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ESA fracture control requirements

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ABSTRACT

This document specifies the fracture control requirements to be imposed on ESA space systems.

DOCUMENTATION CHANGE RECORD

Issue number and Date	Sections Affected	Remarks
Issue 1, March 1989	All.	New document.
Issue 2, November 1994	All.	Document completely revised.

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LIST OF FIGURES AND TABLES

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SECTION 1. SCOPE

This document specifies the fracture-control requirements to be imposed on ESA space systems.

The requirements contained in this document, when implemented, also satisfy the requirements applicable to the NASA STS as defined in the NASA document NHB 1700.7. Since this document and the NASA document NHB 1700.7 are subject to different independent approval authorities, and recognising that possible changes to documents may occur in the future, the user of this document is advised to confirm the current status with the ESA Fracture Control Board.

The definitions used in this document are based on ESA nomenclature and are given in Appendix A. The NASA nomenclature differs in some cases from that used by ESA. When STS-specific requirements and nomenclature are included, they are identified as such.

Unless explicitly stated otherwise, the units used throughout this document are SI units or metric units.

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SECTION 2. GENERAL

2.1 INTRODUCTION

ESA PSS-01-40 (System safety requirements for ESA space systems) requires that fracture-control principles be applied where structural failure could result in a hazard which has catastrophic or serious consequences. The terms "catastrophic consequences" and "serious consequences" are defined in Annex A to this document.

In addition, NASA NHB 1700.7 (Safety policy and requirements for payloads using the Space Transportation System [STS]) requires that the payload structural design shall be based on fracture-control procedures when the failure of an STS payload structural item can result in a NASA STS payload catastrophic event (see NHB 1700.7).

The assumptions and prerequisites which are the basis of the requirements contained in this document are the following:

(i) All real structural elements contain crack-like defects located in the most critical area of the component in the most unfavourable orientation. The inability of non-destructive inspection (NDI) techniques to detect such defects does not negate this assumption, but merely establishes an upper bound on the initial size of the cracks which result from these defects. For conservatism, this crack size then becomes the smallest allowable size to be used in any analysis or assessment.

(ii) After undergoing a sufficient number of cycles at sufficiently high stress amplitude, materials exhibit a tendency to initiate fatigue cracks, even in non-aggressive environments.

(iii) Whether, under cyclic and/or sustained tensile stress, a pre-existing (or load-induced) crack does or does not propagate depends on:
- the fracture toughness of the material;
- the initial size and geometry of the crack;
- the presence of an aggressive environment;
- the geometry of the item;
- the magnitude and number of loading cycles;
- the temperature of the material.

(iv) The engineering discipline of linear elastic fracture mechanics provides analytical tools for the prediction of crack propagation and critical crack size.

(v) For non-metallic materials (other than glass and glass-like materials) and fibre-reinforced composites (both with metal and with polymer matrix), linear elastic fracture mechanics technology is agreed by most authorities to be inadequate. Fracture-control of these materials, therefore, relies on the techniques of containment, fail-safe assessment, proof testing and cyclic load testing.

(vi) A scatter factor is required to account for the observed scatter in measured material properties and fracture mechanics analysis uncertainties.

2.2 APPLICABLE DOCUMENTS

The following documents are applicable to the extent specified herein. Where the date and issue of a document is not cited, that document shall be used in its latest issue.

AD-1	ESA PSS-01-20	Quality assurance requirements for ESA space systems.
AD-2	ESA PSS-01-40	System safety requirements for ESA space systems.
AD-3	ESA PSS-01-70	Material, mechanical part and process selection and quality control for ESA space systems.
AD-4	ESA PSS-01-700	The technical reporting and approval procedure for materials, mechanical parts and processes.
AD-5	ESA PSS-01-736	Material selection for controlling stress-corrosion cracking.
AD-6	ESA PSS-03-209	ESACRACK user's manual.
AD-7	MSFC-STD-1249	Standard NDE guidelines and requirements for fracture control programs.
AD-8	MIL-STD-1522A November 1986	Standard general requirement for safe design and operation of pressurized missile and space systems.

AD-9	MIL-I-6870	Inspection program requirements, nondestructive, for aircraft and missile materials and parts.
AD-10	MIL-STD-410	Nondestructive testing personnel qualification and certification.

2.3 REFERENCE DOCUMENTS

RD-1	NHB 1700.7	Safety policy and requirements for payloads using the STS.
RD-2	NSTS 13830	Implementation procedure for STS payload safety requirements.

2.4 DEFINITIONS

The definitions listed in Annex A shall apply.

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SECTION 3. FRACTURE-CONTROL PROGRAMME

3.1 GENERAL

A fracture-control programme shall be implemented for ESA space systems in accordance with the requirements of this specification, when required by PSS-01-40 [AD-2] or the NASA document NHB 1700.7 [RD-1].

This requires the design to be based on fracture-control principles and procedures when the initiation or propagation of cracks in structural items during the service life could result in a hazard which has catastrophic or serious consequences, or NASA STS catastrophic hazardous consequences, or when the structural item is a pressure vessel or is rotating machinery (see Figure 1).

For unmanned, single-mission, space vehicles and their payloads, the reduced fracture-control programme, specified in Section 9, may be implemented.

3.2 RESPONSIBILITIES

3.2.1 Contractor

The Contractor shall be responsible for the implementation of the fracture-control programme required by this specification.

3.2.2 ESA Fracture Control Board

The ESA Fracture Control Board (EFCB) is responsible within ESA for the development, maintenance and implementation of fracture-control requirements. Unless otherwise specified, the responsibility for the proper application of these requirements to a project is delegated to the ESA project manager.

The EFCB, however, reserves the right to review and approve any deviation from these requirements and to audit fracture-control programmes and results.

3.3 FRACTURE-CONTROL PLAN

The contractor shall prepare and implement a fracture-control plan which complies with the requirements of this specification. The fracture-control plan, which shall be subject to approval by ESA, shall define the fracture-control programme that is to be implemented and shall show how the contractor will perform and verify the satisfactory completion of each of the activities in the fracture-control programme.

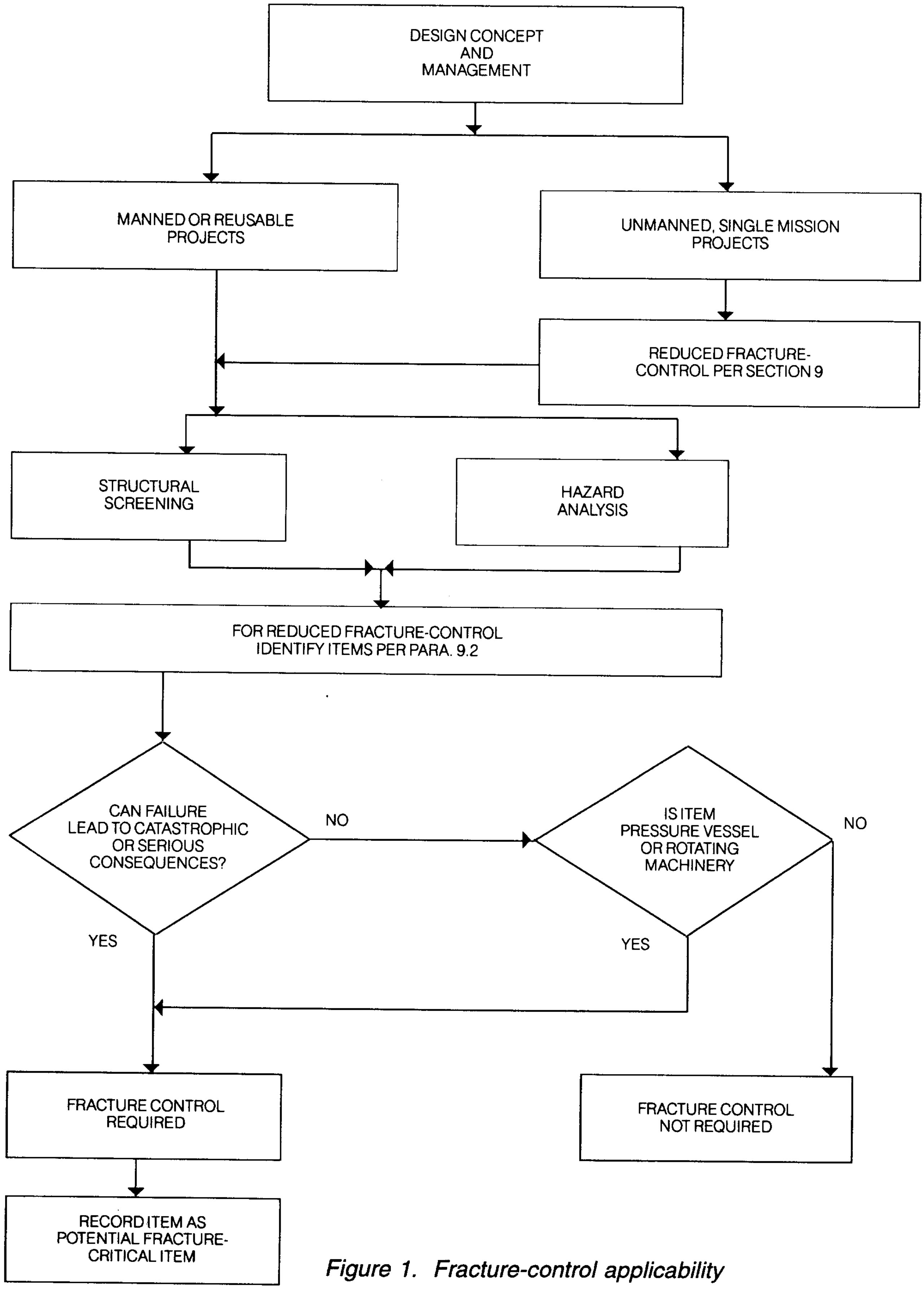

Figure 1. Fracture-control applicability

In the fracture-control plan, each fracture-control activity shall be identified and defined, the method of implementation summarised, and the implementation schedule specified against project milestones. All applicable requirements and procedures shall be identified.

3.4 REVIEWS

3.4.1 General

Fracture-control activities and status shall be addressed during all project reviews.

3.4.2 Safety Reviews

The schedule of fracture-control activities shall be related to, and shall support, the project safety-review schedule. Safety reviews shall be performed in parallel with major programme reviews as required by ESA PSS-01-40 [AD-2].

Fracture-control documentation shall be provided for the safety reviews as defined below:

(a) *For a System Requirements Review (SRR).*
The results of preliminary hazard analysis and fracture-control screening (which follows the methodology given in Figure 1.) and a written statement as to whether or not fracture-control is applicable.

(b) *For a Preliminary Design Review (PDR).*
(i) A written statement which either confirms that fracture-control is required or else provides a justification for not implementing fracture-control;
(ii) Identification of initial fracture-control-related project activities, including:
— scope of planned fracture-control activities dependent upon the results of the hazard-analysis and fracture-control screening performed;
— definition and outline of the fracture-control plan;
— identification of primary design requirements/constraints;
(iii) List of potential fracture-critical items.

(c) *For a Critical Design Review (CDR).*
   (i) A fracture-control plan which has been approved by ESA;
   (ii) Verification requirements for inspection procedures and personnel;
   (iii) The status of fracture-control activities, together with a specific schedule for completion of the verification activities;
   (iv) A description and summary of the results of pertinent analyses and tests (see Subsection 4.4);
   (v) List of potential fracture-critical items.

(d) *For an Acceptance Review (AR).*[1]
   (i) A status report showing completion of all fracture-control verification activities;
   (ii) Relevant test, inspection and analysis reports;
   (iii) List of potential fracture-critical items in accordance with Paragraph 4.4.1;
   (iv) List of fracture-critical items in accordance with Paragraph 4.4.1;
   (v) List of fracture limited-life items in accordance with Paragraph 4.4.1;
   (vi) Pressure-vessel summary log (for ESA payloads of the NASA STS, see NSTS 13830, Paragraph 5.5.2.d).

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[1] Pending the future release of Issue 3 of ESA PSS-01-40, the term "Acceptance Review" is deemed to include a Flight Acceptance Review as defined in ESA PSS-01-40 Issue 2 (September 1988).

SECTION 4. IDENTIFICATION AND EVALUATION OF POTENTIAL FRACTURE-CRITICAL ITEMS

4.1 IDENTIFICATION OF POTENTIAL FRACTURE-CRITICAL ITEMS

Fracture-control screening shall be performed for the complete structure, unless Section 9 applies, the aim being to identify potential fracture-critical items (PFCI) which shall be included in the potential fracture-critical items list (PFCIL), defined in Subsection 4.4 (see also Figure 1). The term "structure" is defined in Annex A.

The structural screening shall be performed in a systematic way and shall be documented in a clear, concise and complete manner.

Hazard analysis of the space system shall be performed as required by ESA PSS-01-40 [AD-2]. This analysis shall identify the hazards and hazardous conditions which may be created by the design of a space system and its operation, possible hazardous events and their causes, and the means by which the hazards may be eliminated or minimised and controlled.

Hazard analysis and structural screening shall be repeated, as necessary, in an iterative manner that takes design progress and design changes into account, in order to ensure that implementation of the fracture-control plan is compatible with the current design and service-life scenario.

4.2 EVALUATION OF POTENTIAL FRACTURE-CRITICAL ITEMS

4.2.1 General

(a) PFCIs can typically be divided into:
- (i) pressure vessels;
- (ii) composites;
- (iii) joints;
- (iv) other items of which the structure is comprised.

Each PFCI shall be damage tolerant. The evaluation logic to be used is the "safe-life" logic or the "fail-safe" logic, depending on the design principle used, as shown in Figure 2. In addition, the special requirements defined in Section 6 shall be implemented.

(b) For ESA payloads on the NASA STS, the following additional criteria for selection of PFCIs shall be applied. Where failure of the item would:
- (i) result in the release of any element or fragment with a mass of more than 113.5 grams; or

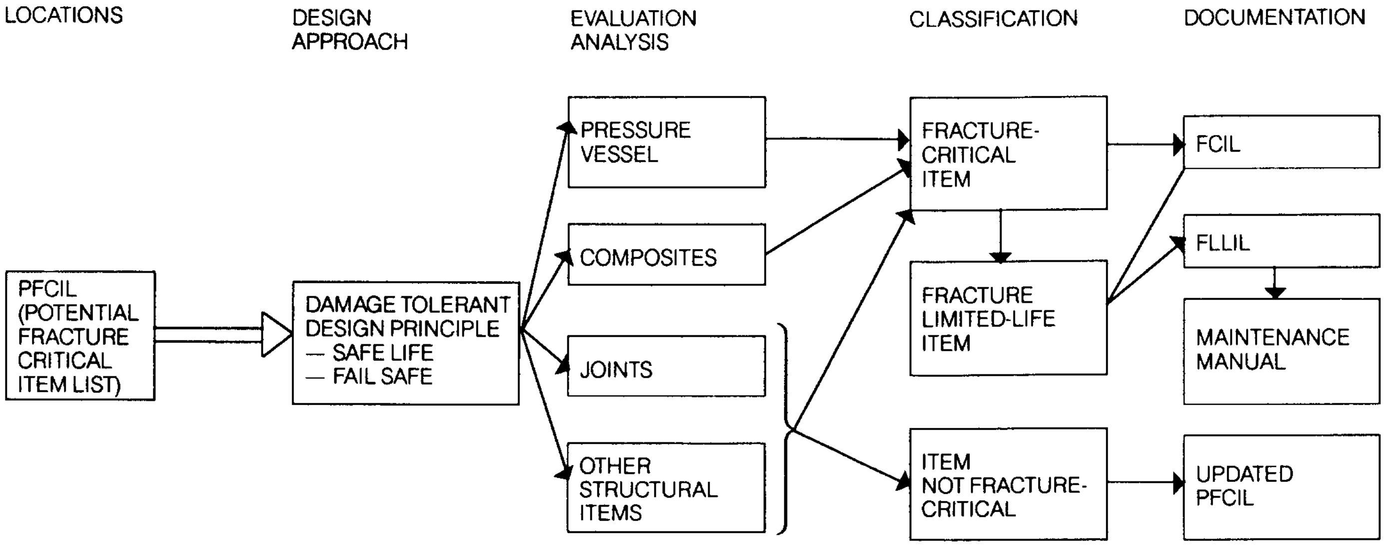


Figure 2. Fracture-control procedures

(ii) result in the release or separation of any tension-preloaded structural element or fragment with a mass of more than 13 grams if the item has a fracture toughness (K_{IC}) to tensile yield strength ratio less than 1.66 $mm^{1/2}$, or if the item is a steel bolt whose ultimate strength exceeds 1240 MPa (180 KSI), or
(iii) result in the release of hazardous substances, or
(iv) prevent configuration for safe descent from orbit,

that item shall be classed as a PFCI.

4.2.2 Selection of the relevant locations on a potential fracture-critical item

The most critical locations on a PFCI shall be identified, to enable fracture analysis to be performed. The following parameters shall be considered as criteria for the selection of PFCIs:

(i) the maximum level of local stress;
(ii) the range of cycling stress;
(iii) locations to be analysed by models showing high stress intensities (correction function);
(iv) areas where material fracture properties may be low;
(v) stresses which, combined with the environment, result in reduced fracture resistance.

If, as a result of the assessment, there is no obvious ranking in criticality, a sufficient number of locations shall be analysed to permit the criticality of the item to be defined.

4.2.3 Damage tolerant design

There are two ways of implementing damage tolerance:

a) *Safe-life*

A PFCI is a *safe-life* item if it can be shown that the greatest defect in the part will not grow to such an extent that the minimum specified performance (for example the limit-load capability or no-leak) is no longer assured within a *safe-life* interval. In no case shall the maximum stress-intensity factor K_{max}, exceed the threshold stress-intensity factor for stress-corrosion cracking K_{ISCC}.

b) *Fail-safe*

A PFCI is a *fail-safe* item if it can be shown by analysis or test that, as a result of structural redundancy, the structure remaining after failure of any element of the PFCI can sustain the new higher loads without losing limit-specified performance. In addition, the failure of the item shall not result in the release of any part or fragment which results in an event having catastrophic or serious consequences or which has a mass in excess of that stated as allowable in Subsection 3.1 of this document.

4.2.4 Classification

The results of the safe-life or fail-safe analysis, the type of non-destructive inspection used and the type of material used will determine whether or not PFCIs are identified as fracture-critical items.

A fracture-critical item (FCI) is defined as any of the following:

(i) any item which requires NDI better than Standard A, as defined in Section 8;
(ii) any pressure vessel as defined in Annex A;
(iii) any item which requires periodic re-inspection in order to achieve the required life. Such items are called fracture limited-life items (FLLI) as a subset of FCI;
(iv) any composite or non-metallic PFCI, unless contained.

4.3 COMPLIANCE PROCEDURES

4.3.1 Safe-life items

The evaluation procedure to be followed for a PFCI considered as a safe-life item is specified in Figure 3.

The term: "two flights" is required in order to take into account one aborted flight.

4.3.2 Fail-safe items

The evaluation procedure to be followed for a PFCI considered as fail-safe item is specified in Figure 4.

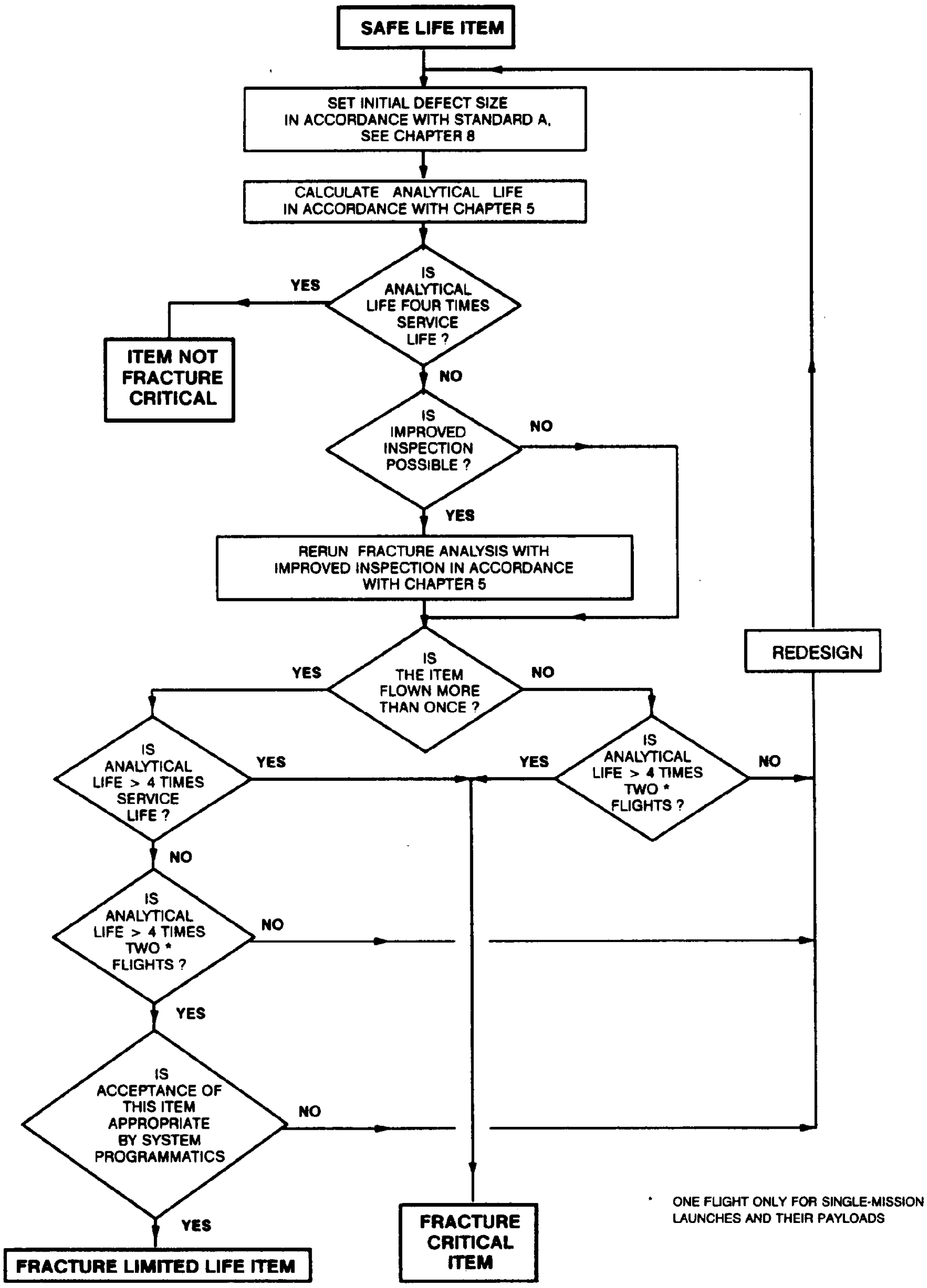


Figure 3. Safe-life item evaluation procedure.

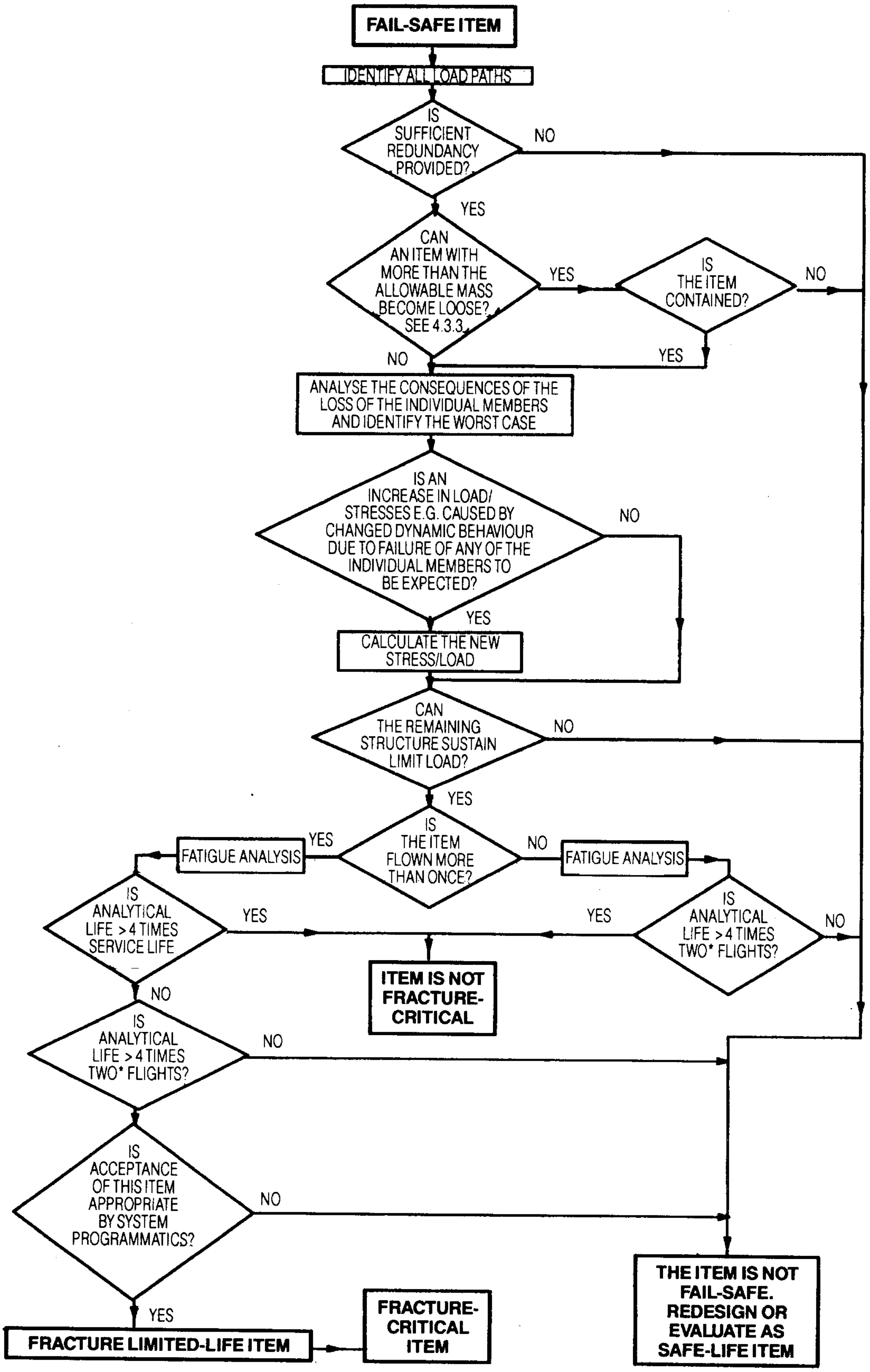


Figure 4. Evaluation procedure for fail-safe items.

* ONE FLIGHT ONLY FOR SINGLE-MISSION LAUNCHES AND THEIR PAYLOADS

4.3.3 Contained items

It shall be demonstrated by analysis or test that the release of any loose item which may lead to a hazard having serious or catastrophic consequences will be effectively prevented.

For payloads of the NASA STS, it shall be shown by analysis or test that any loose item exceeding the allowable mass defined in Subsection 4.2.1 will be prevented from being released into the cargo bay or crew compartment.

4.4 DOCUMENTATION REQUIREMENTS

The following documents shall be prepared and submitted to ESA for approval :

4.4.1 Lists

(a) *Potential fracture-critical items list*

The potential fracture-critical items list (PFCIL) shall be compiled from the results of the fracture-control screening and shall identify the item name, drawing number, material, design principle and required NDI for each item.

(b) *Fracture-critical items list*

The fracture-critical items list (FCIL) shall include the same information as the PFCIL. In addition, the FCIL shall specify a reference to the document which shows for each item the fracture-analysis and/or test results and the analytical life.

(c) *Fracture-limited life items list*

The fracture-limited life items list (FLLIL) shall include the same information as the FCIL. In addition, the FLLIL shall specify the inspection method and period, and shall identify the maintenance manual in which inspection procedures are defined.

4.4.2 Analysis and test documents

An analysis of all PFCI shall be performed and documented. When testing is used in addition to analysis the test method and test results shall also be documented. The analysis and test documentation shall as a minimum contain the following:

(a) *For safe-life items*:

(i) A description of the item with identification of material (alloy and temper), grain direction, and a clear sketch showing the size, location and direction of all assumed initial cracks.

(ii) A description of the analysis performed, including:
- a reference to the stress report;
- the loading spectrum and how it has been derived;
- material data and how they have been derived;
- environmental conditions;
- stress intensity factor solutions and how they have been derived;
- critical crack size;
- analytical life.

(iii) A summary of the significant results.

(b) *For fail-safe items*:

(i) A description of the item;
(ii) Failure modes assumed;
(iii) Stress analysis with new loading distribution;
(iv) Fatigue analysis of the most critical item;
(v) A summary of the significant result.

(c) *For contained items*:

(i) A description of the assumed container, the assumed projectile dimensions, and the material-properties employed in the analysis.

(ii) A containment analysis, which includes the derivation of:
- the velocity and energy of the projectile as it strikes the container;
- all maximum forces and/or stresses in attachments, brackets and other relevant items occurring during impact;
- a summary of the significant results.

SECTION 5. FRACTURE MECHANICS ANALYSIS

5.1 GENERAL

Fracture-mechanics analysis shall be performed to determine the analytical life of a safe-life item in accordance with the requirements of this Section. The data required to permit crack growth prediction and critical crack-size calculation are as follows:

(i) stress distribution;
(ii) load spectra;
(iii) material properties;
(iv) initial crack size,
(v) stress intensity factor solutions.

5.2 ANALYSIS

For the fracture mechanics analysis, the software package ESACRACK (see ESA PSS-03-209 [AD-6]) may be used. This package comprises the ESALOAD software, which generates load spectra, and the fracture mechanics software NASA/FLAGRO, which includes a materials data base. The flight load spectra distributed with ESACRACK shall only be used for ESA payloads of the NASA STS. ESACRACK may be used for other ESA space systems if the relevant load spectra are applied. In cases where it is not planned to use ESACRACK, alternative analysis procedures shall be proposed by the Contractor and submitted to ESA for approval prior to their use.

A fracture mechanics analysis shall include the following two items:

(i) crack-growth calculation;
(ii) critical-crack-size calculations.

5.2.1 Analytical life prediction

Analytical life prediction shall be performed on the basis of crack-growth analysis, which includes:

(a) *Identification of all load events experienced by the item in question.*

The service-life profile shall be clearly defined, in order to identify all cyclic and sustained load events. The following events shall be considered:

(i) manufacturing/assembly;
(ii) testing;
(iii) handling, e.g. by dolly or hoists;
(iv) transportation by land, sea and air;

(v) ascent;
(vi) stay in orbit, including thermally induced loads;
(vii) descent;
(viii) landing.

(b) *Identification of the most critical location and orientation of the crack on the item.*
For each item only the most critical location and orientation of the crack needs to be analysed. To identify the most critical location, stress-concentration, environmental and fretting effects must be considered (see Subsection 4.2.2). In cases where the most critical location or orientation of the initial crack is not obvious, the analysis shall consider a sufficient number of locations and orientations such that the criticality of the item can be defined.

(c) *Derivation of detailed stresses for the critical location.*
For the critical location, stresses in X-, Y- and Z-direction, including temperature and pressure stresses, must be derived. For pressure vessels, both primary membrane and secondary bending stresses resulting from internal pressure shall be calculated to account for the effects of design discontinuities and design geometries. Where applicable, rotational accelerations shall be considered in addition to translational accelerations. Residual stress due to fabrication, assembly, welding, testing or preloading shall also be included.

(d) *Derivation of a stress spectrum by use of the load events identified in* (a) *and the stresses derived in* (c).
A stress spectrum shall be generated for each analysis location, and shall include the stresses for all loading events which occur throughout the service life. Each stress step in the stress-spectra has to contain the number of cycles in the step, the upper value of the stress amplitude and the lower value of the stress amplitude.

(e) *Derivation of material data.*
Material properties used in the analytical evaluation shall be valid for the anticipated environment, grain direction, material thickness, specimen width and load ratio (R). Material data shall be used as follows:
(i) mean values of crack growth rate, da/dN, da/dt;
(ii) mean value of threshold stress intensity range, ΔK_{th};
(iii) Lower boundary values, defined as 70% of mean values for:
— critical stress intensity factor, K_{IC} or K_C (fracture toughness);
— environmentally controlled threshold stress intensity for sustained loading, K_{ISCC};

(iv) Upper bound values, defined as 1.3 times the mean values, shall be used for the critical stress intensity factor, K_{IC} or K_C, when proof loading is used for identification of initial crack sizes.

The material data in the NASA/FLAGRO database are mean values, and a reduction as described above will therefore have to be applied for the toughness parameters. (This reduction is automatically implemented when the ESACRACK software is used.)

(f) *Identification of the initial crack size and shape.*
The initial crack shape shall be identified by considering the geometry of the item and the critical location. The analysis shall be based, where applicable, on the geometry and crack shapes shown in Section 8, Figures 6 and 7. The initial crack sizes used in the analysis shall be consistent with the inspection level or proof load screening used for the item. The analysis shall consider crack aspect ratios (a/c) of 0.2 and 1.0.

(g) *Identification of an applicable stress intensity factor solution.*
Stress intensity factor solutions for the relevant item geometry, crack shape and loading shall be used.

(h) *Performance of crack growth calculations.*
Crack growth calculations shall be performed, using the variables as defined earlier. The methodology used shall account for the two-dimensional growth characteristics of cracks, multiple loading events with variation in amplitude, excursions between mean stress levels and negative stress ratios, as required. The complete loading spectrum shall be analytically imposed at least four (4) times in sequence, one after another. Any beneficial effects of crack-growth retardation from variable amplitude loading shall be ignored.
For components where it is necessary to consider the propagation of a crack into a hole, the analysis shall assume that crack propagation is not arrested or retarded by the hole.

5.2.2 Critical-crack-size calculation

The critical-crack-size (a_c), defined as the crack size at which the structure fails under limit load, shall be calculated for brittle fracture as follows:

$$a_c = \frac{(K_c)^2}{\pi(\sum F_i S_i)^2}$$

where S_i are the limit stresses and F_i are the stress intensity magnification factors for the different load cases and K_C is the critical stress intensity factor. The factors F_i normally depend on the crack size a, and this effect shall be accounted for in the calculations, e.g. by use of an iterative method.

SECTION 6. SPECIAL REQUIREMENTS

6.1 PRESSURISED SYSTEMS

6.1.1 Pressure vessels

Pressure vessels shall always be classified as fracture-critical and shall always be subject to the implementation of fracture-critical item tracking, control and documentation procedures.

The design of a pressure vessel shall account for pressures, temperatures, internal and external environments, and stresses whether imposed by internal or external forces or other sources of stress to which the vessel may be exposed.

Pressure vessels must comply with MIL-STD-1522A, November 1986 [AD-8], with the following modifications:

(i) The use of Paragraphs 5.1.3 and 5.2.3 of MIL-STD-1522A (i.e. the strength-of-materials oriented Approach B of Figure 2) is not acceptable;

(ii) The use of Paragraphs 5.1.4 and 5.2.4 of MIL-STD-1522A (Approach C of Figure 2, i.e. the ASME code or DOT TITLE 49) is only acceptable for ground support equipment (GSE);

(iii) The use of the Appendix to MIL-STD-1522A is not acceptable;

(iv) Maximum Design Pressure (MDP) as defined in Annex A of this document, shall be substituted for all references to Maximum Expected Operating Pressure (MEOP). In addition, vehicle acceleration loads shall be included;

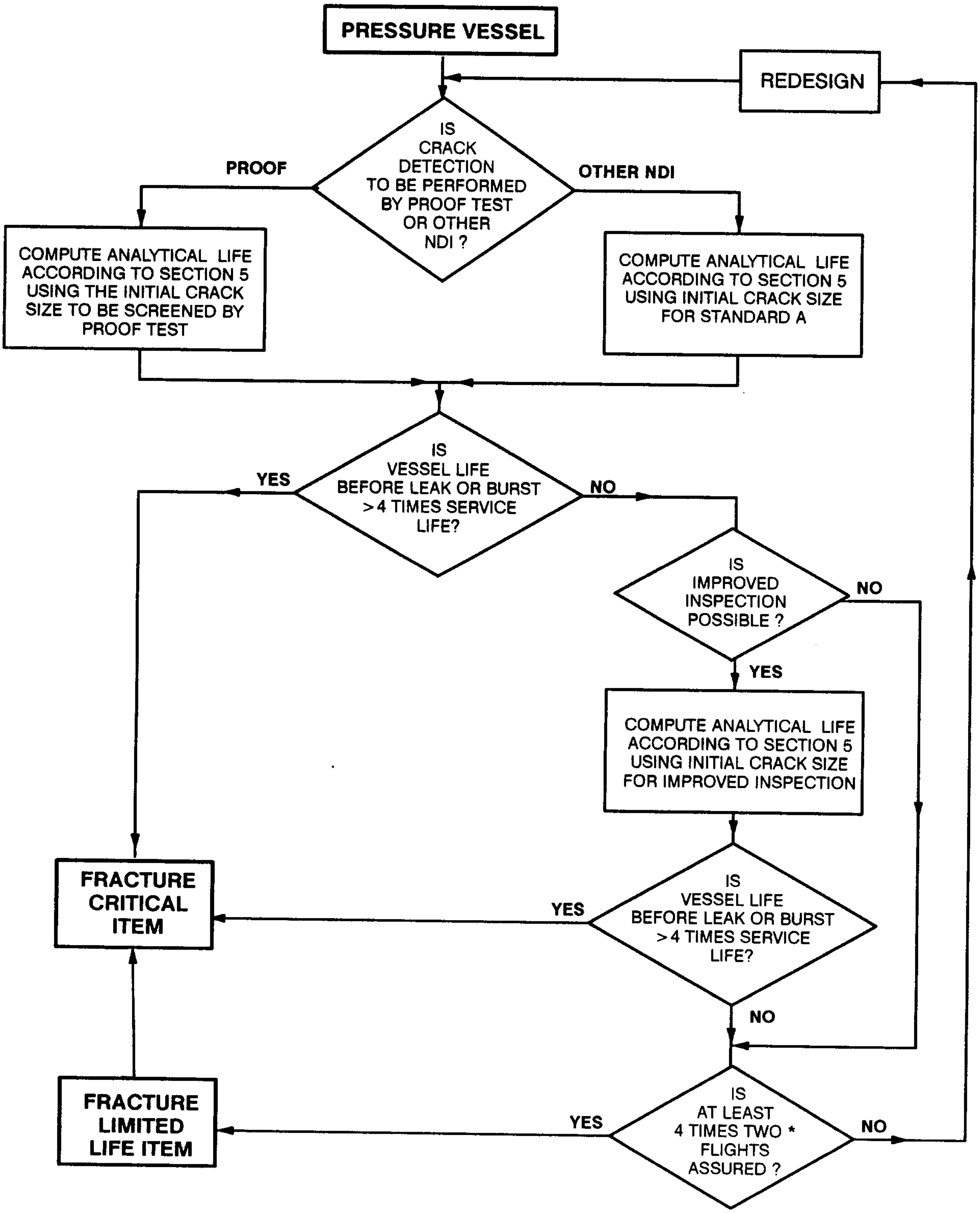
(v) A fracture mechanics analysis of pressure vessels shall, when required by the documents referred to above, be performed in accordance with the procedure set out in Figure 5 of this document and with the requirements of Section 5 of this document. Crack aspect ratios in the range of $0.2 \leq a/c \leq 1.0$ shall be included.

6.1.2 Pressure lines, fittings and components

For pressurised items other than pressure vessels, the complete pressure system shall be proof tested and leak checked in addition to an acceptance proof test of the individual items.

Safe life analysis is not required if the item is proof tested to a level of 1.5 or more times the limit load, including MDP and vehicle accelerations.

All fusion joints shall be 100% inspected by means of a qualified NDI method. Concurrence of ESA is required for NDI to be considered not-practicable.



* ONE FLIGHT ONLY FOR SINGLE-MISSION LAUNCHES AND THEIR PAYLOADS

Figure 5. Logic for pressure vessel evaluation

6.2 WELDS

For welds, the fracture mechanics analysis shall be performed with the aid of the material properties applicable to the weldments, including weldment repairs.

When such material properties are not available, they shall be derived by means of a test programme covering:

(i) ultimate and yield strength and Young's modulus for all welding conditions used, including mechanical properties (as above) in the presence of different mismatches, angles between joints or typical defects, so that their impact on the material degradation can be evaluated with respect to the strength requirements;

(ii) the fracture toughness K_c, the stress corrosion cracking threshold K_{ISCC}, and crack propagation parameters for each type of thickness to meet the requirements for structural integrity and leak-before-burst, if applicable.

These tests shall be performed on a sufficient number of specimens to permit a statistical evaluation of final values.

Possible residual stresses, both in the weld and in the heat-affected zone, must be accounted for. Even though inspected for embedded cracks, the initial crack geometry for the analysis shall always be assumed to be a surface part-through-crack or through-crack, as defined in Section 8.

6.3 COMPOSITES

Potential fracture-critical items made of fibre-reinforced composite or non-metallic material other than glass are to be treated as fracture-critical items. They must comply with the following requirements:

(a) *For fail-safe items:*

An item shall not be accepted as a fail-safe item unless:

(i) it meets all the requirements for the fail-safe approach described in Subsections 4.2 and 4.3; and

(ii) it has been demonstrated that, for the item, there is no unacceptable degradation of the alternative load path, due to cyclic loads or environmental effects.

(b) *For safe-life items*:

An item shall not be accepted as a safe-life item unless:

(i) it has been demonstrated by analysis and by test that, during a time period of four times the service life, there is no unacceptable degradation due to cyclic loads or environmental effects in the presence of induced flaws, compatible with NDI techniques;

(ii) it undergoes a proof-test of all flight hardware to not less than 1.2 times the limit load.

Special problems may arise in certain instances such as a region of high load transfer where compliance with the proof test requirements for the composite structure introduces local yielding of the metal component. These shall be treated on a case-by-case basis.

The test and analysis programme is subject to ESA approval.

6.4 ROTATING MACHINERY

Rotating machinery shall be proof (spin) tested and subjected to NDI before and after proof testing. The proof test factor shall be derived by means of fracture mechanics analysis.

6.5 GLASS

The design of all potential fracture-critical glass components shall include an evaluation of flaw growth under conditions of limit stresses and the environments encountered during their service life.

A fracture mechanics analysis for possible sustained crack growth (*da/dt*) shall be performed for each glass item. This analysis shall demonstrate that the item sustains after four (4) times its service life at least one and one tenth (1.10) times the design limit load without fracture.

The initial flaw depth used for design and analysis of glass items:

(i) shall not be smaller than three (3) times the detectable flaw depth based on the NDI methods used;

(ii) shall be subject to approval by ESA.

Long flaws with respect to depth shall be used for analytical life predictions. When using ESCRACK, the long aspect ratio a/c = 0.1 shall be applied. Crack growth properties at 100% moisture shall be used for life predictions.

Proof testing or NDI, consistent with the loading expected during service life, shall be conducted to screen for manufacturing flaws in each potential fracture-critical item based on the result of the fracture mechanics analysis. Proof testing is required for acceptance of pressurised glass components (such as windows and viewports) to screen the flaws larger than the initial flaw depth. The minimum proof pressure for these components shall be two (2) times the limit pressure.

Proof testing shall be performed in an environment suitable to limit flaw growth during test.

6.6 FASTENERS

Fasteners shall be classified and analysed as any other structural item. Fasteners smaller than diameter 5 [mm] shall not be used in safe-life applications. For fasteners equal to or larger than diameter 5 [mm], the following requirements apply:

(i) titanium alloy fasteners shall not be used in safe-life applications;

(ii) all potential fracture-critical fasteners shall be procured and tested according to aerospace standards or specifications with equivalent requirements.

(iii) all safe-life fasteners shall be marked and stored separately following NDI or proof testing.

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SECTION 7. MATERIAL SELECTION

Materials to be used shall be selected and controlled in accordance with the requirements of ESA PSS-01-70, "Material, mechanical part and process selection and quality control for ESA space systems" [AD-3] and ESA PSS-01-700, "The technical reporting and approval procedure for materials, mechanical parts and processes" [AD-4]. The selection process shall take into account structural and non-structural requirements. The materials selected shall possess the appropriate fracture toughness, crack-growth characteristics, and structural properties, such as Young's modulus and yield strength.

Where validated properties needed for analysis are not available, or available properties are not validated by standard or other adequate test procedures, an appropriate statistical basis for average and minimum values shall be established from coupon tests.

In applications where failure of a material can result in a hazard having catastrophic or serious consequences, alloys which possess high resistance to stress-corrosion cracking shall be used. (See Table 1 and Annex B of ESA PSS-01-736 [AD-5].)

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SECTION 8. QUALITY ASSURANCE REQUIREMENTS

8.1 GENERAL

Quality assurance requirements as specified in ESA PSS-01-20, "Quality assurance requirements for ESA space systems" [AD-1], and the materials selection and quality control requirements specified in ESA PSS-01-70, "Material, mechanical part and process selection and quality control for ESA space systems" [AD-3], are applicable.

8.2 NON-CONFORMANCES

Dispositioning of non-conformances for PFCIs requires reassessment of these items to verify compliance with the fracture-control requirements. All non-conformances which affect fracture-critical items and primary structural hardware designed to safe-life principles shall be dispositioned as "major non-conformances" and shall be subject to the disposition of a Material Review Board defined in ESA PSS-01-20) [AD-1].

8.3 NON-DESTRUCTIVE INSPECTION

8.3.1 General

Relevant non-destructive inspection (NDI) levels are categorised as NDI Standard A, NDI Standard B and Special NDI. In addition, proof testing is also defined as a NDI.

8.3.2 Non-destructive inspection categories versus initial crack size

Table 1 defines the initial crack sizes of Standard A.

Table 2 defines the initial crack sizes of Standard B.

Table 3 defines the initial crack sizes of Standard A that shall be applied in the case of welds and castings.

Initial crack geometries are shown in Figures 6 and 7.

(a) *NDI Standard A.*

This level of inspection requires the use of one or more of the standard industrial NDI techniques: *dye-penetrant, X-ray, ultrasonic or eddy current*. Visual inspection is not acceptable. Standard NDI shall be performed in accordance with MIL-I-6870 [AD-9] and shall provide crack detection to at least 95 percent confidence and 90 percent probability level. Tables 1 and 3 give, for various NDI techniques and part geometries, the largest crack sizes that may remain undetected at these probability and confidence levels.

TABLE 1: Initial crack size summary Standard A

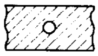
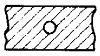
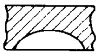
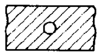
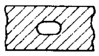
Type of defect	No.	Crack aspect ratio *a/c*	Standard A (mm)
Surface defect:			
— Semi-elliptical	1, 3	1.0 0.2	a = 3.0 a = 1.5
— Corner crack	2	1.0 0.2	a = 3.0 a = 1.5
Through crack:			
— Centre crack	4	not applicable	c = 3.0
— Edge crack	5	not applicable	c = 3.0
Cracks from hole:			
— Corner crack	7	1.0	a = 3.0
— Surface	8	1.0	a = 3.0
— Through	9	not applicable	c = 3.0

The numbers in the second column (No.) refer to the crack configurations shown in Figures 6 and 7. Crack sizes for other aspect ratios can be calculated with the aid of equivalent area.

TABLE 2: Initial crack size summary Standard B

Crack location	**Part thickness, *t*** (mm)	**Crack type**	**Crack dimension *a*** (mm)	**Crack dimension *c*** (mm)
		Eddy Current NDI		
Open surface	$t \leq 1.27$	Through	t	1.27
	$t > 1.27$	Surface	0.50	2.50
			1.27	1.27
Edge or hole	$t \leq 1.91$	Through	t	2.50
	$t > 1.91$	Corner	1.91	1.91
		Penetrant NDI		
Open surface	$t \leq 1.27$	Through	t	2.50
	$1.27 \leq t \leq 1.91$	Through	t	$3.82 - t$
	$t > 1.91$	Surface	0.63	3.20
			1.91	1.91
Edge or hole surface	$t \leq 2.50$	Through	t	2.50
	$t > 2.50$	Corner	2.50	2.50
		Magnetic Particle NDI		
Open surface	$t \leq 1.91$	Through	t	3.20
	$t > 1.91$	Surface	0.96	4.80
			1.91	3.20
Edge or hole surface	$t \leq 1.91$	Through	t	6.30
	$t > 1.91$	Corner	1.91	6.30
		Radiographic NDI		
Open surface	$0.63 \leq t \leq 2.72$	Surface	$0.7t$	1.91
	$t > 2.72$		$0.7t$	$0.7t$
		Ultrasonic NDI Comparable to Class A quality level as defined in MSFC-STD-1249		
Open surface	$t \geq 2.50$	Surface	0.76	3.80
			1.65	1.65

Table 3. Initial cracksize summary Standard A for welds and castings.

NDI TECHNIQUE	DEFECT TYPE	SHAPE	No.	APPLICABILITY	DEPTH a, 2a [mm]	LENGTH C [mm]	APPLICABLE THICKNESS
X-RAY	PORE		6	▷ 5	2a = 0.7 × t	0.35 × t	all
X-RAY	INCLUSION		6	▷ 1	2a = 0.7 × t and 2a = 0.6 × t	0.35 × t 0.6 × t	all
X-RAY	INCOMPLETE PENETRATION		1, 2 3	▷ 2	a = 0.6 × t and a = 0.4 × t	0.6 × t 2.0 × t	all (welds only)
X-RAY	SURFACE CRACKS		—	▷ 3	not applicable	not applicable	
ULTRASONIC	PORE AND INCLUSION		6, 4	applicable	5.2 through and 3.5 through	2.6 2.6 3.5 3.5	t>5.2 t≤5.2 t>3.5 t≤3.5
ULTRASONIC	INCOMPLETE PENETRATION		1, 2, 3, 4, 5	applicable	3.5 through and 1.65 through ▷ 4	3.5 3.5 8.25 8.25	t>3.5 t≤3.5 t>1.65 1.0≤t≤1.65
ULTRASONIC	SURFACE CRACKS		1, 2, 3, 4, 5	applicable	3.5 through and 1.65 through ▷ 4	3.5 3.5 8.25 8.25	t>3.5 t≤3.5 t>1.65 1.0≤t<1.65
PENETRANT	PORE		—	not applicable			
PENETRANT	INCLUSION		—	not applicable			
PENETRANT	INCOMPLETE PENETRATION		1, 2, 3, 4, 5	▷ 2	a = 3.0 and a = 1.5	C = 3.0 C = 7.5	t>a; ▷ 5
PENETRANT	SURFACE CRACKS		1, 2, 3, 4, 5	applicable	a = 3.0 and a = 1.5	C = 3.0 C = 7.5	t>a; ▷ 5

REMARKS

t thickness during application of X-ray

▷ 1 only if elliptical geometry is determined (no geometry with sharp corners acceptable)

▷ 2 applicable to welds only

▷ 3 not applicable for Standard Inspection

▷ 4 support by surface sensitive inspection method recommended (e.g. penetrant inspection)

▷ 5 for t≤a apply through crack

In no case shall the thickness dependent crack sizes be smaller than Standard A shown in Table 1.

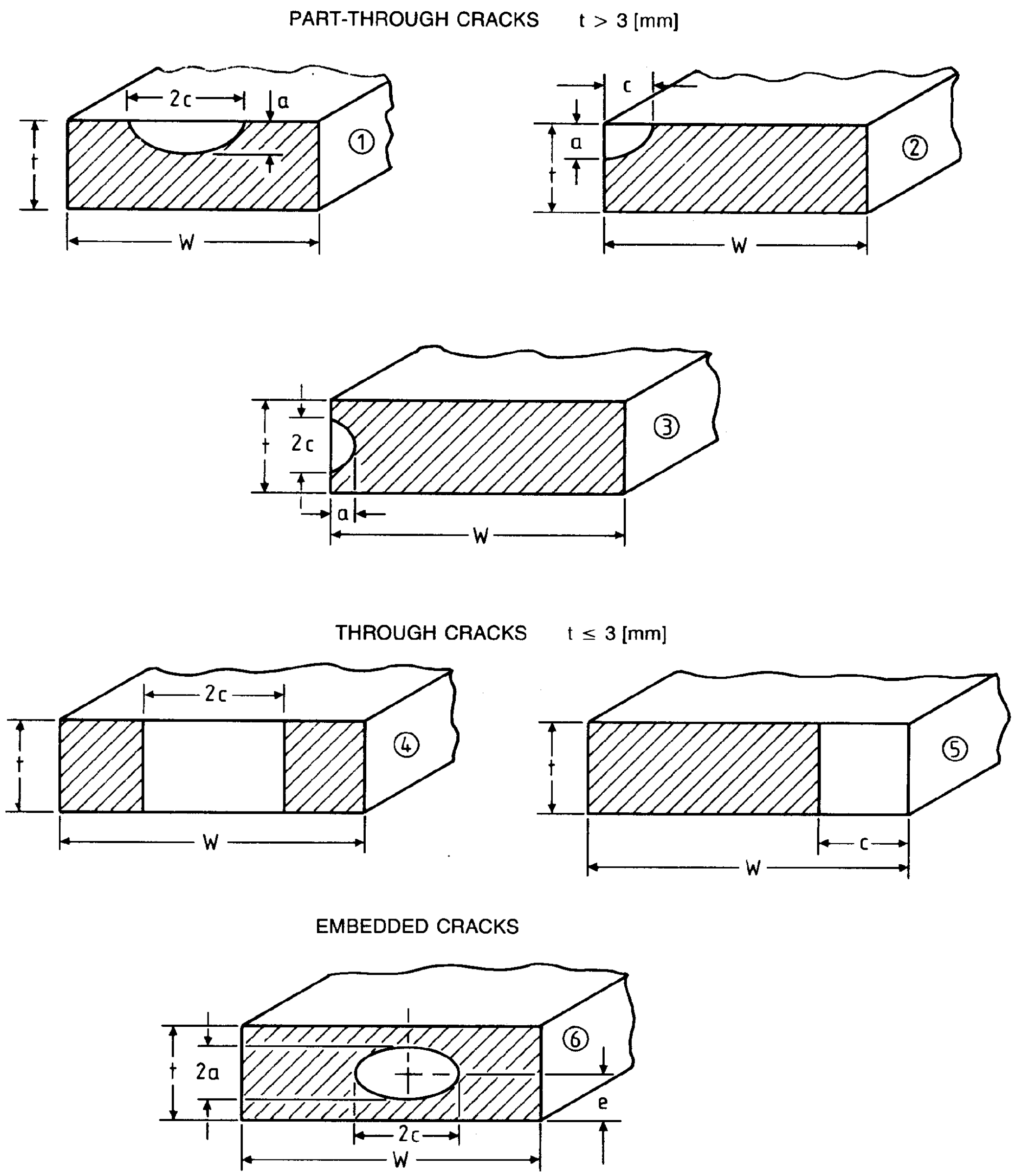
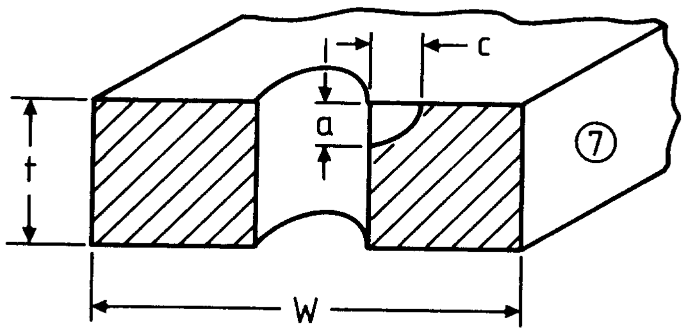
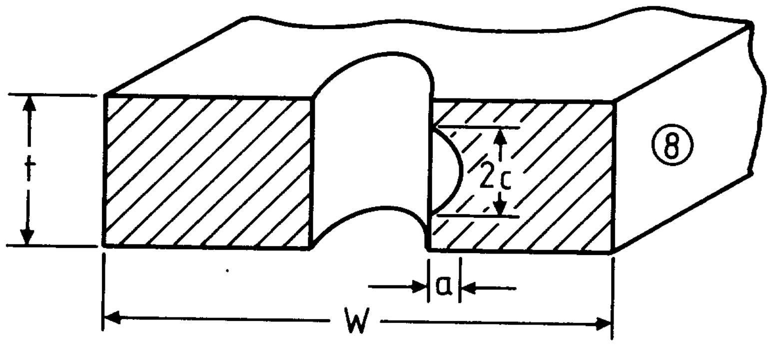


Figure 6. Initial crack geometries for parts without holes

PART-THROUGH CRACKS $t > 3.0$ [mm]



OR



THROUGH CRACKS $t \leq 3.0$ [mm]

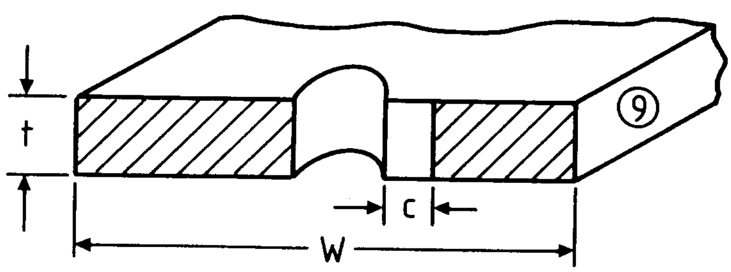


Figure 7. Initial crack geometries for parts with holes

(b) *NDI Standard B.*
In order to demonstrate that defects (as defined in Table 2) of this standard will be detected with a probability of 90%, the inspection procedure must be verified and requires ESA approval prior to use. In preparing the procedure for qualification, jigs and fixtures may have to be developed in order to ensure repeatable coverage of critical areas. The data to be generated by performing such verification shall show at least 20 results (representative samples and/or inspections) that will permit simplified statistical evaluations.

(c) *Special NDI.*
This level of inspection shall be used only in special cases where limited life is demonstrated and serious problems may occur as a result of redesign or acceptance of the limited life. A statistical demonstration of 90% probability and 95% confidence shall be performed for the method. The demonstration results and resulting procedures are subject to ESA approval. Such demonstration shall be carried out on specimens representative of the actual configuration to be inspected.

(d) *Proof Testing.*
Proof testing of a flight item is acceptable as a screening or inspection technique for cracks. However, proof testing may require loads substantially in excess of those usually imposed on flight hardware in order to screen out flaws of sufficiently small size. In the proof tests performed, procedures and stress analysis predictions shall be sufficiently reliable and coordinated to ensure that the predicted stress level and distribution are actually achieved, and that the absence of test failure ensures that the cracks of the sizes to be screened out are not present in any critical location or in any orientation of the item. Proof-test procedures shall be submitted to ESA for approval prior to the start of testing.

8.4 INSPECTION REQUIREMENTS

The fracture-control programme requires inspection in order to validate the analytical life predictions and to permit hardware to be released as acceptable. Such inspection must include at least:

(i) Inspection of raw materials to Standard A to ensure absence of embedded defects;

(ii) Initial inspection of all finished items by the NDI method (Subsection 8.3) relevant to the assumed initial crack size. The NDI shall be performed for the total item even though only one location is analysed. Items to be inspected using dye penetrants, shall have their mechanically disturbed surfaces etched prior to inspection. Rolled threads shall not be etched.

(iii) Inspections as may be required for limited life items;

(iv) Verification of structural redundancy for fail-safe items before each flight;

(v) Post test NDI for all proof-tested items;

(vi) Inspection of all welds shall include a search for surface defects as well as embedded defects;

(vii) 100% inspection of all fusion joints of pressurised lines before and after proof test, using a qualified NDI method;

(viii) Applicable NDI requirements shall be stated on design and manufacturing documentation.

Inspection shall be performed by qualified personnel, certified for the relevant inspection method, in accordance with MIL-STD-410 [AD-10] or equivalent.

Special jigs, fixtures and non-standard equipment needed to perform re-inspection shall be deliverable with the fracture-critical items.

8.5 TRACEABILITY

8.5.1 General

Traceability of structural materials and items shall be implemented to provide assurance that the material used in the manufacture of structural hardware has properties fully representative of those used in the analysis or verification tests.

Traceability shall also provide assurance that structural hardware is manufactured and inspected in accordance with the specific requirements necessary to implement the fracture-control programme. The traceability requirements of ESA PSS-01-20 [AD-1] shall be applied.

8.5.2 Requirements

The following traceability requirements apply:

(i) All associated drawings and manufacturing and quality-control documentation shall identify that the item is a potentially fracture-critical item;

(ii) Each fracture-critical item shall be traceable by its own unique serial number;

(iii) Each fracture-critical item shall be identified as fracture-critical on its accompanying tag and data package;

(iv) For each fracture-critical item a log shall be maintained, which documents the environmental and operational aspects (including fluid exposure for pressure vessels) of all storage conditions during the life of the item;

(v) For each fracture-critical item a log shall be maintained, which documents all loadings due to testing assembly and operation, including torquing of fasteners.

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SECTION 9. REDUCED FRACTURE-CONTROL PROGRAMME

9.1 GENERAL

For unmanned, single-mission, space vehicles and their payloads, a reduced fracture-control programme (RFCP) as defined in this Section shall, as a minimum, be implemented.

9.2 REQUIREMENTS

A reduced fracture-control programme shall satisfy all requirements given in this document, with the modifications defined below:

(a) *Subsection 4.1 (Identification of PFCIs).*
The identification of PFCIs shall be limited to the following items:
- (i) pressurised systems;
- (ii) rotating machinery;
- (iii) fasteners used in safe-life applications;
- (iv) items fabricated using welding, forging or casting and which are used at limit stress levels exceeding 25% of the ultimate tensile strength of the material;
- (v) non-metallic structural items.

(b) *Identification of potential fracture-critical items.*
The identification of potential fracture-critical items shall be performed according to the procedure given in Figure 1.

(c) *Subsection 4.4 (Documentation).*
The information required in Paragraph 4.4.1 may be consolidated; separate lists are not required.

(d) *Subsection 6.3 (Composites) and Subsection 6.5 (Glass).*
The requirements of these two sections shall be replaced by the following requirement: non-metallic structural items shall be proof-tested at 1.2 times the limit load.

(e) *Subsection 6.4 (Rotating Machinery).*
The requirements of this section shall be replaced by the following requirements: rotational machinery (wheels and gyros) shall be proof-spin-tested at 1.1 times nominal operational speed.

(f) *Subsection 6.6 (Fasteners).*
The requirements of this section shall apply to all fasteners equal to or larger than M5 or 5 mm in diameter.

ANNEX A. DEFINITIONS

AGGRESSIVE ENVIRONMENT
Any combination of liquid or gaseous media and temperature that alters static or fatigue crack-growth characteristics from "normal" behaviour associated with an ambient temperature and laboratory air environment.

ALLOWABLE LOAD
The load that induces the allowable stress in a material.

ALLOWABLE STRESS
The maximum stress that can be permitted in a material for a given operating environment to prevent rupture, collapse, detrimental deformation or unacceptable crack growth.

ANALYTICAL LIFE
Life evaluated analytically, i.e. by crack-growth analysis or fatigue analysis.

BURST PRESSURE
The pressure at which a pressure vessel ruptures or collapses.

CATASTROPHIC CONSEQUENCE
For ESA space systems, the applicable definition is: a potential risk situation that "may result in loss of life, in life-threatening or permanently disabling injury or in occupational illness".
For ESA payloads of the NASA STS, the applicable definition is: a potential risk situation that may result in personnel injury, loss of the NASA orbiter, ground facilities, or STS equipment (see NHB 1700.7, Paragraph 302). This definition shall replace the ESA definition in the case of mission phases when the payload is installed in the NASA Orbiter or is being deployed or retrieved during Orbiter in-orbit operations.

CONTAINMENT
A technique that, if a part fails, will prevent the propagation of failure effects beyond the container boundaries.

CRACK OR CRACK-LIKE DEFECT
A defect that behaves like a crack that may be initiated during material production, fabrication or testing or that may develop during the service life of a component.
NOTE: The term "crack" in this specification includes flaws, inclusions, pores and other similar defects.

CRACK ASPECT RATIO

For a part-through crack, the ratio of crack depth (*a*) to half crack length (*c*), i.e. *a/c*.

CRACK GROWTH RATE (*da/dn* or *dc/dn*)

The rate of change of depth *a* or length *c* with respect to the number of load cycles *n*.

CRACK GROWTH RETARDATION

The reduction of crack-growth rate due to intermittent overloading of the cracked structural member.

CRITICAL CRACK

See Paragraph 5.2.2 of this document.

CRITICAL STRESS INTENSITY FACTOR

The value of the stress-intensity factor at the tip of a crack at which unstable propagation of the crack occurs. This value is also called the fracture toughness. The parameter K_{IC} is the fracture toughness for plane strain and is an inherent property of the material. For stress conditions other than plane strain, the fracture toughness is denoted K_C. In fracture mechanics analyses, failure is assumed to be imminent when the applied stress-intensity factor is equal to or exceeds its critical value, i.e. the fracture toughness.

CYCLIC LOADING

A fluctuating load (or pressure) characterised by relative degrees of loading and unloading of a structure. Examples are loads due to transient responses, vibro-acoustic excitation, flutter and oscillating or reciprocating mechanical equipment.

DAMAGE TOLERANT

A structure is considered to be damage tolerant if the amount of general degradation and/or the size and distribution of local defects expected during operation do not lead to structural degradation below limit-specified performance.

ESACRACK

ESACRACK is a software package distributed by ESA (see ESA PSS-03-209). The package consists of the load- and stress-spectrum generation program ESALOAD, and the crack-growth program NASA/FLAGRO.

ESALOAD
The software that generates a load spectrum and a stress spectrum for a payload. The stress spectrum is generated using unit stress values.

FAIL SAFE (STRUCTURE)
A damage-tolerance acceptability category in which the structure is designed with sufficient redundancy to ensure that the failure of one structural element does not cause general failure of the entire structure.

FAILURE (STRUCTURAL)
The rupture, collapse, seizure, excessive wear or any other phenomenon resulting in an inability to sustain limit loads, pressures and environments.

FASTENER
Any item which joins other structural items and transfers loads from one to the other across a joint.

FATIGUE
In materials and structures, the cumulative irreversible damage incurred by cyclic application of loads in given environments. Fatigue can initiate and extend cracks, which degrade the strength of materials and structures.

FRACTURE LIMITED LIFE ITEM
Any item which requires periodic reinspection to comply with safe-life or fail-safe requirements.

INITIAL CRACK SIZE
The maximum crack size, as defined by non-destructive inspection, that is assumed to exist for the purpose of performing a fracture mechanics evaluation.

ITEM
The lowest subdivision of a subassembly in which each item is a separate and distinct element not normally separated into further subdivisions or disassembly without destruction of designed use.

JOINT
Any metallic element which connects other structural elements and transfers loads from one to the other across a connection.

K_{IC} (PLANE STRAIN FRACTURE TOUGHNESS)
See CRITICAL STRESS INTENSITY FACTOR.

K_{ISCC}
Threshold stress-intensity factor for stress-corrosion cracking. The maximum value of the stress-intensity factor for a given material at which no environmentally induced crack growth will occur at sustained load for the specified environment.

ΔK_{th}
Threshold stress-intensity factor for dynamic loading. The stress-intensity range below which crack growth will not occur under cyclic loading.

LIMIT LOAD OR STRESS
The maximum load or stress assumed to act on a structure in the expected operating environments.

LOADING EVENT
A condition, phenomenon, environment or mission phase to which the payload is exposed and which induces loads in the payload structure.

LOAD SPECTRUM (HISTORY)
A representation of the cumulative static and dynamic loadings anticipated for a structural element during its service life.

MAXIMUM DESIGN PRESSURE
For a pressure vessel, maximum design pressure is the highest possible pressure occurring from maximum relief pressure, maximum regulator pressure, maximum temperature or transient pressure excursions.

NASA/FLAGRO
Fracture mechanics analysis software developed by NASA.

NON-DESTRUCTIVE INSPECTION
Inspection techniques that do not cause physical or chemical changes to the item being inspected or otherwise impair its adequacy for operational service, and that are applied to materials and structures to verify required integrity and detect and characterise cracks. NDI method refers to the specific technique used such as dye penetrant, X-ray etc. NDI level refers to the degree of resolution of the technique.

PAYLOAD

Any equipment or material carried by the launcher that is not considered part of the basic launcher itself. It therefore includes items such as free-flying automated spacecraft, individual experiments and instruments. The term "payload" also includes payload-provided ground support equipment (GSE) and systems and flight ground systems software.

PRESSURE VESSEL

A pressurised container which:

(i) contains stored energy of 19 310 joules (14 240 foot-pounds) or more, the amount being based on the adiabatic expansion of a perfect gas; or

(ii) contains a gas or liquid which will create a hazard if released; or

(iii) will experience a design limit pressure greater than 0.69 Mpa (100 psi).

PROOF TEST

The test of a flight structure at a proof load or pressure which will give evidence of satisfactory workmanship and material quality or will establish the initial crack sizes in the structure.

R

The ratio of the minimum stress to maximum stress.

RESIDUAL STRESS

A stress that remains in the structure, owing to processing, fabrication or prior loading.

ROTATING MACHINERY

Any rotating mechanical assembly that has a kinetic energy of 19 300 joules or more, the amount being based on 0.5 $I\omega^2$ where I is the moment of inertia and ω is the rotational frequency.

SAFE LIFE

A fracture-control acceptability category which requires that the largest undetected crack that could exist in the part will not grow to failure when subjected to the cyclic and sustained loads and environments encountered in the service life.

SERIOUS CONSEQUENCE

A potential risk situation that may result in:

— temporarily disabling but not life-threatening injury, or temporary occupational illness;

— loss of, or major damage to, flight systems, major flight system elements or ground facilities;

— loss of, or major damage to, public or private property; or long-term detrimental environmental effects.

SERVICE LIFE

The interval beginning with an item's inspection after manufacture and ending with completion of its specified life.

SPECIAL NON-DESTRUCTIVE INSPECTION

The formal inspection of items using non-destructive procedures involving the use of techniques and/or equipment that exceed common industrial standards.

STATIC LOAD (STRESS)

A load (stress) of constant magnitude and direction with respect to the structure.

STRESS CORROSION CRACKING (SCC)

The initiation and/or propagation of cracks, owing to the combined action of applied sustained stresses, material properties and aggressive environmental effects.

STRESS INTENSITY FACTOR (*K*)

A calculated quantity which is used in fracture mechanics analyses as a measure of the stress-field intensity near the tip of an idealised crack. Calculated for a specific crack size, applied stress level and part geometry.

STANDARD NON-DESTRUCTIVE INSPECTION

The formal inspection of items using non-destructive procedures consistent with common industrial standards. These include standard dye-penetrant, eddy-current, ultrasonic and X-ray procedures.

STRUCTURE

All items and assemblies designed to sustain loads or pressures, provide stiffness and stability, or provide support or containment.

SUBASSEMBLY

A subdivision of an assembly consisting of two or more items.

SUBSYSTEM
A functional subdivision of a payload consisting of two or more items.

THERMAL LOAD (STRESS)
The structural load (or stress) arising from temperature gradients and differential thermal expansion between structural elements, assemblies, subassemblies or items.

THRESHOLD STRESS INTENSITY FACTOR
See K_{ISCC} or ΔK_{th}.

ULTIMATE STRENGTH
The strength corresponding to the maximum load or stress that an unflawed structure or material can withstand without incurring rupture or collapse.

VARIABLE AMPLITUDE SPECTRUM
A load spectrum or history whose amplitude varies with time.

YIELD STRENGTH
The strength corresponding to the maximum load or stress that an unflawed structure or material can withstand without incurring permanent deformation.

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ANNEX B. LIST OF ACRONYMS USED

AR	Acceptance review.
ASME	American Society of Mechanical Engineers.
CDR	Critical design review.
DOT	United States Department of Transportation.
EFCB	ESA Fracture Control Board.
ESA	The European Space Agency.
FCI	Fracture-critical item.
FCIL	Fracture-critical item list.
FLLI	Fracture-limited life items list.
GSE	Ground support equipment.
MDP	Maximum design pressure.
MEOP	Maximum expected operating pressure.
M5	Metric screw thread with an external diameter of 5 mm.
NASA	The United States' National Aeronautics and Space Administration.
NDI	Non-destructive inspection.
PDR	Preliminary design review.
PFCI	Potential fracture-critical item.
PFCIL	Potential fracture-critical item list.
RFCP	Reduced fracture-control programme.
SI	The international system of units published by the International Standards Organisation.
SRR	System requirements review.
STS	The NASA Space Transportation System.

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