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SPACE SHUTTLE STRUCTURAL INTEGRITY AND ASSESSMENT STUDY

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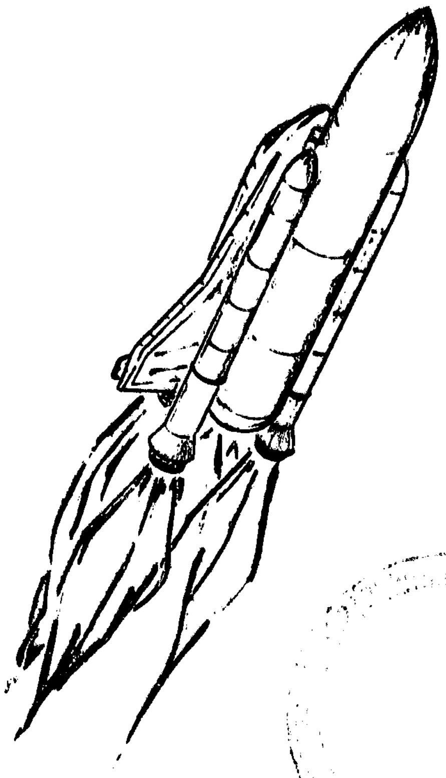

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MARIETTA, GEORGIA

FOR:

JOHN F. KENNEDY SPACE FLIGHT CENTER, FLORIDA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SPACE SHUTTLE

STRUCTURAL INTEGRITY AND ASSESSMENT STUDY

FINAL REPORT

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16. Abstract

This document describes the work performed under Contract NAS10-8018, "Space Shuttle Structural Integrity and Assessment Study", for the National Aeronautics and Space Administration, John F. Kennedy Space Center. The primary objective of the study program was to determine the nondestructive evaluation (NDE) requirements and to develop a preliminary nondestructive evaluation manual for the entire Space Shuttle vehicle. The report includes a discussion of the rationale and guidelines for structural analysis and NDE requirements development. Recommendations for development of NDE technology for the Orbiter thermal protection system and certain structural components are included. Recommendations to accomplish additional goals toward Space Shuttle inspection are presented. A major product of the program is the Preliminary Nondestructive Evaluation Manual for the Space Shuttle which comprises the Appendix to this report.

17. Key Words
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FOREWORD

This final report is submitted to the National Aeronautics and Space Administration, John F. Kennedy Space Center, in fulfillment of the requirements of Contract NAS10-8018. The work was performed at the Lockheed-Georgia Company in Marietta, Georgia, with the exception of the Solid Rocket Booster analysis which was accomplished at the Lockheed Propulsion Company in Redlands, California.

The objective of this study program has been to determine the nondestructive inspection requirements, guidelines, and criteria for the entire Space Shuttle vehicle, directing particular attention to areas where defects could cause catastrophic failures and which should be inspected during vehicle refurbishment/turnaround to detect post-flight or pre-flight defects, and to provide recommendations for inspectability and further nondestructive evaluation (NDE) technology development.

The main body of this report contains the discussion of the rationale, guidelines and criteria for structural analysis and NDT requirements development; recommendations for NDE technology development; and recommendations for future Space Shuttle NDE efforts. An Appendix to the report consists of the Preliminary Nondestructive Evaluation Manual for the Space Shuttle, containing nine sections detailing the NDE requirements, defect description, access factors and applicable NDE techniques for each of the structural critical areas and thermal protection system requiring post-flight or pre-flight inspection.

The study program was directed by Mr. W. H. Lewis, Program Manager. Mr. W. M. Pless was the Principal Engineer, who developed the NDT requirements for the Orbiter vehicle. Mr. Gus Richmond performed the initial structural analysis to define critical areas for the Orbiter and External Tank. The NDE requirements and structural analysis for the Solid Rocket Booster were conducted on Lockheed inter-company Work Authorization (IWA LI-13450) at the Lockheed Propulsion Company under the direction of Ms. Judith Schliessmann.

The program was conducted under the cognizance of Mr. Rocco Sannicando of DD-SED-4, NASA/KSC, the Contract Technical Representative, who established contacts and

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channels of communication to sources of Shuttle design information.

Lockheed greatly appreciates the important contributions derived from discussions and design information from Messrs. Sam Bohrer, Thermal Protection System Design and QA/NDE; Ron Bishop and Ralph Sugg, Structural NDE concepts; Lee Crockett, design information; and many others - all from the Space Division of Rockwell International. Additional discussions and information were obtained from Dr. Ross Quinn of Lockheed Missiles and Space Company in the area of Thermal Protection System design and NDE, and Ms. Judith Schliessmann, Messrs. Gene DeRieux, Bob Carrol and George Brocker of Lockheed Propulsion Company in the area of SRB/SRM design and NDE concepts.

Special appreciation is expressed for the continued guidance and direction of Mr. Sannicandro, NASA/KSC, during the entire program.

The final report and Preliminary NDE Manual are published under the NASA identifications NASA CR-134454 and NASA CR-139180, respectively. They also have the Lockheed-Georgia engineering report numbers LG74-ER-0074 and LG74-ER-0075, respectively.

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INTRODUCTION

The composite Space Shuttle vehicle, shown in Figure 1, combines the features of a rocket booster, orbiting space capsule and conventional air-freighter to provide a means for transporting persons, materials and equipment to and from an earth-orbiting space platform. Because of the various mission profiles, the primary Shuttle vehicle - the Orbiter - will experience total flight loads and environments not experienced by previous space vehicles. Since the Orbiter and the Solid Rocket Booster will be re-used time and again and refurbished between flights, cumulative fatigue, overstress, thermal and corrosion damage become a major concern in the task of assuring reliability. The detection of such damage must be undertaken and correctly characterized and repaired to assure the readiness for subsequent flights.

To this end, this study program was initiated for the purpose of assessing potential structural problems, identifying specific fracture-critical areas, and determining the means for detection of induced damage in these areas. The results of this study are not all-inclusive, since they were derived from analysis based on limited preliminary design and load information that was available through April, 1974. Experience with numerous aircraft inspection and overhaul programs coupled with considerations of an unprecedented combination of loads and environments to be experienced by the Shuttle were primary bases for the analysis. Therefore, recommendations are also presented in this report bearing on continuation of tasks to develop a full inspection program for refurbishment operations. The stated objective of the program was to determine the nondestructive inspection requirements, criteria and guidelines for the entire Space Shuttle vehicle and to develop a preliminary nondestructive evaluation (NDE) manual for the Oribter and booster for use during vehicle refurbishment/turn-around. The specific tasks involved in conducting the program were:

TASK I - Space Shuttle Structural NDE Requirements

1) Analysis of the Space Shuttle vehicle design to identify specific areas and points where NDE is required during routine refurbishment, considering normal and abnormal flight and ground operations.

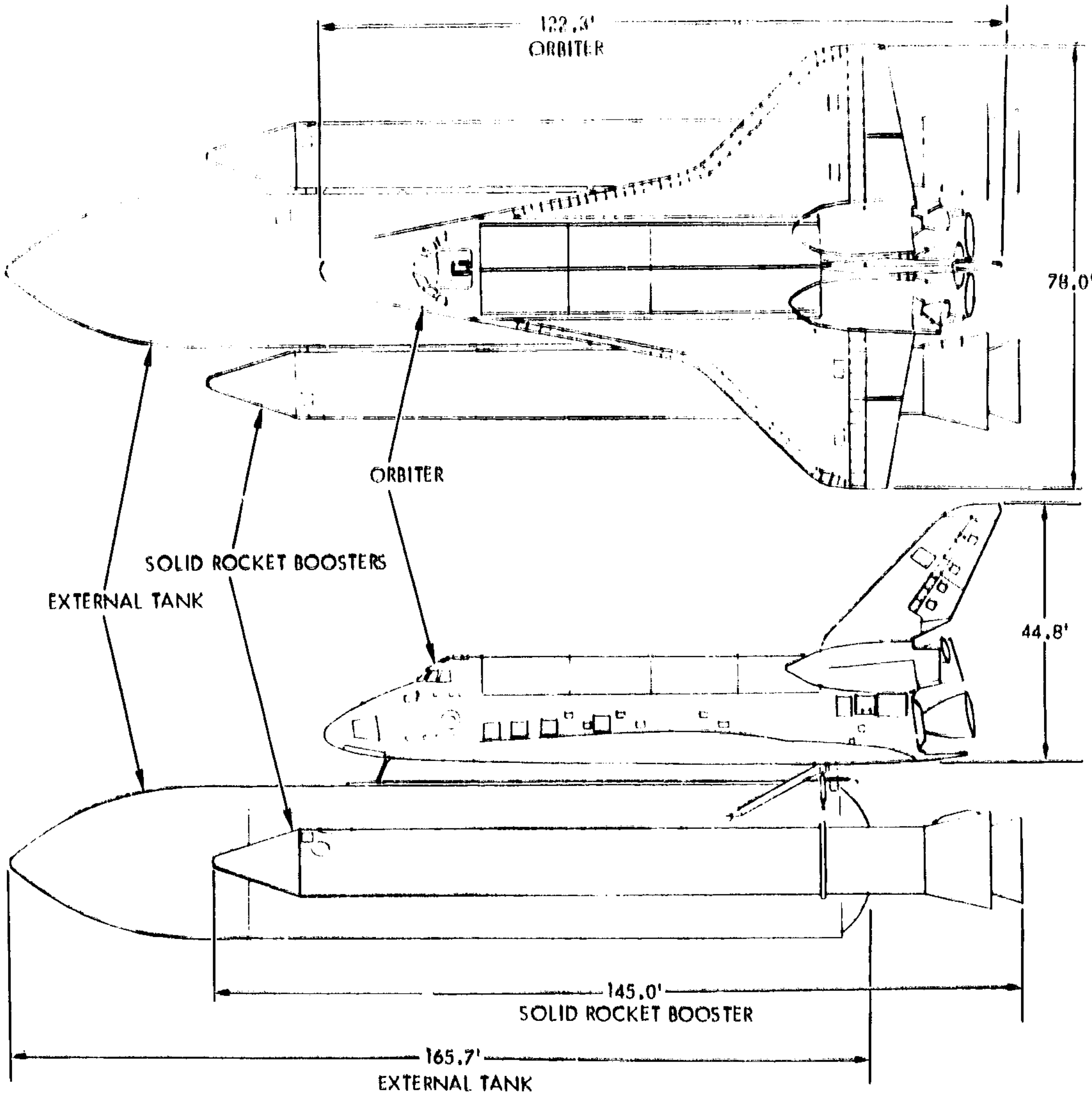

Figure 1. The Space Shuttle

INTRODUCTION (continued)

2) Describe access requirements to perform the NDE of each specific area.
3) Identify and describe the NDE technique and equipment required to detect structural defects.
4) Identify areas which cannot be adequately inspected because of design or NDE technology limitations and make recommendations concerning same.

TASK II - Preliminary NDE Manual

Prepare a Preliminary NDE Manual containing the NDE requirements for the critical areas of structure in accordance with the provisions of MIL-M-38780 (USAF). "Manual, Technical: Nondestructive Inspection".

Task I was performed by reviewing available Space Shuttle study reports, design drawings and other applicable documents to extract design concepts, load information, environmental interfaces and fracture control and inspection factors. Early analysis in the program was performed with ATP (May 1972) and PRR (November 1972) baseline design information which continued to evolve throughout the program performance period. Most of the fracture-critical areas were identified on early baseline drawings and were re-evaluated later. Many other inspection-critical areas were added later as a result of data from Rockwell International originating from a Shuttle Fracture-Control Study Program sponsored by NASA (Reference 1). The final analyses and NDE requirements update were based principally on MCR 0200 baseline and subsequent baseline revision drawings and data whose status were reasonably current through April 1974.

Task II is essentially the compilation of the results of Task I into manual format in accordance with the MIL-M-38780 specification. This final document is included as the Appendix to this report and is the Preliminary Nondestructive Evaluation Manual for the Space Shuttle vehicle. It includes inspection-critical area descriptions, defect information, access factors and recommended NDE techniques for inspection of each critical area identified. In conformance with MIL-M-38780, this document is divided into sections according to the following arrangements; Section 1. General; Section 2. Orbiter-Forward Fuselage (Zones 1, 2, and 3) and subsequent sections dealing with the specific Orbiter assemblies (zones), the Solid Rocket Booster and External Tank and the TPS. The arrangement follows the Space Shuttle zone designation system described later.

Detailed nondestructive inspection procedures are not provided in this document since the Space Shuttle design is still evolving and no Shuttle hardware is available at this point in time to adequately develop detailed procedural instructions. It is uneconomical and impractical to draft detailed procedures for manuals without firm and sufficiently detailed design information and/or availability of production hardware based on the design. Detailed calibration procedures are, however, provided in Section I - General for most of the instrumented NDT techniques. These calibration procedures are based on typical commercially available NDT equipment and have been validated by Air Force personnel on production aircraft. These procedures serve to describe the type of inspections involved and are referred to in the specific requirements by their paragraph number.

The Orbiter's thermal protection system (TPS), consisting of reusable surface insulation tiles and panels, is included in the analysis since it is essential that the integrity of the TPS be maintained at a very high level. The TPS description and NDE requirements are included in the final section of the Appendix. Since the TPS inspection will require additional technology development, a major recommendation concerning this fact is included in this Report.

Leak testing of pressurized compartments, containers, or lines was not included as an area for analysis or NDE development in this program, since NASA/KSC has been occupied with leak testing of pressure vessels for considerable time. Leak testing techniques and practices are well-established functions at the space flight installation. However, for the purposes of inspection management, NASA might consider incorporating the leak testing techniques into the final NDE manual in order to provide a more integrated control of the inspection program.

SUMMARY

This study program has resulted in (a) the development of a preliminary nondestructive evaluation (NDE) manual for the Space Shuttle vehicle for post-flight and pre-flight structure and thermal protection system inspection, (b) description of areas where further development of NDE technology and approaches is needed, and (c) recommendations concerning further development of the NDE manual, and its use during refurbishment operations. The program was begun in June 1972 and was originally scheduled for completion in thirteen months. A twelve-month extension was negotiated in order for the program to coincide with design information resulting from Shuttle design milestones. The extended program was completed in July 1974.

The program was conducted primarily by engineering evaluation of the best available information which includes Shuttle design drawings, NASA contractor reports, and other government-industry reports applicable to the Shuttle system. Through analysis of the design drawings and NASA contractor reports, a large number of candidate inspection areas and structural components were identified on the Orbiter and booster vehicles. Through further evaluation the NDE requirements for each of these areas were defined. The NDE manual was prepared containing these requirements which consist of critical area description, defect description, access factors and applicable NDE techniques for primary and back-up inspection, and sketches of the structural area or component. Program guidelines and criteria were developed largely from experience and information found in government-industry reports.

The primary NDE manual which comprises the Appendix to this report consist of nine sections as given below:

Section I - General
Section II - Orbiter Forward Fuselage Structure
Section III - Orbiter Mid-Fuselage Structure
Section IV - Orbiter Aft-Fuselage Structure
Section V - Orbiter Wing Structure

SUMMARY (continued)

- Section VI - Orbiter Vertical Stabilizer Structure
- Section VII - External Tank Structure
- Section VIII - Solid Rocket Booster Structure
- Section IX - Thermal Protection System

This arrangement as well as the contents of the manual generally follows the provisions of Specification MIL-M-38780 (USAF): "Manual, Technical; Nondestructive Inspection". About 134 structural areas on the combined Orbiter, ET, and SRB vehicles, excluding the TPS, are included in the manual as candidate inspection-critical areas. The General Section contains vehicle descriptions, access provisions, NDT technique and equipment information.

The program identified several areas where further development or study is needed in order to provide effective, reliable NDE methods for their inspection. These areas include (1) development of primary NDE techniques and inspection routines for the TPS, (2) development of an NDE method for honeycomb disbond detection without removal of local TPS, and (3) considerations for deployment of built-in NDE devices in access-restricted areas, particularly for crew module inspection. Conventional NDE methods are applicable without further development to primary structure inspection with the exceptions given in (2) and (3). The techniques for inspection of all areas require development and validation of detailed procedures.

Recommendations for further development of the overall Space Shuttle refurbishment/inspection program involve further work on the NDE manual, contents of the final manual, and incorporation of Shuttle inspection into fully integrated refurbishment activities.

DISCUSSION

A. Structural Analysis Rationale

Structural Design Characteristics

The primary structure of the Space Shuttle Orbiter has been reviewed in its preliminary form to establish critical areas for NDE purposes. For the purposes of this study, a critical area is defined as one which is determined by analysis or experience with similar hardware to be prone to develop sc.vice defects in normal or abnormal usage and which would affect the serviceability of the equipment. The first selection of inspection-critical areas is largely based on experience gained on similar structures. Areas of the type initially chosen have shown a tendency to develop fatigue cracks in the life of similar structures in both laboratory tests and in-service experience. Areas chosen generally may have a relatively small margin of safety or have area proportions such as would result in greater likelihood of early fatigue damage. Typical areas considered are:

- Corners of cutouts
- Splices and joints
- Discontinuous members
- Continuous members to which discontinuous members are attached
- Members with sudden area transitions, especially with fasteners in the vicinity of the transition
- Structures without multi-load path fail-safe provisions
- Parts which change planes for some or all their elements to maintain load continuity
- Structure where internal loads analysis is less reliable for various reasons
- Parts operating frequently near limit load
- Blind areas where fretting, corrosion and thermal stresses can contribute to early fatigue damage
- Critical inaccessible areas
- Points where fittings and brackets are attached
- Stress corrosion susceptible materials or heavily machined parts
- Parts made of materials with low stress intensity properties or with high growth rate potential

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- Primary load path members across which a heavy member such as a frame or rib cap is attached
- Regions of possible bimetallic corrosion which would accentuate fatigue

On this basis, about 86 areas were initially identified on the Shuttle-system drawings VL 70-004015 and VL 70-000044 for potential NDE purposes. Use was made of the Preliminary Fracture Control Plan (Reference 2) to identify pertinent materials and design stresses. For these materials a complete set of constant amplitude S-N curves were developed for rough assessment of performance as a function of effective working stress and potential damage. These data were reported to NASA in Reference 3, which presented early analysis rationale in data form.

Crack propagation and initiation data were accumulated in Reference 3 for:

2219 T851	2024 T851	7075 T6511
2219 T87	2024 T62	7075-T7311
	2024 T3	

Data of the following type were also generated:

Crack growth rate, dl/dn - ΔK at constant stress smplitude, ΔK thresholds (upper and lower), N_{TOT} and N_R -1 curves for constant σ_{max} and R, N_{TOT} and N_R - σ_{max} curves for various initial crack lengths.

For the purpose of tracking the performance of the inspection critical areas later, a more complete analysis of a few of the selected areas can be made with spectrum loads as they become available to indicate how the design might be expected to perform. On the basis of experience on similar structure, perhaps some correlation can be made to indicate the probability of having crack damage equal or exceeding a given length at a given lifetime. These data could be used to verify the potential effectiveness of the NDE requirements established.

Later during the program, additional fracture critical areas were added to the analysis of NDE requirements. The selection of these areas resulted from a study performed for NASA/LRC by Rockwell International, under Contract NAS3-16765, <u>Fracture Control Design Methods</u> (1). The areas were given in Quarterly Progress

DISCUSSION (continued)

Report 73MA5769 with structural configurations presented previously in reports 73MA4334 and 73MA5059. Thus, the inspection-critical areas included in the Appendix to this report were derived from both Lockheed and Rockwell analysis.

Flight Loads and Environments

The Space Shuttle vehicles, particularly the Orbiter, will be subjected to flight loads representative of a launch vehicle, an orbiting space capsule, a re-entry vehicle and a conventional air transport. The external tank (ET) and solid rocket booster (SRB) vehicles will experience only the prelaunch, ignition and ascent, max_q boost, and staging loads. The SRB will also see parachute recovery loads and sea-water immersion.

The repetitive flight loads and environments will potentially produce damage in certain locations of the structure depending on many factors such as material strength and toughness, stress levels, load cycles and environment. Damage will accumulate or grow with progressive load cycles until it reaches a critical size relative to the stress the material can withstand. At this time fracture may cause the part to fail catastrophically in overstress. It is the purpose of inspection routines to detect stably growing cracks before they reach the unstable size. Loads the Space Shuttle structure is designed to accommodate and which were considered in selection of the inspection-critical areas are summarized below

Types of Loads the Space Shuttle must accommodate: (References 2 and 4)

- Prelaunch — Loads resulting from assembly operations, hook-up stresses, static post-assembly loads and winds.
- Ignition — Transient loads due to ignition of the MPS and SRB combined with ground wind loads.
- Acoustic and Vibration — All acoustic and vibration loads experienced during liftoff and ascent.
- Acceleration — Maximum acceleration during SRB burn, and transients occuring at burnout .

DISCUSSION (continued)

o Max q-alpha and q-beta	Loads resulting from the maximum combination of dynamic-pressure (q) and resultant pitch (alpha) and/or yaw (beta) angles induced by winds aloft environment.
o SRB Separation	Transient loads at SRB burnout and separation.
o Orbiter/ET Ascent	Transient loads at initiation of throttling of main engine burn and subsequent main engine thrust termination.
o ET Separation	Separation loads and RCS thrust during separation maneuvers.
o On-Orbit Operations	a) The OMS and RCS thrust during orbit circularization, rendezvous, and docking maneuvers; b) docking and undocking loads; c) payload handling reactions; and d) RCS and OMS firings while in docked mode.
o De-Orbit Maneuvers	OMS and RCS thrusts during de-orbit.
o Orbiter Entry	The thermal, acoustic and structural loading conditions compatible with the nominal entry trajectories.
o Approach/Terminal Area Energy Management	Loads resulting from: a) Symmetric flight maneuver load factors of 2.5g positive and 1.0g negative b) Symmetric and unsymmetric maneuver and gust loads consistent with transport category airworthiness requirements (MIL-A-8861A)
o Landing and Rollout	Landing loads resulting from criteria established in MIL-A-8862, based on a design limit sinking speed of 9.6 ft./sec. for both symmetrical and drift landings at the design weight associated with a 32K lb. payload. The landing gear and wheelwell structure shall sustain taxi and turning loads.
o Heating Rates and Total Heat Load Distribution	The TPS shall sustain, without loss of operational capability, the SRB plume heating rates, the ascent heating rates and total heat loads, the ET interference heating, the re-entry heating rates and temperature extremes de-

DISCUSSION (continued)

	fined for a mission profile.
Environments	Hot day sea atmosphere, winds, troposphere and stratosphere, space vacuum, direct radiation from sun, entry plasma, rain and sleet.

These loads may be accompanied by abnormal loading conditions which can have adverse results in the component. Such abnormal loads may consist of:

1. Long stay on launch pad in salt-prone atmosphere and high winds
2. High winds aloft
3. Staging mishaps
4. Boost engine-out
5. Insufficient thermal conditioning
6. Erroneous entry angle
7. Extreme turbulence
8. Hard landing, tail down landing, or high cross-wind landing
9. Landing gear collapse

DISCUSSION (continued)

B. Nondestructive Inspection Rationale

NDE Specifications

Nondestructive inspection (NDE) methods for the Space Shuttle structure for turnaround/refurbishment inspection are described along the lines of the requirements of Air Force specification MIL-M-38780, "Military Specification Manual, Technical: Nondestructive Inspection ". To the extent possible, all nondestructive test (NDT) techniques were derived from ultrasonic, eddy current, radiographic, penetrant, magnetic particle and optical/visual methods. Instructional information concerning these NDT methods can be found in various NASA and military technical manuals and Technical Orders such as those listed in the Appendix, Section I - General, paragraph 1.5. These methods are widely used, time-proved, and readily applied with a minimum of auxiliary equipment and interpretation aids and are the most reliable NDT methods available at the present time. In some cases, advanced refinements of these methods may be desirable, such as the use of image-enhancement practices for radiography.

Many NASA documents contributed information which led directly to formulation of rationale, guidelines and criteria for the NDE analysis. Some of these are:

NASA SP 8057	Structural Design Criteria Applicable to a Space Shuttle	Jan. 1971
Contract NAS10-7250	Methods of Assessing Structural Integrity for Space Shuttle Vehicles	Jan. 1971
Contract NAS10-7679	Space Shuttle Structural Integrity Test and Assessment	Feb. 1972
Contract NAS1-10184	Study of Damage Control Systems for Space Station	Oct. 1971
Contract NAS7-200	On-Board Checkout of the Structural Integrity of Cryogenic Tanks	
NASA SP-8095	Preliminary Criteria for the Fracture Control of Space Shuttle Structures	June 1971

Application of NDT Techniques

Both primary and backup NDT methods have been suggested for critical area inspection

DISCUSSION (continued)

where applicable. The primary method will be applied to search for cracks in specified critical areas for first-order inspection. The primary method should therefore be effective, reliable, and require little or no structure disassembly or component removals. The back-up techniques are applied to verify the results of the primary technique when the latter cannot indicate the crack with reasonable certainty. Additional disassembly, removal or area preparation may be necessary to apply the back-up technique. The application of all NDT techniques are closely tied to accessibility factors which may give rise to the need for structure disassembly or removal of components or equipment. This point is discussed more fully in the "Accessibility Factors" paragraph.

The selection of a NDT technique for inspection of a given area is made after considering all relevant factors of the area, defect characterization and applicable NDT methods. Factors which affect the choice of the primary technique can be listed as:

(a) capabilities and limitations of the applicable techniques,
(b) reliability and positiveness of the applicable techniques,
(c) location, orientation, and size of potential defect,
(d) material and geometry of critical area,
(e) configuration of part with respect to adjoining structure, attachments, etc.
(f) accessibility to area with respect to specific NDT techniques and personnel,
(g) amount of disassembly and/or removals to gain access,
(h) amount of preparation to the inspection area relative to the various techniques,
(i) structure design concept - safe-life or fail-safe,
(j) safety problems and unusual human factors,
(k) set-up and inspection time.

Some general considerations for applying the NDT methods are described below. (References 5, 6 and 7).

Ultrasonic - Ultrasonic techniques can be applied when the fracture parameters are well defined. The location and orientation of suspected cracks must be known so that the ultrasound can be beamed accurately for target (crack) acquisition. Hand-scan techniques are not appropriate for general searching over large inspection areas and are better utilized when they can be confined to specific locations in the part. Automated C-scan techniques can cover larger areas on a nearly 100 percent coverage basis, providing the part geometry is uniform and the part can be removed for immersion or is suitable for mechanized wheel search unit or water-column scanning. Access surfaces must be smooth and clean. Smooth layers of paint are usually acceptable in ultrasonic inspection except perhaps in the use of surface-wave techniques. Loose or flaking paint, thick sealant of non-uniform thickness and grime must be removed from the inspection surface. Scanning motion for the search unit must not be unduly restricted for adequate inspection because of fasteners, edges, stiffeners, or other structural elements.

Ultrasound cannot be directed through a sealed faying interface with consistency or reliability. Thus adjoining members must usually be inspected from their own surfaces. Nonmetallic material is usually highly attenuating to ultrasound because of scattering and absorption. Primarily, ultrasonic techniques have been specified for inspection of clevis lug attachments, butt and lap splices fastener holes, hinge fittings, hidden areas, landing gear components and honeycomb skin panels.

Eddy Current - Eddy current techniques also are not appropriate for general large area inspection. Suspect areas should be well defined so that searching can be confined to specific locations on the part. Most surface cracks and cracks in bolt holes with the bolt removed are readily detectable by this method.

The techniques can be applied to aluminum, titanium and low-magnetic steel alloys. Uniform coats of paint and other nonmetallic coatings normally are easily tolerated. Problems can arise when the technique is applied to plated steels, particularly when the plating is worn, spalled, or cracked. Inspection of aluminum structure immediately around steel fasteners is very difficult, so that probe guides for maintaining a constant probe-to-fastener distance while scanning around the fastener are necessary. Even though eddy current techniques are confined to detection of cracks which intersect the surface, aluminum structure under thin

DISCUSSION (continued)

(< 0.18 inch) stainless steel or titanium doublers and straps can be inspected by low-frequency (< 6000 hertz) eddy current techniques, since the magnetic field from the probe can sufficiently penetrate these materials wi'' in the stated thickness.

Radiography - Radiographic methods have severe limitations when small cracks must be detected. Large, tight cracks are often missed even in thin sections. Inspection for small cracks in aluminum under steel fastener heads is impractical. Cracks in built-up structure that may be open because of transverse tensile loads are sometimes appropriate for radiographic inspection if more readily applied techniques are not applicable.

X-ray techniques have excellent application to evaluation of honeycomb internal damage, water-entrapment in honeycomb, metal fiber composites, certain types of corrosion, part misalignment, eccentric fastener holes, internal conditions of pumps, valves, and the like. Neutron radiography, highly complementary technique to X-ray radiography, described in the Appendix in Paragraph 1.5.6. Gamma-ray radiography can be used in lieu of X-ray techniques in confined places since small, self-contained gamma radiation sources are available, providing the longer exposure times can be tolerated. Gamma-ray techniques for material evaluation are well established, though not commonly used.

Although immediate access to a critical area is not necessary with radiographic techniques as is the case for eddy current and penetrant techniques, two-sided access to a built-up area is always necessary for target illumination and film placement. The removal of insulation and other low-density materials is usually unnecessary to apply X-ray inspection but may be desirable when removal is practical. When applying neutron radiography, the chemical composition of these materials should be considered to assure that their absorption coefficients will not excessively affect penetration and film contrast. Safety practices to isolate personnel from dangerous radiations is mandatory.

Radiography is specified in the Space Shuttle Preliminary NDE Manual for inspection of such items as honeycomb skin panels, solid skin panels when large areas are to be inspected, built-up sheet materials such as skin/strap/cap combinations, and sheet structures where access is not available for the use of other techniques. Many areas of skin on the Orbiter must be inspected by radiographic techniques because the RSI/TPS materials on the skin exterior restricts access for other NDT techniques.

Consideration should be given to the Orbiter static loads in the inspection environment in view of the possibility that transverse tensile loads tend to open up cracks and transverse compressive loads tend to close them. When possible, it is recommended that the structure be unloaded or reverse-loaded in order to open up cracks for improving the detection probability not only for radiography, but other NDE methods as well. For example, raising the wing tips slightly by jacks can open up wing lower surface chordwise cracks, thus enhancing detection.

The criteria for applying radiography for primary inspection of the Space Shuttle usually involves the following points: a) relatively large cracks can be tolerated in the structure, b) thin sheet materials where through-cracks are most likely to occur, and c) direct access is not available for use of other techniques because of build-up or presence of TPS materials.

Penetrants - Liquid penetrants can be applied to large exposed areas and to complete parts. Geometry is rarely a problem. Aluminum, steel, titanium alloys and nonporous nonmetallic materials can be inspected with penetrants, but only defects open to the surface are detectable by this means. The inspection surfaces must be bare and clean. Paints, sealants, insulation and other coatings must be removed from the inspection surface. After removing all surface coatings, the part must be thoroughly cleaned and degreased prior to application of the penetrants. Rough surfaces can hinder penetrant inspection.

Some penetrant solutions should not be used on titanium and high-strength steel alloys. Precautions should always be taken to assure that no harm such as oxidation and hydrogen embrittlement will occur to the part as a result of applying the penetrant solutions. Consideration should be given to the possible deleterious effects of penetrant residues left on the part. Special penetrants must be used on parts or components that are exposed to LO_2. Penetrant inspection has been heavily specified as a backup or verification technique since the use of this method requires surface finish stripping, removal of TPS, or limited area disassembly. It has been specified as a primary technique when the material surface is normally exposed or finish stripping is a minor problem.

Magnetic Particle - This method can be used to locate surface and near-surface defects in magnetic steels. The parts must be magnetizable in a direction generally transverse to the orientation of the suspected defect. The detection sensitivity is directly proportional to the magnetization of the part. However, overly magnetized material collects too many test particles and tends to degrade resolution and sensitivity.

It is desirable to remove paints and other thin coatings from the part, although a smooth, single layer of paint or coating material is often acceptable. When the part is plated with another metal, it may be difficult to discriminate between a crack in the plating and a crack in the parent steel material. The inspected parts must be demagnetized after inspection, as residual magnetism can have undesirable effects on the vehicle's navigation systems or nearby solenoids.

Magnetic particle inspection has been specified in the Preliminary NDE Manual largely for inspection of the steel landing gear components. Any magnetizable steel part for which there is access for applying the magnetizing head to properly orient the magnetic field may be amenable to inspection by this high-reliability NDT method.

Visual/Optics - Optical methods depend on achieving a clear, unimpeded view of the inspection area. Surface defects, large cracks, misalignments, discolorations, displaced components, and spillages can be detected. Optical methods are usually applied to inspect areas that are not accessible to other NDT methods. Optical methods are best used for crack detection when defect sizes are about a half-inch or more in length and have propagated through the thickness or to the edge of the part.

For visual detection, paints, sealants and other coatings must not conceal the surface. Local deformation, crack opening or severed parts are characteristics to look for in optical crack detection. Verification of suspected cracks by other NDE techniques may be necessary. The use of a back-up technique will probably necessitate removing the suspected component or partially disassembling the local structure to gain access.

Optical techniques may be used to inspect heat-sensitive color-change tape or paints placed at certain locations within the structure to detect local failures in insulation (TPS) effectiveness by undergoing color changes when they reach selected temperatures above the design maximum reentry temperature for structure (350° F). In inaccessible locations, the tapes or paints can be observed by use of optical borescopes.

Accessibility Factors - Critical-area accessibility heavily influences 1) the choice of NDT techniques to be applied, 2) NDT effectiveness and reliability, and 3) the extent of vehicle preparation prior to and following inspection. Adequate access for personnel and equipment is a prerequisite for effective inspection. Lack of ready access to a critical area should not preclude the use of some NDT technique in that area, since access can be gained by removing access panels, fairings, ducting, insulation, fittings, straps, bolts, equipment and the like, as necessary. Additional preparation such as sealant and paint stripping is sometimes required as previously discussed. In rare cases, metallic plating must be removed from a steel part. Cleaning of the part to remove alien oils, hydraulic fluids, grease, dirt and grime is practically a universal requirement for most inspection methods.

When specifying primary and backup NDE techniques for specific areas, the following considerations were made:

a. Primary inspection techniques:

- Due to the relatively small amount of time available for inspection during orbiter turnaround, removals and disassembly of components and finishes should be kept to a minimum in order to conserve time.

- Of the applicable techniques, those that can be applied with little or no disassembly or removals will be selected if practical and NDT sensitivity and reliability is not compromised.
- Where adequate disassembly or removal is not practical or advisable, consideration should be given to the feasibility of on-board permanently installed inspection paraphenalia or aids such as bonded-in-place ultrasonic search units or optical viewing ports.
- Before disassembly or removal is specified, consideration should always be given to structural effects of doing so: possible misalignment, likelihood of structural damage, level of difficulty, relative manhours required, personnel safety hazards, and operational factors.

b. Back-up or verification inspection techniques:

- All of the above considerations.
- When necessary to apply back-up techniques, the applicable NDT technique requiring the minimum amount of additional disassembly or removal should be selected providing inspection reliability can be maintained.

The expected location, orientation and size of a potential defect can determine the applicable NDE technique as well as some accessibility requirements. The NDE technique and access requirements are strongly interrelated so that one will affect the other. Occasionally the crack parameters and access factors may "lock in" a given NDE technique to the exclusion of all others. Generally, however, a choice between two or three applicable techniques may be possible. The selection of an NDT technique for a given area clearly rests on having an accurate definition of the potential problem and a knowledge of the local design factors.

Reliability - Very little data are available relating to crack detection reliability of the various NDT methods. Of the data that have been published, some disappointing results have been presented for the statistical reliability of some methods. Detection statistics have been published by Packman (Reference 8) and Pearson (References 8 and 9), Sproat (Reference 10), Pettit and Hoeppner (Reference 11), and Sattler (Reference 12). Ultrasonic, penetrant, X-ray and eddy current techniques are represented in the works referenced above. The Martin-Marietta Corporation - Denver Division, has evaluated the detection threshold sensitivity for small cracks using optimized X-ray, penetrant, eddy current and ultrasonic techniques (Reference 13). These efforts are largely concerned with maintenance inspection reliability as opposed to production or fabrication inspection. Production parts are usually considerably easier to inspect in their pre-fab condition than are built-up or installed airframe structure. The Boeing Company has reported depot level maintenance/inspection reliability data for eddy current NDT of some 33,000 fastener holes in aircraft wing structure (Reference 14).

Caution should be used when attempting to relate reliability values for a given NDT technique to any inspection situation. The reliability of a technique can vary widely due to combination of many factors, which are related in part to (1) material and fabrication characteristics, (2) crack characteristics, (3) equipment characteristics, (4) accessibility factors, (5) human factors, (6) environmental factors, and (7) inspection schedule factors.

However, some generalizations can be derived from published reliability data, which are:

(1) Reliability for any technique is expected to be less than 100%.
(2) The smallest surface cracks are most reliably found by penetrant techniques and magnetic particle inspection for steels.
(3) Only the penetrant and magnetic particle techniques have high detection reliability for surface cracks in the 0.05 inch to 0.15 inch (1.25mm to 3.75mm) size range.
(4) Generally, penetrant, eddy current, magnetic particle, ultrasonic shear-wave techniques all have good reliability for cracks greater than 0.15 inch (3.75mm) long.
(5) Radiographic techniques have acceptable reliability for detection of fatigue cracks greater than 0.5 inch (12.5mm).

DISCUSSION (continued)

In addition to these considerations, reliability of defect detection is usually enhanced by the presence of a tensile stress transverse to the crack, application of a proof load prior to and during NDE (Reference 10) and by use of redundant inspections. In the last case, the critical area is inspected at least twice by different inspectors, and the inspectors are aware of the results of any previous inspections so that they can concentrate on "accepted" areas.

Reliability data are usually developed as the number of cracks detected in a given size range relative to the actual number of cracks in the size range. Reliability confidence limits established are dependent on the number of data points available. If only one data point is present, showing that one crack was detected during one inspection when only one crack actually exists, the inspection reliability for that event appears to be 100 percent. However, the confidence that the results can be repeated in subsequent inspections may not be very high. The inspection should be repeated for a sufficient number of times (about 30) if reasonable statistical confidence limits for that part/NDT method are to be established.

Detection reliability was a prime consideration in selection of NDE techniques for the Shuttle. When two or more techniques were applicable to an area, the technique expected to yield the most reliable inspection was selected unless accessibility restraints appeared to be a factor.

NDT Standards - Ultrasonic and eddy current standards are necessary to optimize the technique and establish adequate sensitivity, resolution or lift-off. Standards contain simulated defects in sizes, locations and orientation representative of the actual part to be inspected. The material, heat-treat and finish must also be representative.

An NDT standard for each specific critical area is often necessary for ultrasonic inspection. On the other hand, for eddy current inspection, a universal standard made of the appropriate material and containing fastener holes of all pertinent sizes, fillets and lands can be fabricated with simulated cracks in the holes, along edges, on the lands and in radius areas. Simulated defects may be either real fatigue cracks or slots made by a fine saw or electrical discharge machine (ELOX).

Slots do not always closely simulate real cracks. The primary differences are related to the widths of the openings and to the texture of crack faces. Fatigue cracks are usually tightly closed as opposed to the open nature of slots. Eddy current techniques do not respond with equal sensitivity to cracks and sawcuts. Ultrasonic response can be affected somewhat by the crack opening displacement and is certainly affected by the granular texture of the fatigue crack face which tends to scatter ultrasound more profusely than the relatively smooth faces of a machined slot. The difference in response is often great and cannot be tolerated when small cracks must be found. For this reason, it is desirable that the NDT standard should contain a real fatigue crack of appropriate dimensions when small cracks must be detected.

Crack Size - Primary inspection techniques were chosen for their ability to detect cracks smaller than 0.15 inches (3.75mm) except where fail-safe or fracture toughness design features may permit larger cracks. Cracks as small as 0.050 inches (1.25mm) in length can reliably be detected repeatedly by ultrasonic, eddy current, penetrant and magnetic particle techniques when all or most of the relevant influencing factors are favorable. This situation often exists but usually several unfavorable factors will exist so that detectable crack sizes will be in the range of 0.10 inch to 0.15 inch (2.50mm to 3.75mm). Allotted time and access will be prime influence factors. Radiography has been specified when access is not available for other techniques or when the sub-critical crack size may exceed 0.25 inches (6.25mm).

Where fracture-mechanics analysis has not provided detection crack sizes for an area, the technique should be optimized to detect the smallest size that can be indicated with reasonable certainty in the presence of the local "noise". An arbitrarily small crack size may be chosen in this event for simulation in an NDT standard - for example, a 0.1 inch X 0.1 inch (2.5mm X 2.5mm) triangular simulated defect sawcut. The minimum crack size should be indicated in the NDT equipment by a response which is significantly above the "noise" level. As an example, an ultrasonic response equal to at least 50 to 80 percent of CRT saturation is usually specified for the standard simulated flaw. Where critical crack sizes are given, the NDT technique should be able to indicate a crack significantly smaller than the critical size. The detection reliability and confidence of the various NDT methods begin to decrease rapidly for cracks smaller than some given size dependent on NDT technique, part geometry and accessibility factors.

Structural Design Concepts

The design concepts considered for the reusable Shuttle structure, safe-life and fail-safe, influence the application (References 2 and 4) of NDE techniques. The safe-life concept assumes either an initial subcritical flaw or nucleation after a given number of load spectrum cycles. Then crack growth under the applied load spectra is evaluated and the safe-life is determined as the number of missions or load cycles until the flaw grows to a size that could cause failure under limit design conditions. The size of initial defect that is assumed to exist in the structure depends on the assumed or demonstrated capabilities of available nondestructive testing techniques relative to the type of defect, material and structural configuration - defining the largest crack that can be routinely missed during inspection. Flaw growth characteristics under the applied load spectra will determine the inspection intervals or life of the component or vehicle.

The fail-safe concept is also applied to a damage-tolerant design which requires that the failure of any single structural component will not degrade the strength or stiffness of the remaining structure to the extent that the vehicle cannot complete the mission. Damage tolerance is achieved through the use of tough materials, redundant load paths and crack arrest provisions such as geometric boundaries and stiffeners. The fatigue life of the remaining structure after failure of a single principal element must be adequate to prevent significant additional damage before the next regular inspection period. The fail-safe design will usually permit the use of visual, optical or radiographic inspection on accessible structure.

The safe-life design will generally require the use of more sensitive NDT techniques for inspection of accessible structure. When possible, bolts, fasteners or secondary structural attachments should be removed so that small concealed cracks can be detected and characterized. If possible, the dimensions of the crack should be ascertained through use of the NDT methods or visually, so that the flaw size can be used to help predict the remaining service life.

Critical areas that are inaccessible will necessitate incorporation of inspection devices into the vehicle design, such as inspection ports and built-in transducers. The criteria established for this study program suggests the use of ports for borescopes and x-ray film holders when fracture-critical fail-safe design is involved and the use of carefully placed built-in ultrasonic transducers when fracture-critical safe-life design is involved. The reasoning behind this criteria is that the larger flaws allowed in fail-safe structure is more suitable to detection by optical or x-ray techniques, where as the smaller cracks encountered in safe-life structure requires more sensitive and precise techniques.

Inspection Time

The time necessary to perform individual inspection is very important in maintaining the tight refurbishment schedules. However, performing the actual NDT is only a relatively small portion of the inspection activity. Nominal inspection times for actually applying the NDT techniques in average situations are given in Table I in terms of elapsed time or manhour time. These times are appropriate only for performing the inspection, just one of the many factors listed below. Much depends upon the management approach, degree of coordination with other activities, proficiency of the NDT operators, NDT reporting system and other factors. A listing of some of the pertinent factors affecting inspection time are:

- timely availability of appropriate NDT standards
- familiarity with NDT procedures needing to be performed
- preparation of structure for inspection - gaining access and cleaning
- NDT equipment check-out, set-up and calibration
- performing the inspection (see Table I)
- recording results
- interpreting results
- verification of results when defects are found
- reporting results
- removing equipment
- restoring the paints, finishes, components to flight configuration

Much depends on being ready to perform a set of scheduled inspections when the vehicle comes in for refurbishment. Prior to this stage, all necessary NDT standards,

DISCUSSION (continued)

TABLE 1 NOMINAL INSPECTION TIMES FOR NDT TECHNIQUES (INCLUDES ONLY INSPECTOR/OPERATOR FUNCTIONS)

TYPE OF STRUCTURE	NDT TECHNIQUE, PROCESS (Does not include disassembly/removal operations)	TIME, MINUTES TE = ELAPSED TIME TM = MANHOUR TIME
Bolt Hole in Lug	Ultrasonic Shear Wave	TE, 3-6 min/hole
Clevis or Butt Splice	Eddy Current Bolt-Hole, Single-Layer Construction, 3 Scans	TE, 3 min/hole
	Eddy Current Bolt-Hole, 3 - Layer Construction, 9 Scans	TE, 15 min/hole
	Magnetic Particle (Clevis/Lug), (includes magnetization, inspection, demagn.)	TM, 25 min/hole
Fastener Holes	Ultrasonic Shear Wave	TE, 10 min/15 fasteners
	Eddy Current Scan Around Fastener	TE, 5 min/15 fasteners
Fillets, Edges	Ultrasonic Shear or Surface Wave	TE, 4 min/ft (13 min/meter)
	Eddy Current Surface Probe	TE, 1/2 min/ft (1-2/3 min/meter)
	Penetrant (includes pre-cleaning, dwell times, inspection, post-cleaning)	TM and TE 35 min/area
Skin Panels, Splices	X-ray, 1/2-inch thick (12.5mm) thick alum. (includes equip. set-up, film placement, exposure, equip. tear down)	TM, 30 min/shot
	X-ray film processing and reading	TM or TE 20 min/film
	Penetrant (as above)	TM and TE 35 min/area
Cylindrical, Bar Shapes	Penetrant (as above)	TM, 25 min/piece
	Magnetic Particle	TM, 25 min/piece
Honeycomb	X-ray (as above)	TM, 25 min/shot
	Film Processing and Reading	TM or TE, 20 min/film
	Ultrasonic Resonance	TE, 5 min/sq. ft. (54 min/sq. meter)

DISCUSSION (continued)

probe guides, materials, supplies and equipment should be on hand and ready for application. Inspectors should be familiar with the individual procedures they are to perform and with the given areas on the vehicle. The necessary items for removal or disassembly should be coordinated with the maintenance people. Paper work should be prepared and minimized for reporting and control purposes.

The actual inspection time for a given area may range from a few minutes to over a half hour, depending mostly on the NDT technique used. Ultrasonic and eddy current inspection may range from 3 to 10 minutes per area. Ultrasonic lug inspection can be typically performed in 4 to 6 minutes. Penetrant and X-ray techniques take longer to apply because of pre-cleaning, penetrant and developer dwell times, and post-cleaning, or film placement and exposure time for radiography. Film development and readout combined may take twenty minutes or more. However, the actual inspection times may amount to only a small proportion of the time required for all the functions pertaining to the inspection if the inspections are coordinated and "overlapped" in order to minimize time.

Schedule Factors

During the planned two-week refurbishment turnaround period, limited time will be available in which to inspect the orbiter's critical load-bearing structure and thermal insulation. According to the ATP baseline Ground Operations Schedule and discussions with Rockwell International, approximately 72 hours will be available for performing the structural inspection functions, commencing early in the refurbishment schedule. These functions will consist of preparing the areas for inspection (i.e., disassembling, removing, and/or cleaning components), applying the actual NDT techniques, data evaluation, then restoring the areas to flight-readiness configuration.

The inspection data must be quickly and accurately interpreted so that decisions can be made regarding possible structural analysis and repair of structure or materials found to be damaged. Interpretation should be accomplished prior to restoration of the inspected areas to flight configuration in order to avoid the possibility of having to repeat disassembly or removal of components for repair or replacement.

The time constraints thus imposed upon the total inspection process necessitate the use of NDT techniques which can be applied readily and the results interpreted in real time as far as possible. This demands the selection of simple, proven NDT techniques which provide minimum equipment, set-up time, inspection time, and interpretation functions. The establishment of a reasonable inspection frequency for each area is important from this standpoint, since the number of areas requiring inspection can be kept to a minimum during most refurbishment periods. An inspection routine should be worked out to deploy manpower and NDT procedures so as to minimize the overall inspection period and to totally integrate the routine into the overall refurbishment effort.

DISCUSSION (continued)

New NDT Methods

Acoustic emission and holography NDE methods for structural assessment have not been specified in this preliminary manual. The use of acoustic emission techniques in accompaniment with pressure proof testing has become a practical way to determine the presence of crack-like defects in pressure vessels and is thus recommended for use during proof testing of all types of cryogenic tanks used on the Space Shuttle.

Acoustic emission techniques and equipment for crack-growth monitoring of primary load-bearing airframe structure is presently receiving interest in the aerospace industry. The technique has proven to be feasible on monolithic and complex built-up laboratory specimens. The Lockheed-Georgia Company, under funding from the Air Force, has designed acoustic emission systems for dynamically monitoring structure on flying aircraft and presently are flight-testing both low-level and high-level acoustic monitoring systems on a fleet-operated C-5A Galaxy (Reference 15). Present indications are that such systems can be developed to the point that they are routinely installed on flying aircraft and spacecraft within the next two to four years.

Likewise, laser interferometric holography has been applied on laboratory specimens to signal the presence of cracks around fastener holes, edges and other locations in structure (Reference 16). The interferometry patterns are established under conditions of loading and no-loading so that light fringes are established due to material deformation around the crack during loading. Necessary static loads can be easily and readily applied to many portions of structure. Increasing developments in holography

DISCUSSION (continued)

may produce several techniques for field or depot type inspection of structure within a few years.

Recent developments in neutron sources for radiographic inspection have produced relatively portable systems in the sense that a stationary reactor is no longer necessary for production of neutrons (References 5, 17, and 18). Relatively small 252-Californium isotope sourc can be housed in a shielded container that can easily be transported on a small truck to the craft for inspection of accessible components. The source itself can then be lifted by a self-contained boom for emplacement near the component to be inspected. Components for which neutron radiography is particularly suited are honeycomb skin panels, boron/epoxy laminates, pump and valve seals, hydrogenous compounds, pyrotechnic devices such as frangible bolts, lubricant-containing systems and other devices that contain hydrogen or boron. Many materials that are opaque to x-rays, such as lead, are relatively transparent to neutrons. Neutron radiography is suggested as an alternate inspection technique for some of the Shuttle structure in the Preliminary NDE Manual (Appendix).

The acoustic sonic ringing (ASR) method (Reference 19) is being considered for inspection of RSI/TPS materials installed on the Orbiter. Although acoustic resonance techniques are not new, the ASR method is new in the sense of the computerized system needed to apply it and in its application to the new TPS material system. The ASR method has been used successfully at the Lockheed Missiles and Space Company to detect delaminations, cracks, voids, disbonds, and severe emissivity coating erosion in the RSI/TPS material. The technique is essentially a measurement of the sound reverberations produced in the material when the surface is lightly tapped with a weight of a few grams. The presence of flaws produces a change in the reverberation frequencies which provide the signature for flaw detection. The technique uses a sonic transducer to receive the reverberations which are amplified and displayed on a spectrum analyzer. Good material may produce a frequency of 8 KHz or less, and material with flaws may produce frequencies from 12 to 25 KHz. Frequencies generated depend on tile thickness, attachment system properties, material of construction of tapper, emissivity coating thickness, defects and other factors. To use the ASR technique, a data-bank must be compiled for each RSI panel consisting of frequencies relating to RSI, the internal defects, RSI tile coating defects, bondline defects, and sound material. This promising technique takes only a very short time to interrogate each panel.

SPACE SHUTTLE STRUCTURAL INSPECTION REQUIREMENTS

A. Refurbishment NDE Requirements

For the purpose of this study, a structural critical area is defined as an area of structure or component which is determined by analysis or experience to be prone to develop service defects which would affect the serviceability of the equipment. These are referred to as fracture-critical parts and are usually considered to fall into one of the following categories of criticality:

(a) failure can cause loss of the mission, loss of the vehicle, and/or loss of life; example: fracture of a vertical stabilizer/fuselage attach fitting;

(b) failure will lead to a loss of one or more mission goals, or reduced performance of the vehicle; example: fracture of a wing spar cap;

(c) failure may not threaten the mission, vehicle or life, but the integrity of an on-board system or subsystem is indirectly affected; example: fracture of a feedline support bracket.

Items which can be described by critical category (a) are high-risk parts whose integrity must be assured for each mission. Many items in category (b) must be considered high-risk items in terms of accomplishing mission goals. Assurance of integrity is accomplished through fracture-control design methods, inspection and maintenance activities and other fracture control practices.

In the early part of the program, Orbiter ATP and PRR baseline drawings were analyzed to define areas where flight loads or environments might cause structural damage. With a knowledge of the types of loads the Shuttle vehicles will encounter in a typical mission profile, about 86 areas and components of structure were initially defined as "candidate" inspection areas. In the absence of design and load details for these areas, it was not possible to define positive requirements. Later baseline drawings, design information and fracture analysis data were used to define the 134 areas that are now included in the Preliminary NDE Manual comprising the Appendix of this report. Of particular help in this respect were the progress reports made available from the contract study program NAS 3-16765: Fracture Control Design Methods (Reference 1), performed by the Rockwell International Space Division.

Table 2 presents a matrix summary of the structural NDE requirements for the Orbiter, SRB's and ET that are applicable to post-flight or pre-flight assessment. The matrix gives component/area name, number of parts per vehicle, NDE techniques, general location of the parts and pertinent comments. It should be noted that not all these areas are to be inspected after each flight. Some areas will probably need to be inspected very infrequently. Other areas may need to be inspected only in the event that unusual loads or mishaps are encountered. The NDE manual should include the NDE requirements for such areas so that "how to" instructions will exist in the event they should be needed.

The structural areas included in the Manual should not be regarded as complete or conclusive. Some of the areas may be dropped or new areas added when more complete design and load data are available for a more rigorous analysis of the structure. Future component testing and flight test programs will strongly influence the contents of the final NDE manual for the Shuttle. A list of additional candidate areas and components which were not included in the present Preliminary NDE Manual is given in Table 3, and should be given consideration for future inclusion in the manual.

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT

PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
	SECTION 2, FORWARD FUSELAGE STRUCTURE:					
2-101	CABIN FUSELAGE SHELL SUPPORT LINK AND BRACKET ASSY	BRACKETS, THREADED EYEBOLT, SLEEVE	23	OPTICAL OR ULTRASONICS AND PENETRANT	RESTRICTED ACCESS MAY REQUIRE BUILT-IN NDE PRO-VISIONS	PO
2-102	FWD FUS FRAME CAPS	CAP, ATTACH-MENTS		OPTICAL OR RADIOGRAPHY	RESTRICTED ACCESS	PO
2-103	FWD FUS SKINS	SKIN STRINGER		RADIOGRAPHY AND OPTICAL	RESTRICTED ACCESS	PO
2-104	FWD FUS SHELL WINDOW FRAMES		6 WINDOWS	RADIOGRAPHY AND OPTICAL	RESTRICTED ACCESS	PO
2-201	NLG DRAG LINK SUPPORT FITTING	MACHINED FITTING	2	ULTRASONIC		
2-202	NLG TRUNNION SUPPORT FITTING	MACH. FITTING	2	ULTRASONIC		
2-203	NLG AXLE	SPLINED MACHIN-ING	1	MAGNETIC PARTICLE	FULL INSPEC-TION REQUIRES DISASSEMBLY	PO
2-204	NLG SHOCK STRUT PISTON	MACH. FORGING	1	MAGNETIC PARTI-CLE AND ULTRA-SONIC		PO
2-205	NLG SHOCK STRUT CYLINDER	MACH. FORGING	1	ULTRASONIC AND MAGNETIC PARTI-CLE		PO
2-206	NLG TORQUE LINKS	MACH. FORGINGS	2	ULTRASONIC AND MAGNETIC PARTI-CLE		PO
2-207	NLG LOWER DRAG BRACE	WELDED TUBING	1	ULTRASONIC AND MAGNETIC PARTI-CLE		PO
2-208	NLG UPPER DRAG BRACE	WELDED TUBING	1	ULTRASONIC AND MAGNETIC PARTI-CLE		PO
2-209	NLG LOWER DOWN LOCK BRACE	MACH. FORGING	1	ULTRASONIC		PO
2-210	NLG UPPER DOWN LOCK BRACE	MACH. FORGING	1	ULTRASONIC		PO
2-211	NLG DRAG BRACE CROSS TIE	MACH. FORGING	1	MAGNETIC PARTICLE		PO
2-212	FWD ET/ORBITER ATTACH FITTING	MACHINED LUG	1	ULTRASONIC AND PENETRANT		PO & PR
2-213	FWD RCS MODULE STRUCTURAL ATTACH	MOTOR ATTACH FITTINGS AND HINGES	24+	EDDY CURRENT		PO

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT

PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA/COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS /VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
2-214	CREW MODULE ENTRANCE HATCH OPENING, FWD FUS SHELL	FRAMING STRUCTURE	1 HATCH	EDDY CURRENT AND ULTRASONIC		PO
2-301	CABIN FWD BULKHEAD	WELDED WAFFLE PLATE	1 BLKHD	ULTRASONIC AND PENETRANT		PO
2-302	CREW MODULE WINDOW FRAMES	WELDED PLATE	6 WINDOWS	RADIOGRAPHY AND ULTRASONIC		PO
2-303	CABIN CANOPY PANELS	WELDED PLATE		ULTRASONIC OR RADIOGRAPHY	RESTRICTED ACCESS	PO
2-304	CABIN MLG ACCESS PANEL	WELDED PLATE	1 PANEL	RADIOGRAPHY		PO
2-305	CABIN FLOOR - BULKHEAD BEAMS	BUILT-UP FRAMES AND FITTINGS		EDDY CURRENT RADIOGRAPHY	RESTRICTED ACCESS	PO
2-306	CABIN SKIN PANELS	WELDED PLATE		ULTRASONIC, RADIOGRAPHY OR OPTICAL	RESTRICTED ACCESS	PO
2-307	CABIN AFT BULKHEAD	WELDED WAFFLE PLATE AND ATTACHMENTS	1	ULTRASONIC AND/OR EDDY CURRENT		PO
	SECTION 3. MID FUSELAGE STRUCTURE:					
3-401	PAYLOAD BAY FWD SILL LONGERON	EXTRUSION	2	EDDY CURRENT AND ULTRASONIC	SPLICE AREA	PO
3-402	PAYLOAD BAY LOWER FWD LONGERON	EXTRUSION	2	EDDY CURRENT AND ULTRASONIC		PO
3-403	GLOVE FAIRING SKINS	FORMED SHEET	2	EDDY CURRENT AND VISUAL		PO
3-404	MID FUS ACCESS OPENINGS	SKIN/ FRAME	6 OPENINGS	EDDY CURRENT AND VISUAL		PO
3-405	FWD ECS RADIATOR PANEL HINGES	MACHININGS	8 HINGES	ULTRASONIC AND EDDY CURRENT		PO
3-406	WHEEL WELL FUSELAGE INNER/ OUTER ACCESS OPENINGS	SKIN/ FRAME	2 OPENINGS	EDDY CURRENT AND VISUAL		PO
3-407	LOWER SKIN PANELS	MACH. PLATE		RADIOGRAPHY	COVERED WITH TPS ON LOWER SURFACE	PO
3-408	PAYLOAD DOOR POWER HINGES	MACHININGS	12	ULTRASONICS		PO
3-409	PAYLOAD DOOR IDLER/SHEAR HINGES	MACHININGS	26	ULTRASONIC		
3-410	PAYLOAD SIDELOAD RETENTION FITTINGS	MACHININGS	14+	EDDY CURRENT		PO
3-411	SIDE SKIN PANELS	MACH. PLATE		RADIOGRAPHY, EDDY CURRENT AND VISUAL	TPS ABOVE WING ML	PO

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT

PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA/COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS /VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
3-412	WING CARRY-THRU SKINS	MACH. PLATE		RADIOGRAPHY, & EDDY CURRENT OR ULTRASONIC	TPS ON LWR SURFACE	PO
3-413	WING CARRY-THRU SPAR FRAMES	MACH. PLATE	4 FRAMES	ULTRASONIC & EDDY CURRENT		PO
3-414	WING-TO-FUS LOWER AFT LONGERON TENSION TIE	EXTRUSION, MACH.	144 BOLT HOLES	ULTRASONIC		PO
3-415	MID FUS LOWER AFT LONGERON	EXTRUSION, MACH.	2	ULTRASONIC	SPLICE AREA	PO
3-416	PAYLOAD BAY AFT SILL LONGERON	EXTRUSION, MACH.	2	ULTRASONIC	SPLICE AREA & ATTACHMENTS	PO
	<u>SECTION 4.</u> <u>AFT FUSELAGE STRUCTURE:</u>					
4-501	AFT ORBITER/ET ATTACH FITTING	DIFFUSION BONDED MACHINING	2	ULTRASONIC & RADIOGRAPHY		PO PR
4-502	AFT JACKING POINTS		2	PENETRANT		PO
4-503	AFT FUS/WING SPAR LOWER ATTACH PADS	BUILT-UP PLATE	4 PADS	RADIOGRAPHY & EDDY CURRENT	TPS ON LOWER SURFACE	PO
4-504	LOWER THRUST SHELF ATTACH TO X_o1307 AND FLOOR	MACH. DIFFUSION BONDED	2	ULTRASONIC & EDDY CURRENT		PC
4-505	UPPER THRUST SHELF ATTACH TO X_o1307 BULKHEAD	MACH. FITTING	2	ULTRASONIC & EDDY CURRENT		PO
4-506	AFT HOIST POINT	DIFFUSION-BONDED FITTING	2	ULTRASONIC & RADIOGRAPHY		PO
4-507	VERTICAL STABILIZER FWD SPAR TO FUSELAGE ATTACH	MACH. FITTING	1	ULTRASONIC, EDDY CURRENT RADIOGRAPHY		PO
4-508	AFT FUSELAGE FRAMES	BUILT-UP CAPS, WEBS, STIFFENERS	4 FRAMES	EDDY CURRENT & RADIOGRAPHY	SPLICE AREAS	PO
4-509	AFT FUSELAGE LOWER SKINS	MACH. PLATE		RADIOGRAPHY & EDDY CURRENT	TPS ON LOWER SURFACE	PO
4-510	WING AFT SPAR CARRY THRU FRAME AT X_o1365 AND FLOOR BEAM AT X_o1470	BUILT-UP CAPS, WEBS, STIFFENERS	2 FRAMES	EDDY CURRENT, RADIOGRAPHY AND ULTRASONIC	BULKHEAD & LWR CAP/FLOOR ATTACH	PO
4-511	UPPER THRUST SHELF SUPPORT TRUSS ATTACH	DIFFUSION-BONDED FITTINGS	2 ATTACH-MENTS	ULTRASONICS & EDDY CURRENT		PO
4-512	LOWER THRUST SHELF SUPPORT TRUSS ATTACH	DIFFUSION-BONDED FITTINGS	2 ATTACH-MENTS	ULTRASONIC & EDDY CURRENT		PO
4-513	BORON EPOXY/THRUST STRUCTURE BONDS	REINFORCED TUBES	NUMEROUS	ULTRASONIC		PO
4-514	MAIN ENGINE GIMBAL ACTUATOR SUPPORT POINTS	DIFFUSION-BONDED FITTING	6 POINTS	ULTRASONIC & EDDY CURRENT		PO

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT

PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA/COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS /VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
4-515	MAIN ENGINE SUPPORT AND GIMBAL POINTS	DIFFUSION-BONDED BEAMS	3	ULTRASONIC & EDDY CURRENT		PO
4-516	LOWER THRUST SHELF AND MAIN ENGINE FEEDLINE SUPPORT ATTACHMENTS	DIFFUSION-BONDED FITTINGS	2 SUPPORT STRUCTURES	ULTRASONIC & EDDY CURRENT		PO
4-517	UPPER THRUST SHELF AND MAIN ENGINE "1 FEEDLINE SUPPORT ATTACHMENTS	DIFFUSION-BONDED FITTINGS	1 SUPPORT STRUCTURE	ULTRASONIC & EDDY CURRENT		PO
4-518	CANTED FRAME, LOWER PORTION	MACH. PLATE	1 FRAME	ULTRASONIC	SPLICES AND TRUSS ATTACHMENTS	
4-519	CANTED FRAME, UPPER PORTION	DIFFUSION-BONDED FRAME	1 FRAME	ULTRASONIC & EDDY CURRENT	SPLICES AND TRUSS ATTACHMENTS	PO
4-520	VERTICAL THRUST TRUSS ATTACHMENTS	DIFFUSION-BONDED TRUSSES	3 TRUSSES	ULTRASONIC & EDDY CURRENT		PO
4-521	FIN SUPPORT FRAME, CLEVIS ATTACH	DIFFUSION-BONDED FRAME	1 FRAME, 16 HOLES	EDDY CURRENT OR ULTRASONIC		PO
4-522	BASE HEAT SHIELD FRAMING STRUCTURE	FORMED PLATE	8 PLACES	EDDY CURRENT		PO
4-523	BASE HEAT SHIELD DOME JUNCTURES	FORMED PLATE	3 PLACES	EDDY CURRENT		PO
4-524	OMS POD ATTACH TO AFT FUS	MACH. FITTINGS	10 PLACES	RADIOGRAPHY, EDDY CURRENT AND OPTICAL		PO
4-525	UPPER LONGERON, OMS DECK	EXTRUSION	6 PLACES	RADIOGRAPHY	RESTRICTED ACCESS	PO
4-526	OMS ENGINE GIMBAL ACTUATOR ATTACH	MACH. FITTINGS	4 FITTINGS	ULTRASONIC & EDDY CURRENT		PO
4-527	OMS ENGINE THRUST SUPPORT STRUCTURE	MACH. FITTINGS AND TRUSSES	4 FITTINGS AND TRUSSES	ULTRASONIC & EDDY CURRENT		PO
4-528	AFT RCS POD ATTACH STRUCTURE	FITTINGS BUILT-UP STRUCTURE	6 PLACES	ULTRASONIC AND EDDY CURRENT		PO
4-529	AFT RCS ENGINE MOUNTS	MACH. FITTINGS	24 FITTINGS	ULTRASONIC & EDDY CURRENT		PO
4-530	AFT BODY FLAP HINGES	MACH. FITTINGS	4 HINGES	ULTRASONIC		PO
4-531	AFT BODY FLAP HINGE SPAR/RIB ATTACH	FORMED SHEET, FITTINGS	4 PLACES	ULTRASONIC OR EDDY CURRENT		PO
4-532	AFT BODY FLAP FRONT SPAR	FORMED SHEET	4 AREAS	EDDY CURRENT		PO
4-533	AFT BODY FLAP HONEYCOMB SKIN PANELS	HONEY-COMB	UPR AND LWR FLAP SURFACES	RADIOGRAPHY AND SONIC OR ULTRASONIC	TPS ON UPR AND LWR SURFACES	PO

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT

PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA/COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS /VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
	SECTION 5, WING STRUCTURE:					
5-601	MLG DRAG LINK SUPPORT FITTING	MACH. FITTING	4 FITTINGS	ULTRASONIC AND EDDY CURRENT		PO
5-602	MLG TRUNNION SUPPORT FITTING	MACH. FITTING	4 FITTINGS	ULTRASONIC AND EDDY CURRENT		PO
5-603	MLG MAIN STRUT UPLOCK SUPPORT	MACH. FITTING AND BUILT-UP STRUCTURE	2 AREAS	EDDY CURRENT AND VISUAL		PO
5-604	WING-TO-FUSELAGE CLEVIS ATTACH FITTINGS	MACH. FITTINGS	20 AREAS	ULTRASONIC AND EDDY CURRENT		PO
5-605	WING LOWER WING-TO-FUSELAGE TENSION TIE	EXTRUSION MACH. PLATE	144 BOLT HOLES	ULTRASONIC		PO
5-606	MLG BOX FWD SPAR	BUILT-UP CAPS, WEBS ATTACH-MENTS	8 PLACES	EDDY CURRENT OR ULTRASONIC		PO
5-607	MLG OUTER RIB	BUILT-UP CAPS, WEB, & ATTACH-MENTS	12 PLACES	EDDY CURRENT OR ULTRASONIC		PO
5-608	MLG BOX AFT SPAR	BUILT-UP WEB & ATTACH-MENTS	8 PLACES	EDDY CURRENT OR ULTRASONIC		PO
5-609	MLG AXLE	SPLINED MACHIN-ING	2	MAGNETIC PARTICLE	FULL INSPECTION REQUIRES DISASSEMBLY	PO
5-610	MLG CROSS TUBE	MACH. FORGING	2	MAGNETIC PARTICLE		PO
5-611	MLG SHOCK STRUT PISTON	MACH. FORGING	2	ULTRASONIC & MAGNETIC PARTICLE		PO
5-612	MLG SHOCK STRUT CYLINDER	MACH. FORGING	2	ULTRASONIC & MAGNETIC PARTICLE		PO
5-613	MLG TORQUE ARM	MACH. FORGINGS	2	MAGNETIC PARTICLE		PO
5-614	MLG LOWER LOCK BRACE	MACH. FORGING	2	ULTRASONIC		PO
5-615	MLG UPPER LOCK BRACE	MACH. FORGING	2	ULTRASONIC		PO
5-616	MLG LOWER DRAG BRACE	MACH. FITTING	2	ULTRASONIC & MAGNETIC PARTICLE		PO
5-617	MLG UPPER DRAG BRACE	MACH. FITTING	2	ULTRASONIC & MAGNETIC PARTICLE		PO
5-618	WING LEADING EDGE SPAR CAPS AND RCC ATTACH BRACKETS	EXTRUSIONS & MACH. FITTINGS	28 LOCA-TIONS	EDDY CURRENT AND ULTRASONIC		PO

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT
PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA/COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS /VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
5-619	WING LOWER SKIN PANELS	MACH. PLATE	NUMEROUS	RADIOGRAPHY	TPS ON LOWER SURFACE	PO
5-620	WING SPAR CAPS	FORMED SHEET	NUMEROUS	EDDY CURRENT OR ULTRASONIC		PO
5-621	WING RIB CAPS	FORMED SHEET	NUMEROUS	RADIOGRAPHY		PO
5-622	WING SPAR/RIB SPLICES	FORMED SHEET, MACHININGS	NUMEROUS	RADIOGRAPHY & EDDY CURRENT		PO
5-623	ELEVON ACTUATOR ATTACH FITTING	MACHININGS	4	ULTRASONIC & SHEAR WAVE		PO
5-624	ELEVON HINGES	MACH. PLATE	12	ULTRASONIC & PENETRANT		PO
5-625	ELEVON HONEYCOMB SKIN PANELS	HONEYCOMB	4 ELEVONS	RADIOGRAPHY & ULTRASONIC, SONIC OR THERMOGRAPHY	TPS ON EXTERIOR SURFACES	PO
5-626	ELEVON WEB STIFFENERS	FORMED SHEET	NUMEROUS	OPTICAL		PO
	<u>SECTION 6.</u> <u>VERTICAL STABILIZER STRUCTURE:</u>					
6-701	VERTICAL STABILIZER FRONT SPAR	BUILT-UP CAPS, WEB AND STIFFENERS	4 AREAS	EDDY CURRENT & RADIOGRAPHY	REMOVE V.S.L.E FAIRING	PO
6-702	VERTICAL STABILIZER-TO-FUSELAGE AFT ATTACH FITTING	MACH. PLATE	8 BOLT HOLES	EDDY CURRENT		PO
6-703	VERTICAL STABILIZER SKINS	FORMED SHEET		RADIOGRAPHY	TPS ON EXTERIOR SURFACES	PO
6-704	VERTICAL STABILIZER REAR SPAR AT RUDDER LWR FWD EDGE	BUILT-UP CAPS, WEB OR TRUSSES AND STIFFENERS	2 AREAS	EDDY CURRENT AND RADIOGRAPHY		PO
6-705	RUDDER/SPDBRK ACTUATOR AND HINGE ATTACH TO VERTICAL STABILIZER REAR SPAR	HINGE FITTINGS, SPAR CAPS AND WEB	4 AREAS	EDDY CURRENT		PO
6-706	RUDDER/SPDBRK ACTUATORS AND HINGES	MACH. FITTINGS, ASSEMBLY	4 HINGES	ULTRASONIC & EDDY CURRENT		PO
6-707	RUDDER FRONT SPAR	BUILT-UP CAPS, WEB, STIFFENERS	4 AREAS	EDDY CURRENT, & OPTICAL OR RADIOGRAPHIC		PO
6-708	RUDDER/SPDBRK REAR SPAR	BUILT-UP CAPS, WEB, ATTACHMENTS	2 RUDDER SECTIONS	OPTICAL AND RADIOGRAPHIC		PO
6-709	RUDDER/SPDBRK HONEYCOMB SKIN PANELS	HONEYCOMB	2 SURFACES EACH RUDDER SECTION	RADIOGRAPHIC & SONIC, ULTRASONIC OR THERMAL	TPS ON EXTERIOR SURFACES	PO

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT
PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA/COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS /VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
	<u>SECTION 7.</u> <u>EXTERNAL TANK STRUCTURE:</u>					
7-801	ET/ORBITER FWD ATTACH FITTINGS AND TRUSSES	MACH. PLATE	2	ULTRASONIC & PENETRANT		PR
7-902	FWD SRB ATTACH THRUST LONGERON	MACH. FORGING	2	PENETRANT, EDDY CURRENT		PR
7-803	FWD SRB/ET ATTACH FITTING	MACH. FITTINGS	2	ULTRASONIC & PENETRANT		PR
7-804	AFT ET/ORBITER ATTACH FITTINGS	MACH. FITTINGS	6	ULTRASONIC & PENETRANT		PR
7-805	AFT ET/ORBITER ATTACH TRUSSES	DIFFUSION-BONDED TUBES	6	ULTRASONIC & PENETRANT		PR
7-806	AFT ET/SRB ATTACH FITTINGS AND TRUSSES	MACH. FITTINGS AND DIFFUSION BONDED TUBES	4	ULTRASONIC & PENETRANT		PR
	<u>SECTION 8.</u> <u>SOLID ROCKET BOOSTER STRUCTURE:</u>					
8-901	SRB RECOVERY SYSTEM (PARACHUTES AND ATTACHMENTS)	FITTINGS, CHUTE CANOPY AND SHROUDS	FITTINGS, 3 CHUTES	PENETRANT AND VISUAL		PR PO
8-902	SRB SEPARATION MOTORS	MOTOR ASSY	8 TO 10	RADIOGRAPHY AND VISUAL PENETRANT		PM PO
8-903	SRB INTERFACING	MECHANICAL, ELECTRICAL, ALIGN-MENT & RELEASE	4 ATTACH AREAS	VISUAL, PENETRANT & OPTICAL		PR PO
8-904	ET/SRB FWD ATTACH FITTING	MACH. FITTING	2 ATTACH AREAS	PENETRANT & VISUAL		PR PO
8-905	SRM IGNITER	IGNITER MOTOR ASSY	2	RADIOGRAPHY & VISUAL		PR
8-906	SRM SEGMENT MEMBRANE		7 TO 11	PENETRANT & VISUAL ULTRASONIC		PO
8-907	SRM SEGMENT CLEVIS JOINT	CASING	7 TO 11	PENETRANT, ULTRASONIC & VISUAL		PO
8-908	SRM ASSEMBLY HARDWARE	STEEL PINS	NUMEROUS	MAGNETIC PARTICLE & VISUAL	PINS REMOVED	PO
8-909	SRM NOZZLE AND IGNITER ATTACHMENT BOSSES	BUILT-UP CASING	2 EACH	PENETRANT, ULTRASONIC & VISUAL		PO

TABLE 2. SUMMARY MATRIX OF SPACE SHUTTLE NDE REQUIREMENTS

PO - POSTFLIGHT
PR - PREFLIGHT

PROCEDURE NUMBER	LOCATION AND AREA/COMPONENT DESCRIPTION	TYPE OF PART	PARTS, AREAS /VEHICLE	PRIMARY NDT TECHNIQUES	REMARKS	TYPE INSP.
8-910	SRM PROPELLENT SURFACES	PROPELLENT GRAIN	EXTENSIVE	VISUAL/OPTICAL		PR
8-911	SRM PROPELLENT-TO-INSULATION BOND	PROPELLENT GRAIN & INSULATION	ALL SEGMENT JOINTS	ULTRASONIC		PR
8-912	SRM INSULATION-TO-CASE BOND	INSULATION & CASING	ALL SEGMENT JOINTS	ULTRASONIC		PR
8-913	SRM INSULATION-TO-RELEASE FLAP BOND	INSULATION & FLAP COMPONENTS	ALL SEGMENT JOINTS	ULTRASONIC		PR
8-914	ET/SRB AFT ATTACH FITTINGS AND TRUSSES	MACH. FITTINGS, & TUBING	4	ULTRASONIC AND PENETRANT		PR PO
8-915	SRB THRUST VECTOR CONTROL, STRUCTURE & ASSY	ATTACH FITTINGS	2 TO 4	ULTRASONIC & PENETRANT		PO
8-916	SRB FLEXIBLE SEAL	METAL RINGS & ELASTOMERIC PADS	2	VISUAL & OPERATIONAL		PO
8-917	SRB NOZZLE SHELL	STEEL SHELL & ABLATIVE PLASTIC	2	VISUAL, PENETRANT, ULTRASONIC		PO
8-918	SRB NOZZLE ABLATIVES	ABLATIVE PLASTICS	2	VISUAL/OPTICAL		PR
	<u>SECTION 9.</u> <u>THERMAL PROTECTION SYSTEM:</u>					
9-1001	RCC LEADING EDGES AND NOSE CAP	REINFORCED CARBON-CARBON PANELS	NOSE AND WING LEADING EDGES	RADIOGRAPHY, ULTRASONIC, PENETRANT		PO
9-1002	HRSI/TPS AND LRSI/TPS	SILICA TILES WITH STRAIN ISOLATION PAD	ORBITER EXTERIOR SURFACES	THERMAL, SONIC RINGING, PENETRANT		PO

STRUCTURAL INSPECTION REQUIREMENTS (continued)

TABLE 3

STRUCTURAL AREAS THAT SHOULD BE CONSIDERED FOR FUTURE INCLUSION IN MANUAL (Reference 1)

Additional Areas (Not Included in present Preliminary NDE Manual

Fwd. Fus. Zones 1, 2 and 3

Cabin, Frame Webs

Cabin, Frame Caps

Fwd. Fus. Stringers

Fwd. Fus. Frame Webs

Fwd. Fus. Fwd. Bulkhead

Fwd. Fus. Longerons

Fwd. Hoist Fittings (X_o 582, Z_o 345, $Y_o \pm$ 105)

Mid-Fuselage Zone 4

Glove Fairing Ribs

Payload, Glove and Intermediate Frame Webs

Payload, Glove and Intermediate Frame Caps, Stiffeners and Trusses

Frame Support Ribs

Access Doors (other than those included)

Bracketry

Payload Bay Liner

Payload Bay Doors, Skin

Payload Bay Doors, Stringers

Payload Bay Doors, Frame Web

Payload Bay Doors, Frame Cap

Payload Floor Longerons, $Y_o \pm$ 61, Z_o 312

STRUCTURAL INSPECTION REQUIREMENTS (continued)

TABLE 3 (continued)

Aft Fuselage Zone 5

Fuselage Frames
Skin/Stringers
Floor (Waffle Plate)
Floor Beam Caps
Floor Beam Webs
Truss Tubing
Fuel Line Support Fittings
Fuel Line Support Beam Web
Fuel Line Support Beam Caps

Wing Zone 6

Stringers
Rib EMF Tubes
Rib EMF Tube Fittings (included in high-risk areas)
Rib/Skin Shear Channels
Access Doors (Intra-spar)

Vertical Stabilizer Zone 7

Stringers
Box Ribs
Ribs
Spar Web
Drag Chute Frame
Rudder Ribs

STRUCTURAL INSPECTION REQUIREMENTS (continued)

TABLE 3 (continued)

External Tank   Zone 8

- LO_2 Tank Frame Y-Ring
- LO_2 Tank Bulkhead
- LO_2 Tank Frame (X_t 715)
- Intertank, Skin/Stringer
- Intertank, Frames (96 Places)
- Intertank, Frame (X_t 947)
- LH_2 Tank, Fwd Bulkhead
- LH_2 Tank Frame (X_t 1078)
- LH_2 Tank Aft Bulkhead
- LH_2 Tank, Frame (X_t 2058)
- Compression Strut

Solid Rocket Booster   Zone 9

- Nose Cone
- Recovery System Supt. Structure
- Forward Cylinder
- Forward Closure
- Cylindrical Body
- Aft Closure
- Nozzle
- Aft Skirt

B. Inspection Criteria

The inspection criteria for this program are defined in terms of (1) sizes of cracks that must be detected and (2) the inspection frequency. These criteria are part of the overall NDE requirements which require development for the Shuttle critical inspection areas.

Crack Size

In conventional design/NDE concepts, parts containing cracks are assumed to be screened out by go/no-go NDE methods and the part presumably enters service without defects. Little thought is given to the probability that flaws are missed and some design concepts do not account for them other than through a margin of safety which is applied to accommodate scatter in design allowables.

In presently applied safe-life damage-tolerant design concepts, the probability that flaws exist in parts is assumed and the service life of the part is predicted after considering 1) possible initial flaw size missed by production inspection, 2) stress intensity factors, 3) type and intensity of applied loads, 4) environment, and 5) frequency of loading. This approach alters the concept of NDE in that a greater burden is placed on it to reliably detect and characterize defects for both production and in-service applications. The objective is to detect cracks before they grow to some critical size and to quantitatively assess the crack size, shape and orientation. It is important in this respect to know the ability of an NDE technique to find or miss cracks of a given size. The fracture mechanics design assumes the presence in the material of the largest flaw that could be routinely overlooked by a particular NDE approach (See Reference 20 for a discussion of this concept).

The largest allowable flaw size for a structural element can be derived at any time by the use of the type of data presented in References 1 and 3. This is the largest flaw that should exist in the structure for a specified number of cycles remaining with consideration given to maintaining the margin of safety. The applied NDE techniques must detect all flaws of this size and larger. Where sufficient load, material, geometry and environmental data are available, flaw size criteria can be generated for NDE accept/reject considerations and for use in the design of NDE standards for ultrasonic and eddy current NDE techniques.

Critical crack size limits for Space Shuttle structure have not been determined for specific components. Since damage-tolerant designs and materials having good fracture toughness are used throughout the Shuttle airframes, it is presently assumed that critical crack sizes will generally lie within the capability of present NDE methods. There may be a few exceptions to this assumption. The NDE techniques specified in the Manual for inspection of safe-life structures are, with the exception of radiography, capable of reliably detecting cracks within the range of 0.10 inch to 0.150 inches (2.5mm to 3.75mm).

Inspection Frequency

The frequency of inspection for euch critical area can be established from consideration of crack growth data. Crack initiation and growth rates will vary over the Orbiter structure depending upon the stress levels and materials involved so that some components should be inspected more often than others. Where crack propagation values are small, i.e., the flaw will not attain a critical length within the service life, the inspection frequency will be minimum. However, the realization that nondestructive inspections may not be 100 percent reliable and cracks can be missed during an inspection period should have some bearing on establishing the inspection frequency. An increased inspection frequency would have to be established to partially compensate for low inspection reliability.

High-risk components should generally receive a frequent inspection even though these components may be generously designed. The failure of a high risk component can place the vehicle or mission in extreme danger and should be prevented through adequate inspection. Other components which are not high-risk items but which traditionally have a short mean-time-to-failure should also be inspected frequently.

Information sufficient to determine inspection frequency of the components or areas considered in this study was not available during the study period. Due to severe time constraints during vehicle refurbishment, it is paramount that reasonable inspection frequencies be established for each area eventually considered to be critical to the mission, vehicle, systems and to personnel safety. Inspection frequencies are generally established through analysis of detailed design/load factors, mission profile, component test and flight test histories, NDE capabilities and adequate safety margins. Initial inspection frequencies are often altered during the vehicle lifetime to reflect the "learning curve" and remaining vehicle life guarantees.

SUGGESTIONS FOR FURTHER NDE DEVELOPMENT

A. Inspectability Versus Design

One objective of this Study was to identify areas or components that cannot be inspected adequately because of design factors such as access, material, geometry, or configuration, thus posing a possible requirement for redesign or further development of NDE techniques. Structure inspectability is one of the design requirements for the Shuttle system, which provides, through design, adequate personnel access, NDE equipment access and provisions, and inspectable structure.

With due consideration to the limited design details that were available, this study program did not reveal any design features that would justify a redesign effort to permit inspection. This statement is made on the assumption that, in certain cases, a particular item of structure can be removed to provide adequate inspectability. Examples include removal of the bolts, one at a time, in the mid-fuselage sill longeron forward splice at the X_o 578 bulkhead or in the vertical stabilizer/aft fuselage attachments. In the event these bolts are not removable for routine inspection, the NDE efforts of these areas could be unduly restricted. Overall, the Space Shuttle appears to be a very inspectable structure, and design iterations for inspectability will probably be very minimal.

The level of design detail was not available during this Study effort to the extent that design geometry factors could be fully evaluated, for example, in terms of sufficient clearance for NDE probe manipulation. The use of ultrasonic shear wave probes for inspecting around fastener holes requires sufficient surface space for scanning the probe in at least one preferred direction adjacent to the fastener. When such space is not available, the ultrasonic inspection cannot be performed. The task of evaluating areas for sufficient clearance remains to be accomplished in future NDE procedures development. This effort should interface with structure design so that design/inspectability iterations can be accomplished when necessary.

The RSI/TPS panels generally deter access for airframe surface inspection. The TPS prevents visual inspection of skin panels, fasteners, exterior access openings and the like. Ultrasonic, eddy current, and penetrant techniques are eliminated from exterior surface inspection unless the local TPS is removed. Radiography, on the other hand, can penetrate the TPS with little attenuation, albeit the crack sensitivity relative to other NDE methods is low. Since relatively large skin cracks can usually be tolerated, radiography has been specified for skin and thin-sheet multi-layered structure inspection without removing the TPS.

As expected, some areas of the Orbiter structure may have limited access. But redesigning for better access is probably not justifiable since to do so could compromise structural integrity from the design standpoint. Areas where access appears to be restricted include the following:

1. crew module skin, frames, and floor beams
2. crew module forward and aft bulkheads
3. crew module-to-fuselage link assemblies
4. crew ingress/egress hatch frame structure
5. forward fuselage shell frames
6. forward fuselage skins
7. vertical stabilizer/aft fuselage attach fittings and shelf
8. rudder/speed brake aft spar
9. elevon aft spar
10. honeycomb skin panels (disbond detection).

In the event that access is unduly restricted in these areas, consideration should be given to providing built-in inspection aides and devices if criticality warrants. For example, built-in X-ray film holders for radiographic inspection of crew module and forward fuselage skin, built-in optical fiberscopes for inspection of link assemblies, or built-in ultrasonic transducers for vertical stabilizer/fuselage attachment fittings may be advisable. The access-restricted areas should be evaluated further for determining adequate inspection access, criticality of component and cost-effectiveness of using built-in NDE provisions. Table 4 summarizes areas where further NDE development efforts appear to be needed.

B. NDE Technology

NDE for Structure

As discussed above, the need for determining the necessity and cost-effectiveness for using built-in NDE devices and aides exists for some structural components where access is restricted. Feasible technology appears to have already been developed for this purpose by the Rockwell International Space Division (References 20 and 21). Fixed and rotatable ultrasonic transducers are feasible, bond-coupled to the metallic structure to withstund extremes of temperature, vibration and aging. In order for these devices to be effective and reliable, the location and orientations of potential cracks must be exactly pre-determined. The added weight of built-in provisions is a consideration. Rockwell International has also developed applications technology for built-in optical systems and film-holders. Further developments along this line should deal with advantageously locating built-in devices within the structure, determining the cost-effectiveness for using them and determining read-out modes and equipment for applying the devices.

Another potential development area involves inspecting honeycomb skin panels for detection of disbonds between the core and face sheets without having to remove the local external TPS. Present NDE techniques require a clean bare skin surface, which means that the TPS and adhesive debris must be removed. An obvious advantage lies with a technique which can reliably detect rejectable disbonds with the TPS intact. Such a technique must either be insensitive to or be able to discriminate against TPS material signatures. A candidate NDE method may involve the use of sonic energy at the right frequency and beam shape. The feasibility of the sonic or any other NDE method for this application must be proven, and the techniques further developed for use during Shuttle refurbishment.

FURTHER NDE DEVELOPMENT (continued)

TABLE 4

SUMMARY OF NDE DEVELOPMENT AREAS

Structure Inspection:	1.	Determine need and cost-effectiveness of installing built-in NDE devices in restricted-access areas in forward fuselage and at aft/fus vert-stabilizer juncture.
	2.	Develop feasible NDE technique to inspect honey-comb skin panels without removing TPS.
	3.	Assess desirability of monitoring critical pressure vessels with acoustic emission system.
	4.	Assess desirability of monitoring structural areas with acoustic emission system.
	5.	Study to define effects of residue from NDE and cleaning materials and establish guidelines for their use.
Thermal Protection System:	1.	Develop NDE procedures and inspection routine for use on installed or removed RCC/TPS leading edge panels to detect significant defects.
	2.	Develop NDE techniques and inspection routine for use on RSI/TPS panels for quick primary assessment and verification.

Critical pressure vessels such as the liquid hydrogen and oxygen fuel tanks, ECLSS cryogenic tanks, and the orbiter crew cabin should be considered for the desirability of monitoring crack initiation and flaw growth by acoustic emission techniques. Such techniques are able to detect and locate extensions of part-through cracks in the vessel walls during pressurization cycles (References 22 and 23. Development should satisfy the following points: (a) identification of the most likely failure zones in the pressure vessels, (b) best placement of A. E. transducers, (c) identification of system equipment for installation on spacecraft, (d) identification of system equipment for pre-flight and/or post-flight data analysis, (e) optimization of the system to produce high signal-to-noise ratio, accurate crack location ability, and acceptable operation under flight conditions.

NDE for the Thermal Protection System (TPS)

The TPS was evaluated for NDE refurbishment requirements early in this Study since this system, though not part of the basic structure, appeared to represent an area in which considerable NDE development is required. The TPS affects the access to structure inspection in addition to requiring inspection of its own. In the event that the TPS suffers catastrophic damage in high heat areas, the underlying airframe skin and adjacent structural attachments can be severely damaged. Thus, TPS inspection is a major concern. The TPS applications on the Orbiter are shown in Figure 2.

In the early evaluation, candidate TPS materials such as the ceramic (mullite) HRSI/TPS, the elastomeric LRSI/TPS, and the RCC/TPS leading edge system as then envisioned, were evaluated in terms of material characteristics, environment, and possible failure modes. An analysis was made of these TPS factors in relationship to the capabilities of state-of-art NDE technology. Feasible techniques were selected for detection of the various defects in each of the TPS systems. Since the applicable NDE techniques were not well established for the types of materials, development was needed in order to completely define the capabilities and limitations of the techniques and to devise a complete inspection approach for the individual and combined techniques.

TPS APPLICATIONS

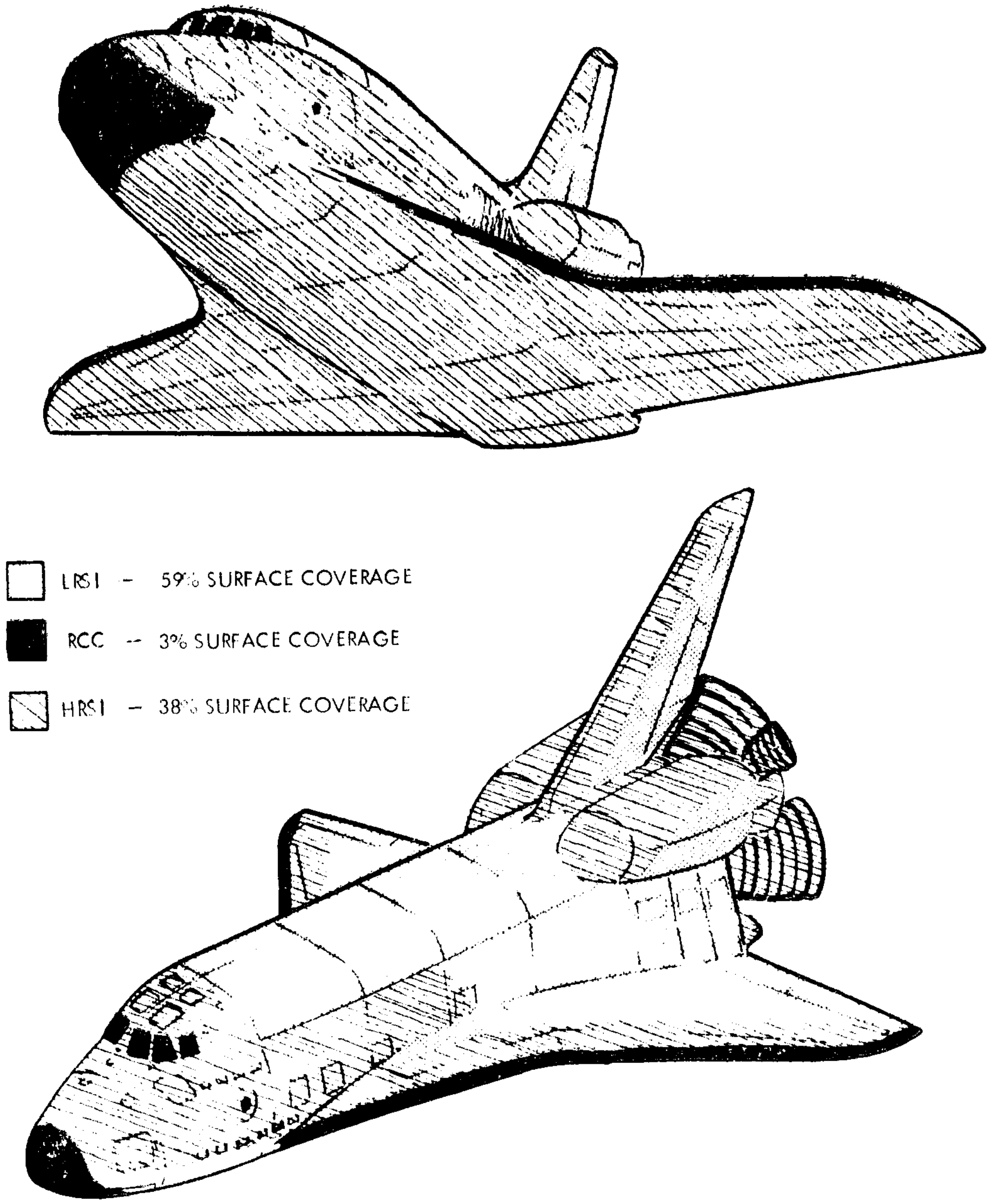

Figure 2. TPS Applications

FURTHER NDE DEVELOPMENT (continued)

The results of the TPS evaluation and a development plan were reported in an interim report, LG73ER-0042, "Nondestructive Inspection Requirements for the External Reusable Thermal Protection System", which was distributed as an Appendix to the program mid-term report (Reference 24: NASA CR-134452, "Space Shuttle Structural Integrity and Assessment Study", June 1973). The modified TPS development plan is reprinted at the end of this section. Since that evaluation was performed, a coated silica system was selected for both the HRSI and LRSI which is known commercially as LI-900 developed and produced by the Lockheed Missiles and Space Company (References 19 and 25). An updated summary of the interim report appears in the Preliminary NDE Manual as Section 9 - Thermal Protection System, including both the RCC and LI-900 TPS systems.

The TPS NDE development program is presently being conducted by the Rockwell International-Space Division who has that responsibility. An approach is to develop a "broad-brush" inspection to detect damaged tiles in high-risk areas depicted in Figure 3. The approach might use both infrared remote scanning and the acoustic sonic ringing (ASR) techniques as primary inspection means to detect damage. These would be performed in consonance with a walk-around visual inspection which would survey the entire TPS.

TPS tiles which are not considered to be in high-risk areas would be inspected on a cyclic sampling basis such that all tiles are inspected periodically. The infrared method is presently restricted to tiles less than 0.5-inch (12.5mm) thick for detection sensitivity to the full spectrum of gross defects. Above this thickness only surface related defects such as moisture and gross coating failures can be detected. The ASR technique likewise is limited because of its complexity and the need to place the ASR sensor on each tile inspected. The technique requires the ASR "signature" history of each tile to be stored in computer memory for real time comparison. Any bulk defect such as disbond, delamination, or crack will change the signature and cause the ASR system to provide a reject signal.

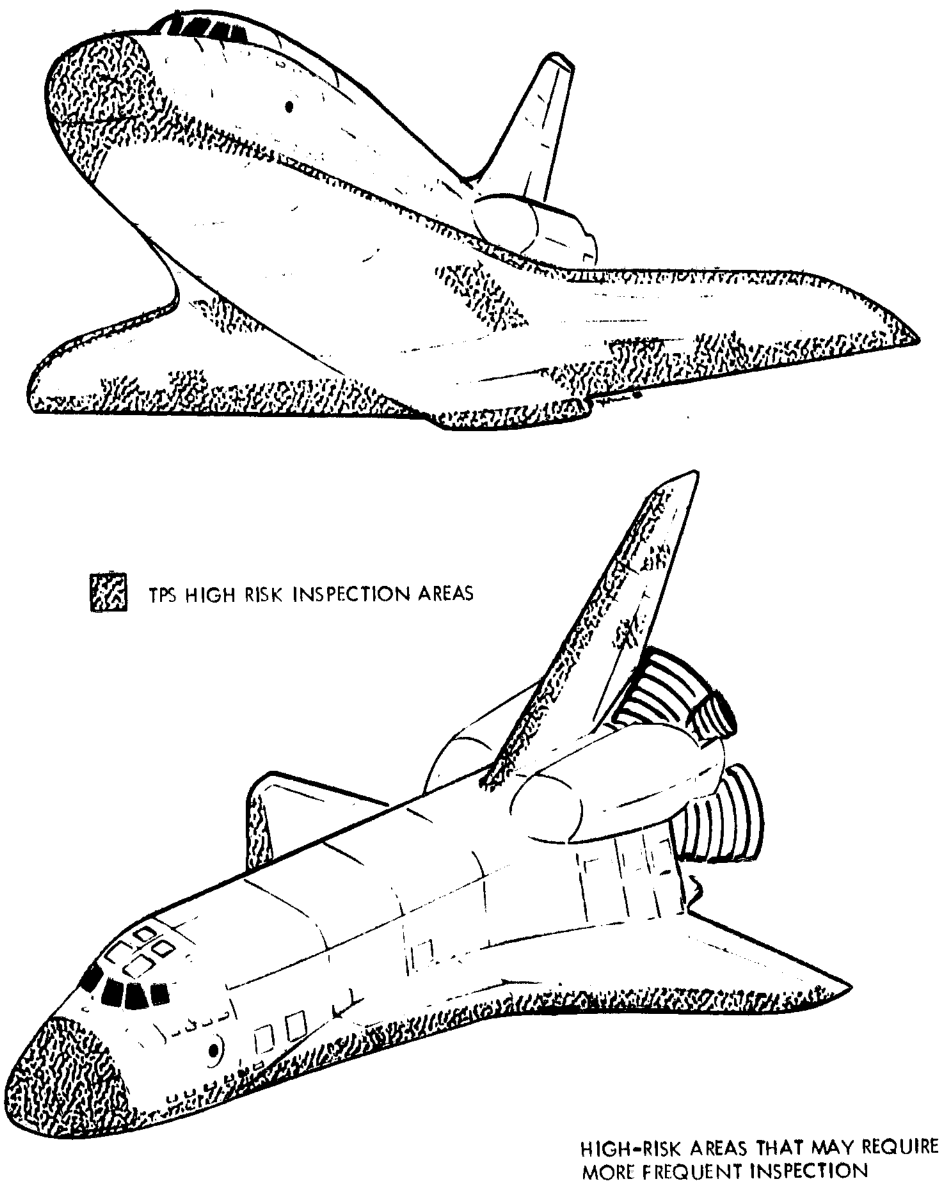

Figure 3. High Risk Areas for Thermal Protection System

The limitations of these two primary NDE techniques or, in other words, the absence of a single technique which can quickly scan the Orbiter TPS and identify flawed TPS tiles, has given rise to the approach involving high-risk area inspection and sampling of remaining tiles. Once a flawed tile is indicated by any primary technique, a decision would be required regarding continued investigation of the suspect tile through the use of back-up NDE methods, or to disregard additional NDE and simply replace all suspect tiles with new ones, and to extend the investigation to adjacent tiles.

C. Development Approach

Structure

1. Restricted access in some Orbiter subassemblies may reduce the potential of NDE techniques in these areas. Special attention should be given to the crew module and forward fuselage shell where lack of access may penalize inspection by reducing reliability and by requiring more time for inspection than is reasonable in view of the tight turnaround schedule. To alleviate these potential problems consideration should be given for built-in provisions in these areas for optical devices, bonded-in-place ultrasonic transducers and X-ray film holers.

Structural areas in the forward fuselage that may be affected include the cabin-to-fuselage link assemblies and fittings, fuselage shell frame caps, fuselage skins, crew ingress/egress hatch, fuselage and cabin window frames, and cabin skins.

The following points should be considered:

a. Does adequate access provisions exist for applying NDE techniques suggested in the Preliminary NDE Manual for the various areas.

b. If not, are subcritical crack sizes sufficiently large for the fail-safe design components to permit use of visual/optical techniques or extended use of radiographic techniques.

c. In safe-life design components, where subcritical crack sizes may be relatively small, can potential crack locations and orientations be predicted with sufficient accuracy to provide for built-in ultrasonic devices.

d. Compare added weight penalty and cost benefits of built-in NDE provisions against conventional teardown (limited to present access provisions) inspection.

2. Core-to-facesheet disbonds in honeycomb skin panels are usually detectable by ultrasonic, sonic or thermal techniques. These techniques require a clean, bare skin surface. The honeycomb skin panels that exist on the Orbiter elevon, aft body flap, and rudder/speed-brake assemblies, are covered externally by bonded RSI/TPS tiles and thus do not fulfill these requirements without removal and cleaning of the skin surface.

A desirable NDE technique is obviously one that could be used to detect disbonds without disturbing the RSI/TPS materials. Feasibility for doing this may exist in the sonic technique. Further development is required to prove feasibility and to develop technique effectiveness and reliability. The following points may be involved to accomplish the development.

a. Design and fabricate laboratory test panels of suitable size, consisting of a honeycomb panel with bonded RSI/TPS tile on one side. The honeycomb core thickness, core depth, core material, facesheet thicknesses (including doublers where appropriate) and facesheet thickness would all be fully representative of the particular portion of honeycomb skin panel. The TPS density, thickness, strain-isolation pad, coating and bonding system would also be fully representative. Realistic simulated core-to-facesheet disbonds of several diameters should be contained in the test panels.

b. Select several sonic test systems such as described in subsection 1.5.5 in Section 1 of the Preliminary NDE Manual or other source, and an array of sonic transducers representing various diameters and frequency ranges.

c. Apply each sonic instrument, according to the manufacturers instruction manual, with the various transducers over the frequency range of the instrument, comparing "disbond" areas in the test panel to good areas.

d. If feasibility is shown to exist for one or more of the instruments in detection of the "disbonds" further development is required to select the most effective instrument and optimize the equipment and technique by determining best frequency, sensitivity level, transducer type and size, and other relevant factors.

e. Determine the smallest disbond that can be reliably and consistently found with the instrument. Assess reliability.

f. Devise test panels that contain TPS defects or standard deviations to determine their masking effect on honeycomb disbonds.

g. Develop the sonic honeycomb disbond detection procedure for inclusion in the Space Shuttle NDE Manual.

3. Acoustic emission systems can detect dynamic crack growth when the structure to which the sensors are bonded is under adequate stress. Acoustic stress wave emissions may be released when an existing crack extends or a new crack neucleates at a small material defect or design discontinuity. Crack growth has been detected in pressure vessels by acoustic emission systems when the vessel is being pressurized or proof tested.

Consideration should be given to the desirability of using acoustic emission systems to monitor all Space Shuttle cryogenic and gas-filled pressure vessels as they are being filled on the launch pad in both the Orbiter and ET. The technology exists adequately for doing this and very little development is necessary in this respect. It would be necessary to design and develop the specific acoustic emission systems that would be applied to the various vessels and the readout modes and equipment needed for applying them. Weight penalties for attached sensors, wiring, preamplifiers and system hook-ups should be assessed.

Adapting the acoustic emission technology for Space Shuttle use that is being developed now for monitoring structure on aircraft (Reference 15) should be given serious consideration. Specially designed acoustic emission systems can be used to monitor key structural areas and components during the entire flight or at any selected portion of the flight. Signals are accumulated in a small computer memory or stored on tape for later readout. The success of such systems have the potential of greatly reducing the need for conventional NDE inspections and can thus impact cost, manpower and schedule factors. Development would include:

a. Defining or selecting the structural areas for acoustic emission monitoring.

b. Designing the acoustic emission sensors, preamplifiers and overall system -- "tailor make" the system to do only the specific tasks required.

c. Perform an acoustic noise survey on a flying Orbiter vehicle to determine the magnitude and spectral content of the normal operational noise in the specific structural areas.

d. Design the acoustic emission system to exclude background noise both in amplitude and frequency response while maintaining adequate sensitivity for detection of acoustic emission from growing cracks.

e. Define real-time or stored information readout modes for the system.

f. Flight test the system on a flying Orbiter to determine problems, sources of false signals and to "fine tune" the system.

Thermal Protection System (TPS)

An NDE development plan for the TPS was presented in the program mid-term report and also was summarized in Tables 1 and 2 of that report (Reference 24). Since considerable NDE development is required to produce individual NDE techniques and an overall NDE inspection approach for the TPS, the modified plan is repeated in this Final Report. Rockwell International is conducting material characterization and Design Development Test programs for the Shuttle TPS (Reference 25).

PLAN FOR DEVELOPMENT OF NONDESTRUCTIVE EVALUATION METHODS FOR THE SPACE SHUTTLE EXTERNAL REUSEABLE SURFACE INSULATION

Introduction

The spirit of the Space Shuttle is embodied in the reusability of the craft and its systems. The practical effects of repetitive flights into space on a vehicle and its thermal protection systems (TPS) are largely speculative at this point. Experience in many space programs can be used to project the first-flight performance of all systems. The extent and effects of cumulative damage caused by the rigors of space flight during subsequent flights is presently assessed on the basis of projection and calculated risk factors.

The types and severity of damage that will be induced in the Shuttle's external thermal protective shield will be known with certainty only after many flights of the system into space. Reasonable expectations of damage to the TPS have been used to determine the nondestructive inspection requirements described in Section 9 - Thermal Protection System of the Appendix. The major factors which may produce damage in the TPS are:

- o High vibration loads during lift-off and ascent
- o High aerodynamic pressures and gust loads

FURTHER NDE DEVELOPMENT (continued)

- Impingement of rain, dust, sleet and other debris
- Thermal soak during orbit
- High entry temperatures
- Cross-range flight
- Landing
- Ground handling
- TPS/Structure mechanical and thermomechanical incompatibility

The NDT techniques which appear to be the best candidates for detecting and assessing the potential damage in the HRSI, LRSI, and the RCC composite leading edge were discussed in the mid-term report Appendix (NASA CR-134452) and summary in Section 9 of the Appendix to the final report. Most of these techniques have been used on similar materials with acceptable results. All of the techniques described have at least been demonstrated to have applicability to the specific problem. In general, further development effort is needed for all techniques to produce reliable, optimized inspection methods for post-flight and/or pre-flight assessment of the TPS.

Development Plan

To develop the candidate NDT techniques to their full potential, the following plan is suggested:

1. Define the TPS failure modes. (An objective of the Thermal Protection System Test Plan is described in Reference 25.)
2. Design and fabricate realistic inspection standards for each material/defect combination, containing various sizes and/or severity of the defective conditions; vary other parameters such as defect depth, orientation, etc., when practical; use real or realistically simulated defects; and reflect the actual geometric and material variables which will affect the particular NDT techniques.
3. Determine and optimize the NDT equipment test parameters to achieve the necessary sensitivity, resolution, discrimination.

4. Screen the techniques for a given material/defect application and derive reliability and cost-effectiveness considerations for the various techniques.

5. Determine the most appropriate means to display, record, and interpret the NDT data for refurbishment operations.

6. Determine the most practical approaches in applying the techniques, e.g., methods and equipment for scanning, whether parts are installed or removed for inspection.

7. Determine the sensitivity, reliability, and confidence limits of the techniques, particularly of the relatively new untried techniques.

8. Determine an effective sequence for applying primary, verification (back-up), and exploratory techniques.

9. Write inspection procedures to instruct inspectors in the use of the techniques. Define the accessibility factors and all equipment, standards, and calibration needs for each technique.

10. Evaluate the cost-effectiveness and reliability of the techniques after they have gone into operational refurbishment use in early Shuttle deployment period.

Development should be broad enough to provide for evaluation of physical properties as well as detection of defects. This approach will be particularly applicable to the carbon-carbon composite material in which degradation of physical properties may occur as a result of oxidation or repeated exposure to re-entry temperatures. Physical property evaluation may have limited applicability to the silica RSI, except possibly for surface coating integrity.

Development should include the consideration of enhancement techniques, particularly to radiographic and C-scan presentations. The elimination of "noise", sharpening of images, and pattern recognition/rejection features should be considered to improve significantly the interpretability of such presentations.

Since the RCC leading edge and nose cap may require multiple NDT techniques for complete assessment, consideration should be given to removing these components from the craft after each flight and taking them to an NDT laboratory for inspection.

Inspection of the approximately 36000 RSI panels (HRSI and LRSI) bonded to the Orbiter outer surface during refurbishment turnaround will be time-consuming unless one or more fast-scan techniques capable of detecting most anomalies can be developed. If only NDT methods capable of interrogating a single panel by contact are applicable, an inspection approach may be devised whereby only those panels in the more severely exposed portions of the Orbiter are inspected at each refurbishment period. The remaining panels are inspected on an alternating basis to conserve time and costs. Walkaround visual inspections should be applied regardless of the applicability of other methods. Many surface defects and RSI tile deformations resulting from internal defects may be detectable by visual means. The development should concern itself with arranging an overall inspection approach in which the applied techniques can be used in a reliable, effective, and economical manner.

Development of the NDT techniques for the TPS should extend beyond their initial application to operational vehicles. Use of the techniques at the maintenance base will provide a better proving ground for their effectiveness than will the laboratory. The cost-effectiveness of the applied techniques should be continually assessed regarding the results of NDE on the actual Shuttle hardware. NDE techniques and approaches that are found to be ineffective should either be improved through modification or discarded in favor of better techniques. The ultimate effectiveness of inspection techniques is determined by intrinsic technique limitations and by human factors that yield to training and experience. All applied techniques should improve in cost-effectiveness and reliability as experience is gained with them in the maintenance environment.

FURTHER NDE DEVELOPMENT (continued)

Study to Define Acceptable NDE and Cleaning Materials

Additional studies should be conducted to determine the possible harmful effects of NDE materials residues on structural areas and in enclosed environments and guidelines for use of such materials. Residues may result from the use of cleaning solvents, penetrant or magnetic particle materials, and acoustic couplants. They may result in corrosion, hydrogen embrittlement, surface finish breakdown, or crew environmental contamination. The study should define acceptable and rejectable cleaning and NDE materials capable of leaving residues, particularly in view of the potential effects produced by both natural and induced Shuttle environments.

The study should include the effects of high temperature on material/residue interactions and the susceptibility of the residues for contamination of the crew module environment and air supply, which may ultimately affect both the crew members and equipment.

RECOMMENDATIONS

Background

One of the important features of this Study Program was to review the nondestructive evaluation plans for the Space Shuttle and formulate approporate recommendations regarding the refurbishment requirements.

Nondestructive evaluation has been generally recognized as a basic engineering discipline with the capability to enhance safety and product reliability as well as reducing test and evaluation costs. However, it is no longer considered just a tool of quality control but now interfaces as a major parameter in the basic engineering design process. Entire structures have their design integrity based on the ability of NDE to detect critical defects. Consequently, NDE cannot be considered as an after thought, particularly where in-service NDE is concerned. The increasing reliance on damage-tolerant design concepts dictates the need for a strong NDE influence throughout the entire design-manufacture-operational life cycle. Several independent studies of major programs in recent years have pointed out the lack of emphasis placed on nondestructive evaluation. The USAF Scientific Advisory Board Ad Hoc Committee Report on Lessons Learned from the F-111 Structural Experience (Reference 26) stated that "Too often NDI has been employed as an after-the-fact tool; following the catastrophic failure of some component, it has been used to assess the integrity of other aircraft of the same design". Their findings indicated that "... designers and production planners must carefully consider what appropriate NDI techniques are required and can be used with confidence by production and inspection personnel, and the average capability of personnel performing field operational inspections". They concluded that "adequate NDI can be obtained only by proper consideration during the planning and design phases of new systems".

The National Materials Advisory Board Ad Hoc Committee on Nondestructive Evaluation concluded in their report (Reference 27). "If materials are to be

RECOMMENDATIONS (continued)

designed to their limits to satisfy the ever-increasing demands of sophisticated military, aerospace, and industrial systems, it is necessary that nondestructive evaluation be deliberately considered for incorporation into every phase of the design - production - service cycle. This is specially important in the screening and qualification of candidate materials to meet new design criteria and in monitoring production processes and service life".

It is for these reasons that the strong recommendation is made for the establishment of a single point of responsibility to provide overall NDE guidance and direction throughout the entire Space Shuttle Program. The many benefits would include placement of necessary recognition and emphasis upon NDE technology. A single NDE Program Management source would be in a sense a Program Integrator which would:

- o provide effective coordination of all contractors to require proper design emphasis on inspectability,
- o insure adequate design consideration of in-service inspection capabilities,
- o appraise the NDE technology requirements and provide guidance and direction for necessary research and development to meet design criteria,
- o coordinate the compilation and use of a Space Shuttle NDE Manual,
- o provide guidance and direction to all contractors in the preparation of NDE procedures for the NDE manual,
- o verify and validate NDE procedures to ensure that they are commensurate with design criteria,
- o establish and monitor training and certification requirements for NDE refurbishment personnel,

RECOMMENDATIONS (continued)

- coordinate planning and scheduling of NDE operations during refurbishment.

The responsible entity for coordinating the NDE Program for the Space Shuttle could be either NASA in-house personnel or an experienced contractor. In either case, great care should be taken to select individuals of demonstrated technical as well as administrative ability.

Space Shuttle NDE Manual

It is recommended that NASA develop an NDE Manual containing the detailed NDE procedures to be accomplished during refurbishment inspection of Space Shuttle hardware. The actual NDE procedures should be developed by the prime and major subcontractors in accordance with a Space Shuttle NDE Manual Preparation Guide discussed later. The Shuttle design contractors have available the necessary detailed structural information to determine the inspection requirements and develop the detailed procedural data. Overall coordination and management of the final document should be provided by a single entity to produce an effective and consistent NDE Manual. The procedures from the various contractors and sub-contractors must be integrated into a unified consistent final document usable by refurbishment inspection personnel.

It is important that each contractor that provides NDE data for the final Manual develop efficient management tools to coordinate information flow between the many and varied technical groups having inputs to the manual. The design, stress, fracture mechanics, structural test, manuals illustrators/writers and validation/verification disciplines have to interface in a manner to produce NDE procedures that are accurate, effective, and workable as well as be responsive to design changes and serialization. This requires very intricate management control not readily apparent and which is never instituted in many companies.

RECOMMENDATIONS (continued)

Military Specification MIL-M-38780 and the C-5A Nondestructive Inspection Manual which was developed to that specification are reasonably good documents to form guidelines for development of The Space Shuttle NDE Manual. However, there are some suggested deviations that should be made to render the Shuttle Manual more responsive to refurbishment requirements. These recommendations include:

- o The Manual should contain only NDE procedures that are valid requirements for either routine maintenance or special inspections and not include procedures for components that will probably never require inspection.
- o A comprehensive index should be provided in the Manual that could be used as a management aid in decisions regarding scheduling, additional evaluations, etc.
- o Visual inspections should be included in the NDE Manual. This includes such visual aided inspections as borescopes, magnifiers, etc.
- o Procedures for leak checking components should be included in the NDE Manual.
- o The Space Shuttle NDE Manual should contain a minimum of references to other documents. It should be as inclusive as possible.
- o The numbering system for the procedures and figures should be flexible for ease in making changes and revisions to the Manual.
- o The NDE Manual should be developed in time to provide advanced training of refurbishment personnel.
- o Details on when the procedure is to be used should be included in the manual but under a separate "Inspection Requirements" section.

RECOMMENDATIONS (continued)

- o A realistic estimate of manhours and span time should be included for each procedure.
- o Both line artwork and photographs should be permissible depending upon which provides the clearest presentation. Photographs may be especially helpful for visual inspections.

Validation and Verification of NDE Procedures

Once NDE procedures have been developed, the validity of the procedure must be assured. This involves proving that the procedure works, that the NDE technique is the best one for the part in terms of meeting the criteria, that all necessary steps and data are included for performance of the procedure, that all necessary instructions for providing access and removal are included and that the part is adequately represented in the illustrations in terms of design details and inspection coverage. There are many other factors that the validation effort should be concerned with. The NDE procedures should be validated on complete structural assemblies as far as possible by the organization that will be performing the NDE work during refurbishment. Since the number of Shuttle vehicles will be small, availability of actual hardware will be limited. If an NDE contractor is to be utilized they should be selected at the earliest possible time to allow maximum cognizance and input by the contractor, which is then the using organization.

NASA should verify the validity of the NDE procedures by having their own or their NDE contractor personnel perform the procedures on actual hardware. Validation and verification activities are performed on a given NDE procedure before it is approved for inclusion in the manual. When a procedure must be corrected to satisfy validation/verification requirements, the procedure may need to be revalidated on either a partial or complete basis, then re-verified by NASA.

NASA should consider where and how often procedures should be verified. It is likely that verification at both final assembly and flight test locations may be required in order to efficiently utilize hardware of the correct configuration. Verification of groups of procedures sufficient to provide one to two weeks working time has proved reasonable and efficient and should be considered.

NDE Advisory Group

It is recommended that NASA establish a Space Shuttle NDE Advisory Group to enhance communications between affected organizations and ensure the best possible resolution of NDE related problems. The Advisory Group should be composed of technical representatives from the various NASA centers and the major Shuttle contractors and should have scheduled meetings chaired by the source responsible for the Shuttle NDE Program. The Group would provide the ideal forum for:

- review of recommendations regarding new NDE technology development,
- resolution of design interfaces between contractors influencing NDE requirements,
- overall scheduling of NDE Manual development,
- continued NDE support from major contractors during service life of the Shuttle,
- publication of periodic status reviews of the Shuttle NDE Program.

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