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SPACE SHUTTLE ORBITER
FRACTURE CONTROL PLAN

MARCH 1973

Contract NAS9-14000

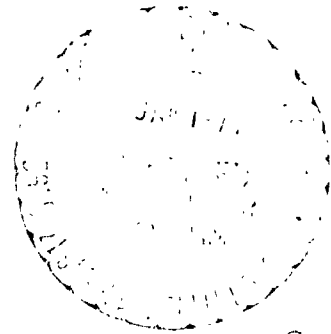
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Space Division
Rockwell International

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1.0 GENERAL POLICY

It is the policy of the Space Division to design products which provide adequate safety while limiting the use of fracture critical parts to those essential to vehicle safety which are subject to potential fracture during use.

2.0 OBJECTIVE

To establish responsibilities, criteria, and procedures for the prevention of Space Shuttle structural failure associated with the initiation or propagation of cracks or crack-like flaw during fabrication, testing, handling and transportation, and the operational life of the vehicle.

3.0 SCOPE

All activities influencing the structural integrity of deliverable 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 structures design, analysis, and test; materials selection, purchase and storage; fabrication process control; quality assurance tests and non-destructive evaluation; and operations and maintenance.

4.0 PREREQUISITES AND ASSUMPTIONS

1. It is assumed that data generated for both critical and noncritical 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 design structural analysis including fatigue analysis.
2. A comprehensive test program will be conducted to verify the basic vehicle design and structural integrity.
3. 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 noncritical.

5.0 ORGANIZATION, FUNCTION, AND RESPONSIBILITIES

The following organizations have been identified as necessary to an effective fracture control program:

1. Engineering
2. Assurance Management
3. Production Operations
4. Tests and Operations
5. Procurement

Organization of the resources of these elements into an effective team is described in the following paragraphs.

5.1 Fracture Control Board

Implementation of the fracture control plan is the responsibility of a fracture control board appointed by the Rockwell International Space Shuttle Orbiter Vice-President and Program Manager. Prime responsibility for managing this program rests with the board chairman.

Board members are responsible for ensuring implementation of the fracture control program and board directives within their own organizations and for maintaining board awareness of fracture control progress or problems arising within these organizations. Minutes of board meetings shall be maintained. All board actions and directives shall be recorded in writing and maintained for NASA review, if requested. A NASA observer may attend board meetings to provide full visibility into the fracture control program. This board shall function as a Material Review Board (MRB) for fracture control parts.

5.1.1 Board Membership

The fracture control board shall consist of the following members:

1. Chairman (appointed by Space Shuttle Chief Program Engineer)
2. Engineering Design Representative

3. Engineering Analysis Representative
4. Engineering Materials Representative
5. Assurance Management Representative
6. Production Operations Representative
7. Test and Operations Representative

Responsibilities of each of the organizational representatives and their organizations is described in the following paragraphs:

5.1.1.1 Engineering

Engineering is responsible for the design, analysis, and selection of materials for fracture critical parts. Engineering is also responsible for defining the characteristics to be considered in the selection of parts which will be subject to fracture control. In exercising these responsibilities Engineering shall seek and include design features which improve inspectability or manufacturing operations.

Engineering shall establish and implement a system for identifying all fracture critical parts on engineering drawings and other related documentation and shall prepare, maintain, and distribute a summary listing of all parts subject to fracture control for the Space Shuttle.

5.1.1.2 Assurance Management

Assurance Management is responsible for providing data to Engineering relative to the size, location, and character of flaws that can be reliably detected in materials or parts by inspection and for contributing available information regarding size, character, location and frequency of defects that may be induced by the selected fabrication techniques based on records developed in applicable production efforts on Space Shuttle and other programs. Assurance Management is also responsible for verifying that fracture control requirements defined by engineering documentation have been met during production of raw material, in-house and supplier

fabrication processes, testing, and operational service, and for maintaining all required documentation pertaining to fracture control parts including historical and operational data. This also includes qualification of processes and the certification, qualification or indoctrination of personnel as required.

5.1.1.3 Production Operations

Production Operations is responsible for the detailed definition of fabrication techniques to be used in producing fracture critical parts and for contributing information regarding the type and probable location of defects that may be induced in the structural component by these techniques (based on related experience). They are also responsible for ensuring that both tooling and techniques used in manufacturing are reviewed and approved by the board as acceptable for use with fracture critical parts.

5.1.1.4 Operations and Test

Operations is responsible for ensuring that processes used during test, and operation of fracture critical parts are compatible with fracture control requirements. This involves incorporation of fracture control requirements defined by engineering documentation into all test and operational procedures.

5.1.2 Procurement Responsibility

Although not represented on the board, Material is responsible for the inclusion and implementation of fracture control requirements defined in engineering documentation into contractual agreements with suppliers of materials, parts, or processes subject to the fracture control system.

Material is also responsible for obtaining cost and contractually-required technical information from suppliers and subcontractors and for warehousing-controlled fracture toughness material separately from conventional material.

6.0 CRITICAL PARTS SELECTION CRITERIA

The identification of fracture critical parts is based on parts function, load and thermal environment, life analysis, material and accessibility for inspection during fabrication and operation of the vehicle.

Figure 1 presents the selection logic to be used in the evaluation and disposition of parts with respect to the fracture control programs.

The Shuttle Program Fracture Control Board has final Rockwell International approval authority for selection of the components subject to the fracture control system. Fracture control requirements and their identification will be verified at Engineering design reviews. NASA Program Office will be informed of any deviation to the requirements.

7.0 PROCEDURES, DOCUMENTS AND REQUIREMENTS

The following specific requirements shall be incorporated and defined in detail in individual fracture control procedures documents developed and tailored to the requirements of each selected fracture critical part. Each such procedures document shall be reviewed and bear evidence of board approval before initiation of manufacturing operations.

7.1 Engineering

7.1.1 Design

All fracture control parts and components shall be designed using sound and established design practices. These practices shall include, although not be limited to the following:

1. Minimizing eccentricities and stress concentrations that could act as fatigue crack nuclei.

2. Providing access, conditions, and clearance, where possible, to implement inspection, test, and maintenance. Materials and their design operating stress levels shall be selected so that the required life for a given component can be evaluated by analysis and available non-destructive evaluation (NDE) techniques, by proof test, or by a combination of the two.

Parts selected for fracture control will be clearly identified in all design documents (engineering drawings, EO's, etc.) which will be identified by serial number to facilitate accumulation and retrieval of fracture control information by part, material, and process.

7.1.2 Materials and Processes

Fracture control considerations shall be an integral part of the material and processes selection task to ensure that the characteristics of the selected material meet required toughness standards. In addition to normal functional requirements, characteristics to be considered include:

1. Fracture toughness and other fracture related properties such as crack growth rate, threshold stress intensity, stress corrosion cracking susceptibility, effects of fabrication and joining processes, effects of cleaning agents, dye penetrants and coatings, effects of temperature and other environmental considerations.
2. The adequacy and validity of data for candidate materials under particular usage requirements.
3. The effects of processes, geometric configuration, fiber or grain orientation, and manufacturing tolerances on flaw initiation and growth.
4. Stress corrosion, dissimilar metal corrosion, and other environmental effects leading to crack nucleation or growth; nonsensitive materials and/or providing for environmental control will be considered.

Materials and Processes shall prepare Space Division (SD) material specifications when fracture control requirements are not adequately defined by existing government or industry specifications. The specification shall incorporate any special requirements for fracture control. It shall also specify test method, test specimen configuration and material sampling requirements to verify compliance with these requirements. Requirements for special environmental control of fracture critical parts during inactive periods of operational service (maintenance, standby, inspection, storage) will be determined to prevent general corrosion and stress corrosion cracking.

The material specification shall include any special nondestructive evaluation techniques and inspection standards to be used to verify the quality of the mill product. No subsequent changes to production methods by the primary subcontractor or any sub-tier contractor will be allowed without the approval of SD.

Fracture properties used in the materials selection process and their sources shall be documented and maintained.

Test programs to determine the fracture properties of materials when sufficient data do not exist will employ initial screening tests to minimize the need for subsequent detailed tests.

Where possible, uniform test procedures conforming to recognized standards will be employed for determination of material fracture properties. The test specimens and procedures utilized will provide valid test data for the intended application.

Material suppliers will be surveyed by Materials and Processes before procurement to evaluate their ability to produce materials that meet fracture control requirements.

The primary raw material supplier or any sub-tier suppliers of Certified Special Processes (CSP) such as heat treating, plating, or testing which could influence fracture behavior must be on the SD Qualified Source List (QSL). These suppliers will be identifiable in the QSL and will not be changed without prior approval from SD.

7.1.3 Structural Analysis

A fracture mechanics analysis that supplements nominal structural static and fatigue analyses will be conducted for all fracture critical parts. This evaluation will consider all significant conditions during fabrication, preoperational test, and operational phases that may affect fracture behavior, including the following, as appropriate:

1. Size, character, orientation, and location of initial flaws that could become critical during the service life.
2. Proof test or nondestructive inspection to verify that no flaws exist that could become critical during operational service.
3. Analyses and definition of test requirements and evaluation of test results, including structural development and qualification tests, and proof tests.
4. Evaluation of the presence of residual stresses in the selection of manufacturing and assembly processes and sequences.

7.2 Assurance Management

The quality assurance system applied to fracture control parts and components will verify that material, production processes and parts conform to engineering requirements.

Assurance Management will review the potential initial flaws (size, character, orientation) described on the engineering documentation of fracture control parts to determine optimum NDE technique(s) and equipment to ensure reliable detection. Laboratory testing and evaluation will be performed as required to establish procedures for each specific fracture control part.

The capability of the selected NDE technique(s) to reliably detect initial flaws defined by Engineering documentation for fracture control components will be verified based on data from applicable production experience or by laboratory demonstration which incorporates realistic simulation of flaw characteristics and actual production inspection conditions. Data that permits the confidence of flaw detection to be expressed quantitatively, with a statistical basis, is required.

Assurance Management shall immediately notify the Fracture Control Board of any case in which it is determined that the best available NDE techniques will not reliably detect specified initial flaws.

Receiving and/or source inspection will be conducted on all raw materials procured for use in the fabrication of fracture control hardware. Tests, as required, shall be conducted to insure compliance with Materials Processing Specifications requirements and to ensure that line inspection points and methods are adequately established to verify all significant processing steps for fracture control parts. Pertinent fracture properties measured as a part of inspection shall be maintained and available for review. Significant fracture data on production operations of fracture control parts will be collected and maintained to determine which inspection points should be adjusted during the remainder of the production program. Destructive testing of initial fracture control production parts will be performed on the finished item or after critical processing steps as required to verify compliance with fracture control requirements.

7.2.1 Quality Review and Reporting

Inspection data indicating non conformance with specifications associated with fracture control material and parts will be compiled and reported to the Fracture Control Board and to NASA. A summary assessment will be prepared and reported to the Fracture Control Board. These data will include, but are not limited to, the following:

1. Incidence of material defects, including range of size, character, location and cause.
2. Incidence of weld defects including size, location, and cause of cracking.
3. Incidence of cracks caused by fabrication processes.
4. Departures from required values for fracture toughness, mechanical properties, critical dimensions, or surface finishes.

7.2.2 Failure Documentation

A complete documentation will be made of fracture significant failures involving fracture control components during manufacture and acceptance testing. The cause of failure and any contributing factors will be documented to the extent possible and the document will include recommendations for corrective actions required in the control of material procurement, fabrication processes, quality assurance methods, or operational procedures.

A report of failure evaluation results and recommended corrective action will be prepared and disseminated to the Fracture Control Board and to NASA and Rockwell International program management.

7.2.3 Traceability

Fracture control parts will be serially numbered and detailed process and inspection records will be traceable to a given part and fracture control lot of raw material. In addition, all discrepancy documentation shall be clearly identified as fracture critical hardware.

7.2.4 Personnel Certification

Manufacturing and Assurance Management will jointly identify any special qualification levels required to ensure that critical operations are performed with skills that meet fracture control requirements. The general requirements for these qualification levels will be coordinated with Personnel, which is responsible for detailed definition and implementation.

When supplier and subcontractor personnel must be specially trained and/or qualified to perform critical operations on fracture control hardware, these requirements will be implemented through Material.

7.3 Production Operations

Production Operations will select and define fabrication techniques to be used in producing fracture critical parts and will prepare processing procedures to implement the manufacturing activities.

7.3.1 Manufacturing and Tooling Orders

Manufacturing orders and tooling orders will be clearly identified as applicable to fracture controlled parts or components and will be approved by the Fracture Control Board for compliance with the appropriate materials processing documents prior to Manufacturing Planning release.

The designs for tooling, fixtures, and manufacturing aids used on fracture control parts shall be compatible with fracture control requirements and objectives. Fracture control aspects to be considered in the design of tooling, fixtures, etc. will include, but are not limited to:

1. Protection of components from damage during hoisting, positioning, transporting, etc.
2. Elimination or minimizing of residual stresses during processing.
3. Maintenance of satisfactory and consistent control over critical process variables that are a function of the tooling, such as diffusion-bond tooling, welding chill and backup bars, etc.

4. Maintenance of tolerances and meeting of surface finish requirements.

7.3.2 Fabrication Processes

Production Operations will ensure that fabrication processes used on fracture control components are compatible with fracture control requirements. This includes participation in qualification of processes and the certification, qualification, or indoctrination of personnel as required.

Fabrication operations to which fracture control requirements may apply include, but are not limited to, the following:

1. Material removal
2. Forming
3. Joining (welding, brazing, bonding)
4. Thermal treatment
5. Chemical (cleaning, plating)
6. Assembly
7. Material handling

7.4 Operations and Tests

Operations and Test will ensure that structural testing is conducted in a manner compatible with fracture control evaluation requirements when fracture critical parts are involved. Board approval of all test plans involving specific investigation of fracture critical parts is required.

7.4.1 Fracture Control Verification Tests

Sufficient testing will be performed to provide confidence that the design will result in satisfactory service life and fracture characteristics.

Test specimens will include preflawed material specimens, joint specimens, or components as needed to demonstrate fracture control requirements.

Test requirements and procedures will include verification by inspection of the effectiveness of fracture control procedures and identification

of areas in which improvement is needed. Where possible tests shall utilize test article hardware obtained for standard structural tests and testing shall follow completion of structural tests unless it is feasible to conduct parallel evaluations.

7.4.2 Structural Verification Tests

Data obtained through structural qualification tests will be reviewed to determine if changes to design or materials of fracture critical parts are needed. Where possible, test loading and environmental simulation shall reproduce critical design conditions for fracture control parts.

Anticipated critical sections of fracture control parts or components should be identified prior to the start of testing. These sections should be given particular attention during the test to identify crack propagation characteristics and rates. Repair of any cracks detected in fracture critical parts shall receive prior approval of the fracture control board.

7.4.3 Service Testing

Fracture control requirements will be considered in the planning of in-service structural test and/or evaluation programs.

Data from flight tests will be analyzed to improve the prediction of maximum service stresses, environment spectrum, and critical flaw sizes.

7.4.4 Proof Testing

Proof testing of fracture controlled non-integral pressure vessels such as propellant tanks and gas storage bottles is mandatory.

For integral tankage, where conventional proof-testing (i.e., pressure loading only) does not include all critical flight-load conditions, a combined pressure and external loading test will be conducted unless it can be demonstrated to be unnecessary because of adequate NDE.

Unpressurized structural fracture control parts will require proof testing only if it can be shown that the proof testing adequately defines critical flaws for all significant loading conditions or if proof testing is required to enhance inspectability.

7.5 Operations and Maintenance

Operations and Maintenance shall submit procedures involving fracture control parts for board approval to ensure compatibility with fracture control requirements.

7.5.1 Periodic Inspection/Verification

Required inspection procedures will be defined for all fracture control parts that have been designed for operational periods of less than the total service life of the vehicle.

These procedures will be based on the total experience gained over the fracture control program, including data derived from fabrication, structural development, and structural verification tests.

The capability of appropriate NDE techniques and procedures to reliably detect the specified flaw sizes in the field will be verified.

For any cases in which the NDE capabilities are not adequate to reliably detect specified flaws, and the entire service life capability has not been verified by initial proof testing, periodic inspection proof test will be conducted. Proof test procedures shall include descriptions of proof loading and environment, and appropriate post test inspection requirements.

7.5.2 Actual Service Accumulation

An accurate record of actual service experience shall be maintained for each critical part to permit early identification of problem areas and development of corrective action for the remainder of the operational articles.

Consideration will be given to obtaining accelerated service exposure experience on a limited number of typical operational parts prior to installation in the vehicle.

The accumulated operational experience data shall be continually monitored and documented to update fracture control information and to permit engineering review of any areas that require corrective action.

7.5.3 Environmental Control

Requirements for special environmental control of fracture control components during inactive periods of operational service (maintenance, standby, inspection, storage) will be implemented to protect against general corrosion and stress-corrosion cracking. Particular attention shall be devoted to any areas that are inaccessible for inspection during normal inactive periods. Responsibility for implementation of special environmental controls during inactive periods of operational service will depend on specific contractual requirements of the program.

8.0 DEFINITIONS

For the purpose of this plan the following definitions are applicable:

Fracture Control - The rigorous application of those branches of Engineering, Assurance Management, Manufacturing and Operations Technology dealing with the understanding and prevention of crack propagation leading to catastrophic failure.

Fracture Control Plan - A Space Division Plan which controls those parts identified as "fracture critical" and is directed toward preventing catastrophic structural damage associated with cracks or crack-like flaws during fabrication, acceptance testing or operational service.

Fail-Safe - The ability to sustain failure and retain the capability to terminate the mission.

Safe-Life - A design approach under which failure will not occur because of fatigue damage during the specified life of the article.

Critical Crack Size - The crack size which, for a given applied stress, causes unstable crack propagation.

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 Critical Part - See Figure 1.

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

Fracture Toughness - An inherent material property which describes the resistance to fracture.

Initial Crack Size - The maximum size crack as defined by proof test or nondestructive inspection which could exist in parts.

Limit Load - The maximum load expected in the structure during operation including abort and loss of one main engine.

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 initial crack size.

Ultimate Load - The product of the limit load multiplied by the ultimate factor of safety. It is the maximum load which the structure must withstand without rupture or collapse.

9.0

REFERENCES

SOM Procedure

D-01.8 Operating Standard for Fracture Control

Publications

527-A-16 Operating Standard for Fracture Control

527-A-12 Operating Standard for Materials and Processing Control

531-A Engineering Procedures Manual

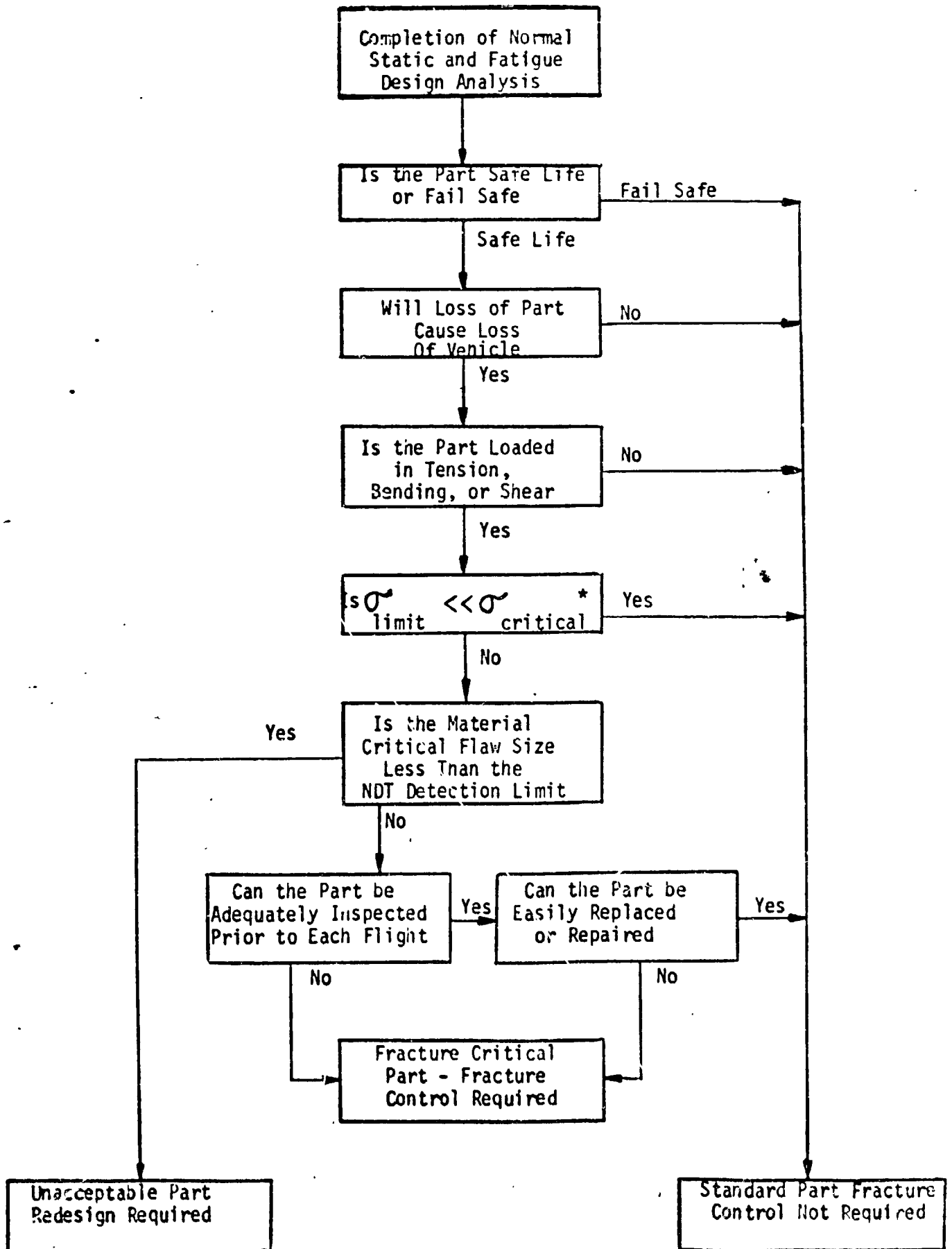
SD72-SH-0172 Space Shuttle Orbiter Materials Control and Verification
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Publication 543-G-36, Rev. 9-68, SD Industrial Safety Operations Standards,

Sect IX F

Figure 1. Critical Part Selection Logic



*As proven by a Safe Life Analysis.