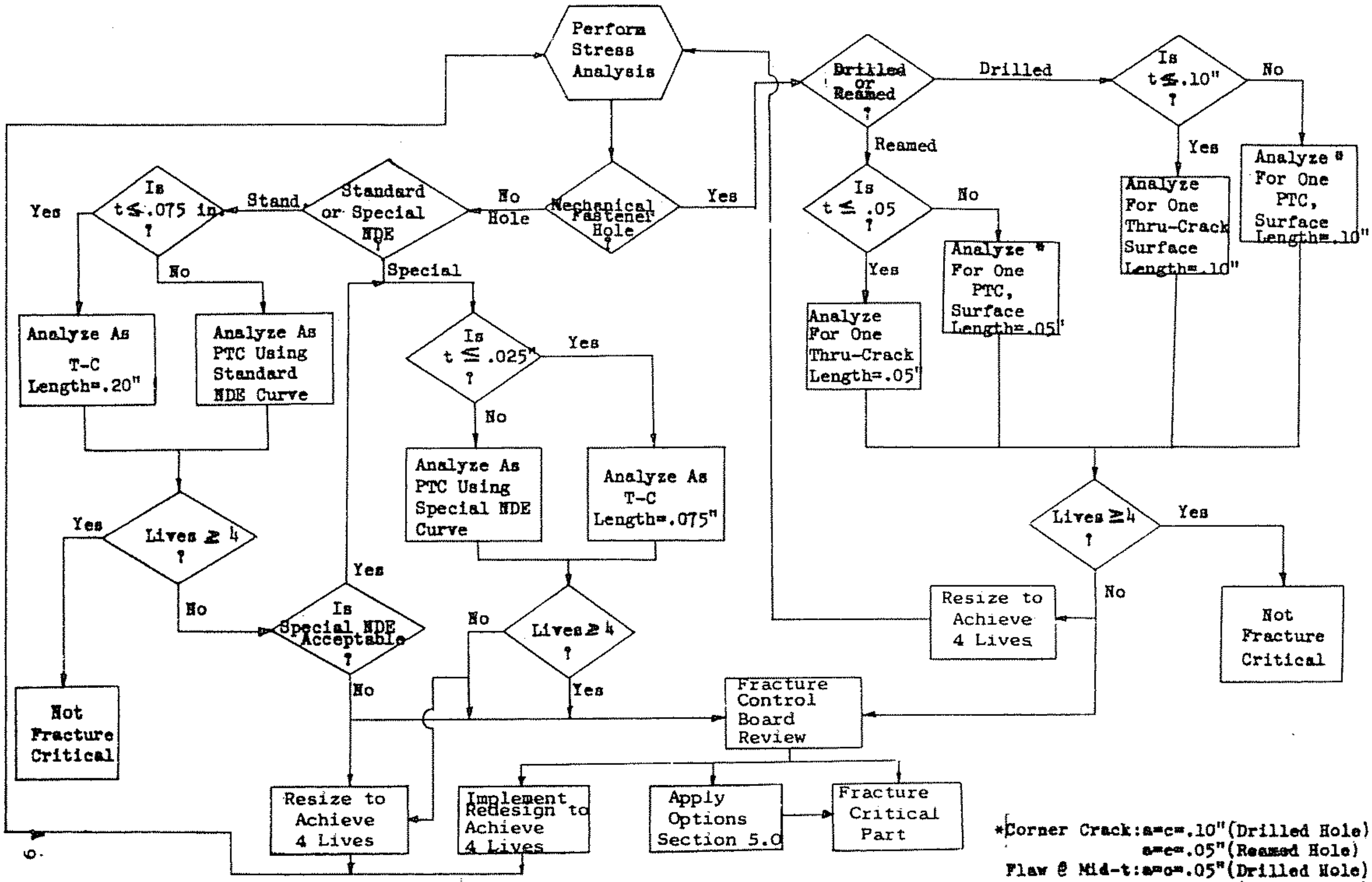
R - Minimum applied stress to maximum applied stress ratio.

C - A parameter which describes the fatigue crack growth behavior in the Collipriest crack growth rate equation.

n - A parameter which describes the fatigue crack growth behavior in the Collipriest crack growth rate equation.

Figure A1

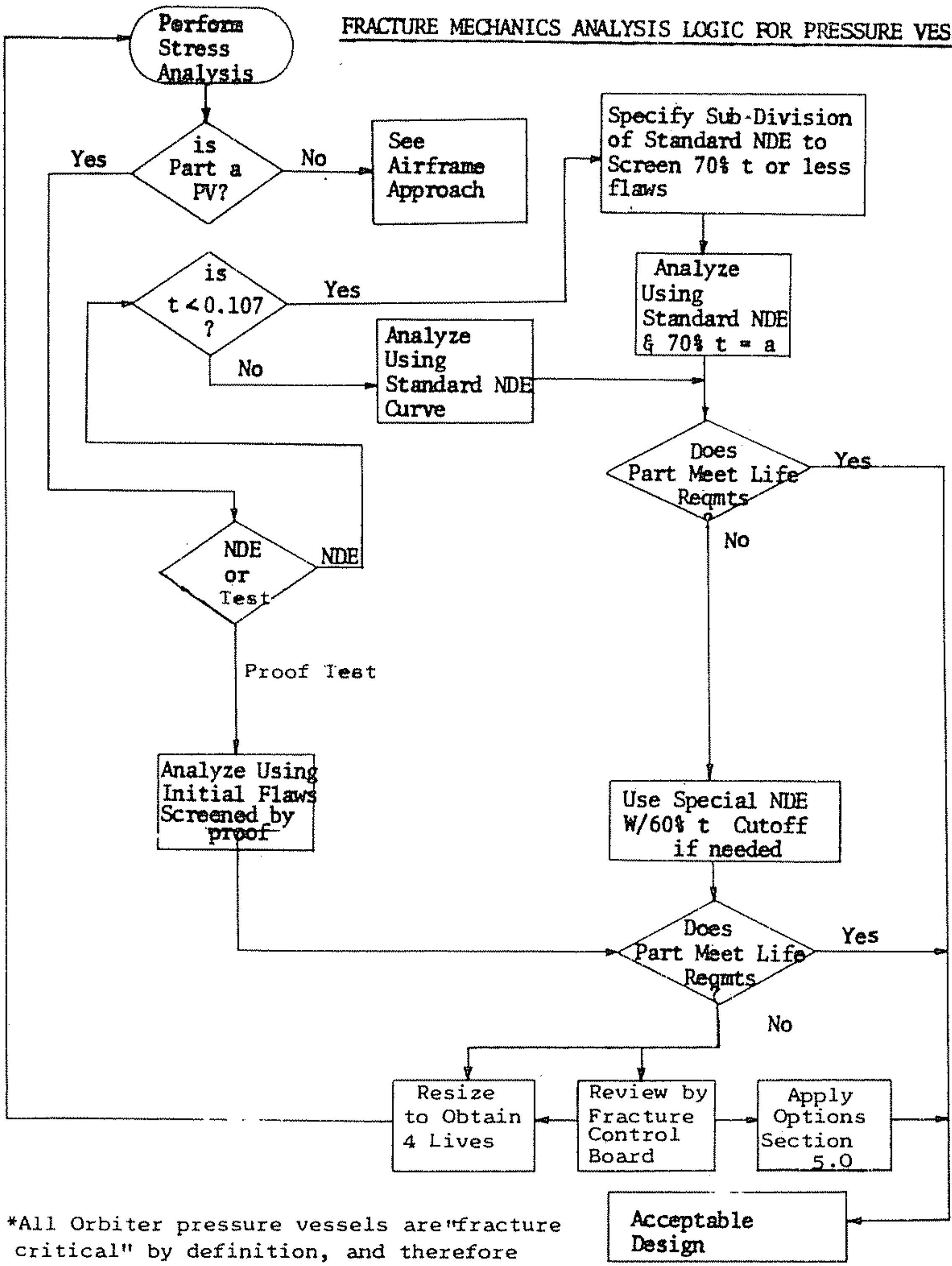
Fracture Mechanics Analysis Logic - Airframe Components



*Corner Crack: a=c=.10" (Drilled Hole)
a=c=.05" (Reamed Hole)
Flaw @ Mid-t: a=c=.05" (Drilled Hole)
a=c=.025" (Reamed Hole)

FIGURE A2

FRACTURE MECHANICS ANALYSIS LOGIC FOR PRESSURE VESSELS*

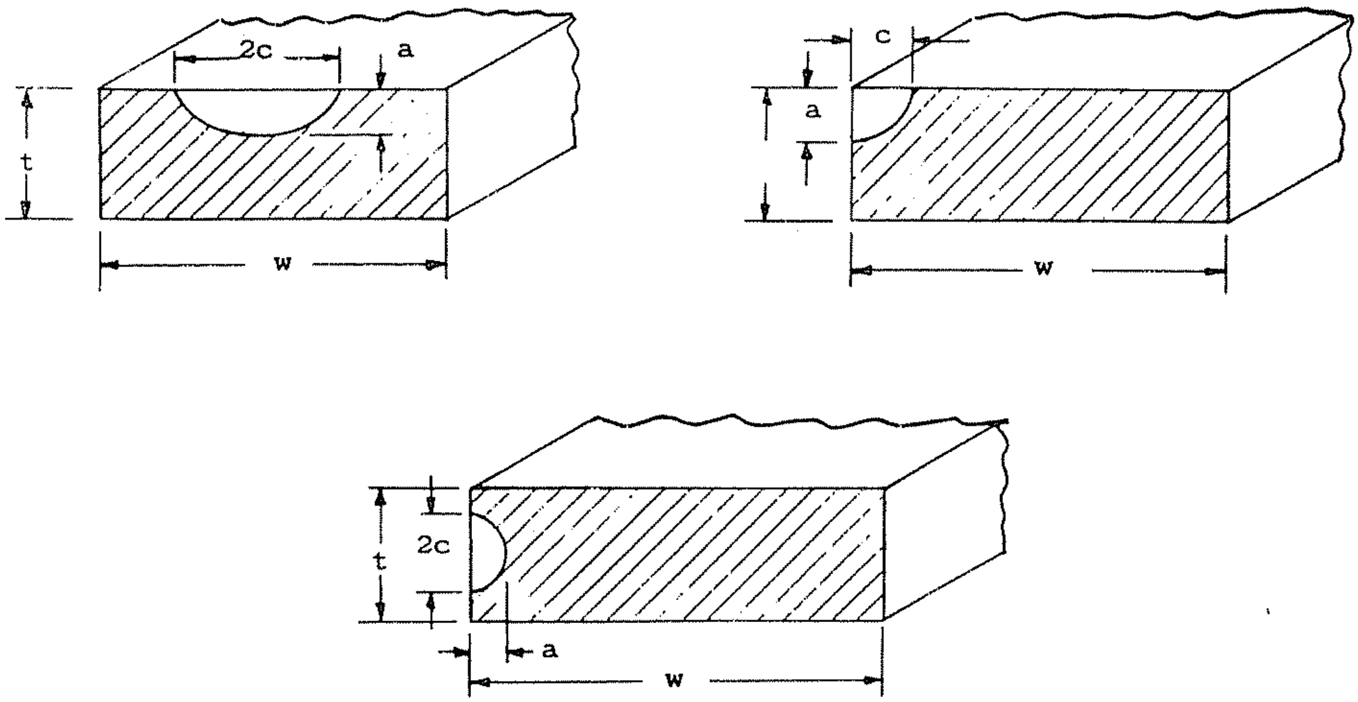


*All Orbiter pressure vessels are "fracture critical" by definition, and therefore require review by the Fracture Control Board

Figure A3

Initial Crack Geometries -
Parts Without Holes

Part-Through Cracks



Through Cracks

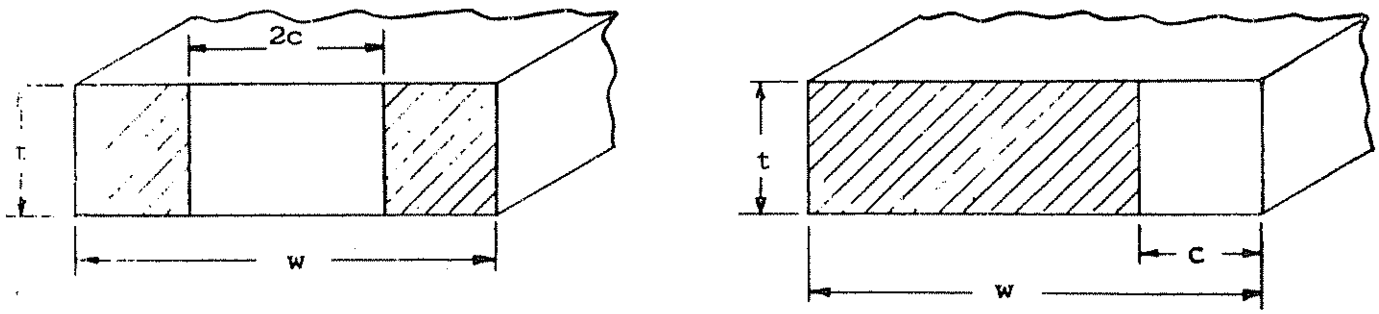
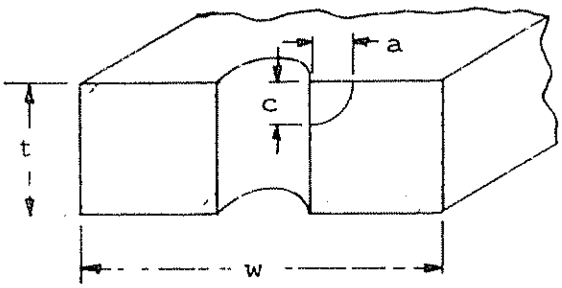


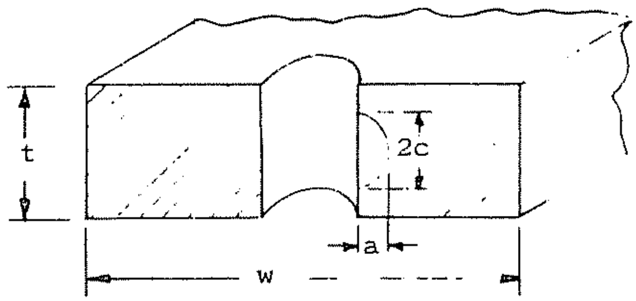
Figure A4

Initial Crack Geometries

Parts with Holes

Part-through Cracks

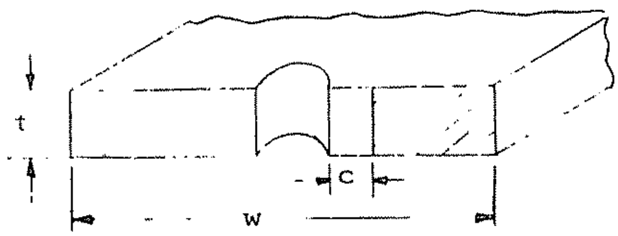




Drilled: t > .10 in.
a = c = .10 in.

Reamed: t > .05 in.
a = c = .05 in.

Through Crack



Drilled: t ≥ .10 in.
c = .10 in.

Reamed: t ≥ .05 in.
c = .05 in.

SHIP TO:

CARLTON PTD
504 MC CORMICK DRIVE
GLEN BURNIE. MD 21061
United States

Attn: JIM HARRIS -

JPL
4800 Oak Grove Drive
Pasadena, CA 91109

SHIPPER #	ORDER #	SHIP TERMS	SHIP DATE
X-09674	68636	PREPAID	07-NOV-01

FOB	WEIGHT	PACKAGES
Origin	1	1

SHIPMENT AUTHORIZATION #
NONE

WAYBILL	CARRIER	ADDITIONAL WAYBILL	ADDITIONAL CARRIER
604217112168	FEDERAL EXPRESS NEXT AM DLVY		

ITEM	DESCRIPTION	NEMS	SERIAL #	TOTAL VALUE
1	1 LOT. DOCUMENTATION RE: SPACE SHUTTLE ORBITER FRACTURE CONTROL PLAN $			$0

Reason For Shipment: FOR REVIEW AND RETENTION.
Est. Return Date: N/A
Requester: DALEO, TIMOTHY M
Preparer: SGUPTILL

Project #: 101025
Task #: 05.08.02
Section #: 3530