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SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

NASA SP-8095

PRELIMINARY CRITERIA FOR THE FRACTURE CONTROL OF SPACE SHUTTLE STRUCTURES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PREFACE

Space vehicle structures are vulnerable to the initiation and propagation of cracks or crack-like defects during their service life, which may lead to structural failure.

Although individual causative factors and preventive measures have been known for some time, and have been accounted for in the design of aerospace structures, the advent of the Space Shuttle has emphasized the problem due to extreme criticality of structural weight and the requirement for reuse of the vehicle.

The term "fracture control" has recently come into use to describe the approach to design which seeks to prevent structural failure due to cracks or crack-like defects.

In order to provide a basic understanding of the nature and magnitude of the subject, it was felt desirable to assemble in one concise volume the complex and multidisciplinary factors that bear on the subject. It should be noted that the elements of the subject are not new--only the consideration of them in an overall manner.

It was the belief that the most effective form of presentation would be by means of succinct criteria statements of what has to be done to assure adequate fracture control. Most of the document consists of such statements. Where appropriate, interpretive information has also been added in medium type. Two references have been used extensively in preparing this document: Structural Design Criteria Applicable to a Space Shuttle (NASA SP-8057) and Fracture Control of Metallic Pressure Vessels (NASA SP-8040).

Preliminary criteria herein are not intended to be requirements or specifications but to serve as a beginning point or check list for generating fracture control requirements or for evaluating the desirability of a fracture control approach to design.

The effort was sponsored by the Structural Design Panel of the NASA Structures and Materials Technology Working Group.

The work of preparing and reviewing the technical subject material was performed on very short notice by an ad hoc government/industry working group composed of specialists in design, structures, materials, fracture mechanics, and other related technologies. Participating were 7 aerospace companies, 4 NASA Centers, NASA Headquarters, and the USAF Flight Dynamics Laboratory. This meeting was chaired by R. W. Leonard of the NASA Langley Research Center. A list of participants is given on page iv.

Compiling, integrating, and editing of the document were performed by the Design Criteria Program Office of the McDonnell Douglas Astronautics Company under the direction of the Langley Research Center's Structural Systems Office (SSO).

Organizations and individuals who participated in the development of this document include:

GENERAL DYNAMICS CORPORATION
C. Dale Little
W. Witzell

GRUMMAN AEROSPACE CORPORATION
A. Alberi
A. Gomza
A. Perigard

LOCKHEED AIRCRAFT CORPORATION
J. C. Ekvall

MARTIN-MARIETTA CORPORATION
L. Loechel
F. R. Schwartzberg

McDONNELL DOUGLAS CORPORATION
H. W. Babel
R. H. Christensen
M. B. Harmon
J. F. Schier
F. R. Smith (Editor)

NORTH AMERICAN ROCKWELL CORPORATION
R. W. Westrup

THE BOEING COMPANY
B. E. Landry
J. N. Masters

U. S. AIR FORCE FLIGHT DYNAMICS LABORATORY
T. L. Haglage

NASA LANGLEY RESEARCH CENTER
W. Elber
J. R. Hall
H. F. Hardrath
R. R. Heldenfels
R. W. Leonard
C. C. Poe

NASA LEWIS RESEARCH CENTER
W. F. Brown
G. T. Smith
J. E. Srawley

NASA MANNED SPACECRAFT CENTER
P. E. Fitzgerald
R. E. Johnson
R. E. Lindemann
L. G. St. Leger

NASA MARSHALL SPACE FLIGHT CENTER
H. R. Coldwater
C. D. Crockett
G. A. Deuel
M. C. McIlwain
E. C. McKannan

NASA OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
D. A. Gilstad

NASA OFFICE OF MANNED SPACE FLIGHT
N. G. Peil

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PRELIMINARY CRITERIA FOR THE FRACTURE CONTROL OF SPACE SHUTTLE STRUCTURES

1. OBJECTIVE

The objective of this document is to provide preliminary criteria for the fracture control of Space Shuttle structures. Fracture control is a set of policies and procedures intended to prevent structural failure due to the initiation or propagation of cracks or crack-like defects during fabrication, testing, and service life. The basic objective of the proposed criteria is to ensure that unacceptable structural failures due to crack-initiated fractures will not occur during the service life of the Space Shuttle. To accomplish this objective, the criteria define the design, fabrication, environmental control, inspection, maintenance, repair, and verification procedures required for adequate fracture control.

2. SCOPE

The fracture control criteria are applicable to those Space Shuttle components which are determined, by engineering analysis and tests, to be (1) susceptible to cracking or fracture on the basis of anticipated loads and environment, and (2) critical to either crew safety or system performance.

The failure modes which are accounted for in the fracture control criteria include as a minimum the growth to the point of leakage or rupture of the following:

- Cracks initiated at existing flaws
- Cracks initiated by fatigue
- Cracks due to stress corrosion
- Cracks caused by material contamination

The criteria are not intended to apply to accidental or inadvertent mishandling which in itself would cause failure. The criteria define fracture control measures covering the entire development of operational life of the vehicle, including engineering design, material selection and procurement, fabrication processes, quality assurance procedures, acceptance and/or periodic proof tests, flight tests, and operational service usage. Fracture control measures also apply to non-flight articles undergoing development and qualification tests.

All disciplines necessary to effective fracture control are treated herein:

- Management
- Design
- Loads and environments
- Materials
- Analyses
- Fabrication process control
- Quality assurance
- Tests
- Operations and maintenance

In the remainder of this document, statements in boldface type are design criteria and statements in medium type provide guidance for interpretation of the criteria.

3. MANAGEMENT

A fracture control plan shall be developed and documented by the contractor. The plan shall include

provisions for the following:

- Identification of components selected for fracture control on the basis of criticality to structural flightworthiness and susceptibility to cracking or fracture

- Definition of organization responsibilities and procedures for communicating and taking action on matters relevant to fracture control

- Appropriate multidisciplinary review

- Establishment of a fracture-control data bank that is accessible and readily available to all interested personnel

- Maintenance of a continuing quality assurance activity directed toward identifying and reporting conditions which could affect the fracture resistance of structural components, and providing visibility to management of the performance and effectiveness of fracture control procedures.

- Appropriate review, performance appraisal, and control by management

The fracture control plan shall treat all subjects and disciplines which affect fracture control, including the following as a minimum:

- Management

- Design

- Loads and environments

- Materials

- Analyses

- Fabrication process control

- Quality assurance

- Tests

- Operations and maintenance

4. DESIGN

4.1 Service Life Philosophy

Each selected component shall be evaluated to determine whether a safe-life or a fail-safe design approach is more appropriate. In general, the fail-safe design approach shall be employed to the maximum extent practicable. The evaluation shall account for the requirements of safety, structural weight, inspectability, maintainability, and replaceability as well as the cost and the influence of environmental factors.

4.1.1 Safe-Life

For structure requiring a safe-life design, such as metallic pressure vessels or landing gears, any flaws that cannot be detected in a regularly scheduled inspection shall not grow enough before the next scheduled inspection to degrade the strength of the structure below that required to sustain (TBD) percent of limit load at the design temperature for that condition. Analysis of flaw growth shall account for material properties and their variability, structural concepts, and operating environments and stress levels. The inspection procedures shall be considered adequate only when they can readily detect all flaws or defects equal to or greater than the allowable sizes.

For components selected for fracture control, the safe-life, as determined by conventional fatigue analysis and test and assuming an initially unflawed structure, shall be at least (TBD) times the specified service life or (TBD) times the inspection interval.

Components selected for fracture control shall be designed so that verification of safe-life is not dependent on unsubstantiated projected improvement in NDE capabilities.

4.1.2 Fail-Safe

Fail-safe designs shall be developed to provide adequate fracture-arrest capability and residual strength in the damaged condition.

All fail-safe structure shall be accessible for periodic inspection. Fail-safe design shall account for the following factors:

- Size, type, and source of flaws
- Critical loading conditions and associated stress levels
- Material properties
- Critical structural components
- Extent of damage which the structure can withstand
- Applicable modes of failure
- The dynamic effect of suddenly failing elements, and
- The concentration of load or stress on elements adjacent to the failed element

4.1.3 Residual Strength

The residual strength of fail-safe structure shall be adequate to withstand (TBD) percent of limit design conditions. The residual strength of fail-safe structure is defined as the strength remaining after failure of any single structural element.

The residual strength of safe-life structure shall be adequate to withstand design limit conditions throughout its operational life. The residual strength of safe-life structure is the strength remaining at any time during its service life. The original strength may be reduced by growth of flaws or by degradation of mechanical properties due to temperature and corrosive environments.

4.2 Fracture Control Precautions

Components selected for fracture control shall be designed to the general criteria and guidelines in NASA SP-8057. Fracture control precautions shall be incorporated into the detail design configuration. These precautions shall include, but are not limited to, the following:

- **Eccentricities and stress concentrations that could act as fatigue-crack nucleation sites shall be minimized**
- **Effects of processes, geometric configurations, and manufacturing tolerance on flaw initiation and propagation shall be accounted for**
- **Strain concentrations under fabrication, test, and operation conditions shall be minimized**
- **Stress-corrosion cracking shall be prevented by material selection, temper selection, or environmental control**
- **Residual stresses shall be evaluated and accounted for in selection of manufacturing processes and determination of assembly fit-up**
- **The capabilities of applicable NDE techniques for detection of critical structural defects shall be utilized**
- **Adequate accessibility provisions shall be incorporated in the design**

5. LOADS AND ENVIRONMENTS

The cumulative static and dynamic loading and thermal and chemical environments anticipated in the various phases of the service life shall be defined for all major structural components or systems. The spectra shall include all flight and ground phases as indicated in Section 2. The load spectrum for each component or system selected for fracture control shall be determined by rational analysis that accounts for the following factors and their statistical variations:

- **The explicitly defined model of vehicle usage upon which the life spectrum is based, including as a minimum conditions such as are cited in Section 5 of NASA SP-8057 and NASA Environmental Specification**
- **The frequency of application of the various types of loads and load levels and environments**
- **The environmentally induced loads**
- **The environments acting simultaneously with loads with their proper phase relationships**
- **The prescribed service-life requirements**

The references cited in Section 4.8.4 of NASA SP-8057 give recommended practices for defining load spectra.

The design spectra shall be used for both design analysis and testing. The load-temperature spectra shall be revised as the structural design develops and the aerodynamic, thermodynamic, and loads data improve in accuracy and completeness.

In many cases it may be necessary to carry out additional analyses to establish a more reliable prediction of useful service life.

Structural data, such as accelerations, strains, and temperatures, shall be measured and recorded for each vehicle mission operation. The contractor's fracture control plan shall specify the frequency with which such data shall be used to reassess the remaining service life.

6. MATERIALS

6.1 Material Selection

Fracture properties which shall be accounted for in material selection include: (1) fracture toughness; (2) resistance to initiation and propagation of fatigue and environmentally induced cracking; (3) threshold values of stress intensity under sustained and cyclic loading; (4) the effect of fabrication and joining processes; (5) the effects of cleaning agents, dye penetrants, and coatings; (6) crack propagation characteristics, including real-time effects (e.g., time at peak load); and (7) effects of temperature and other environmental conditions. Wherever possible, low-toughness materials shall be avoided.

Many high-strength materials, because of their low toughness, are especially susceptible to serious damage from or accidental deviation from the specified fabrication procedures. They are also highly sensitive to the effects of apparently minor damage. For a particular design stress level, therefore, it is often better to use a greater portion of the strength potential of a low-strength material rather than a smaller portion of the strength of a high-strength material due to the greater tolerance for flaws in the lower-strength material.

Materials and their design operating stress levels shall be selected so that the required life for a given component can be evaluated by available NDE techniques, by proof test, or by a combination of the two.

An evaluation shall be performed at the time of material selection to determine whether any unique problems or requirements related to fracture control exist for the material or product form. Examples include: (1) the material's lack of fracture toughness, or its susceptibility to stress-corrosion cracking or to variations in material production techniques; and (2) the requirement for in-process NDE to detect defects that may be obscured in the final product form.

Specific material specifications shall be prepared when fracture control requirements are not adequately expressed by existing government or industry specifications. Where practical, specifications shall incorporate required minimum values for fracture toughness or other fracture properties under prescribed test conditions, and also shall incorporate special NDE requirements.

6.2 Material Characterization

Materials shall be selected, when possible, on the basis of fracture properties listed in reliable sources. Widely recognized sources include MIL-HDBK-5, ASTM Standards, MIL Specifications, and the Aerospace Structural Metals Handbook. **Preference shall be given to sources which provide data on a statistical basis. Material sources shall be approved by NASA.**

Fracture properties used in the materials selection process and their sources shall be documented and stored in a materials data bank. Pertinent fracture properties measured as a part of a standardized receiving inspection shall be compiled in the materials data bank.

When fracture properties data are missing, the contractor shall include in his fracture control plan a list of the sources examined and shall propose a program to obtain the missing information.

When data sources define potential problems associated with the application of a material, the contractor shall include in his fracture control plan an assessment of each problem and a proposed method to overcome it.

Test programs to determine the fracture properties of materials shall employ initial screening tests to minimize the need for subsequent detailed tests.

For example, screening tests can identify the most promising tempers, conditions, and fabrication processes of candidate materials before in-depth materials characterization tests are begun.

Uniform test procedures shall be employed for determination of material fracture properties. Where possible, these procedures shall conform to recognized standards. Acceptable standards include the test specifications of the American Society for Testing and Materials, specifications of the Society of Automotive Engineers, Aeronautical Materials Specifications, and Aeronautical Material Documents. **The test specimens and procedures utilized shall provide valid test data for the intended application. Test procedures shall be approved by NASA.**

7. ANALYSES

Analyses shall be performed to verify the structural adequacy of all components selected for fracture control. Where adequate theoretical techniques do not exist or where experimental correlation with theory is inadequate, the analyses shall be supplemented by tests.

The following analyses shall be performed, as applicable:

- **Analyses of static and dynamic loads and thermal stresses as specified in Section 7.2 of NASA SP-8057**
- **Fatigue-life analyses for unflawed structure**
- **Predicted characteristics of critical structural defects at the most likely locations of occurrence and at other critical sections.**
- **Analyses of flaw growth under predicted operational load environment spectra**
- **Residual strength analyses of fail-safe structure after the failure of a single principal element. The dynamic release of energy during the failure of the single principal structural element due to the maximum spectrum load shall be accounted for**
- **Dynamic analyses to verify that the structure is flutter free with the maximum tolerable crack size (safe-life structures) or with the single principal structural element failed (fail-safe structures). A flutter margin of 1.0 shall be provided on the maximum dynamic pressure expected at any point along the dispersed ascent and entry design trajectories and during atmospheric flight**
- **Risk assessment analyses to quantify the probabilities of crack occurrence, crack detection, load occurrence, and resulting probabilities of in-flight failure**
- **Analyses and definition of text requirements and evaluation of test results. This includes materials tests, structural development and qualification tests, and proof tests**

8. FABRICATION PROCESS CONTROL

Functional responsibilities and procedures shall be established to ensure the following:

- **That pertinent fracture control requirements and precautions are defined in applicable drawings and process specifications**
- **That all parts selected for fracture control are clearly identified throughout the fabrication cycle**
- **That detail fabrication instructions properly implemented the fracture control requirements and special precautions and guard against processing damage or other structural degradation**
- **That quality assurance procedures are defined to validate in-process controls and the integrity of the finished part.** Fracture control practices to be implemented in the preceding steps should account for mechanical and fracture

properties and physical conditions that could contribute to crack initiation or growth.

Procurement requirements and controls shall be implemented to ensure that suppliers and subcontractors employ fracture control procedures and precautions consistent with internal fabrication process practices.

9. QUALITY ASSURANCE

The quality assurance system applied to components selected for fracture control shall insure that materials and parts conform to specification requirements; that no damage or degradation has occurred during manufacture, processing, and operational usage; and that high confidence exists that no defects are present which could cause failure.

Appropriate inspection points and NDE techniques shall be selected for inspection of components selected for fracture control to verify compliance with the above, and with other specifications pertinent to fracture control. In choosing inspection points and techniques, consideration should be given to material, structural configuration, accessibility for inspection, and predicted size, location, and characteristics of critical initial flaws.

The capability of the selected NDE techniques, under production or operational inspection conditions, to reliably detect critical flaws in fracture control components shall be determined experimentally. NDE techniques, which permit the confidence of flaw detection to be expressed quantitatively, on a statistical basis, are desired.

Procedures shall be established to ensure that unplanned events which could be detrimental to the fracture resistance of components selected for fracture control are reported and dispositioned through the contractor's formal material review system.

Inspection data shall be collected regarding fracture control of material and components in an accessible central data bank. The contractor's fracture control plan shall specify the frequency with which these data are assessed to evaluate trends and anomalies and to define any required corrective action.

10. TESTS

10.1 Design-Development and Qualification Tests

Design-development tests shall be performed to confirm the feasibility of a design approach or manufacturing process for fracture control. Qualification tests shall be conducted on flight-quality hardware to demonstrate the structural adequacy of the design.

Maximum use shall be made of the same hardware for test purposes. For example, consideration should be given to use of the same hardware for fatigue tests and fail-safe (residual strength) tests.

In the planning and implementation of structural development tests, fracture control measures shall be accounted for. Sufficient tests shall be performed to provide high confidence that the design will exhibit satisfactory service life and good fracture characteristics.

For safe-life structures, tests shall be conducted to demonstrate that undetected flaws in the structure will not propagate to a critical size during the service life. To confirm this demonstration, periodic inspections shall be conducted at intervals specified in the fracture control plan. Static structure qualification tests shall be performed as described in Section 7.6.1 of NASA SP-8057 using the highest practicable level of structural assembly. Special attention shall be given to fracture-critical structural elements in the planning and conduct of these tests.

Safe-life tests on flight-quality hardware shall be performed as described in Section 7.6.7.1 of NASA SP-8057. Load and environment spectra shall be established to provide proper loads and sequencing of events to simulate the operational service loading environment. Appropriate proof loads shall be included in their proper sequence. Fracture-critical locations in the structure shall be identified prior to start of fatigue testing. During the test, the time of any crack initiation in these locations shall be identified and the crack propagation characteristics and rates shall be recorded.

Fail-safe tests on flight-quality hardware shall be performed as described in Section 7.6.7.2 of NASA

SP-8057. The tests shall be planned and implemented so as to verify the effectiveness of "crack-arrest" provisions as well as the residual strength of the structure in the damaged condition.

10.2 Acceptance and Proof Tests

As a minimum, all pressure vessels and pressurized compartments shall be subjected to proof test. This includes propellant tanks, crew compartment, and gas storage receivers. All structural components should be reviewed to determine when a proof test should be specified and at what point testing should be performed in the fabrication cycle. Particular emphasis should be given to those components designed on a safe-life approach.

For safe-life design, if the structure is not proof-tested in accordance with the principles of NASA SP-8040, NDE shall provide positive assurance of the absence of flaws greater than critical size. If the structure is proof-tested in accordance with the principles of NASA SP-8040, then NDE to determine flaws greater than critical size is desirable but not mandatory. For fail-safe design, proof testing in accordance with the principles of NASA SP-8040 is inappropriate, but NDE to detect flaws is highly desirable.

Fracture mechanics theory and test data shall be used, where practicable and appropriate, to establish proof-test conditions which will verify that no defects are present which could cause catastrophic failure or leakage during its service life. Periodic inspections shall be performed at intervals specified in the fracture control plan to confirm the absence of such defects.

The proof-test conditions shall account for all significant factors which could influence service-life performance. These factors include, but are not limited to, combined loadings, repeated load cycles, acceleration effects, sustained loadings, temperatures, thermal cycles, thermal stresses, and atmospheric or chemical environmental effects. When the linear elastic fracture mechanics theory is invalid (i.e., for thin gages or stresses close to yield), appropriate service tests shall be performed on pre-flawed laboratory coupons which simulate the structure (e.g., thickness and heat treatment) to establish valid proof-test conditions which permit prediction of service-life characteristics.

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 shall be conducted unless it can be demonstrated to be inadvisable on the basis of such factors as risk, cost, weight, and schedule. For those shuttle tanks where the predicted failure mode is clearly "failure before leakage" at proof pressure stresses, the procedures set forth in NASA SP-8040 shall be followed.

During the past decade, the concept of proof testing based on the application of fracture mechanics theory has been used to verify the integrity of high-pressure bottles and pressurized propellant tanks.

The effects of thermal cycling shall be accounted for in the assessment of the service life of shuttle structure. The generation of flaw growth data due to thermal cycling may be required for the life analysis.

For those tanks in which the predicted failure mode at proof stress is "leak before break" (i.e., most areas of the main propellant tanks), the proof test shall be performed at pressure levels exceeding the operational levels by a factor of TBD.

Since adequate analytical procedures for assuring safe life under this failure mode are not yet available, considerable experimental work to study flaw growth to leakage coupled with improved NDE capabilities is necessary.

Unpressurized structural components which have been selected for fracture control shall be proof-tested. This would normally involve components of structural assemblies where allowable defect sizes are estimated to be smaller than the inspection techniques can be expected to detect.

In general, the maximum allowable proof-test stress shall be equal to the yield stress level producing 0.2% permanent strain. As a minimum, the proof test shall apply pressures and/or stresses which exceed design limit loading in critical sections of the test article. When a proof test is conducted at a temperature different from the critical design condition, suitable correction shall be made to the proof loading to account for the difference in structural strength and fracture characteristics at the two temperatures. Materials often exhibit a decreasing fracture resistance with decreasing temperature.

A complete pre-proof-test inspection shall be performed to establish the initial condition of the structure. Post-proof-test inspection shall be mandatory for those fracture-critical structures designed for a safe-life approach where the proof test does not provide, by direct demonstration, complete assurance of satisfactory performance over the specified service life. Multiple proof tests shall be conducted for the special situations described in Section 4.6 of NASA SP-8040. Multiple NDE techniques should be used to improve confidence that all defects have been detected that could cause failure during proof test or operational service.

When critical components are not accessible for post-test inspection after complete assembly, portions of the structure shall be proof-tested prior to assembly.

Temporary and removable fixturing may be used for proof-testing portions of the structure.

11. OPERATIONS AND MAINTENANCE

The contractor's fracture control plan shall define the following:

- The required inspection intervals for all components selected for fracture control on the basis of crack-growth analyses and the results of structural development and qualification tests
- The required inspection intervals for all components selected for fracture control which have a safe life less than the total service life; the required inspection interval shall be no greater than (TBD) times the predicted safe life
- The location and character of defects and critical flaw sizes for all components scheduled for periodic inspection. This definition should be based on total experience gained over the fracture control progress, including data derived from fabrication, structural development, and structural qualification tests
- The capability of the contractor's inspection procedures and NDE techniques to reliably detect critical structural defects and determine flaw size under the conditions of use for components scheduled for periodic fracture control inspection
- The requirements for environmental conditioning or control needed for corrosion protection during turn-around or storage cycles
- The repair techniques for fail-safe structures that will restore their ultimate strength capability

The operational experience data shall be recorded and analyzed as it is accumulated to update fracture control information and to determine any areas that require corrective action. Analysis shall include prediction of remaining life and reassessment of required inspection intervals.

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SP-8001	(Structures)	Buffeting During Atmospheric Ascent, May 1964 – Revised November 1970
SP-8002	(Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	(Structures)	Flutter, Buzz, and Divergence, July 1964
SP-8004	(Structures)	Panel Flutter, July 1964
SP-8005	(Environment)	Solar Electromagnetic Radiation, June 1965
SP-8006	(Structures)	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	(Structures)	Buckling of Thin-Walled Circular Cylinders, September 1965 – Revised August 1968
SP-8008	(Structures)	Prelaunch Ground Wind Loads, November 1965
SP-8009	(Structures)	Propellant Slosh Loads, August 1968
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SP-8011	(Environment)	Models of Venus Atmosphere (1968), December 1968
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SP-8038	(Environment)	Meteoroid Environment Model – 1970 (Interplanetary and Planetary), October 1970
SP-8039	(Chemical Propulsion)	Solid Rocket Motor Performance Analysis and Prediction, May 1971
SP-8040	(Structures)	Fracture Control of Metallic Pressure Vessels, May 1970
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SP-8077	(Structures)	Transportation and Handling Loads, September 1971
SP-8078	(Guidance and Control)	Spaceborne Electronic Imaging Systems, June 1971
SP-8079	(Structures)	Structural Interaction with Control Systems, November 1971
SP-8082	(Structures)	Stress-Corrosion Cracking in Metals, August 1971
SP-8083	(Structures)	Discontinuity Stresses in Metallic Pressure Vessels, November 1971
SP-8085	(Environment)	The Planet Mercury (1971), March 1972

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