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Methods Of Assessing Structural Integrity For Space Shuttle Vehicles

PHASE II REPORT

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16. Abstract

This report describes the results of efforts to satisfy the requirements of NAS10-7250, Phase II. It contains a detailed description and evaluation of nondestructive evaluation (NDE) methods which have application to Space Shuttle vehicles. Appropriate NDE design data is presented in twelve specifications in an appendix. Recommendations for NDE development work for the Space Shuttle Program are presented.

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FOREWORD

This report summarizes the results of the studies conducted under contract NAS10-7250, "Method of Assessing Structural Integrity for Space Shuttle Vehicles." The study was conducted by the Space Division of North American Rockwell Corporation for the John F. Kennedy Space Center of the National Aeronautics and Space Administration. The following individuals contributed to this report: J. Bosler, C. Kammerer, F. Moskal, R. Poe, and E. Scherba of North American Rockwell Corporation and T. DeLacy and R. Anderson of the General Dynamics Corporation.

PREFACE

For the first reusable space vehicle, the Space Shuttle, technology must be determined and/or developed for assessing its structural integrity. These assessments may be necessary prior to launch, from launch to landing, and during turnaround operations. Through the proper use of modern nondestructive evaluation (NDE) technology, high reliability of such operations and structures can be maintained in a cost-effective manner. This Phase II report presents system and equipment specifications and the evaluation of selected NDE techniques as identified in the Phase I report. It is the intent of this report to form a baseline concept of nondestructive testing for application during detailed Shuttle design. An analysis of applicability and specific requirements is made. This report forms a basis upon which to incorporate on-board NDE into the Space Shuttle design; it also details long-term NDE equipment requirements for the launch/turnaround facility.

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

Current Space Shuttle vehicle design concepts project the requirement for repeated flights up to 100 missions. This capability is required to provide low-cost transportation for crew, passengers, and a variety of payloads between the surface of the earth and a space station or satellite, or other alternate missions. The requirement to conduct refurbishment, maintenance, and systems verification in no more than two weeks, necessitates utilizing ground and on-board checkout equipment. Among the variety of available methods to accomplish this purpose are those which fall into the category of nondestructive evaluation (NDE) methodology.

Presently recognized means of nondestructively assessing the integrity of structures and assemblies include penetrant examination, radiography, eddy current, C-scan ultrasonics, visual inspection, and magnetic particle testing. These disciplines are not only limited in flexibility, but are also time-consuming and are not readily adaptable in their present form to rapid assessment. These technologies must be advanced and new ones developed before refurbishment and structural checkout procedures for multimission space vehicles can be established.

The Phase I report identified the state-of-the-art for nondestructive evaluation methods which are capable of assessing Space Shuttle structural integrity. Emphasis was given to those methods which could support Shuttle turnaround requirements. Specific technologies were established based on the Phase I study and designated as candidate methods for Phase II evaluation. These methods fall into two general categories, on-board NDE and ground support NDE. These methods include the following techniques:

On-Board NDE	Ground Support NDE
1. Fiber optics	1. Radiography
2. Ultrasonics	2. Ultrasonics
3. Radiographic tunnels	3. Electromagnetics
4. Acoustic emission	4. Penetrants
	5. Holographic interferometry
	6. Acoustic emission
	7. Thermography
	8. Optics

These techniques are general categories and can be subdivided further. For example, radiography can be broken down into conventional, neutron, stimulated electron emission, isotope, autoradiography, etc. Similarly, ultrasonics, electromagnetics, penetrants and thermography can be further divided.

Experimental efforts to implement some of the techniques discussed in the Phase I report have already begun and initial results are discussed herein.

This report documents the results of a detailed analysis of the above nondestructive evaluation methods to support Space Shuttle prelaunch and turnaround operations. Preliminary specification and design manual information has been generated and is included in the appendices. Critical areas in the Shuttle design and defect criteria for proposed structures are analyzed in terms of existing alternative Shuttle design concepts. The study has been formulated around the NR 180-day review baseline vehicle, SV70-32, and subsequent internal trade studies in various stages of completion. The need to update this study to reflect Shuttle configuration change should be recognized. The specifications and design manual information represent the best presently available information and expert estimates. Limited experimental verification of proposed NDE techniques has been made and is included in the body of the report.

In-depth studies are necessary in many areas and systems specifications changes and a design manual to reflect definitive in-depth studies should be anticipated. Generic to this effort has been the philosophy to generate NDE design criteria, on-board structural checkout equipment, for incorporation into the detailed Shuttle design prior to the establishment of that detail design in Phase C. In the normal course of NDE applications development, the requirements and defect criteria must be identified prior to methods selection and verification. However, these requirements and defect criteria are highly dependent on the specifics of the detailed vehicle design. Only through an effort such as compiled in this report is it possible to generate NDE design criteria for incorporation of NDE techniques into the detailed vehicle design.

Considerable thought and consideration has been given to the problem of data interpretation, both with respect to operator dependence and operator skill/training requirements. This is reflected in a separate section devoted to this subject.

Conclusions and recommendations with respect to scope, direction, and degree of NDE implementation should become evident in subsequent studies as the Space Shuttle vehicle design concepts become firm.

APPLICATION OF NDE METHODS TO THE SPACE SHUTTLE VEHICLE

Phase I effort identified twelve general categories of nondestructive evaluation (NDE) technologies applicable for Shuttle use. No attempt was made at that time to discuss in detail the specific methods which comprise the general categories. For example, ultrasonics was identified as a technology which would have application during an operational environment as well as during maintenance and refurbishment. This general statement however, does not apply to each specific ultrasonic evaluation method available. Through-transmission ultrasonics implemented by a tank and recording system is highly applicable for certain inspections that might be performed during turnaround but has no place at all on board the Shuttle vehicle itself.

The next sections detail application theory for individual NDE methods being proposed for use to assess structural integrity during maintenance and refurbishment.

ULTRASONIC METHODS

Bonded In-Place Transducers

Bonded in-place transducers are piezoelectric angle probes which have been adhesively bonded to selected areas of the Space Shuttle vehicle. A prototype configuration is shown in Figure 1. One angle transducer acts as the ultrasonic transmitter while the other angle transducer acts as the receiver. A cross section of the angle transducer is shown in Figure 2. Figure 3 shows one possible application to the LH_2 bisector tank assembly.

The piezoelectric crystal is anisotropic material which, under the action of a strong electric field, exhibits a dimensional change, normally a contraction. This movement may be along the electric field or perpendicular to it. The degree and manner of movement depend on the cut of the crystal. The best piezoelectric materials, that is those which exhibit the greatest movement, are combinations of fired ceramics including barium titanate, lead zirconates, and lead metaniobates. These ceramics are fired in a strong magnetic field to induce the piezoelectric property. The crystal cuts

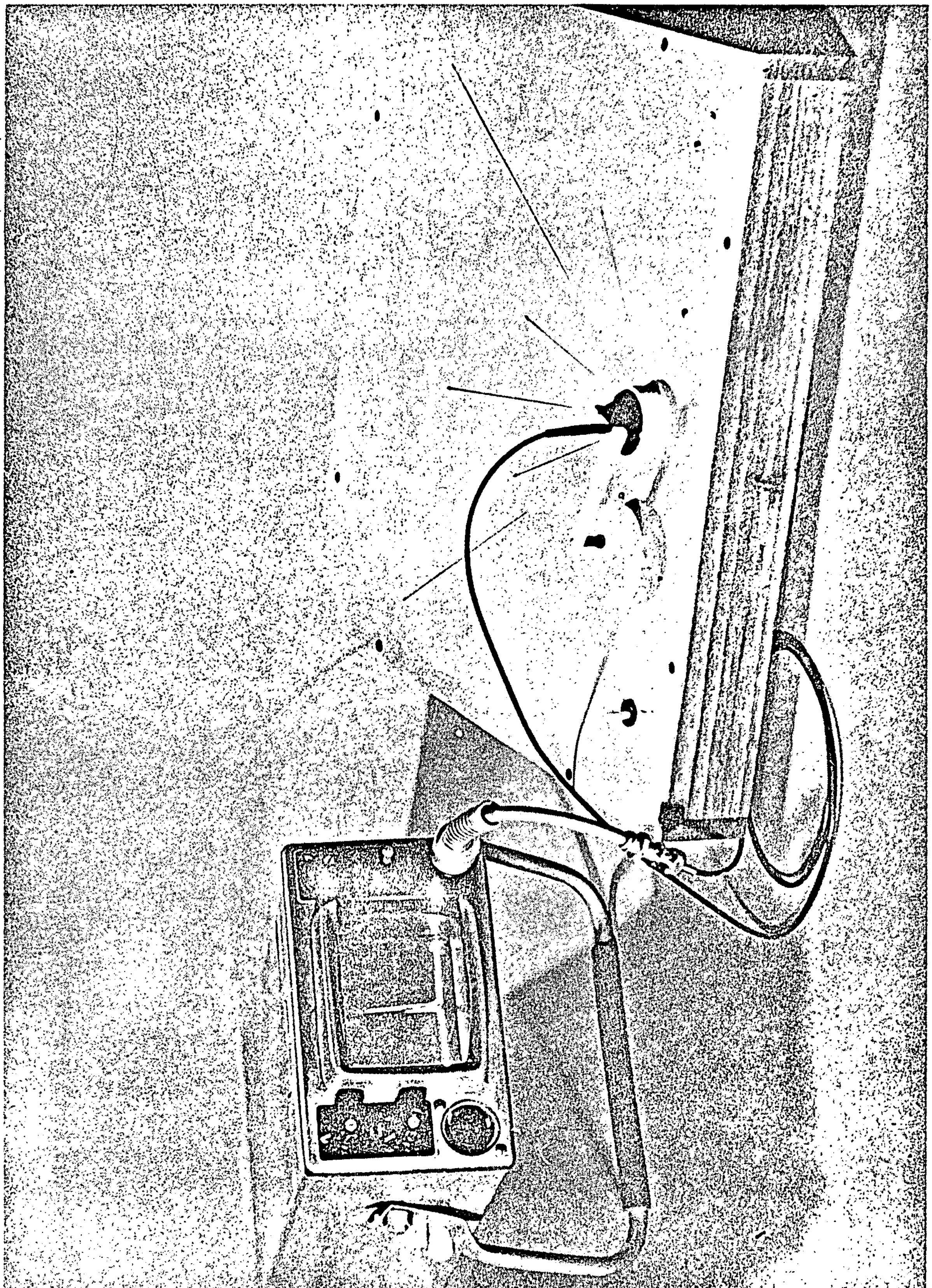

Figure 1. Prototype Bonded In-Place Transducer

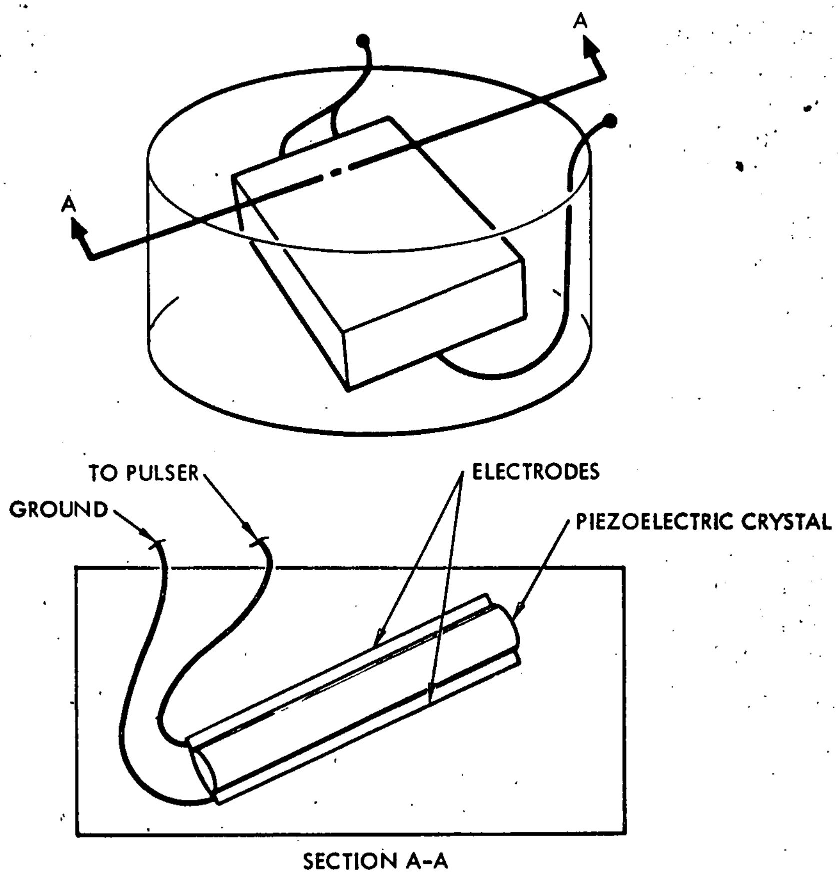

Figure 2. Cross Section of Angle Transducer

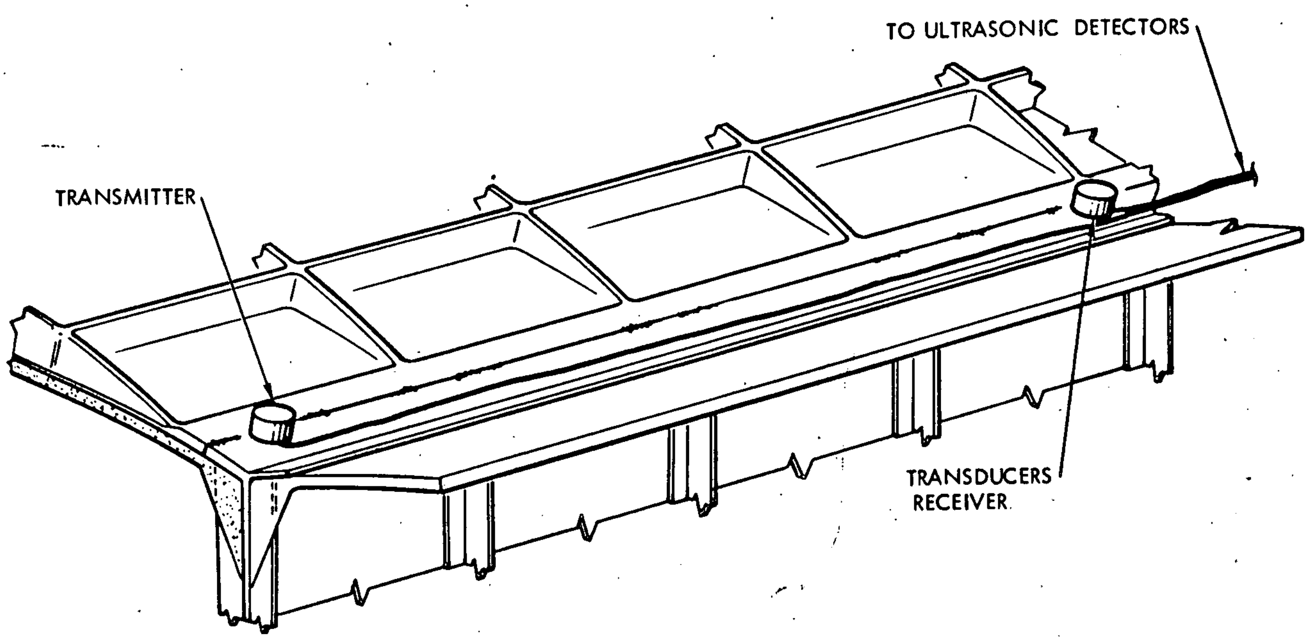

Figure 3. Bonded In-Place Ultrasonic Transducers

are made perpendicular to the axis of magnetization in order to maximize g_{axis}, the piezoelectric coefficient.

$$g_{axis} = \text{strain developed/applied voltage field}$$

Direct bonding of such a crystal disc to the surface of a critical shuttle structure would allow generation of compression waves which are normally less attenuated than other bulk modes such as shear and surface waves. However, compression waves so generated would only serve to dissipate the ultrasonic energy through overlapping internal reflection. If a wide enough edge is present, then effective use of compression wave monitoring may be established by bonding to this edge. By introducing an angle wedge, propagation in a directional pattern is induced. At the critical angle (normally around 30 degrees), compression waves are no longer induced in the plate. Instead, the primary mode of propagation becomes shear waves. At these angles the directional pattern becomes quite pronounced and pulse echo operation is feasible.

The receiving transducer is fixed at the same angle as the transmitter and exhibits a directional reception sensitivity.

In order to monitor a shuttle critical structure or a weld line, the two angle transducers would be bonded at opposite ends of the object on a line facing each other.

High voltage coaxial leads would be necessary to activate the transmitter. Because of the reversibility of the transmission and receiving transducer, similar electrical leads will be used for the receiver although the voltage pulses are substantially lower. The amount of ultrasonic energy generated is directly proportional to the intensity of the induced voltage field.

It is common to use voltages approaching the dielectric strength of transducer crystal. Because the transducer crystals are thin membranes, resonant mechanical vibrational modes are associated with their geometry. By using electrical pulse frequencies near the mechanical vibration resonance, much greater energy may be introduced into the test structure. Greater movement is normally achieved in thinner membranes, but the dielectric strength and mechanical strength limit considerations limit the thinness of such structures. The diameter of the membrane is then fixed at that predetermined by resonance considerations. The frequency becomes larger (or wavelength shorter) as the membrane diameter becomes smaller.

Conventional circuits can be used for on-board ultrasonic checkout equipment. However, it will be necessary to develop miniaturized versions. Selective application of bonded in-place transducers for Shuttle structures will be determined during detail design phases. Only critical structures will be monitored and scheduling of the tests will depend on the particular mission, how far into the program it is, and the operational constraints which would apply to that particular mission.

Rotating Ultrasonic Wave Directors

Rotating ultrasonic wave directors are piezoelectric angle transducers which have been configured into a rotating assembly. A voltage pulse, approximating 1500 volts, is applied to one transducer. The resultant mechanical wave front is radiated into the structure in a directional pattern. Upon encountering a sound wave scattering center, that is a crack, inclusion, or other defect, a secondary sound field is propagated. The receiving rotating ultrasonic wave director, when its directional reception pattern is pointed at the scattering center, receives a maximum secondary acoustical pulse. With sufficient energy in this secondary sound source, the receiving transducer generates a voltage pulse. This quasi-through-transmission mode of ultrasonic inspection is also common to the use of bonded in-place transducers. What makes the rotating wave director more flexible and desirable is the feasibility of using it to scan a surface, as shown in Figure 4. The rotary motion of the transducers is controlled so that the intercept of the directional receiver and directional transmitter is moved across the surface in a logical pattern.

In order to maintain precise angular location data, a small variable resistor or potentiometer is fixed in the scanning head. Small electric motors such as those which drive electric wrist watches may prove a simple inexpensive driver.

Because of the location of edges, holes, etc., and the occurrence of side lobes in the transmitter radiation field, the receiving transducers will never receive a null signal. For this reason, signal signature analysis techniques must be employed. Three methods of handling the background signal can be identified (1) A synchronized signal from a transmitter and all the receiver signal can be directly processed by a computer. The obvious expense and redundant monitoring of acceptable signals make such an approach highly unattractive. (2) A base magnetic disc recording of the acceptable condition could be built directly into the scanning head. The real-time receiver signal would be synchronized, inverted, and its gain automationally controlled, and the signal compared with the acceptable scan recording. The output signal would finally be a null signal for acceptable conditions. Data compression could then be achieved by a counter accumulator with a readout dump. (3) Much of the background variation could be eliminated by mounting the receiver and transmitter transducer in the same rotating scanner. By using shear wave devices, a limited

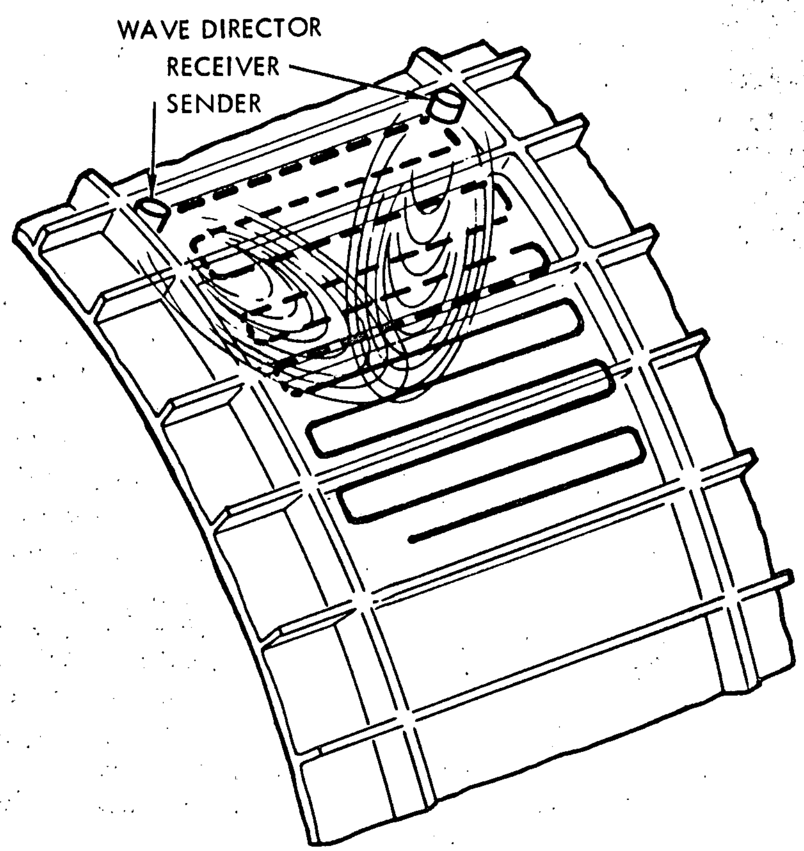

Figure 4. Rotating Wave Director—Scanning

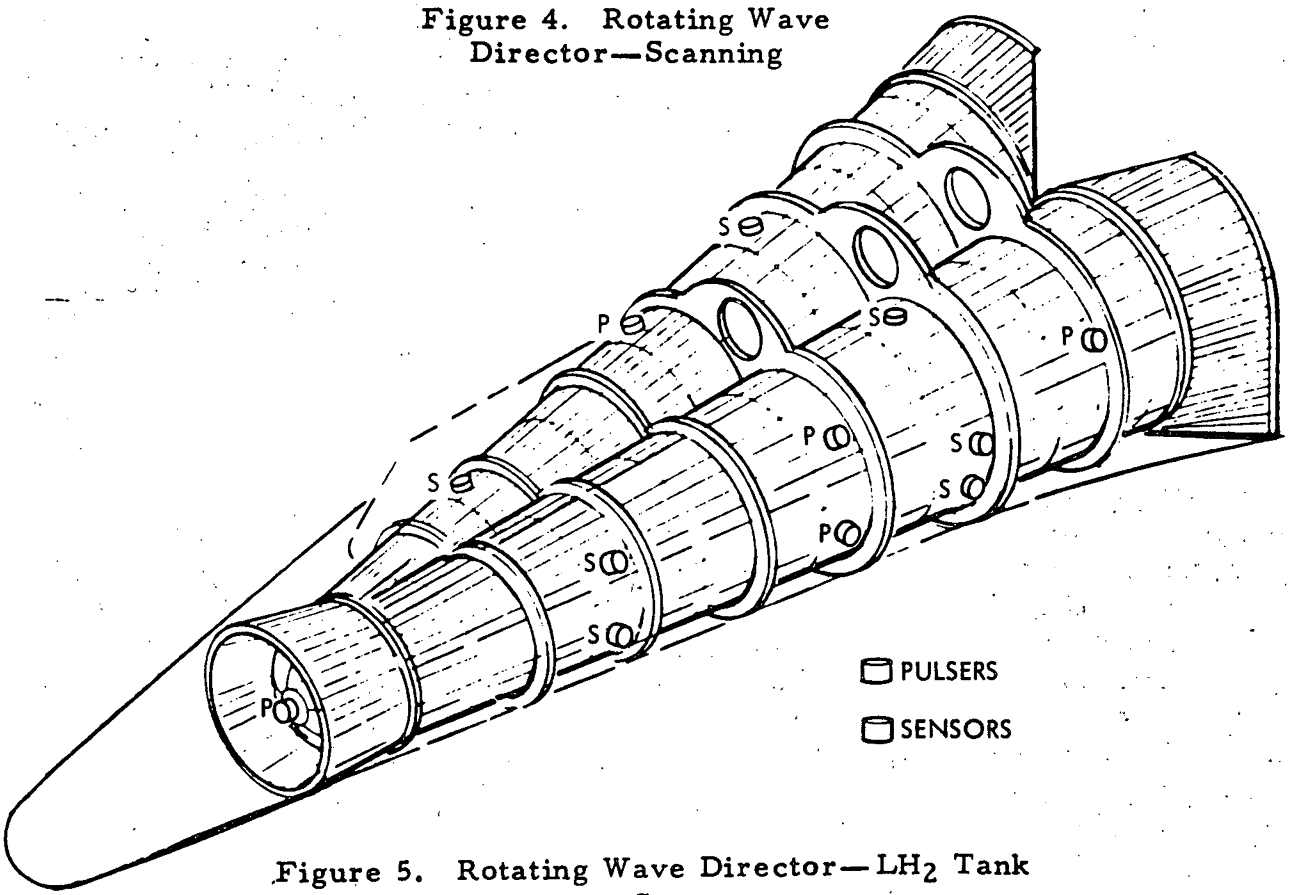

Figure 5. Rotating Wave Director—LH_2 Tank Metallic Structure

area of defect sensitivity would be established, which could be a two-foot diameter circle. This device would be located within the Shuttle structure so that no edges, holes, etc., fall within this small defect sensitivity area. This approach is, at present, the simplest and most advanced in development. Figures 5 through 7 illustrate typical applications of the rotating wave director concept to Shuttle structures and assemblies. These approaches will require strong interfaces with Shuttle design engineering to identify and properly apply the rotating-wave director concept.

Portable Ultrasonic Hand Scanning Techniques

Portable ultrasonic hand scanning is a generic term used to describe those ultrasonic-defect detection methods which are used in the field and more recently classified as portable. They are portable in that equipment is moved to the vehicle to examine the part being questioned with a minimum of disassembly. Many different types of transducer probes can be used. Quite often, one particular transducer gives better response and exhibits better detection levels than others of the same model number. The lack of meaningful specifications and quality standards for ultrasonic transducers undoubtedly contributes to this condition. The fact that ultrasonic inspection is always done with standards which establish the capability of the transducer, provides control of this situation.

The heart of all ultrasonic inspection systems is the pulser/receiver. Great operator capability is required in establishing proper equipment operating conditions. The primary requirements and responsibilities for accomplishing this task may be listed as follows:

1. Interpretation of requirements from specification or print
2. Definition and location of standard
3. Selection of operational mode
4. Selection of transducer
5. Establishing equipment settings from response of standard
6. Verifying expected response from part being tested.

The need for trained and qualified personnel to successfully perform these tasks is evident. Often standards must be made with a limited knowledge of the test structure. These and other problems illustrate the need for qualified personnel.

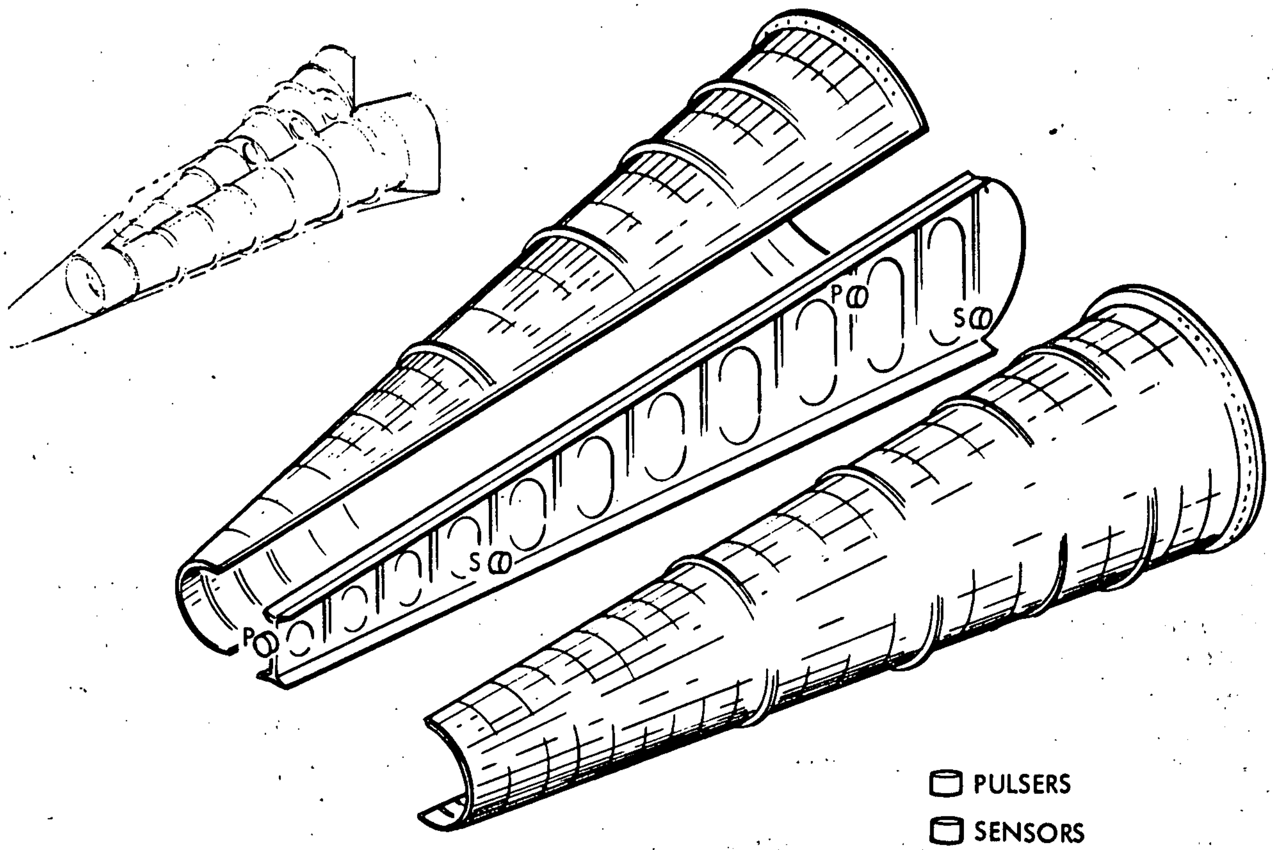

Figure 6. Rotating Wave Director—
LH_2 Splitter Application

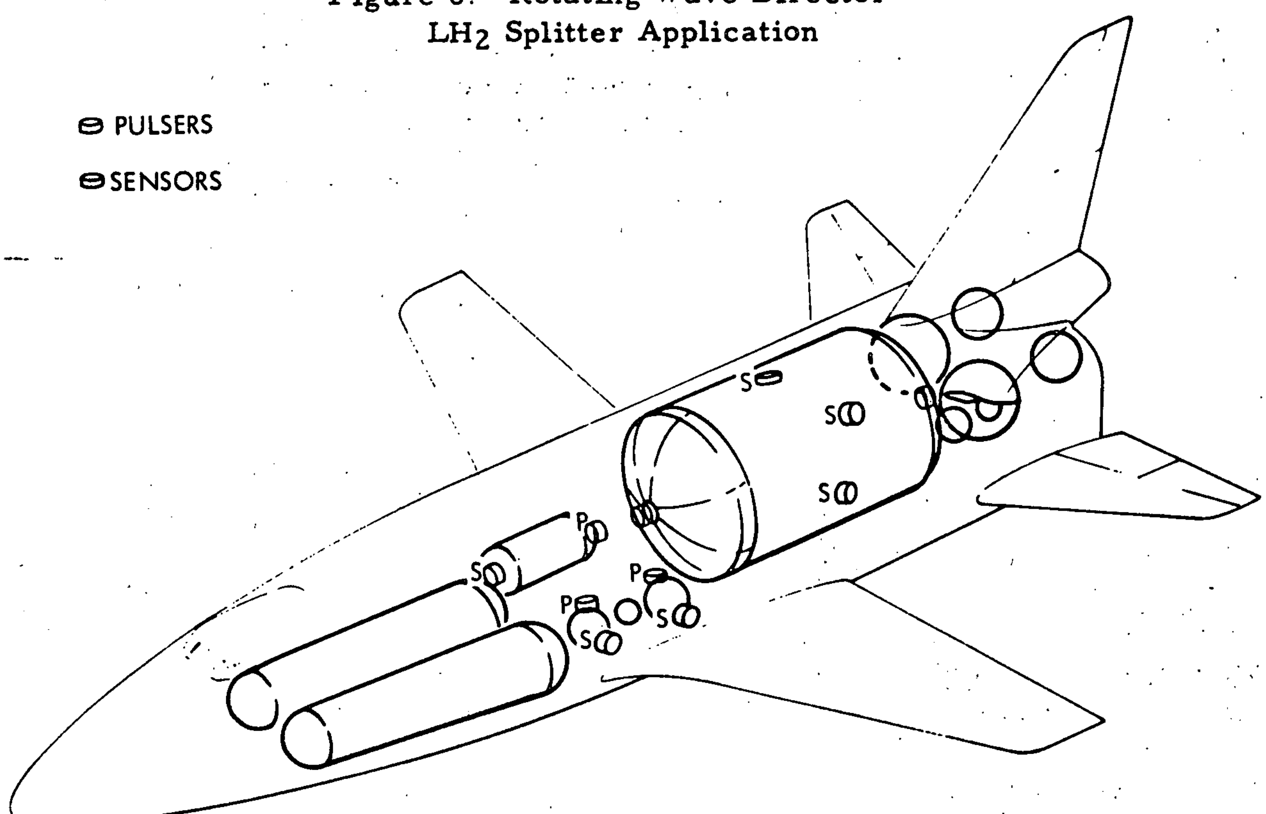

Figure 7. Rotating Wave Director—
LO_2 Tank Application

Data interpretation can be partially automated by using alarm levels, and these are set by an operator. The degree of the signal variation around a pre-set or given alarm gate setting is often a strong clue as to the nature of the indication.

Development costs for these methods for the Shuttle will be very small. Their capabilities and limitations are well known. Specific areas of development activity would involve establishing their particular application to individual Shuttle structures. For a two-week turnaround, the application of ultrasonic hand scanning must be limited. To do any amount of this inspection in so short a period will require a large number of trained inspection personnel. The alternative to this approach is the development of a total on-board capability.

Ultrasonic hand scanning will be used during maintenance operations where a few people can cover many requirements at various stages during the two-week turnaround operation. It would appear that ultrasonic hand-scanning during turnaround would best be applied to unexpected repairs as deemed appropriate. Figure 8 illustrates several applications for ultrasonic hand-scanning during the turnaround phase of the Shuttle vehicle.

Permanent Ultrasonic Systems

Most major aerospace manufacturers have found it desirable to operate permanent ultrasonic inspection systems for large structures manufacture. Typical ultrasonic inspection facilities are pictured in Figure 9 and 10. In order to achieve cost effective operation, three main factors have been dominant.

1. High speed operation

2. Work load

3. Reliability

The ultrasonic equipment is essentially the same as that used for ultrasonic hand scanning. The same ultrasonic probes and pulser receivers are used. Additional electronic equipment is necessary to process the signal from the pulser receiver so that facsimile or other type recordings can be obtained. The scanning and part holding equipment can be quite large and expensive. Digital control has been successfully applied, and future systems for sophisticated structures will probably use numerical and computer control. Longer operating life and higher reliability are being achieved by implementing transistor electronics integrated circuits and large scale integration. However, low turnover and complex circuitry

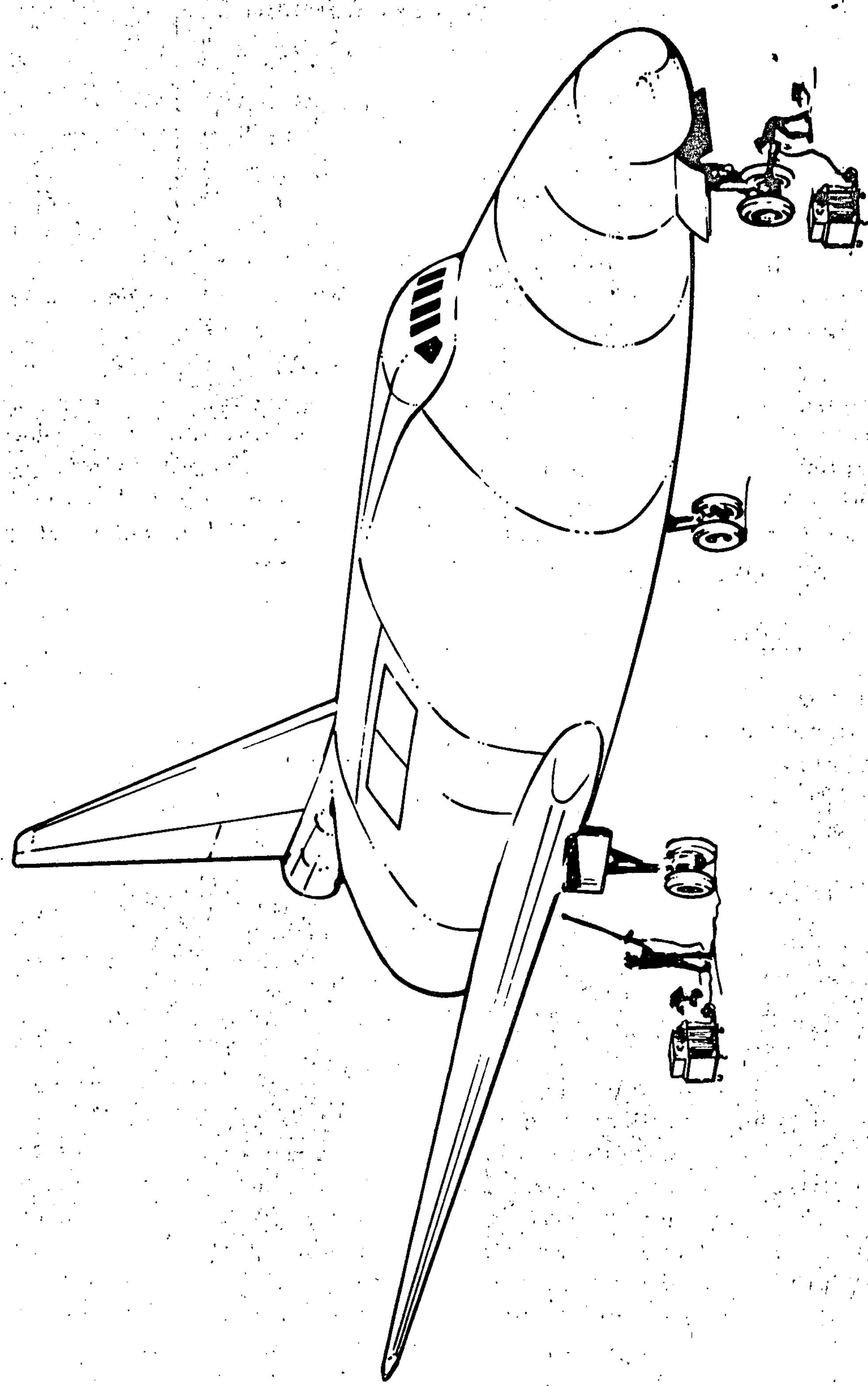

Figure 8. Portable Hand Scanner—Leading Edge RPP

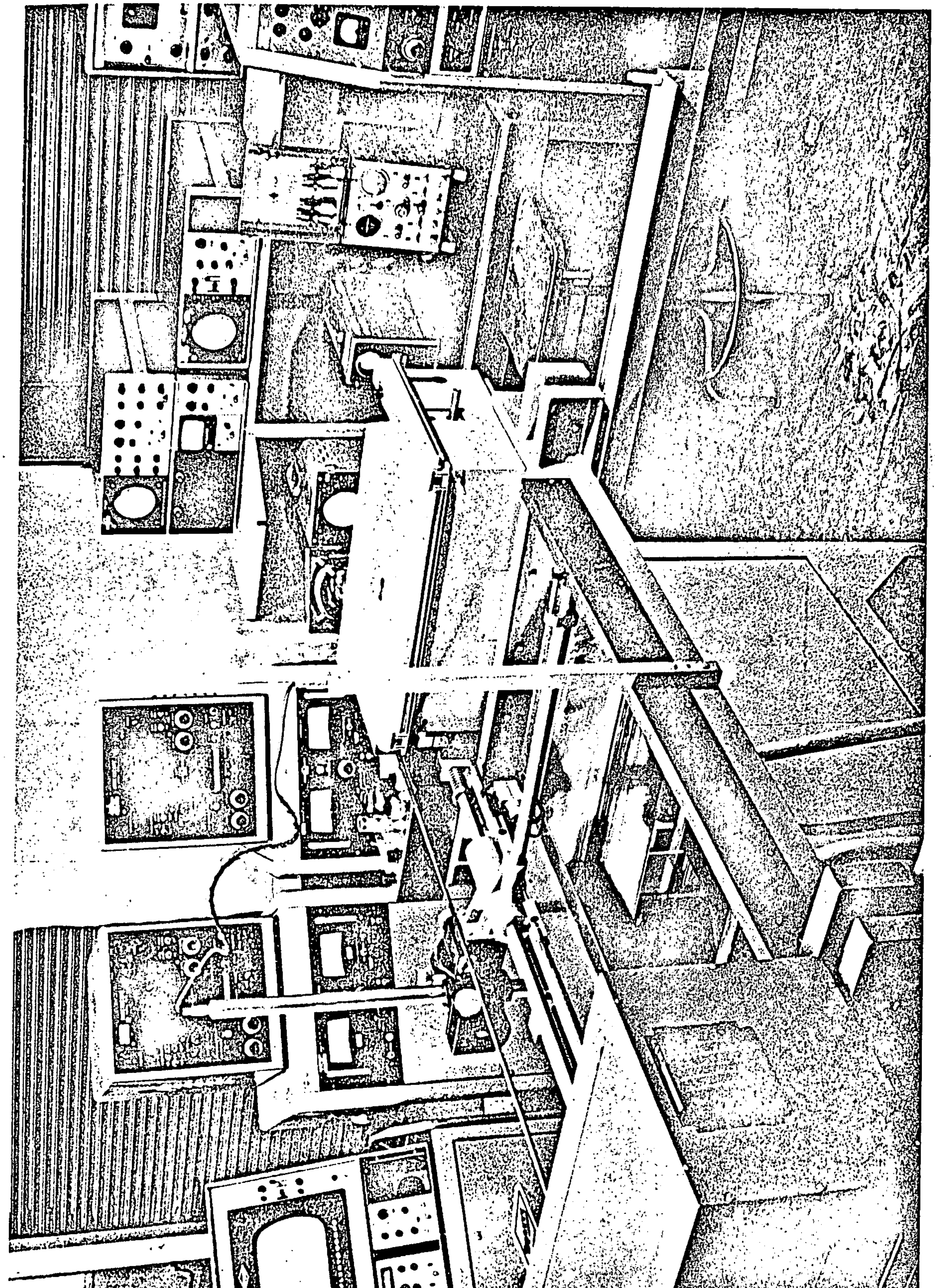

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Figure 9. Typical Ultrasonic Laboratory Facility

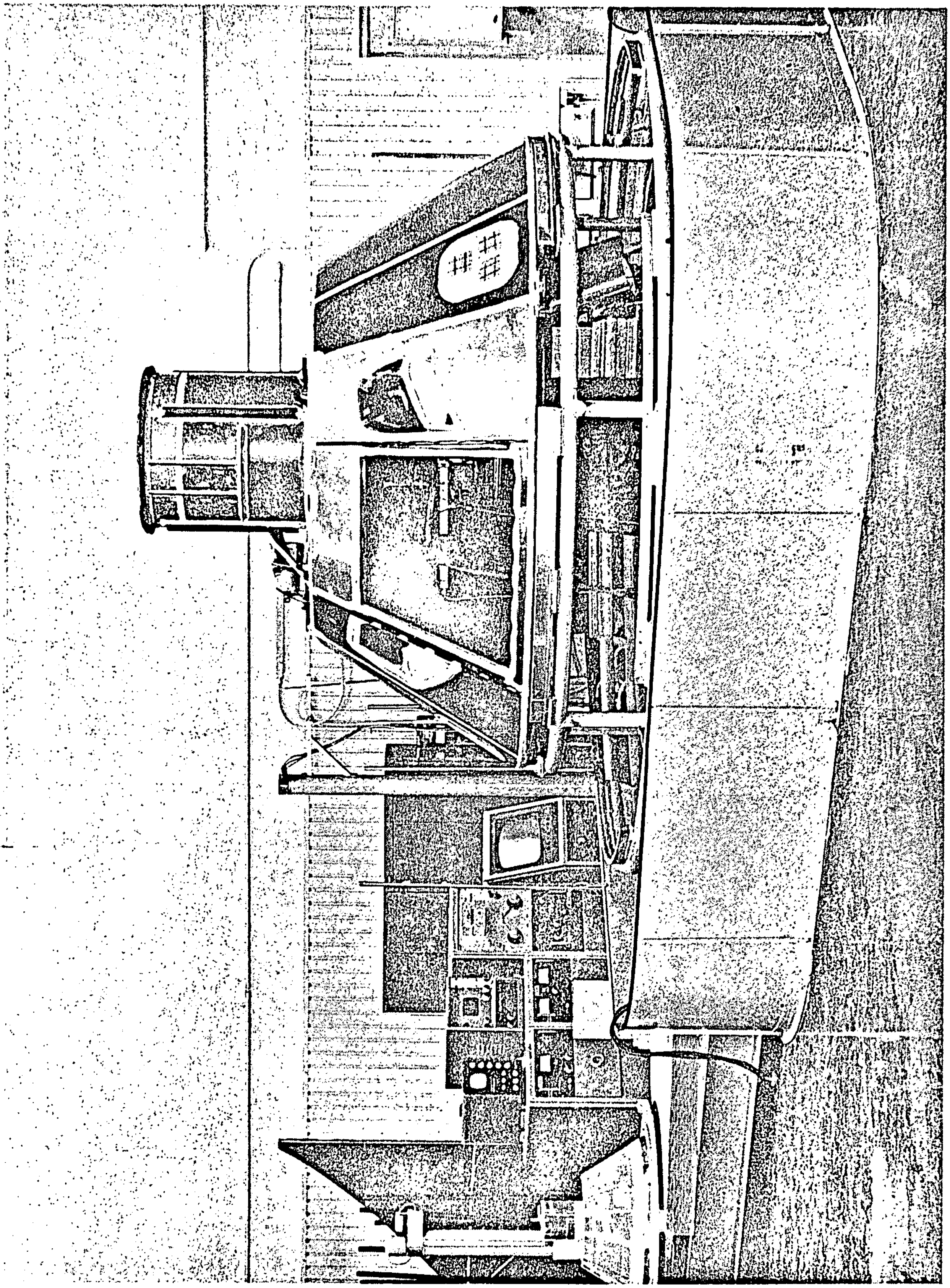

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Figure 10. Typical Ultrasonic Inspection Facility

keep this changeover a slow methodical process. Higher speed operation is being pursued through the development of multiple head scanners. However, for aerospace operation, versatility is probably the primary factor affecting overall long-term cost efficiency.

For smaller structures of approximately two by three feet, commercial equipment is available off-the-shelf. These systems are primarily laboratory development systems. For wrought material, the inspection department normally have their own facilities. For large sophisticated aerospace hardware, the ultrasonic equipment manufacturers normally build custom facilities. Many different overlapping operational modes can be identified. Many of these have been previously discussed in the Phase I report.

Squirter operation implies that sonic entry into the test surface is established through a water stream. A properly applied immersed method provides maximum sensitivity. Also, a great amount of flexibility can be achieved by using metal reflectors, various movement jigs, through-transmission attachments, etc. An explanation of a typical immersed-inspection operation further illustrates the usefulness of such techniques and serves to explain some of the terminology.

In the pulse echo mode, a single ultrasonic transducer is used to inspect the test object. At each interface a certain percentage of the sound energy is reflected. This information is normally displayed on a cathode ray tube. This display of signal amplitude versus arrival time is commonly called an A scan. The theoretical response is illustrated in Figure 11, while the actual photograph of such a trace is shown in Figure 12. The gated portion of the A scan allows a signal proportional to the gated time-averaged amplitude. This signal can be amplified for recording as either a B scan or a C scan. The B scan is usually an oscilloscope presentation of the gated A on the ordinate while the movement of the transducer across the object controls the abscissa.

Lamb Wave Techniques

Lamb wave propagation is of particular interest to Shuttle turnaround application because of the low attenuation associated with the mode. Lamb wave ultrasonic-wave propagation is a resonant wave form which can only be established in plates of uniform thickness. This mode of sound propagation is transmitted and detected, using angle transducers. Methods utilizing rotating wave directors are also envisioned for Lamb wave testing. For a given flat plate configuration, either shear or Lamb waves may be utilized using essentially the same apparatus. The only difference is in the angle at which the piezoelectric transducer is set in the ultrasonic transducer.

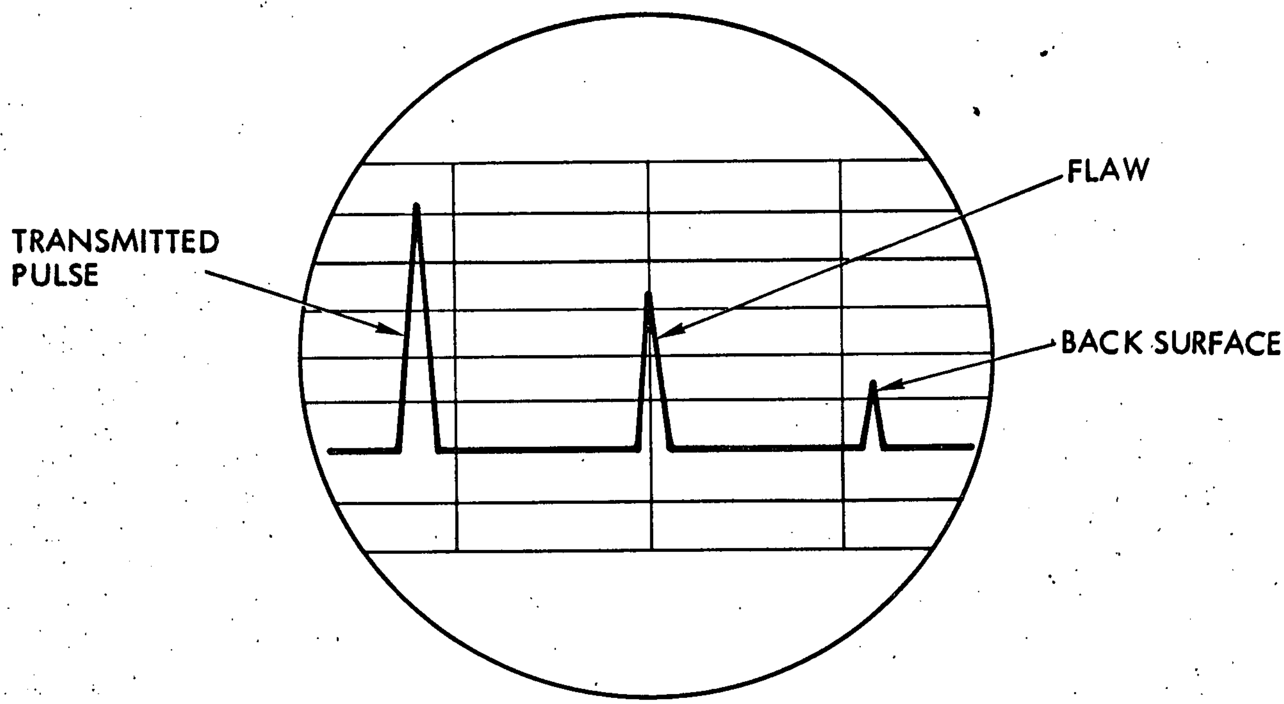

Figure 11. Theoretical "A" Scan for Ultrasonic Pulse Echo Detection

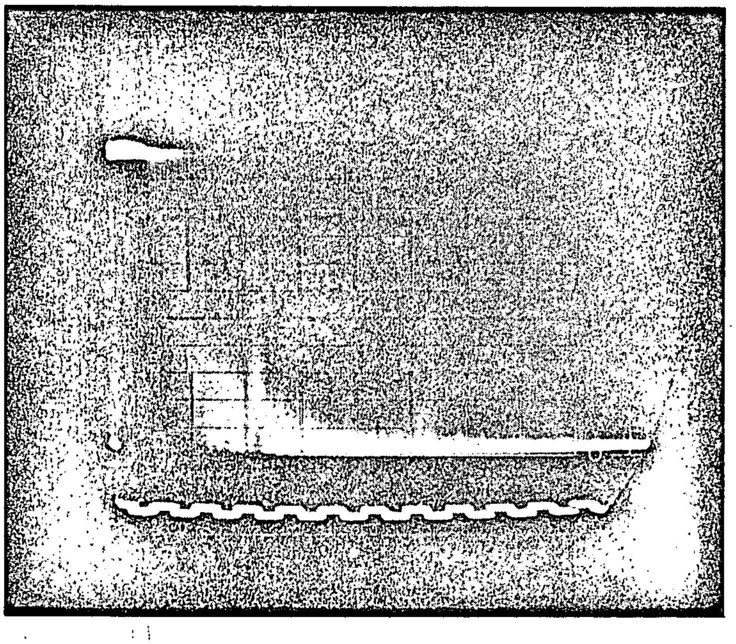

Figure 12. Actual Ultrasonic "A" Scan

The feasibility of using such techniques is dependent on the occurrence of large critical areas of uniform thickness. Primary candidates for Lamb wave monitoring are the various tankages and titanium square tubing in the orbiter of the Space Shuttle. Lamb waves are able to travel in metal sections that are too thin to be resolved by conventional compression and shear wave techniques. This thickness normally corresponds to metal thickness near the ultrasonic wavelength in the metal. Although Lamb waves are normally only considered in terms of plates, it is found that they can be employed to detect certain types of flaws lying close to the surface in work metals of geometry other than plates. In contrast to the single-crystal pulse-echo technique (where the time length of the transmitted pulse becomes a limiting factor in near-surface flaw detection), using Lamb waves the pulse duration time is of no concern and higher energy levels may be used. The front surface echo, which is normally present in immersed testing, can be essentially eliminated from the receiver with the Lamb wave technique. Hence, residual ringing, front surface echoing, etc., do not mask flaw signals. These are, in fact, just the right combination of shear and compression wave components to form the resonant deformation configurations. The Lamb waves travel at velocities intermediate between those of compression waves and shear waves. The velocity with which each mode (harmonics and overharmonics) propagates in a given plate can be calculated.

The resonant nature of Lamb wave propagation makes the mentioning of sympathetic resonance appropriate here. Of course Lamb waves do not propagate across irregularities in uniformity of the plate thickness. However, the possibility of induced sympathetic resonance across such irregularity is worthy of study. The classical sympathetic resonance example is shown in Figure 13. Note that in the figure when pendulum C is excited, pendulum A, B, and D swing in sympathetic resonance.

With the established practice of optimizing tank strength to weight ratios by employing waffle patterns, etc., the feasibility of using Lamb waves in such structures may depend on the strength of the sympathetic coupling rather than the geometric internal reflection.

Digital Ultrasonic Thickness Gages

The use of pulsed ultrasonic testing methods to determine material thickness is a well established art. This technique is primarily used on large assembled structures where the thickness must be measured from one side only. In making such a measurement, the velocity of sound in the material being measured must be known and the test equipment adjusted to that velocity. Often this is accomplished with a reference thickness plate of the same material. Within recent years these thickness gages have become quite small and the data readout has been digitized. Battery-operated models are available.

The output of binary-coded digital signals can be the direct input to computers or similar electronic processing gear with a minimal amount of interfacing. Because of ultrasonic near field effects, the minimum measurable thickness is somewhat limited. Depending on the material, no thickness reading can be obtained for materials thinner than, typically, 0.015 inches. The design of the digital ultrasonic thickness gage has advanced to the extent that it can compete with the mechanical micrometer calipers. The instruments are simple to use and inexperienced operators have little problem. The older ultrasonic thickness gaging method, resonance tuning, is no match for the latest pulse echo techniques. The fine reputation established by the "Vidigage" (a commonly used thickness measuring device) has preceded and accelerated the acceptance of digital pulse-echo equipment.

The need for ultrasonic thickness gaging during Space Shuttle turnaround is not specifically evident as a detailed requirement at this time. However, it is evident that the high versatility and low cost dictate future airline maintenance usage and eventual Space Shuttle turnaround utilization. From present design configurations, only one thickness gaging requirement for Space Shuttle turnaround has been positively identified. Thinning of the silicide coating on columbium heat shield structures can be expected and must be detected and monitored. The use of reinforced pyrolyzed insulation (RPI) would also require measurement of thickness changes. Even if a low density ablator is used, its thickness undoubtedly would be checked during turnaround. All three of these solutions to the high-temperature heat shield problem require thickness gaging; however, none of these applications are appropriate for digital ultrasonic gaging. Future Shuttle detail design considerations will establish appropriate applications for digital ultrasonic thickness gaging.

Four instrumentation methods are applicable to pulsed transit time thickness gaging. The echo height method converts the echo height into a voltage for further evaluation. The integration methods is an accumulation procedure. The starting pulse initiates a charging or discharging process or the flopping over of a bistable circuit. The echo stops this process. The voltage reached is then a measure of the transit time.

The counting method is a gated technique. The initiating pulse starts a counter which then counts the frequency-stabilized oscillations of an oscillator and is switched off again by the echo. It is this technique which is being used in most digital equipment and provides the computer data which can easily be handled. The fourth method involves wave-phase monitoring. The phase method uses continuous waves of constant frequency. To measure the transit time, the phase of the echo wave is compared with the phase of the emitted wave. Because most thicknesses are many ultrasonic wave length long, ambiguity is present and an approximate thickness must be known to identify the proper cycle.

ACOUSTIC EMISSION

Acoustic Emission Proofing Techniques

By monitoring the acoustic emissions during a proof-loading test on specific materials, a precursor of imminent failure can be detected and the condition of the test article, after proofing, can be determined. Monitoring operations for determination of fatigue failure signatures are just now being studied. The present studies are confined to laboratory simulations where accelerated loading conditions are employed. The emission of sporadic low level sound throughout the structural life of a metallic structure destined to fail because of metal fatigue, appears to be theoretically correct but has not been experimentally demonstrated as yet. Acoustic emission proofing techniques, as applied to the Space Shuttle vehicle for turnaround/maintenance operations, would imply the existence of a proof loading facility at the turnaround site to perhaps pressurize a tankage system or apply a controlled weight to wing structures. (See Figure 14.)

Besides the impact on the cost constraints, a major technical problem exists for applying acoustic emission proofing techniques on a repeated basis (such as between flights) because of the Kaiser effect. Once a metal has been stressed to a given value, it will not emit further emissions until that stress level is exceeded in a subsequent test or the metal is heat treated and retested. It still may be feasible to allow a delta measurement of proofing for each scheduled proofing over the life of the vehicle. For example, after the first flight the structure could be proofed at 70 percent of ultimate, and after the second flight, at 72 percent of ultimate. If no emission occurs, then the design limits have been exceeded. After the tenth flight, proofing could occur at 74 percent, and so forth throughout the life of the flight article. Such an approach requires much development, and the ultimate value of such a method is not obvious and needs to be analyzed during the subsequent phases of the Shuttle development.

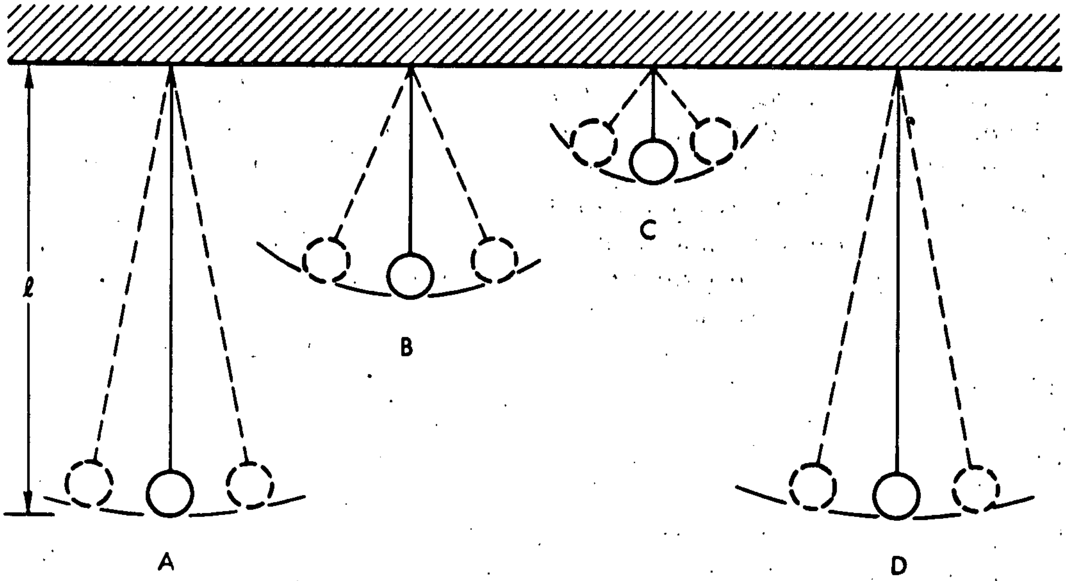

Figure 13. Classical Sympathetic Resonance

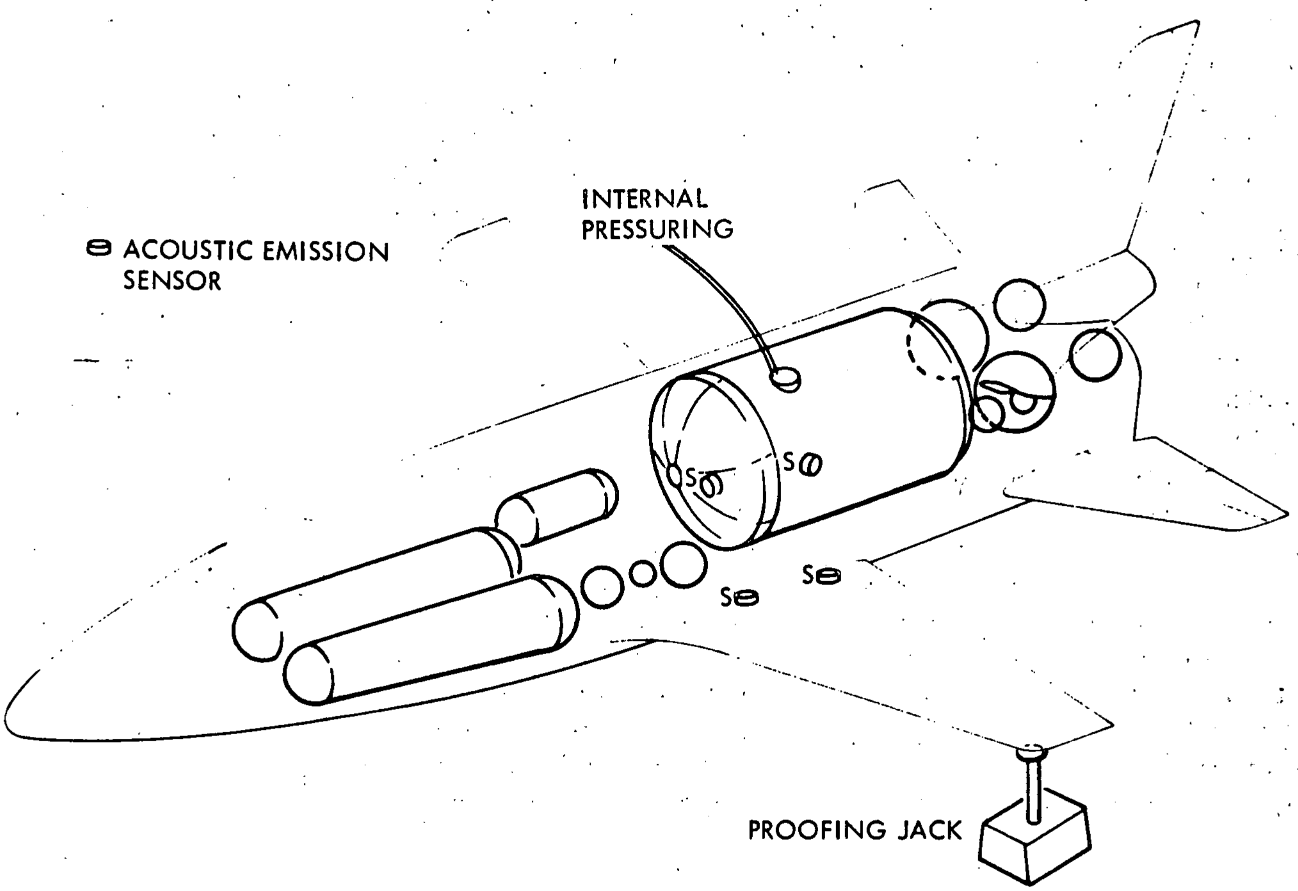

Figure 14. Acoustic Emission Proof Loading Operation

On-Board Acoustic Emission Systems

Based on three critical factors, the natural extension of acoustic emission proofing techniques would be to implement an on-board monitoring system. Acoustic emission monitoring transducers will be placed in strategic positions on Space Shuttle structures, probably with a preamplifier and counter attached (see Figure 15). The total count history should be monitored; however, data time compression must be accomplished. The digital data bus would transmit the accumulated count total onto a tape of the flight record. The central on-board computer would control the data accumulation and perhaps do some analysis, at least to the point of locating gross changes. Effective monitoring would suggest placement of transducers on suspected high stress members, with many monitoring positions possibly being required.

The three critical technical factors for implementing such a system are:

1. The materials must lend themselves to acoustic emission monitoring by emitting a detectible noise level at low stress values. In technical terms, the Frank-Reed dislocation distance must be long enough.

2. A method of eliminating background noise, such as propulsion engine noise and aerodynamic flutter, must be developed.

3. The effect of wide temperature variations on acoustic emission mechanisms must be favorable.

Of course, many other technical questions must be answered including method of count accumulation, best filter bandwidths, etc. However, these questions can be resolved with sufficient time and effort, while the three critical factors just cited determine technical feasibility.

Hybrid Computer Acoustic Emission Techniques

The more successful acoustic equipment now in use normally handles data in analog format through the amplification and filtering stages. A digital counter then accumulates the counts. This digital format is particularly useful in that statistical analysis techniques can conveniently be made with existing digital computer facilities. The need for statistical analysis of burst acoustic emission is well documented. Although filtering techniques are very useful for eliminating background noise, it should be recognized

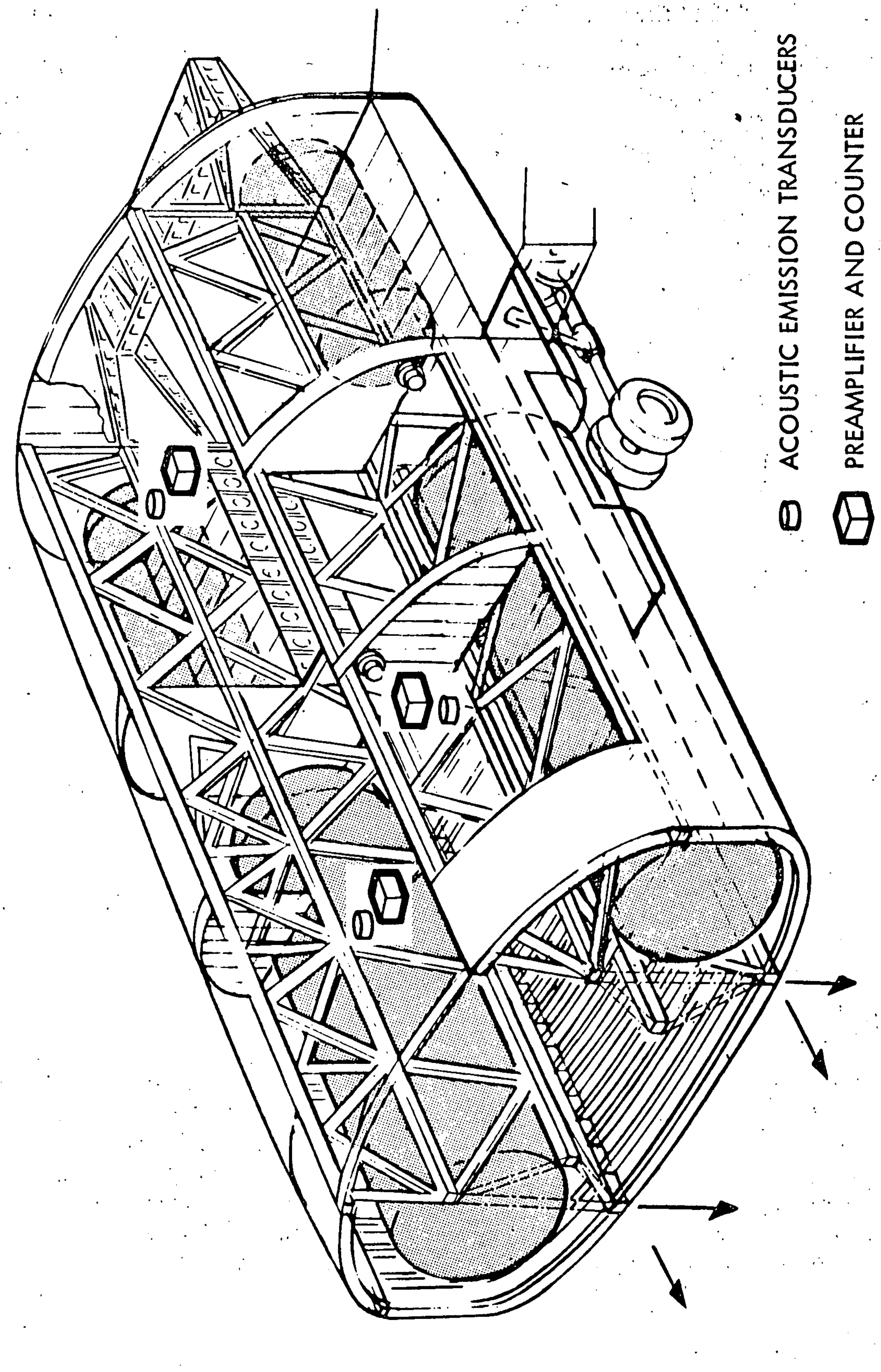

Figure 15. Location of Acoustic Emission Equipment

that the periods of greatest stress loading in the Shuttle vehicle life history occur during launch and reentry. During these periods, the background noise levels will be extremely high. A readily recognizable approach is to use transducers located at different positions in the Shuttle vehicle, with the difference in the sound paths from the different transducers used to employ interference techniques based on phase mismatch of incoming acoustical signals. Although two transducers operated in such a differential amplification mode appear to suffice to accomplish signal sorting, it is evident that more transducers will yield stronger acoustic emission monitoring signals. Such a technique would involve the use of relative complex hybrid computer techniques.

FIBER OPTICS METHODS

Portable Inspection Devices

Commercial fiber optics equipment now exists which will suffice for many Shuttle NDE applications. Some of the fiber optics devices which are currently available are tabulated.

Optics	Relative Light Transmission
A.C.M.I Lateral	100
A.C.M.I. Foroblique	42
Sass and Wolf Lateral	160
Sass and Wolf Foroblique	75
Gardner Lateral	110
Drapier Foroblique	30
Drapier Forward	30
Hopkins Lateral	200
Hopkins Foroblique	170

The interaction of cost and fiber length and diameter is extremely important. With respect to image quality, resolution, and optical flexibility, the individual fiber diameter is critical. Many of the glass fiber optics devices are formed from fibers in the 2 to 8 mil diameter range. The coherent fiber optics devices with individual fibers in the 10-micron size range (about 0.025 mils) represent a dramatic improvement over their predecessors. Image quality will suffer if breakage in the individual fibers occurs. Information on in-service breakage is limited; however, it is generally agreed that it is difficult to make perfect fiber optics devices, and most individual fiber breaks occur during manufacture.

A typical portable fiber optics inspection device is shown in Figure 16. As a portable inspection tool, many aspects of the design are important beside the flexible fiber bundle (which will be discussed later relative to on-board devices).

A lens system is required on each end of the fiber bundle. At the detector end, a lens system must project the object frame, in focus, onto the polished fiber bundle end. At the viewing end, a lens system must take the image on the fiber bundle end and project it on the recording device, i.e., film, vidicon, or eye. Normally, a single adjustment is located at the viewing end which can manipulate the focusing mechanism at both ends of the device. The flexibility achieved by interchanging lenses to vary the field of view or adaption of prisms or mirrors to change the direction of viewing is evident, and the acquisition of all accessory items for a particular fiber optics scope is normally desirable. Further flexibility is achieved by making full use of detector end manipulators. These controllable deflecting tips allow pointing of the final inch of the detector through an angle of about ±45 degrees from on-axis. This movement is controlled by the observer at his viewing end. Although the movement is only in one plane, full conical coverage is achieved by rotating the fiber optics bundle assembly.

The LoPresti Foroblique Fiber Optical Esophagoscope System includes a light source, a light path through an integral bundle, and an optical probe with an optimum field-of-vision using a 90-degree, controllable, articulated tip for direct, right angle, or "foroblique" viewing. The capability for tip manipulation is most important for scanning. This allows maximum movement of the optical end devices. The light bundle has proved to be well within the requirements for NDE studies.

A complementary closed-circuit, high-resolution TV system can be coupled with fiber optics units as illustrated in Figure 17. The tank shown contains the inaccessible area to be viewed for NDE evaluation. The first object at the right side of tank is the intensified light source. The second object from the tank is the TV camera. Directly in front of the TV camera is mounted the integrated-combination flexible fiber optics bundle. This bundle contains fibers to transfer the light from the light source to the area being viewed. It also contains the coherent fiber bundle to transmit the view of the area being evaluated back to the fiber optics eyepiece. With a closed circuit TV camera coupled to the fiber optics bundle, it is possible to have remote or group viewing of the NDE area by looking at the TV monitor screen.

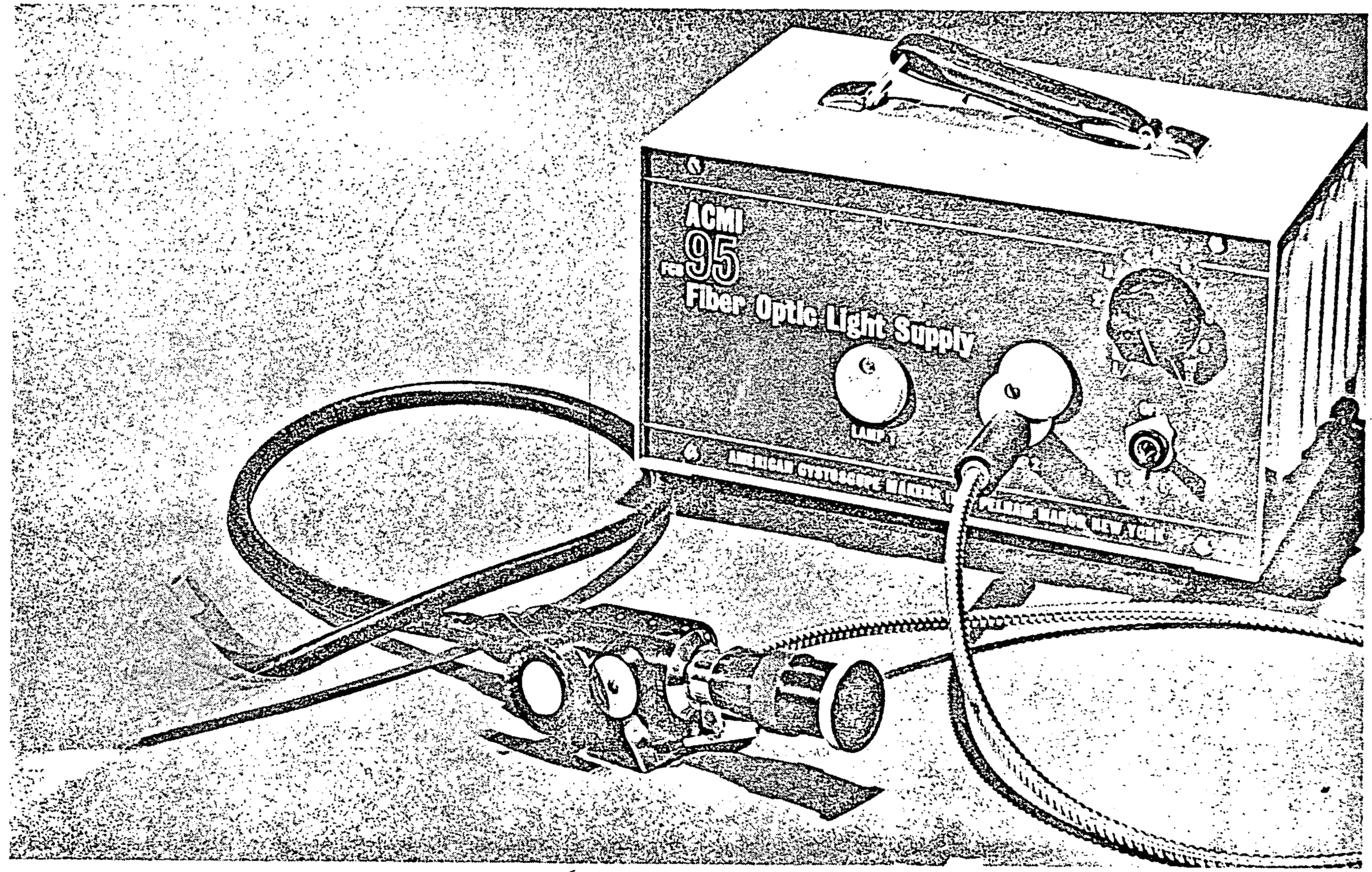

Figure 16. Typical Fiber Optics Device

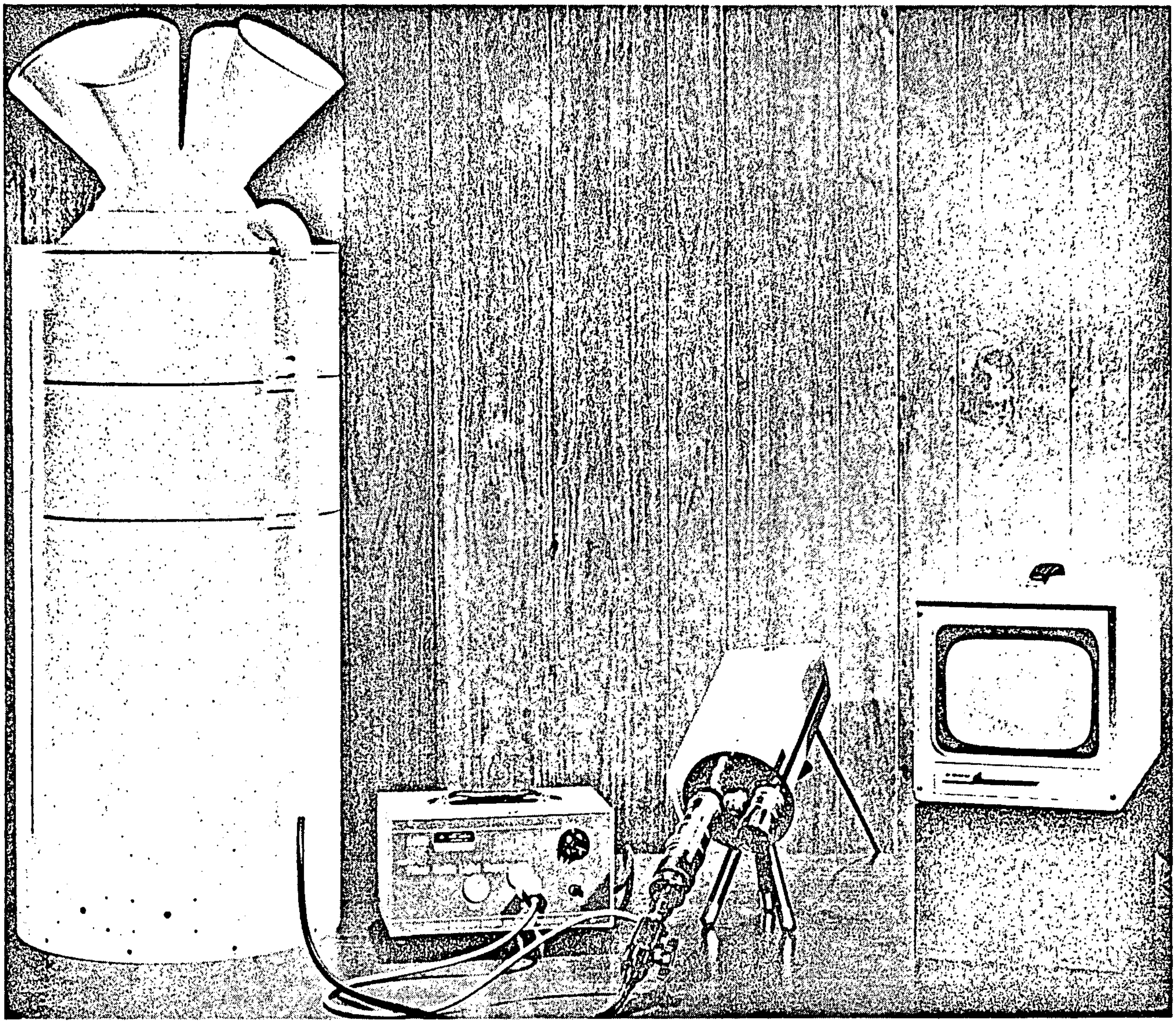

Figure 17. Closed Circuit TV Fiber Optics System

On-Board Fiber Optics Devices

The state of the art of portable fiber optics devices has been reviewed in the Phase I report. If the usage of fiber optics techniques is low, then the presently available models represent the most cost effective approach. However, if widespread usage is anticipated, then methods of speeding up the fiber optics inspection procedure become attractive. One of the easiest approaches is to design access for fiber optics units to those inaccessible areas which must be examined. In the more complex case, perhaps sealed in-place fiber optics devices would be required. In no case would the image be transmitted electronically. The fiber optics channels would terminate in various protected access hatches such as in the landing wheel wells.

Several factors influence the potential of plastics fiber optics, as follows:

1. Fiber cost comparison is 0.6 cents per foot (plastic fiber) versus 10 cents per foot (glass fiber).

2. Maximum bundle length available is 12 feet for best quality glass (estimated 20 feet in mid-1970's) versus unlimited length for plastic.

The relative light transmission light loss for plastic and glass fibers is shown in Figure 18. The influence of the finish of fiber optics bundle ends is quite important and improvements are possible.

The relative weight saving of plastic fiber optics compared to glass fiber optics technology is:

$$(\text{glass density}/\text{plastic density}) = (2.54/1.28) = 2$$

In general, the plastic fiber optics are easier to work with during fabrication, and the individual fibers are less expensive. The plastic fiber optics technology is in an earlier state of development than the glass fiber optics technology. This is reflected by:

1. Only plastic fibers down to 0.010 inches in diameter are now available.

2. Transmission losses are generally greater than in glass.

3. Very little image carrying plastic fiber optics technology exists.

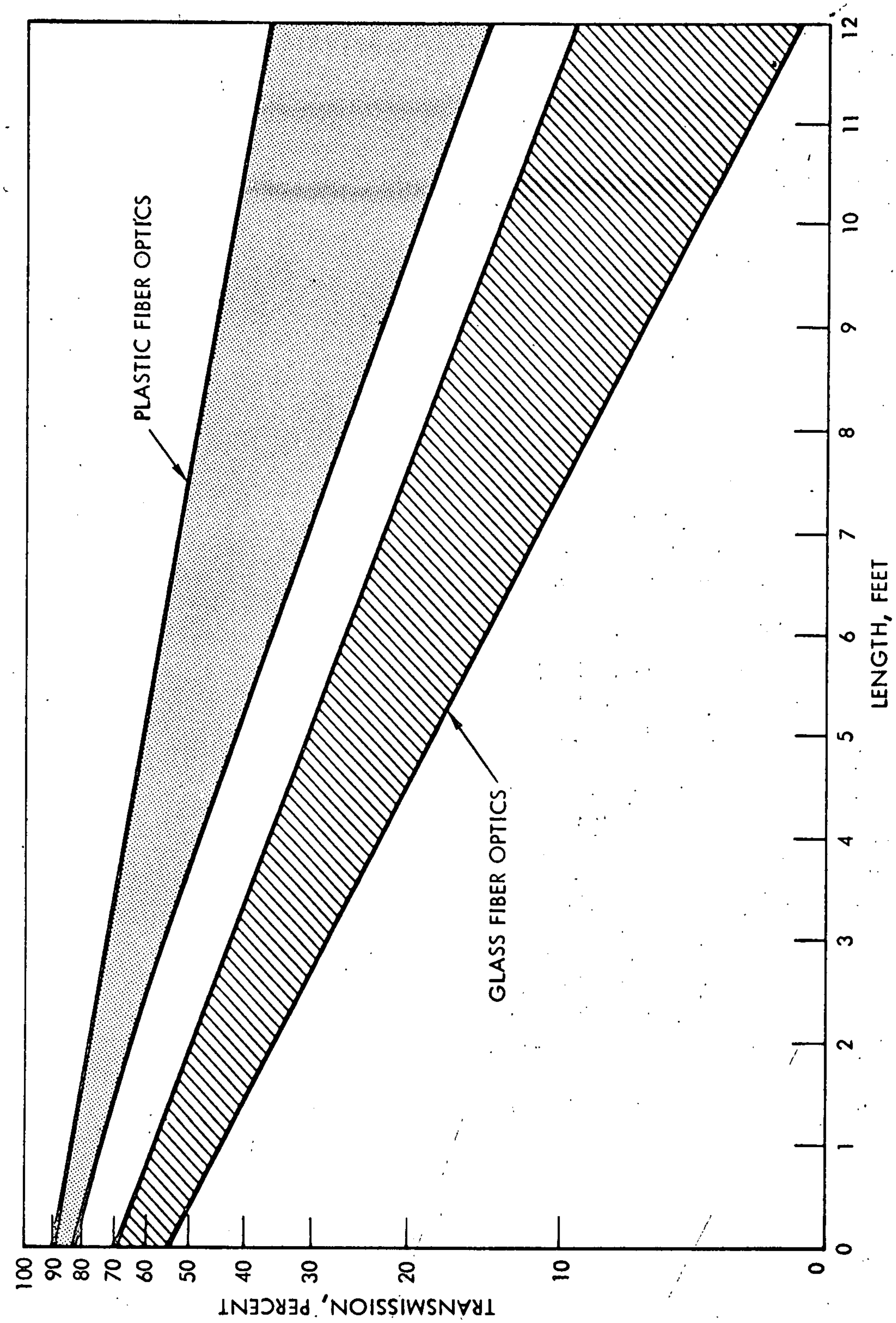

Figure 18. Relative Light Transmission Loss

The effective absorption coefficient for glass is 0.085 per foot while the value for plastics is 0.18 per foot. However, the effects of end losses are significant and improvements can be made.

On-Board Fiber Optics System

An on-board fiber optics system would fundamentally involve the use of a fiber optics system built into the Shuttle design. At its detector termination, a vidicon pickup would be provided with a miniaturized television camera. The vidicon pickup could be either mechanically switched or, more preferably, electro-optically switched to other fiber optic lines which would centrally terminate at the vidicon. Maximum use for this purpose should be made of rigid optical transfer units. For sealed access into a tank or line, the fused high-resolution fiber optics technique appears appropriate. For long, straight lengths, the rod lens concept is most attractive and could possibly extend the maximum line length to 40 feet.

Because of the high information density in optical images, the digital data bus could not readily handle the information load. However, control of optical switching and image sampling can be handled by the bus. The optical information would require an RF data bus.

To attain complete access to all structural parts of the Shuttle vehicle, a minimum of about 1400 central fiber optics terminals would be necessary. Such complete access is neither practical nor required. However, a system of about 20 central points would probably suffice and could provide sufficient information about the condition of critical Shuttle structures. When the number of central pickup points drops below five, this approach becomes unattractive, primarily because the requirements for RF data have not been diminished correspondingly. At this point, only selected on-board fiber optics concepts (No. 2 above) should be considered.

RADIOGRAPHY

Radiography is not a rapid method of nondestructive testing; however, the capability is mandatory as part of turnaround maintenance operations. The extent that this method should and will be used is dependent on the detailed applications and requirements as they are established for the Shuttle vehicle. Suspect problem areas, fatigued parts, repair areas, and replacement parts are probable applications for radiography.

Radiographic support for maintenance operations is considered in essentially three categories: permanent X-ray facilities, portable X-ray equipment facilities, and small cabinet operations.

Permanent X-ray facilities by definition imply that all facilities required to perform radiographic inspection are in a fixed location. This facility should consist of a lead-lined room similar to that shown in Figure 19. This room must be large enough to house removable or replacement structures requiring radiographic examination. X-ray equipment with a sufficient voltage range to provide good contrast over a wide range of object thicknesses and densities should be available. Film development equipment, including an automatic processor which produces consistent processing in minutes, should be included in the facilities planning.

A viewing area for film interpretation and disposition is normally required. Other detailed equipment and accessories as required for a functioning X-ray inspection laboratory normally require half again as much space as the above.

Dependent on the results from the proposed neutron radiography study for space vehicle hardware, a small neutron radiographic facility should be included in the permanent facilities. The neutron radiographic equipment may possibly include a small reactor such as L88. (See Figure 20.) Studies are in progress to define the extent of Shuttle utilization.

A storage area for portable radiographic equipment should be located adjacent to or as part of the permanent facilities. All on-site portable radiography may be assigned and emanate from the central permanent facility.

Portable X-ray equipment facilities are those capable of moving from site to site or spacecraft to spacecraft for performing radiographic examination.

Collimating the X-ray beam and radiation shielding with strict adherence to the safety laws permits X-ray inspection in localized areas. Other maintenance operations may be performed near by. The type of portable equipment necessary to perform on-site radiography depends on the application, part requirements, and accessibility. See Figures 21, 22, and 23 for views of typical equipment. A mobile hydraulic tubestand control console, high-voltage generator, high-voltage cables, and water cooling pump are shown in Figure 22. A Norelco 100-kilovolt tube and a Seifert constant potential unit are typical equipment. The collimator shield is useful for welded tubing and brazed joints. Tripod tubestand, control console,

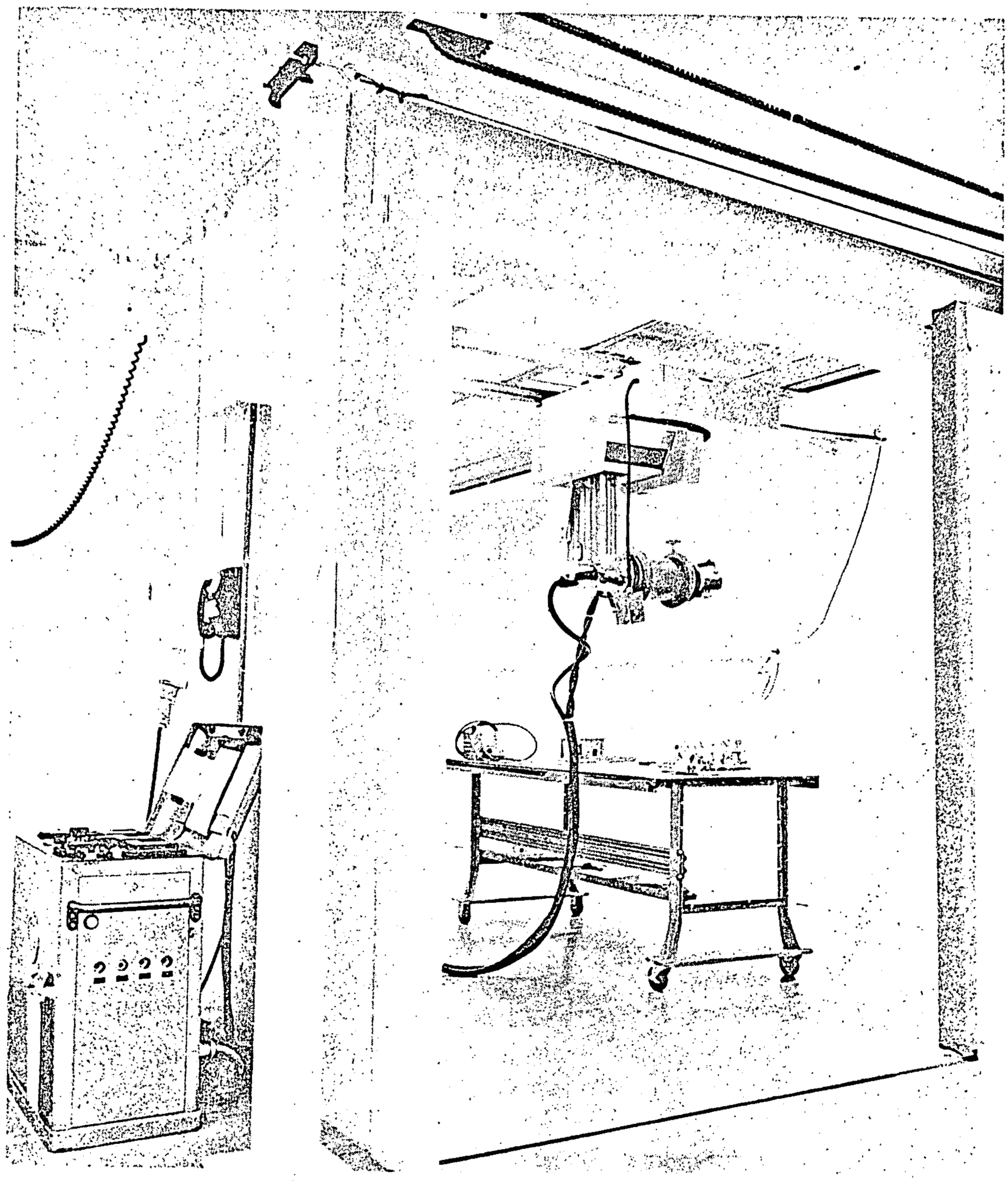

Figure 19. X-Ray Lead-Lined Room

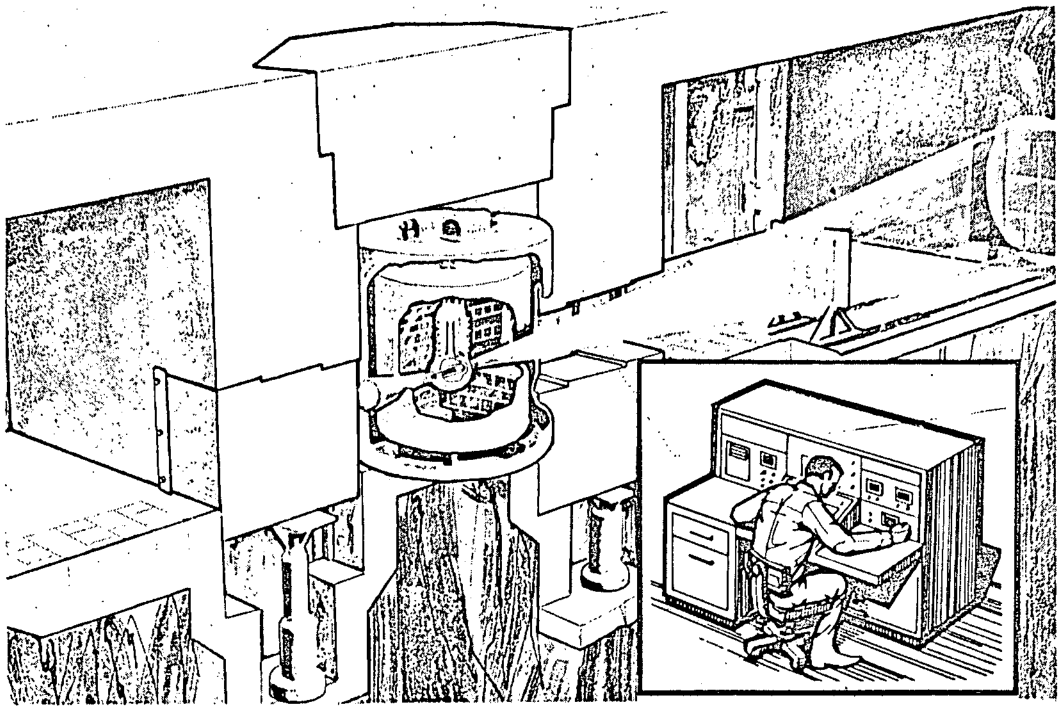

Figure 20. Neutron Radiographic Facility

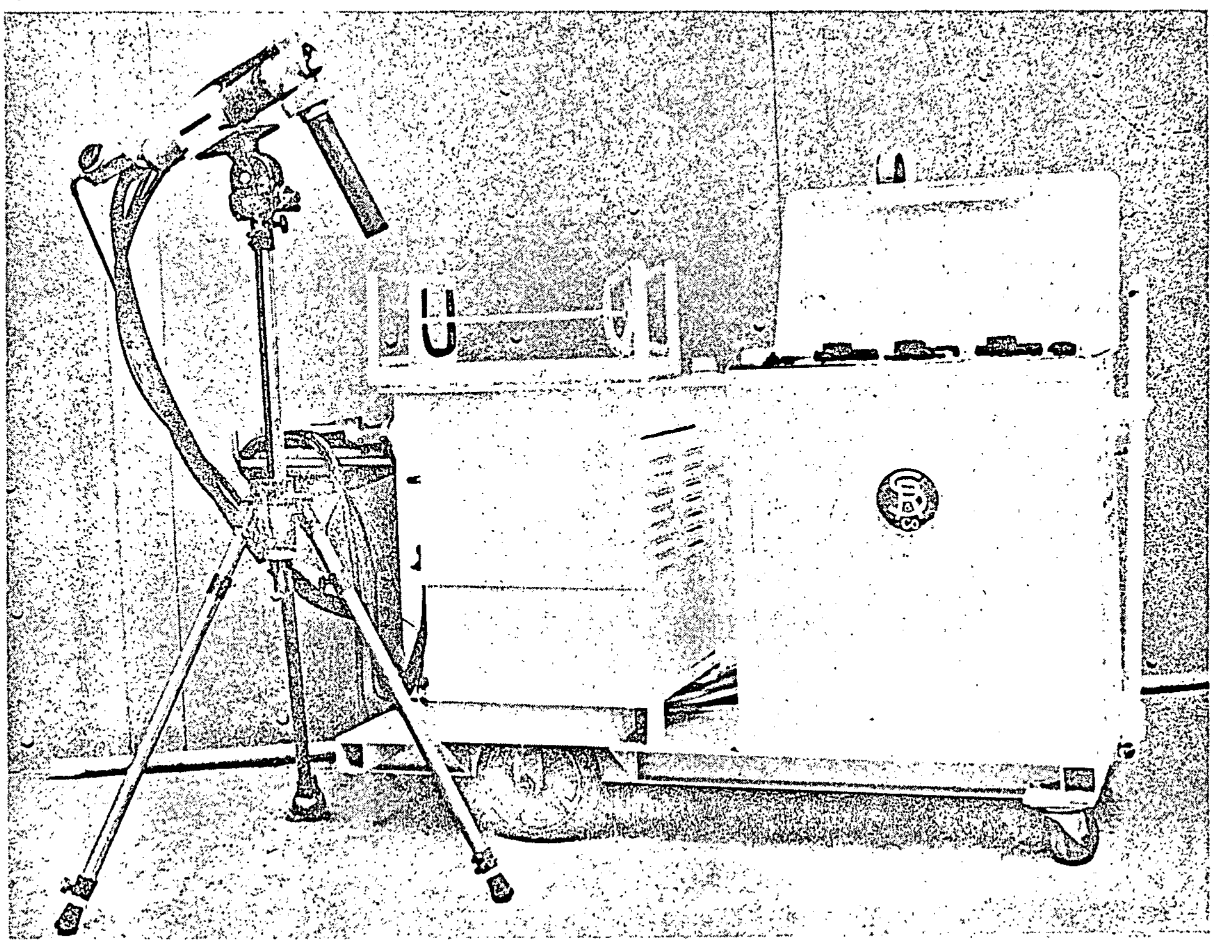

Figure 21. Mobile X-Ray Unit

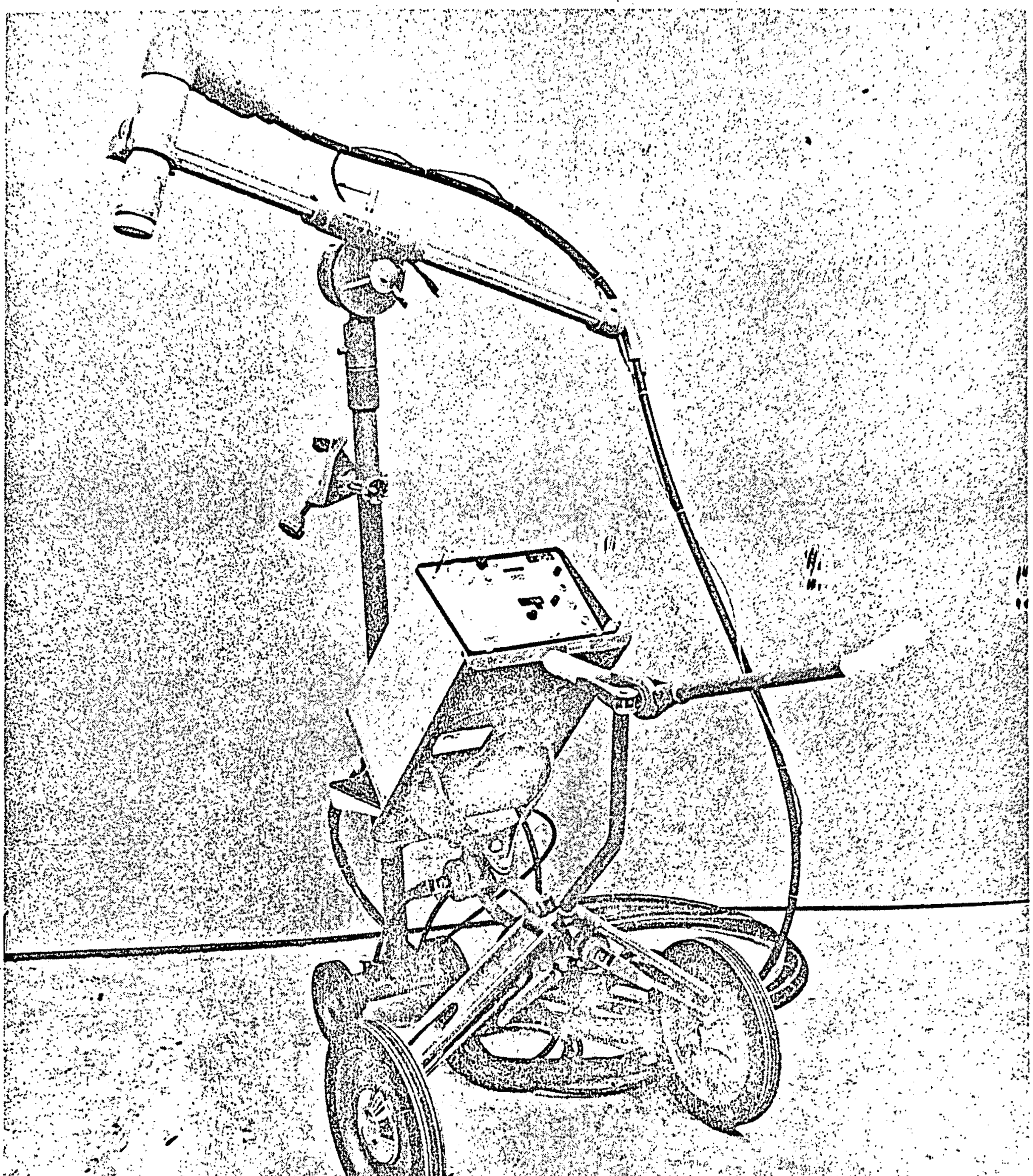

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Figure 22. X-Ray Tripod Tubestand

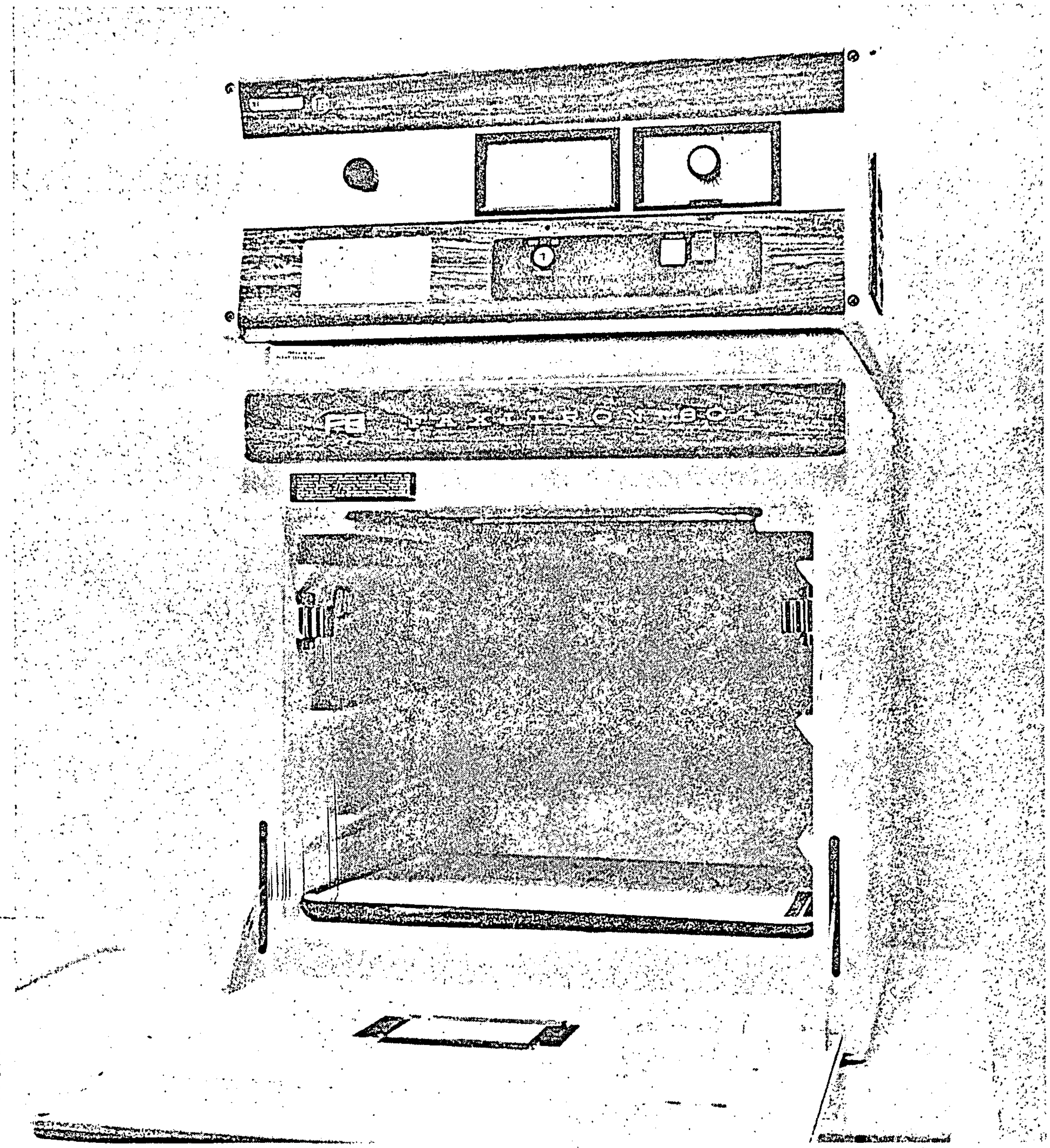

Figure 23. Cabinet X-Ray Equipment

high-voltage generator and water cooling pump are shown in Figure 21. A cabinet X-ray machine, the Faxitron 804 table-top radiographic system, 100 KVP cart is shown in Figure 23.

Among the portable X-ray accessories used in the performance of on-site inspection are radioisotopes. Examples include Americium 241. This has a half-life of approximately 460 years and emits gamma radiation with maximum energy at approximately 60 kilovolts. Ytterbium 169 has a half-life of 332 days and falls in the 65 to 75 kilovolt range. A 2-1/2 curie source camera with a 2-millimeter pellet focal spot size is commonly used. Iridium 192 has a half-life of 75 days with maximum average energy of 0.6 MEV. See Figure 24.

Californium 252, a neutron isotope, is being evaluated by the Atomic Energy Commission for use and market potential. Although a limited quantity of Californium 252 is available at present, increased production is anticipated. If the application of neutron radiography as an inspection procedure for Shuttle hardware is defined, then Californium 252 may be utilized.

A lightweight, compact, automatic developer and processor, the Pakorol CTX has recently been marketed by the Pako Corporation. By means of a daylight loading magazine accessory, it eliminates the need of darkroom facilities for portable X-ray inspection. The operating weight of 100 pounds and the power requirements of 115 volts make it readily adaptable to a cabinet base or cart for on-site X-ray inspection. Automatic replenishment, temperature control, and precise processing time provide consistent processing in minutes. The Pakorol CTX handles film up to 5 inches wide in virtually any length, and the variable speed control permits up to 30 inches of film to be developed per minute.

Film tracks, film tunnels, and isotope tunnels are being considered for inclusion into the Shuttle design. This concept will permit placement of X-ray film to facilitate radiographic inspection during post-flight inspections without structural disassembly. See Figure 25.

Tunnels can be made from a low-density homogeneous material. Structural beams and channels could be used to house film and isotope tunnels to provide an inspection capability for inaccessible areas.

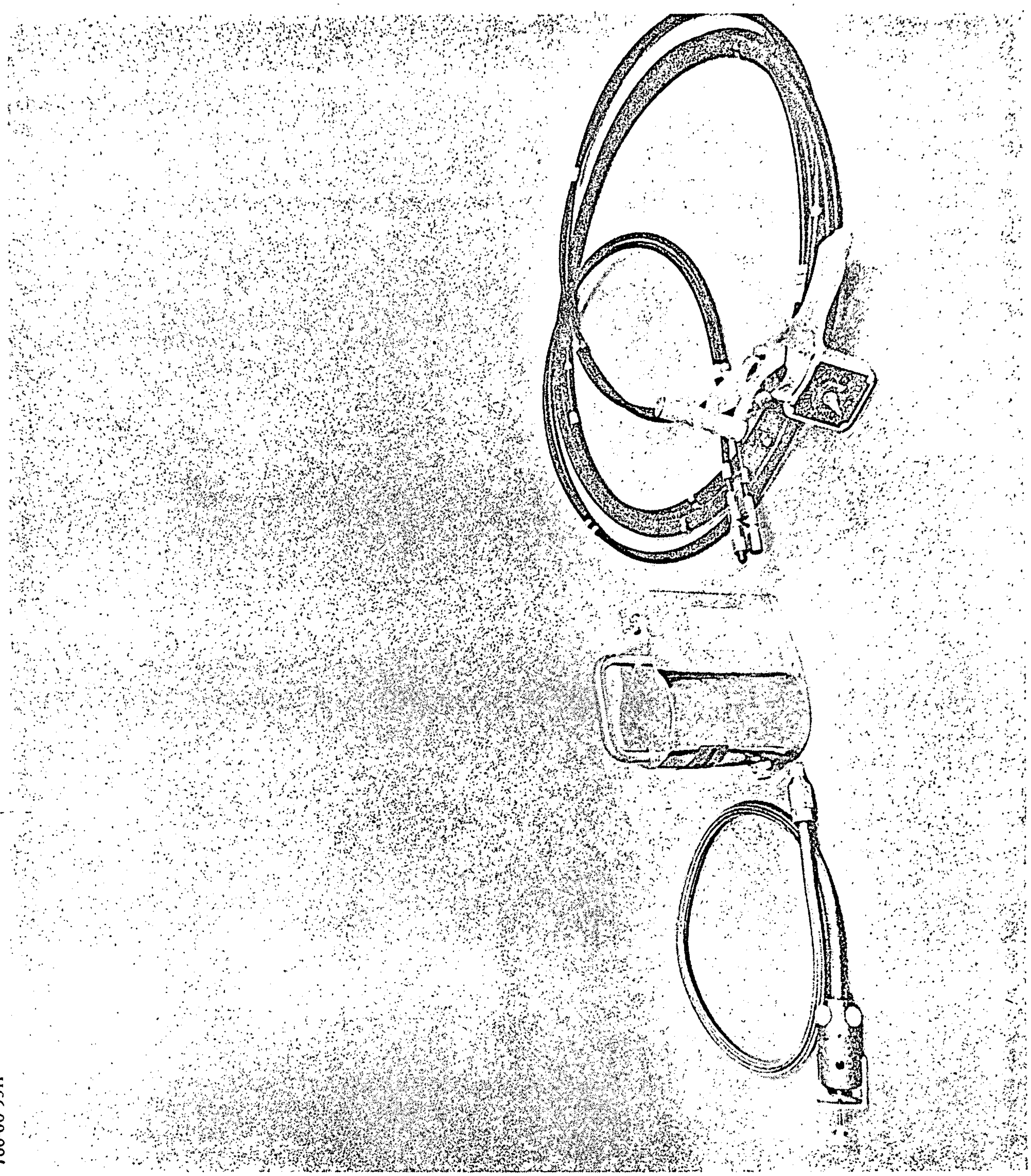

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Figure 24. Isotope Camera—Iridium Source

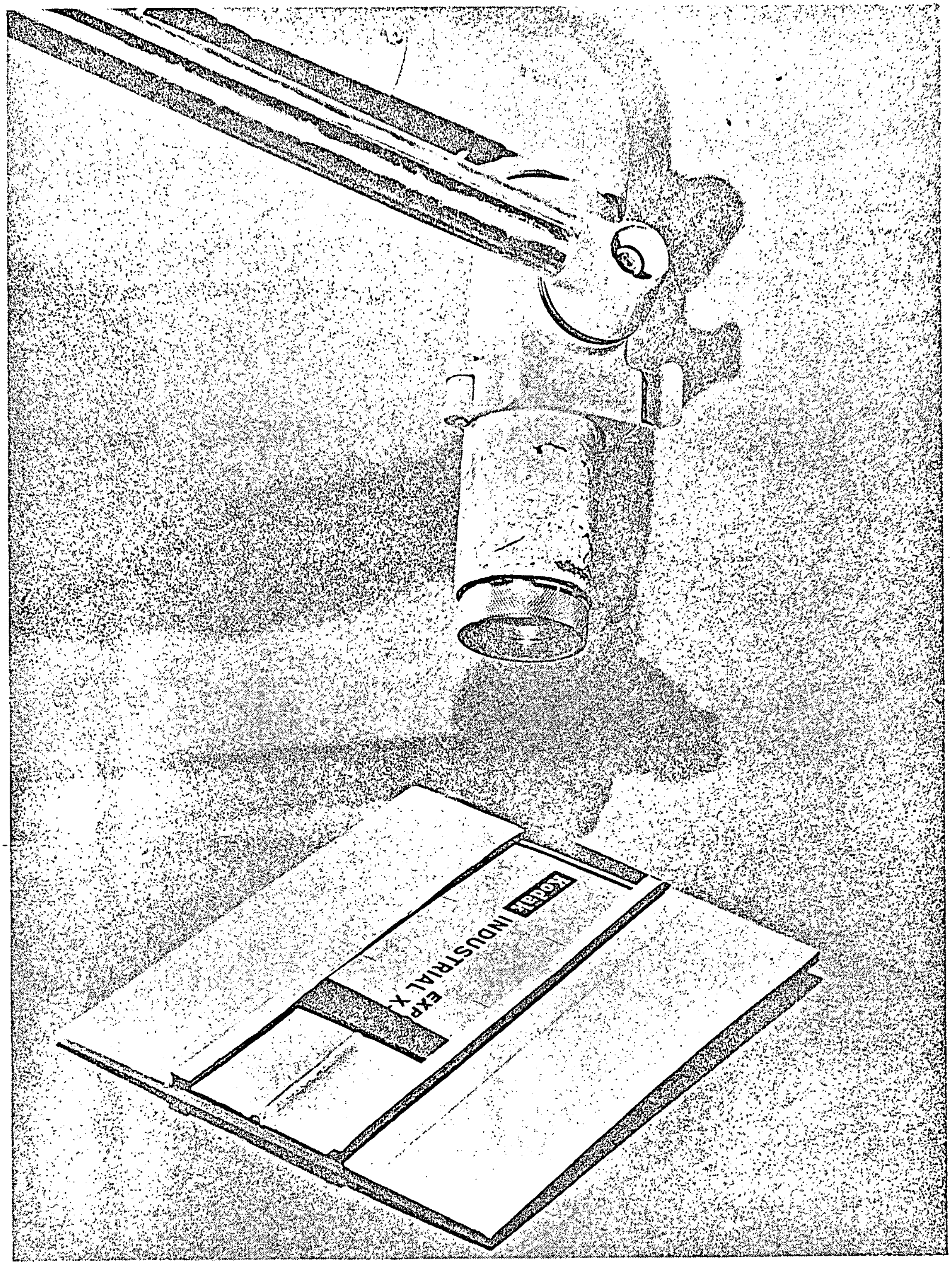

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Figure 25. Film Tracks

HOLOGRAPHIC INTERFEROMETRY

Facility Type Operation

Initial efforts to implement holographic nondestructive testing (HNDT) were based on maintaining a real time capability. The real time capability allows variation and determination of proper loading techniques. To provide this real time capability, the continuous wave holographic system must operate on a vibration-free isolation table. This means that systems are anything but portable, sometimes weighing several thousand pounds. Portabilizing such a system is both impractical and unnecessary. Honeycomb or diffusion bonded panels, brazed structures, etc., are transported to the inspection facility and vacuum-chucked to a Y-Z movement table. Working typically with an 18-inch diameter laser light disc, a hologram of the test panel is made. Typically, this can be done in a few minutes using high speed in process development techniques. The panel is then loaded, using a heat gun or internal pressure, and interference fringes form on the panel surface. Once the proper alignment and loading is established, defects are apparent as irregularities in the fringe patterns. See Figure 26.

A photograph of the real fringes is made, usually using 35mm film. Each section of the panel is tested in a similar manner. The resultant roll of film is then developed and interpreted at a separate facility using established reference interferograms. This type of holographic interferometry facility, shown in Figure 27, can also be used for various engineering tests, including vibration and flutter analysis, stress/strain distributions, etc. As an NDE method, holographic interferometry is best applied to large thin-skinned contoured honeycomb, stress-skin, or similar composite structures.

Because holographic NDE is based on surface movement, this technique cannot compete with ultrasonic techniques for detecting small, deep subsurface defects. However, because the information display is fundamentally multipoint or optical imagery, the holographic technique has the potential to achieve much higher inspection speeds than ultrasonic techniques where, even for C scan type applications, point-to-point data collection techniques are employed. The facility-type holographic operations is modeled after radiographic operation. Standards and standard interferographic images must, in general, still be developed.

Portable Operations

Holographic interferometry was discovered during work on a surface which was anything but vibration free. By using pulsed lasers whose pulse

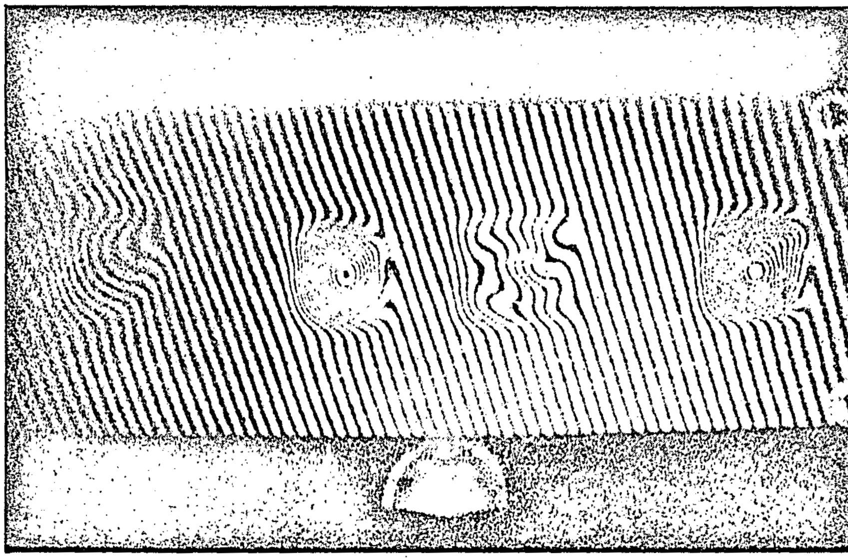

Figure 26. Holographic Interferogram

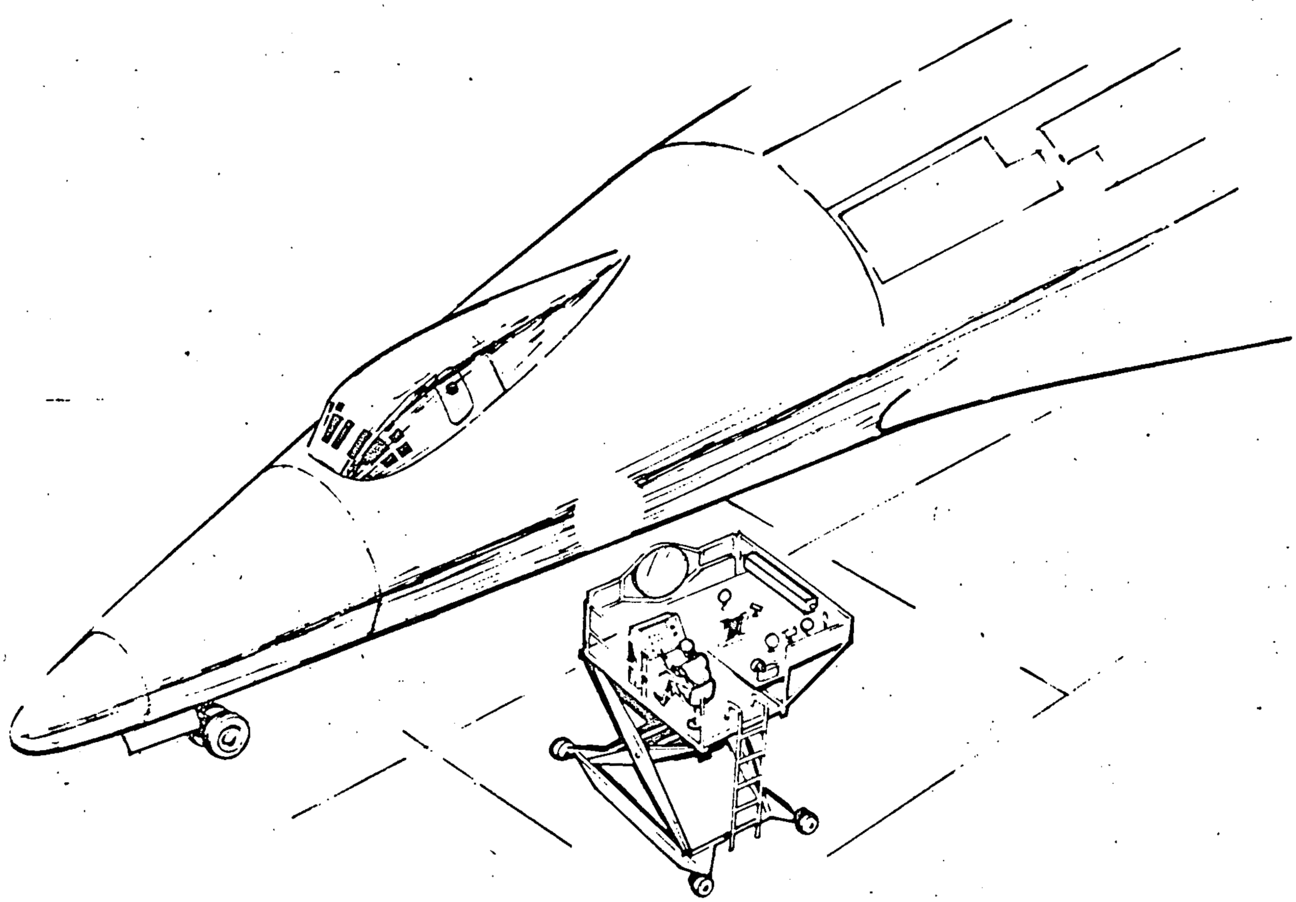

Figure 27. Holographic Facility

length or duration is measured in nanoseconds, the need for vibration isolation is eliminated. Such an operation forms a sound theoretical basis on which to develop a portable-type holographic interferometric tester. Several aerospace/instrumentation manufacturers have been developing equipment along these lines. However, the pulsed holographic interferometric operation has several drawbacks. The most objectionable, at least for holographic NDE, is the lack of a real time capability. The interferographic image is formed either as a time average or a double exposure image. The loading condition cannot be adjusted during set-up operations. Other drawbacks include the difficulty in operating and controlling a pulsed laser compared to continuous-wave gas lasers. Another drawback is the inherent size of the lasers. They are normally too large physically to be practical for portable operations. Development of smaller high powered lasers is progressing, however.

Practical approaches to implement portable continuous-wave holographic interferometry are as follows:

1. Develop a light collecting capability such as the use of large Fresnel lenses to condense the object beam after reflection and diffusion from the object. This allows shortened exposure times. When a continuous wave system is used with exposures in the 0.01 to 1 millisecond range, the majority of the vibration isolation requirements are removed.

2. Develop the concept of double reference beams to allow quadratic transformation of the stored holographic images. Surface movements in excess of 200 microinches can then be tolerated. This technique, which has only recently been devised, greatly reduces the criticality of the loading operation. Maximum load conditions can be applied without the restriction that interference fringes form. It should be noted that maximum load conditions occur at a very low level such as surface heating of no more than 20 degrees Fahrenheit. These thermal loads could not cause internal damage and do not approach proof loading ranges.

The portable holographic system is operated in a manner similar to that used for facilitized operations. The film strip is sent to a development and interpretation laboratory. For portable operation, the holographic system is indexed over the workpiece rather than moving the workpiece itself. Application of holographic NDE methods to Space Shuttle vehicles during turnaround must be predicated on the application of thin-skinned outer panel structures. Original baseline configurations projected extensive use of Haynes 188, Rene 41, silicide coated columbium, and reinforced pyrolyzed plastic, etc., as diffusion bonded, corrugated or stresskin-type structures. Reusable external insulation in the form of porous ceramic blocks with a thickness of inches rather than mils or thick ablator structures do not lend themselves as well to holographic NDE techniques. Laboratory evidence indicates that holographic interferometry is directly applicable to thin-skinned structures for the detection of subsurface unbonding, structural material weakness, and (of the greatest importance), to give information on the attachment of the panels to the substructure. The feasibility of achieving high-speed operation is most promising. Holographic interferometry is a relatively new NDE technique and can benefit from method improvement and development.

Present Shuttle test panels are often small and not structurally configured. Some results of testing on the more applicable larger test specimens is presented in Appendix A. As larger and more varied test panels are made and developed into structural configurations, more appropriate and extensive testing can be done to establish experimental verification data.

Specialized Applications of Holographic Interferometry

The labor efficiency loss inherent in portable inspection operations when compared to facilitized operations has prompted minimal usage of portable equipment. In actual practice, the labor loss results in effort three to ten times greater for portable operations. At the same time, Shuttle operations specify minimal disassembly during turnaround. The solution to resolution of these conflicting requirements has been identified and lies in the implementation of on-board checkout procedures. The ready access of the outer thermal protection shield for inspection makes removal of the panel after every flight impractical. Hence appropriate NDE techniques for these panels should be portable in a facilitized manner. The question of whether the examination should be a visual one for discoloration or fretting, or a sophisticated NDE technique such as holographic interferometry, has not been decided yet.

The extension of holographic interferometric techniques to determination of creep and structural relaxation within Shuttle vehicles would be a natural extension for this developing technology. As an on-board technique, a real time technique could be employed by permanently fixing small holographic film slots in appropriate locations. A holographic system would be bolted into place and a reference hologram exposed. After an appropriate number of flights, a laser of sufficient power would once again be attached to the structure and the object field viewed with real time fringes. Metallic structural creep and relaxation should be detectable and measurable from the fringe patterns. Such a technique might even be applicable for in-flight monitoring when used with a fiber optics vidicon system.

Initial development effort should center around ground engineering tests. Figure 28 illustrates such an approach.

Another holographic interferometry special application is that involving inspection of internal thermal insulation in tankage. The possibility of using internal insulation is being considered for possible application to LH_2 propulsion tanks. The insulation itself is readily accessible to a variety of NDE methods, principally acoustic methods such as acoustic impact, acoustic resonance, sonic brush, etc. These techniques are slow, ineffective and possess inherent sensitivity limitations. The possibility of applying holographic interferometry is plausible but difficult. A holographic system would bolt on to a manhole opening as shown in Figure 29. Double exposure holographic interferograms are made over the complete inside surface using maximum area coverage of 25 square feet to 200 square feet in each exposure. The holographic loading technique would be to apply a slight vacuum between exposures, say one exposure at 1.0 atmosphere absolute and the second exposure at 0.7 (estimated) atmospheres.

The operation would be similar to that now used to examine the inside core of tires using holographic interferometry. That is, the system would index around the inside surface. The nature of the internal insulation, a coated foam, would lend itself well to this type of inspection. One could reasonably expect to find coating blisters 2 inches or greater in diameter, delamination in the foam, 4 to 6 inches in diameter, and crack and crazed foam conditions caused by cryopumping. Because the test object surface is quite far in general from the holographic system, large Fresnel lenses would have to be used to shape the object beam.

Anticipated problems include the need to compensate the reference beam distance for changes in the object beam distance, vibration problems, and probably a higher laser power requirement. Also a relatively short exposure time, 0.1 seconds (estimated), may be necessary. The opening for the holographic system may have to be relatively large, say 2 feet by 5 feet, and should be located either on the longitudinal or vertical bisector of the tank. Development of such a technique may be difficult in that fairly large vacuum tankage would be necessary. If this tankage is of the double or triple bubble concept, the problem becomes even more difficult. The benefits from such an approach may be realized from an examination of the inspection speed and, of course, they are predicated on the establishment of a realistic need (engineering requirement) to inspect such insulation for repeated usage. Perhaps the test subject should be examined after every ten detankings (estimated).

Based on a 4000-square-foot internal area, sonic brush inspection would require 400 manhours. This figure is based on being able to do 10 square feet per hour which is somewhat optimistic if a conscientious effort

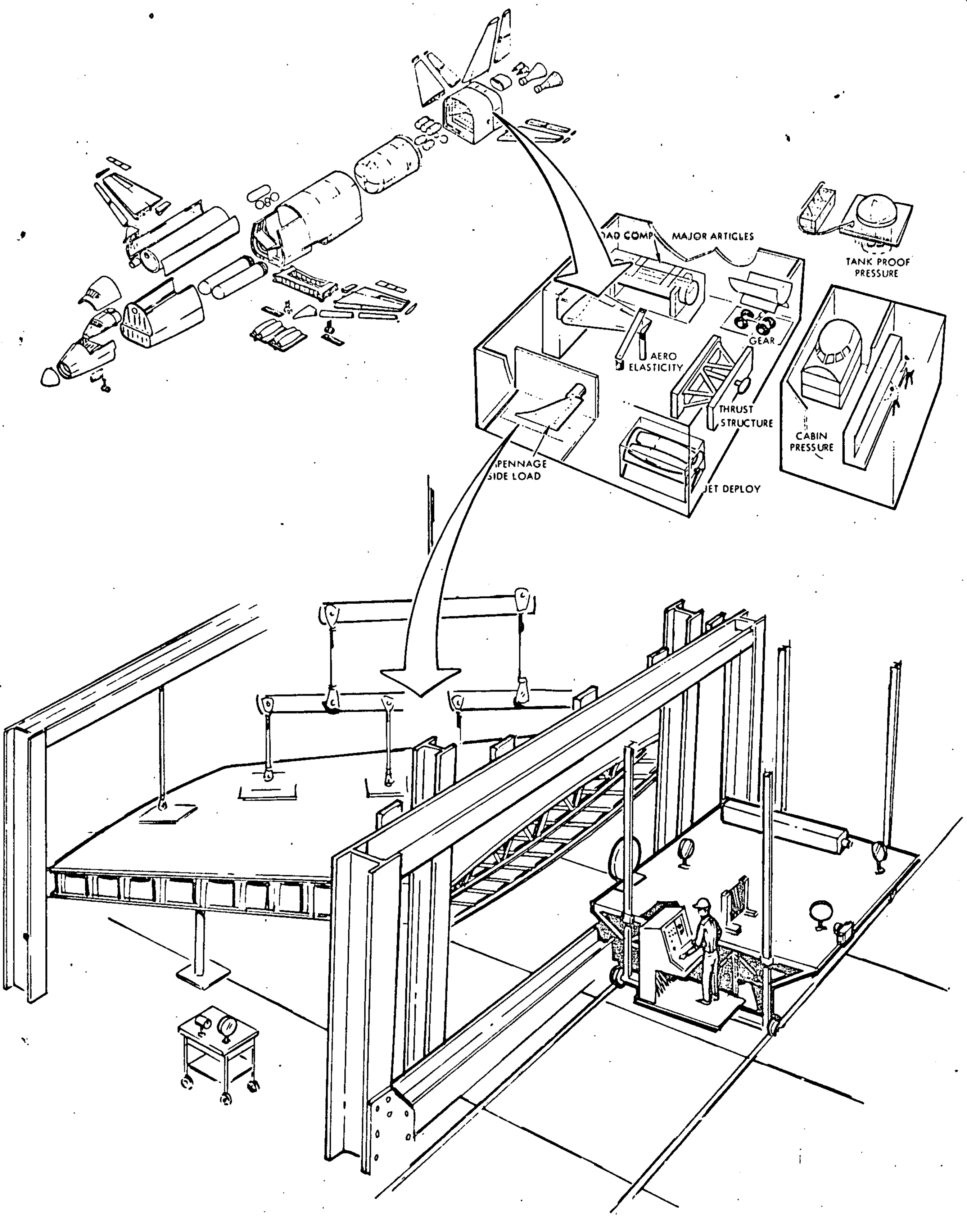

Figure 28. Holographic Engineering Test Facilities

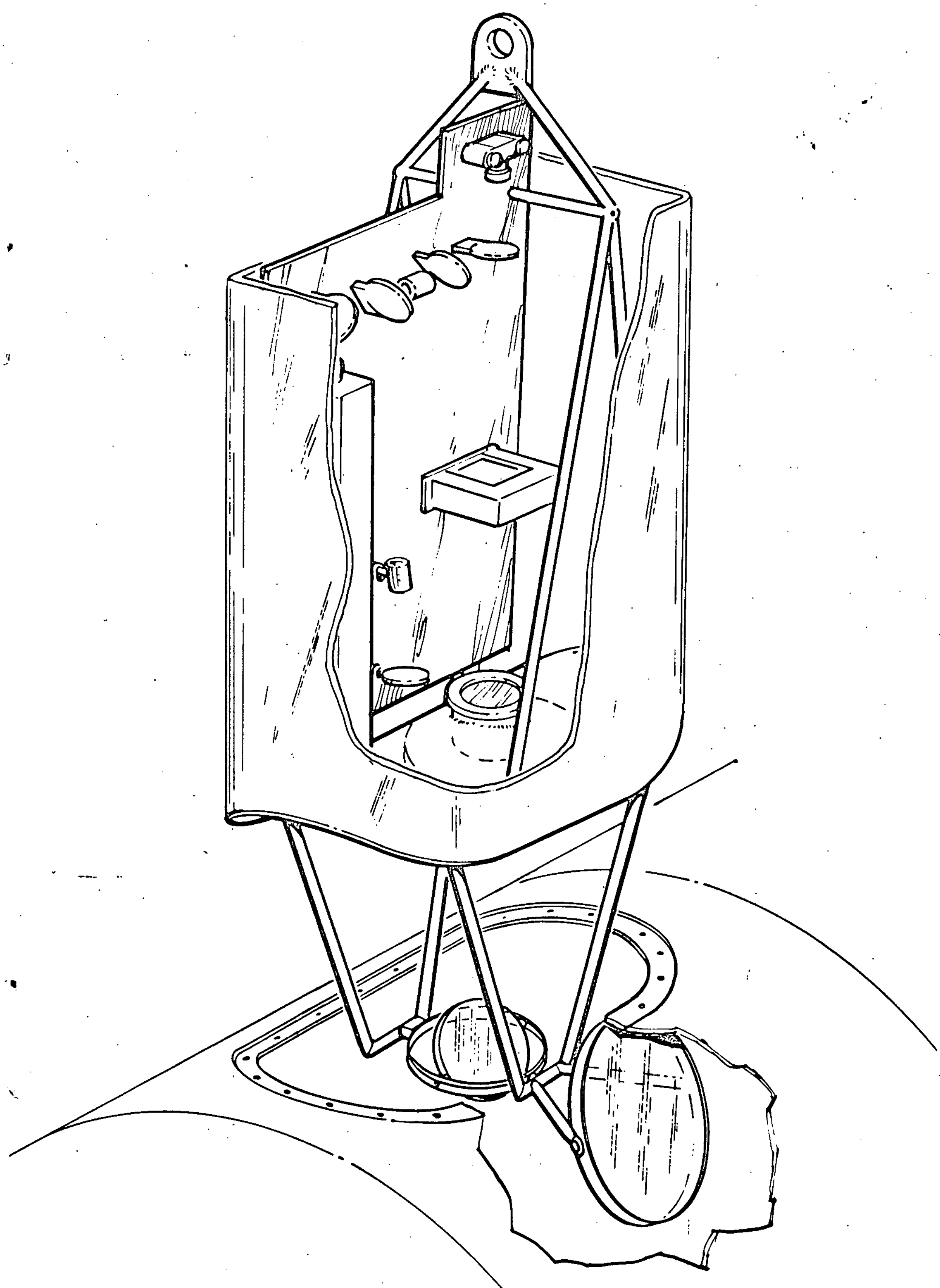

Figure 29. Holographic Interferometry on LH_2 Tank

is to be made. It would be realistic to expect to be able to accomplish the same task in forty hours doing it holographically. This figure is based on only four shots per hour covering only 25 square feet each. Both these figures are conservative, and the possibility of completing the inspection in four hours is well within the realm of plausibility. The application here is ambitious but deserves further study.

With insulation attached directly to the outside of the tank, it is difficult to determine the condition of the insulation itself. Proper on-board techniques should be employed. However, the condition of the bondline is normally readily assessed using pulse-echo ultrasonic methods in a portable operation occurring inside of tank.

ELECTROMAGNETIC TECHNIQUES

Eddy Current Thickness Gaging

Eddy current NDE methods involve establishing an electromagnetic field in the metallic structure rather than transmitting radiation through it. Hence, eddy current techniques evaluate the near surface of a workpiece. Eddy current devices can detect and measure the depth of cracks, measure the thickness of metal sheets and coatings on metals, and determine the electrical resistivity of metal structures (which can often be interpreted as material properties such as the heat treat condition or alloy composition). A wide range of commercial devices is available, many of which can be used for several of the functions mentioned. In custom installations, eddy current devices can be C-scanned or used to control a sorting operation by being scanned over 100 percent of the surface of tube, sheet, and bar stock. Extremely high speeds can be achieved. However, most of these installations are designed to handle wrought stock and would not be applicable to complex and varying finished hardware.

For Shuttle turnaround operations, it is best to think in terms of point measurements rather than total area scans. For stresskin composites and other materials which are only accessible from one side, eddy current devices provide a convenient means to make sample measurements of thickness. They are suited for the range below 0.020 inches where digital ultrasonic thickness gages cannot operate due to wavelength and near field limitations. Determination of coating thickness can in most cases be made. Eddy current thickness gages cannot be applied to metal coatings on a metal substrate when the difference in electrical resistivity is small. Typically, gold plate thickness on copper cannot be measured with eddy current devices. Here, the electrical resistivity difference is less than 20 percent and the electrical conductivity is quite high, so penetration is low. However, nickel platings on iron are readily measured, with the resistivity difference being slightly greater than 20 percent. Eddy current instruments provide a convenient means of verifying the thickness of coatings and thin metal facing sheets.

Eddy Current Flaw Detection

Currently available eddy current flaw detection and measurement devices provide a convenient means of measuring the depth and extent of cracks detected by the on-board ultrasonic and acoustic emission systems. Because of the gross effect of holes, ribs, and the proximity of other metallic structures in structural configurations, eddy current flaw measurement techniques must be developed on an individual basis.

Some Shuttle materials are in the low conductivity range below 10 IACS. Hence, the operating range of the eddy current equipment must be carefully specified to provide capability below this limit.

When detailed design knowledge becomes available, areas where eddy current development would be useful and appropriate can be specified. The primary eddy current parameters are coil diameter operating frequency and coil inductance. Too often the commercial equipment manufacturers are reluctant to provide flexibility in these areas. However, some very excellent variable frequency equipment is now becoming available. Because the probes (packaged coil) are critical with respect to operation and are influenced by many less important factors such as coil insulation potting material, etc., the probe design is often proprietary, and custom coils can be difficult to specify. The primary coil-probe relationships are well known.

Typically

$$\text{phase velocity } \nu = (4\pi f/\sigma\mu)^{1/2}$$

$$\text{self inductance } L_o = K (n^2 A/\ell)$$

$$E = 2\pi f(n)(\pi/4) D^2\mu \; H_o \times 10^8$$

involving

f = test frequency

μ = permeability

σ = conductivity

D = coil diameter

n = number of turns

H_o = excitation field strength

Capability for providing properly designed coils for particular applications can be very useful for eddy current defect detection and analysis.

Possible areas for eddy current applications research are ill defined, but possibilities include measurement of silicide coating thickness on refractory alloys. Initial studies in this area were discouraging, but little sophistication was attempted. The real problem appears to center around the fact that the interface is poorly defined and silicide coatings at the time of these studies were not uniform and homogenous. Interdiffusion occurs in the silicide-coated refractors during usage at high temperature. This complicates eddy current application studies and even raises real questions as to what is really meant by the thickness of the diffused coating.

Carbon-carbon systems represent another area where eddy current or perhaps, more appropriately, radiofrequency field probes may have application. An NDE technique for measuring parent material thickness and coating thickness should be developed for these reinforced pyrolyzed plastic (RPP) materials. The electrical conductance of these materials is quite low—about 0.05 percent IACS and no commercial eddy current equipment extends beyond 1 percent IACS. However, finished RPP materials are expensive and not readily available, development programs in the field of RPP materials research should also include practical NDE development.

Radio Frequency Techniques

From a theoretical standpoint, RF NDE methods are as applicable to nonmetals as eddy currents are to metals. Radio frequency equipment to measure moisture content is commercially available. Metal proximity devices have been used to measure foam thicknesses on metallic substrates. High voltage RF probes are commonly used to locate vacuum leaks in glass systems. The feasibility of using these high voltage probes to detect pinholes and cracks in silicide-coated refractories has been experimentally examined. It appears that the present coatings with their fine microcrack structure are extremely porous. In fact, after water soaking, the coating is electrically conductive to the substrate. If this condition is to be represențive of the silicide coating used on Shuttle vehicles, then it would be feasible to develop a low voltage RF leak current technique to measure the amount of cracking in silicide coatings.

RF dielectric probes have been used to measure the quality of the materials which go into the REI manufacture. (See Figure 30.) The use of RF devices to measure thickness and moisture build-up in REI structures during turnaround will be available soon with some laboratory development effort.

THERMOGRAPHY

Liquid Crystal Techniques

Applications development research using liquid crystals as an NDE method has been pursued by many companies. The prime motive for this intense effort has been the possibility of achieving a high-speed, low-resolution NDE test method. The high-speed possibilities are due directly to the ability of liquid crystals to cover large areas. Thermal NDE methods are inherently low speed. That is to say, it takes time to transfer heat. Diffusion and transporter phenomena are involved. Heat travels slower than sound or X-ray radiation and is harder to control and direct. However, if a large area can be examined at one time, the slow interaction time is dwarfed by the amount of area which is covered at one time. The recently developed films of encapsulated liquid crystals have further stimulated thermal NDE research because the films are easier to handle and to use than the sprayed or painted liquid crystal application techniques.

Thermal NDE techniques are best applied to active heat sources. This is reflected in present usage where the major applications are in the electronic module/circuit board field and in examination of heater blankets, steam lines, electrical junction boxes, etc. For application to a passive structure, the thermal conductivity must be low enough to minimize lateral thermal diffusion but yet high enough to pump heat through the structure. This useful range is estimated to be between 0.1 and 15 BTU/hr/sq ft/F/ft.

The higher conductivity limit is primarily related to the thermal transfer coefficient at the structure/air interface, which is normally 3 to 30 BTU/hr ft^2 F. Many Shuttle materials fall in the correct thermal conductivity range, including titanium, Haynes 188, Inconel 718, etc. Because thermal NDE

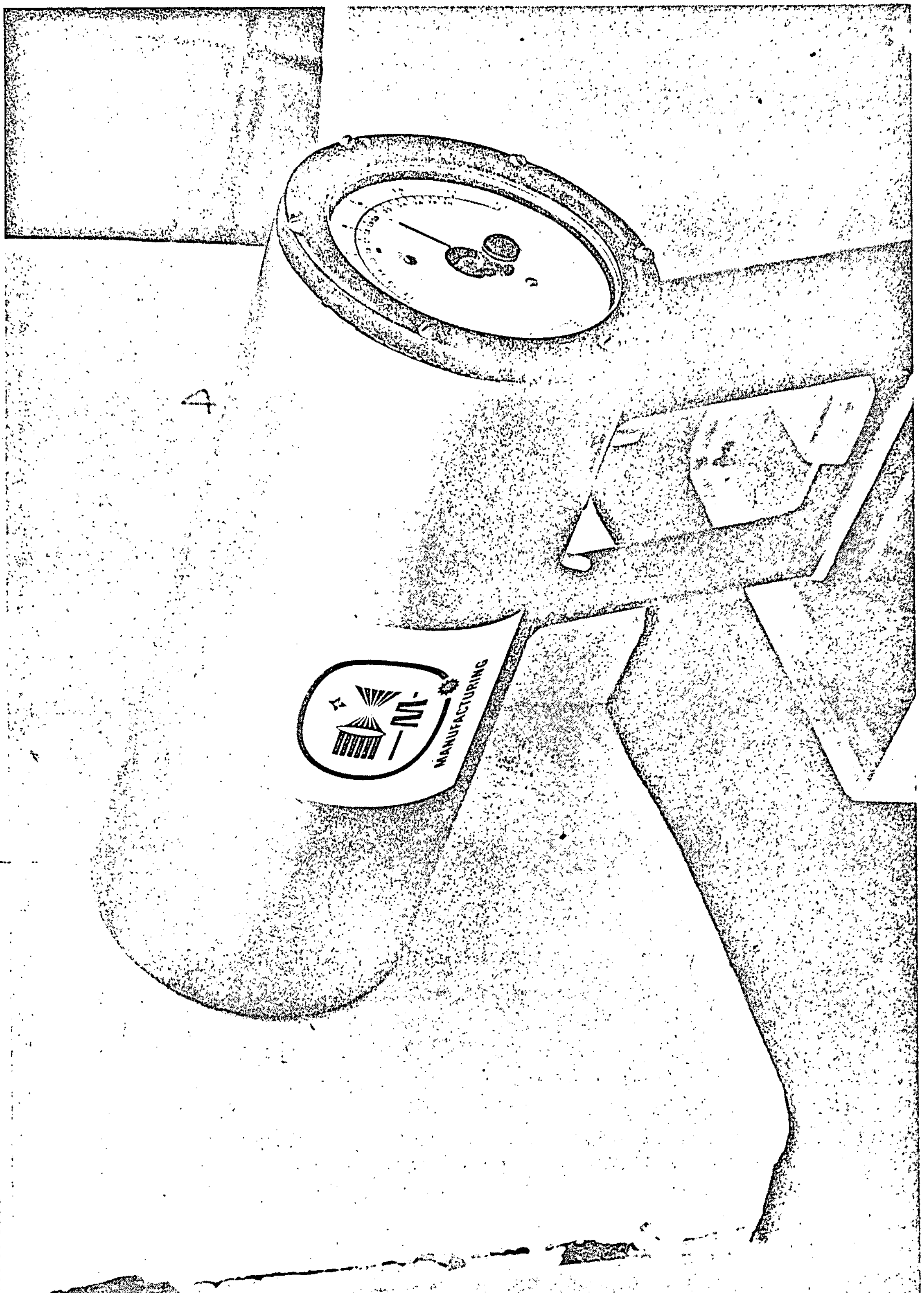

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Figure 30. RF Thickness Gage

techniques are basically surface techniques, resolution of deep defects is not possible. It has been commonly postulated that a defect must have a minimum dimension at least twice the depth from the surface. The true fuctional relationship is considerably more complicated than this linear "rule of thumb."

Typical applications research has been directed toward thin-skinned honeycomb structures and other sandwich-type composites. The most severe and pressing problem has been the availability of uniform heat sources and sinks. In theory, a wide variety of defects should be resolvable if enough heat can be transmitted through the structure in the correct direction.

Experimental data relevant to using thermal NDE methods on the Shuttle structures is presented in Appendix A. Feasibility of application has been shown. Honeycomb cell walls are visible and defects in candidate thermal protection shield (TPS) materials are shown in Figure 31.

Infrared Scanning

Where infrared thermal NDE techniques appear to be applicable to Shuttle turnaround operations, they will be considered. Shuttle vehicles will land with a hot external TPS. The heat loads and temperatures imposed on these materials during atmospheric entry are a major concern. Certainly, the surface temperatures and thermal patterns will be of interest to engineers. The possibility of detecting broken thermal isolator standoffs for the TPS is good. Infrared scanning of the hot outer Shuttle skin just after and/or prior to landing is similar to active thermal NDE techniques. (See Figure 32.) It is also reasonable to think in terms of determining which panels and structures were exposed to the severest thermal environment. These panels perhaps should be subjected to greater scrutiny. Conventional means would be used to accomplish this, and these means were discussed and evaluated in the Phase I report.

Another method to enhance the information gained from thermal testing is to introduce the time variable. When infrared (IR) scans are made at different time intervals, a great deal more information can be made available. For example, if a panel was at temperature T_1 and one hour later was at temperature T_2, ($T_1 > T_2 >$ (ambient temperature)), data can be accumulated describing heat dissipation. It then follows that confidence in the knowledge of a broken standoff would be greater. This conclusion is supported by NDE data showing slow cooling, as opposed to basing the conclusion on the fact that the panel is hotter than expected. Laboratory experimentation on small test samples is relatively meaningless for establishing feasibility and technique limitations for this application. Operational evaluation during the flight test program would quickly reveal the usefulness of such a technique. Some theoretical analyses would be appropriate to form a basis on which to

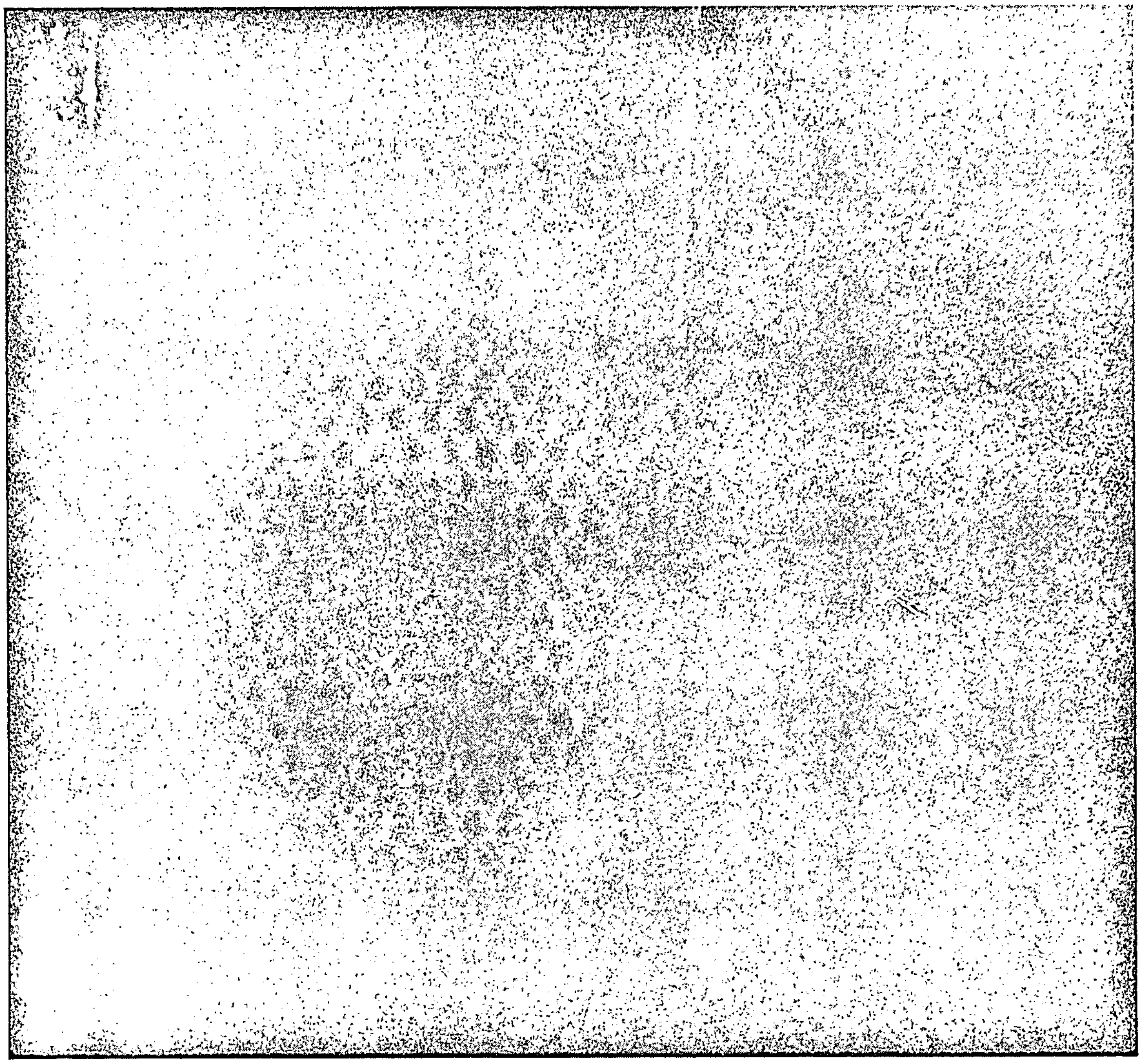

Figure 31. Liquid Crystals—Honeycomb Cell Structure

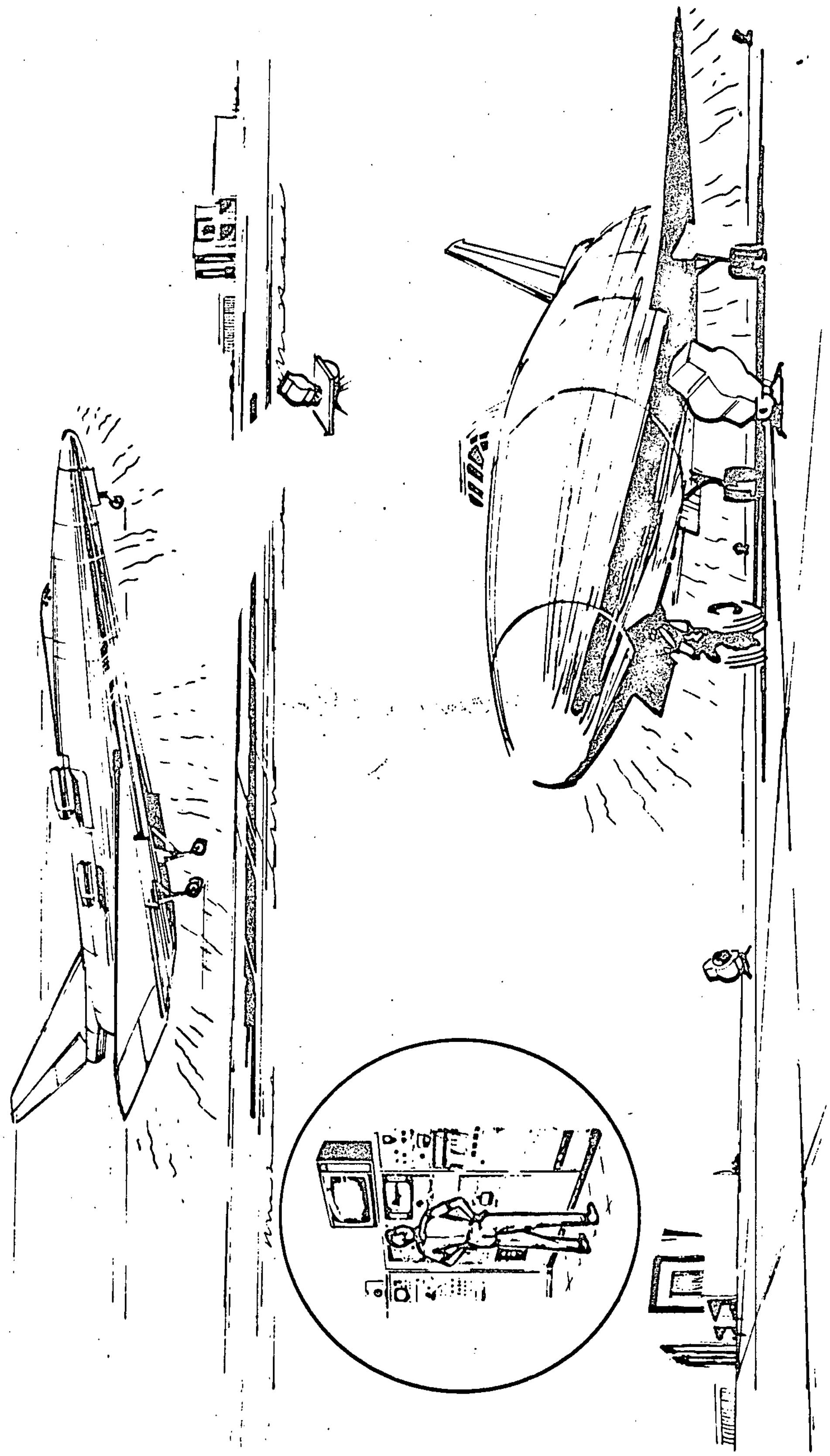

Figure 32. IR Scanning of Shuttle TPS on Landing

operate and to establish what should be expected and what to look for. Once the detailed vehicle geometry and materials are established, the feasibility of using time-integration thermal scanning techniques as a basis from which to extrapolate actual reentry conditions using mathematical modeling techniques would be possible.

It should be noted that the greater the TPS insulating properties, the less appropriate such thermal techniques become. A perfect insulator might make the design of the crew and passenger areas and cryogenic tanks less difficult, but would create other design problems such as TPS cooling, etc. Hence, the TPS structure will probably be moderately insulative and would be most responsive to infrared scanning.

SHUTTLE SYSTEMS APPLICATIONS

CRYOGENIC SYSTEMS

Cryogenic tanks that are repeatedly subjected to high stress loads, superimposed vibrations, and thermal cycling must be carefully designed, fabricated, and tested to maintain adequate structural integrity to accomplish a specific spacecraft mission. To assure that the structure retains this adequate integrity during use, an installed monitoring system is essential. The magnitude of the testing or checkout problem for large tankage makes the use of an automatic monitoring instumentation system necessary to allow the accomplishment of required inspections in a reasonable period of time. Furthermore, limited or difficult access to certain areas makes the use of built-in provisions imperative to reverify structural integrity after fabrication has been completed. Studies are being conducted to define and select advanced nondestructive testing techniques which will give information about the structural integrity of critical vehicle members such as high-stress weldment areas, thermal insulation, etc. The selected techniques have the feasibility of being incorporated into an on-board installed system. After selection of the most appropriate techniques, one or more will be tested under laboratory conditions to determine its response to a previously established defect criteria. The system or systems that respond adequately to defect criteria and indicate the most potential for an on-board structural monitoring capability will be assembled into a prototype system and tested on a large tank under realistic environmental conditions.

The extension of cryogenic tankage to long duration missions suggests that the utilization of on-board systems to measure the structural integrity of cryogenic storage containers may provide important information relevant to various possible mission alternatives. The development of such measuring techniques will probably be required for Shuttle and space station operation. As mission duration is extended even further, such techniques will become a necessity, probably with development of in-flight maintenance and repair. The present state-of-the-art with respect to on-board systems is quite limited. In order to achieve reliable and meaningful structural integrity assessment it is important that development in this field be accelerated.

Three approaches to problems of on-board structural integrity checkout can be recognized:

1. Operational electronic checkout - widely used for electronics and fluid systems.

2. Nondestructive testing in space - essentially proposes using those conventional techniques which can be used in space (man-operated and interpreted).

3. On-board systems - essentially a combination of the above but with nondestructive techniques which can be adapted to automated non-manual operation.

Because of the extreme usefulness of visual inspection, the adaptation of fiber optics through an electronic link seems most attractive. Such devices are not now available but clearly within the grasp of present technology.

The creaking and crackling of cryogenic foam structures during cryogenic tanking is audible to the unaided ear. The feasibility of using acoustic emission techniques to determine on a statistical basis the occurrence of cracking in foam insulation is promising. Using the metal load-bearing structure as a sounding board, large areas could be monitored. The signal levels would be significantly higher than those encountered in acoustic emission monitoring of metals under high stress. Most probably, the emissions from the foam will be quite sporadic, perhaps allowing monitoring of the metallic high stress areas also.

The feasibility of extending present thermocouple and cryogenic flow measurement techniques to a network which might directly reveal the insulation functionality of the cryogenic storage container is being investigated in other studies and deserves consideration.

From the above suggested techniques, it may be surmised that high emphasis is placed on developing gross techniques. The need to achieve completeness yet maintain low-weight requirements has prompted this approach. With increased sophistication and in-use experience, development of spot techniques will become important.

The usefulness of impaired scanning techniques around cryogenic liquid systems is another thermal NDE application. The feasibility of inspecting the cryogenic liquid transfer lines is also a reasonable application.

The investigator would be working with the near-toe of the emittance curve of Figure 33. Subsurface defects can be detected in this manner. Figure 34 shows the infrared film detection of square unbonds in a phenolic honeycomb panel (20-mil thick facing sheet, 1/4-inch to 2-inch square unbonds). Infrared film is easier to work with than infrared scanners, but the majority of the applications are based on reflected light rather than on emittance.

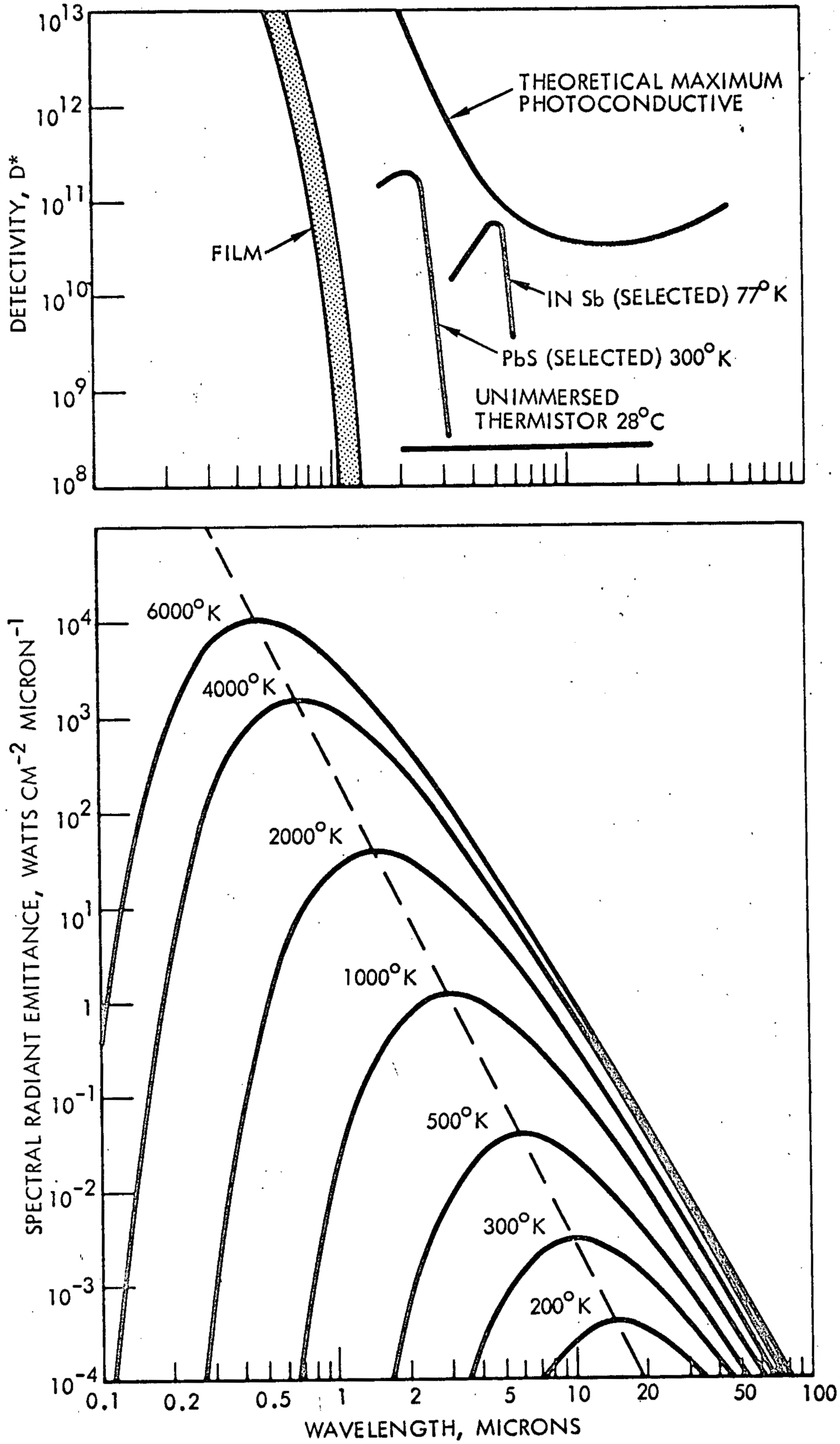

Figure 33. Toe of IR Emittance Curve

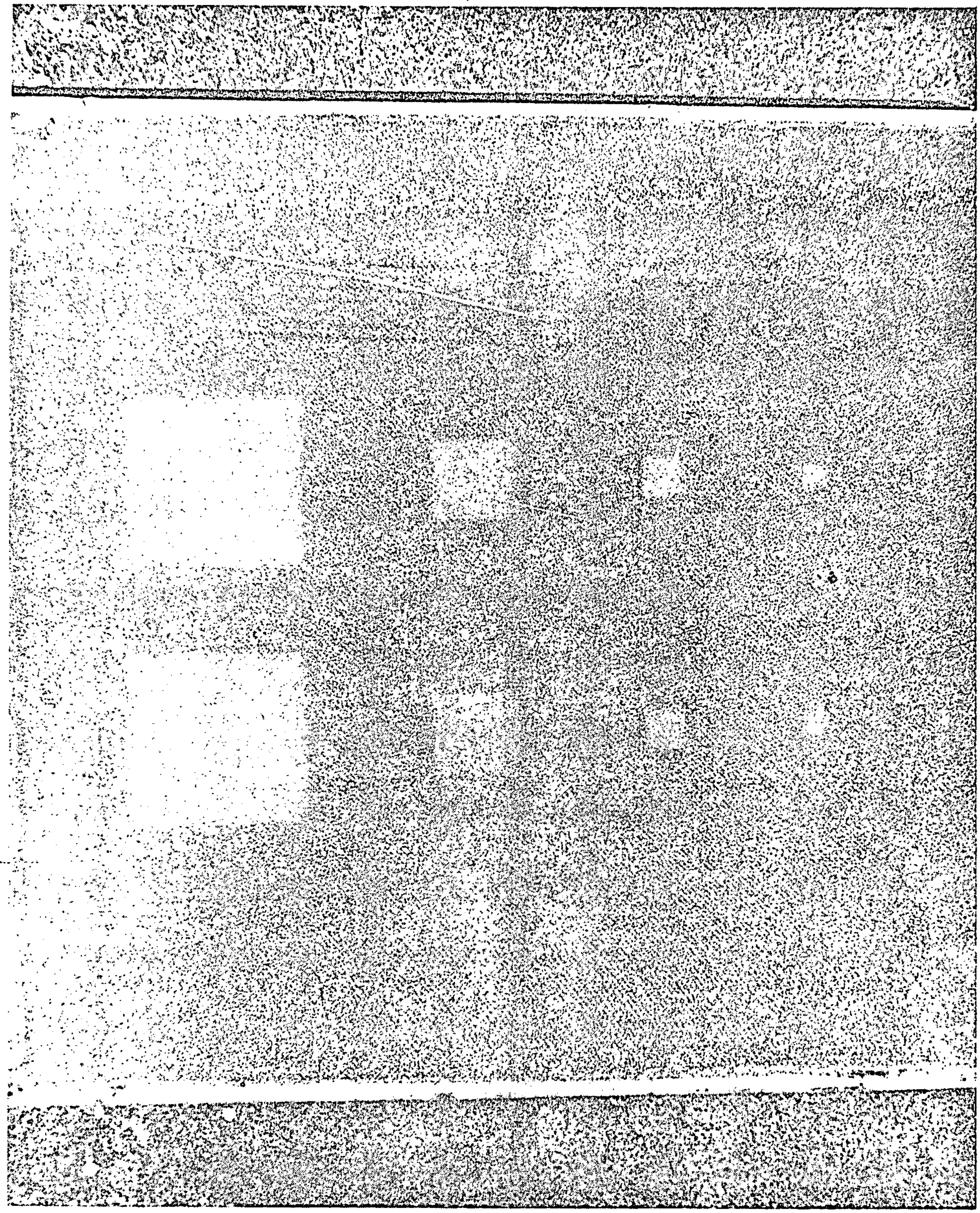

Figure 34. IR Film-Detected Unbonds

SILICIDE-COATED REFRACTORIES

Stimulated electron emission radiography and the use of radioactive labelling has been investigated to determine silicide coating quality. The techniques provide laboratory evaluation data which has been instrumental in identifying appropriate processing techniques and material composition. Stimulated electron emission requires close film-to-silicide-coating vacuum hold-down techniques. Methods to implement these techniques and isotope tagging autoradiography are shown in Figure 35. Both these techniques provide useful material composition and thickness information on silicide-coated panels which have undergone simulated entry thermal cycles. The data correlates well with electron microprobe analysis.

Because of limited application, it does not appear that commercial NDE hardware will result from this method and custom facilities would be required. When realistic materialistic turnaround requirements can be established for the silicide coating, high-speed NDE methods can be developed. It has been found that beta backscatter techniques can be used to measure oxygen concentration in the coating. Low energy sources are necessary and the accuracy is low and ill defined. The questions of how deep to go into the surface and what kind of average value the readings indicate would have to be examined in more definitive studies. Penetrants under high stereoscopic magnification (about 200 times) show the microcrack structure and also indicate the presence of holes or tunnels in the coating. The microcrack structure appears to become filled with oxides while the tunnels grow larger See Figure 36.

High-frequency ultrasonic shear and surface wave techniques should be considered for measuring crack depth, providing the microcrack structure becomes less cluttered, that is having fewer cracks. However, present research seems to indicate that a finer microcrack structure is desirable rather than trying to eliminate the cracks. X-ray fluorescence could be applied to determine chemical composition and coating segregation. All the NDE methods presently applicable require extensive development for turnaround application. The techniques are inherently slow and require highly trained investigators. It is somewhat of a misnomer to call them inspection techniques at this time.

For turning the Shuttle vehicles around within two weeks with present silicide-coated columbium inspection technology, two rather unreasonable approaches are available. A team of inspectors can visually examine the skins for spalling and indications of white and yellow oxide particles and perhaps hit the panel with a rubber mallet to see if it fractures. Alternatively, the panels could be removed and a new set installed. The old set would then be inspected and verified for flight worthiness between alternate flights. The problems are severe and perhaps it is more cost effective to

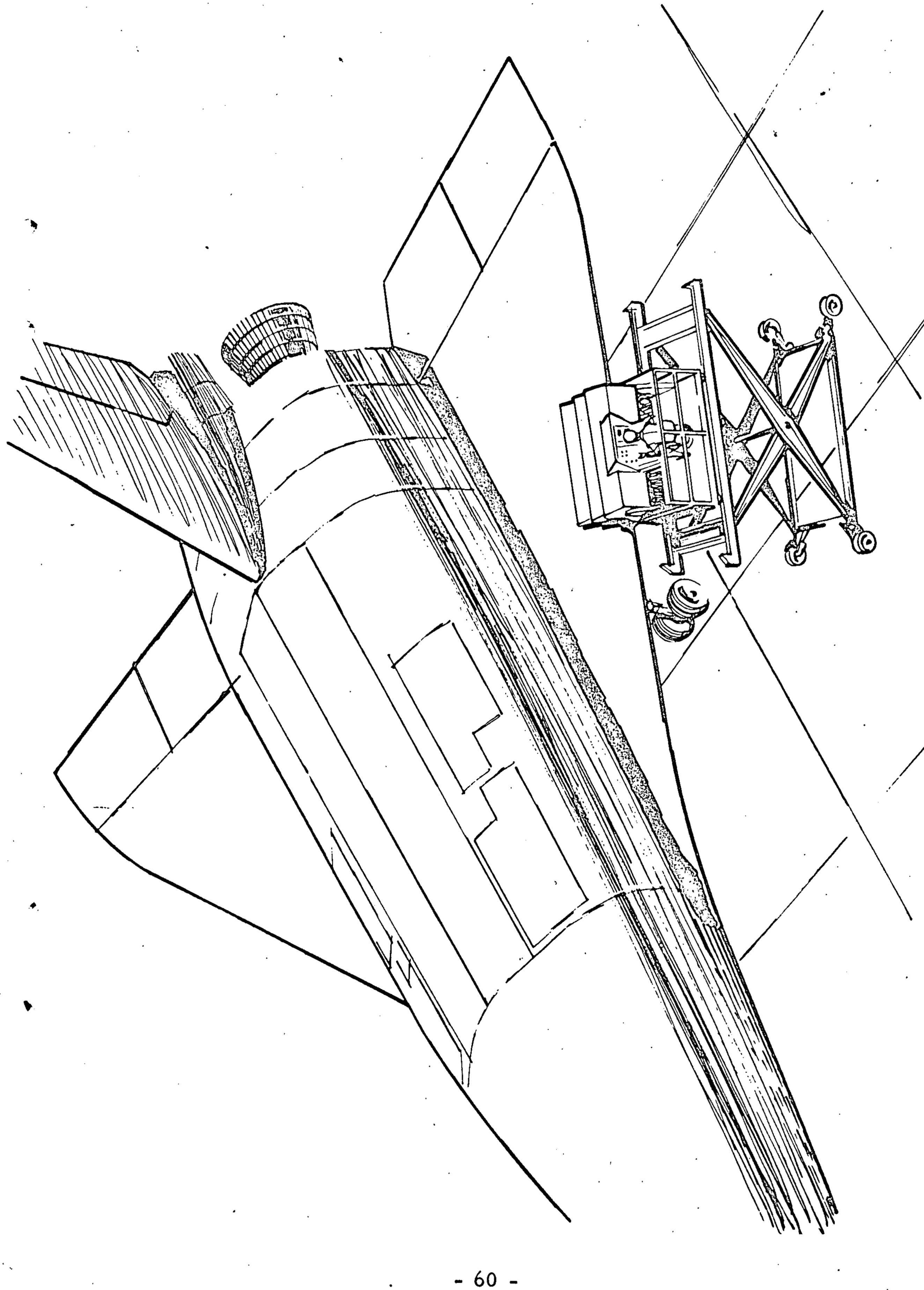

Figure 35. Isotope-Tagged GSE Operations

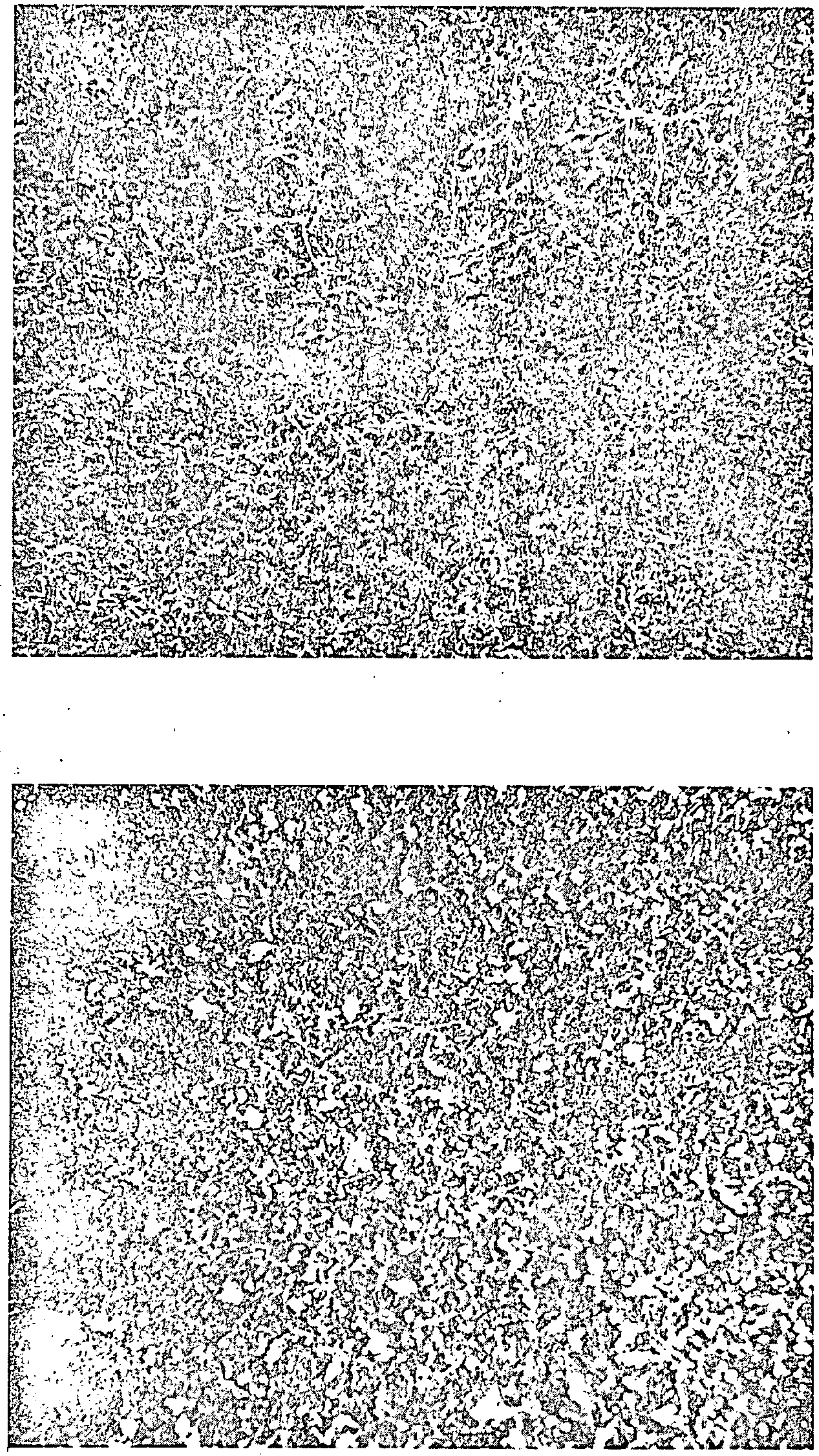

Figure 36. Penetrants on Silicide Coatings

examine the panel structural strength using holographic interferometry or attempt to develop a coated refractory material requiring little examination.

REINFORCED PYROLYZED PLASTIC

Reinforced pyrolyzed plastic (RPP) test specimens were not available during the performance of this study. In the near future, samples will be available and NDE development initiated. Because RPP is a thin material, about 0.060 inches, with a thick coating (0.003 inches), it should respond well to a large variety of NDE techniques. Digital ultrasonic thickness gages can be used to measure the overall thickness. Penetrants should be able to detect cracks in the coatings. Radiofrequency (RF) dielectric probes could detect resin loss, the amount of residual reinforcing material, and absorption of moisture. Modified eddy current and RF techniques should be applicable for measuring coating thickness. Holographic interferometers can detect structural weaknesses caused by cracks or ablation of material. Micro X-ray techniques should provide useful data on porosity and microstructure. Neutron radiography provides a means of determining changes in the residual hydrogen of the pyrolyzed hydrocarbon resin. Ultrasonic techniques should yield interesting data about porosity, reinforcing mat alignment, and delamination. The RPP material should respond well to thermal NDE for detecting large delaminations. Naturally, these suppositions must be experimentally verified, appropriate NDE techniques for turnaround operations selected, and appropriate data display methods developed.

REUSABLE EXTERNAL INSULATION

Thick porous ceramic material attached to metallic substrates and coated with a densified quartz-fiber mat represents another high-temperature material being considered for Shuttle application. REI microwave and RF techniques are considered prime candidate techniques. Wide field metal proximity RF gages can be used to measure the total thickness, and short field capacitance RF devices should be able to determine the quantity of coating. Oxygen penetration and chemical composition changes can be detected with X-ray fluorescence. Low frequence ultrasonic scatter methods based on the delta technique deserve attention. Moisture accumulation can be detected with RF devices or microwave techniques. Holographic interferometry can be expected to detect structural weaknesses caused by extensive cracking and internal damage. Definitive studies of appropriate turnaround NDE methods should be predicated on experimental results based on the above analyses. Engineering analyses to define turnaround requirements for this material are in the development stage. Figure 37 shows a radiograph of REI material.

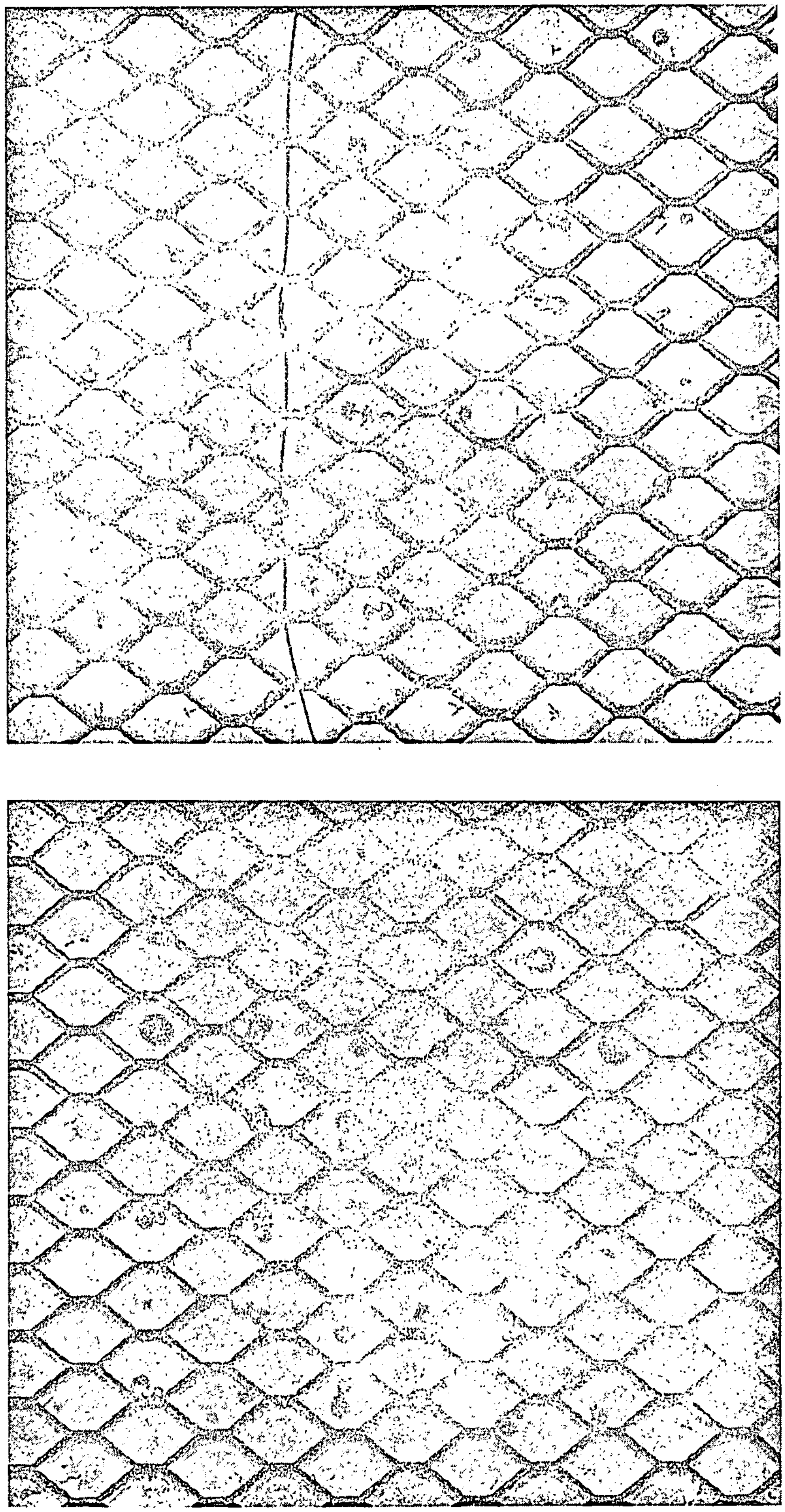

Figure 37. Radiograph of REI Material

DATA INTERPRETATION AND MANAGEMENT

A major concern of this study has been the establishment of methods which minimize operator dependence, operator training, and the need for operator judgment. Completely automated on-board techniques are the most desirable. This can be achieved basically in three ways as follows:

1. Computer automation (real time computer links)

2. Instrument automation (i. e., go no-go lights)

3. Instructional automation (step-by-step instructions with pictures of all possible results)

Only the constraint of cost is of importance relative to the mix of these techniques. All are achievable with existing technology. However, none are available as off-the-shelf hardware. A successful fully-automated operation must concern itself with the marriage of three disciplines: NDE, instrumentation avionics, and computerization. The general relationships of the important underlying cost factors are indicated in Table 1.

Table 1. Type and Cost of Automation

Type of Automation	Development Cost		Implementation Costs		
	Labor	Equipment	Labor	Equipment	Operational Labor
Computer	Moderate	Moderate	Moderate	High	Low
Instrumentational	Low	High	Low	Moderate	Moderate
Instructional	High	Low	Moderate	Low	High

Computer automation would typically involve a signal converter, data compressors, and digitalizers. For on-board systems, the information would then be bused onto a common signal line through a multiplexer where it would be analyzed by the on-board computer, entered into an earth station telemetry system, or be stored in the flight record. GSE equipment would

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take the digitized data, probably either on punched cards or magnetic tape, and feed it to a large computer which converts it to specific repair status, i.e., replace, acceptable "as is," etc. This would compress the present interpretation process from hours to a few minutes and, more importantly, eliminate arguments over the interpretation of the results. A computer would also schedule and direct the operation.

Instrument automation is a well known concept. This essentially involves a go no-go test determination. Ideally, the no-go result is then analyzed further, for example, with a punched card describing the defect and recommended repair procedure. The basic problem of achieving flexibility has been the main difficulty with this approach.

Instruction automation is simply a detailed instructional approach. With proper coordination and direction, this approach has resulted in excellent results. However, speed can only be improved by increasing the number of technicians on the job.

NDE MODES OF OPERATION

On-board Space Shuttle structural-integrity data-processing requirements can be divided into two separate modes. The first is an on-ground complete preflight structural-integrity evaluation. Maximum information is produced to allow rapid maintenance and corrective measures. With the vehicle in an accessible configuration, additional ground support equipment may be utilized for thorough checkout and verification.

The second mode of data processing is performed during spacecraft flight operations, which include launch, orbit, and reentry. Structural integrity testing is performed but exact defect location of identification is not established. As most corrective action can only be performed by ground stations, precise location of defects is not required. Data is passed to the central computer which predicts an impending failure.

Two NDE techniques can be utilized. The first technique is ultrasonic pulse echo. This technique is very similar in operation to standard pulse echo sonar where echo return time and amplitude are the operating variables. The second flaw detection technique is acoustic emission. A count of high frequency bursts of sound is continuously monitored. A large total count or a rapidly increasing count rate are the operating variables. Acoustic emission has the greater capability for predicting impending flaws, but utilization of this capability simultaneously imposes a higher data-processing requirement.

All flaw data will go directly to the flaw detection processor for analysis, as shown in Figure 38. When operating in mode 1, on-ground preflight, complete flaw information is passed to the ground processing interface for recording. These data are ultrasonic transducer parameters including periodic calibrations, a representative continuously recorded acoustic emission sample, and individual acoustic transducer count totals. Operation in mode 2, launch, orbit, and reentry, passes only detected flaws to the on-board computer. Detected flaws include echo returns from an ultrasonic transducer which exceeds a certain established threshold, a rapidly increasing acoustic emission count, a high acoustic emission count, or a dominant recurring pattern statistically removed from the acoustic emission recording.

The ultrasonic module is very similar in operation to standard pulse sonar, except a short pulse of ultrahigh-frequency sonic energy is transmitted in a narrow beam, and returned echoes from structural flaws are detected. Flaws can be accurately located by knowing the direction of the high energy beam and measuring the time from the initial pulse to the returning echo. One transducer is used to both transmit and receive ultrasonic energy. A graph of transducer voltage versus time is shown in Figure 39. Transducers 1-4 are attached to one structural member and are fed to a common mixer. A developing flaw on this member will be received by all transducers with constant time delays. A greater number of these periodic signatures will be generated and can be statistically isolated using existing computer techniques. Count data registers and acoustic mixers both use a commutated output.

The flaw detection processor simultaneously directs the operations of the acoustic emission module and the ultrasonic module. These operations include synchronized signals to trigger the ultrasonic pulser and advance the transducer, count register, and mixer commutators. Output from the two modules is maintained in buffer storage for output to the ground processing interface when operating in mode 1 or for comparison with stored standards when in mode 2. Only out-of-tolerance conditions with stored standards are outputed in mode 2 to minimize the load on the on-board computer.

Flaw size may be approximately determined by comparing the magnitude of the returning echo voltage with a known standard. Continuous monitoring of each individual transducer is not required. A sampling interval of 1 to 10 seconds is more than adequate for establishment of flaw generation time. Multiple transducers can be connected to one ultrasonic module with a commutator as shown in Figure 40. Echo return time and voltage amplitude are required to completely locate, identify, and evaluate a flaw or defect.

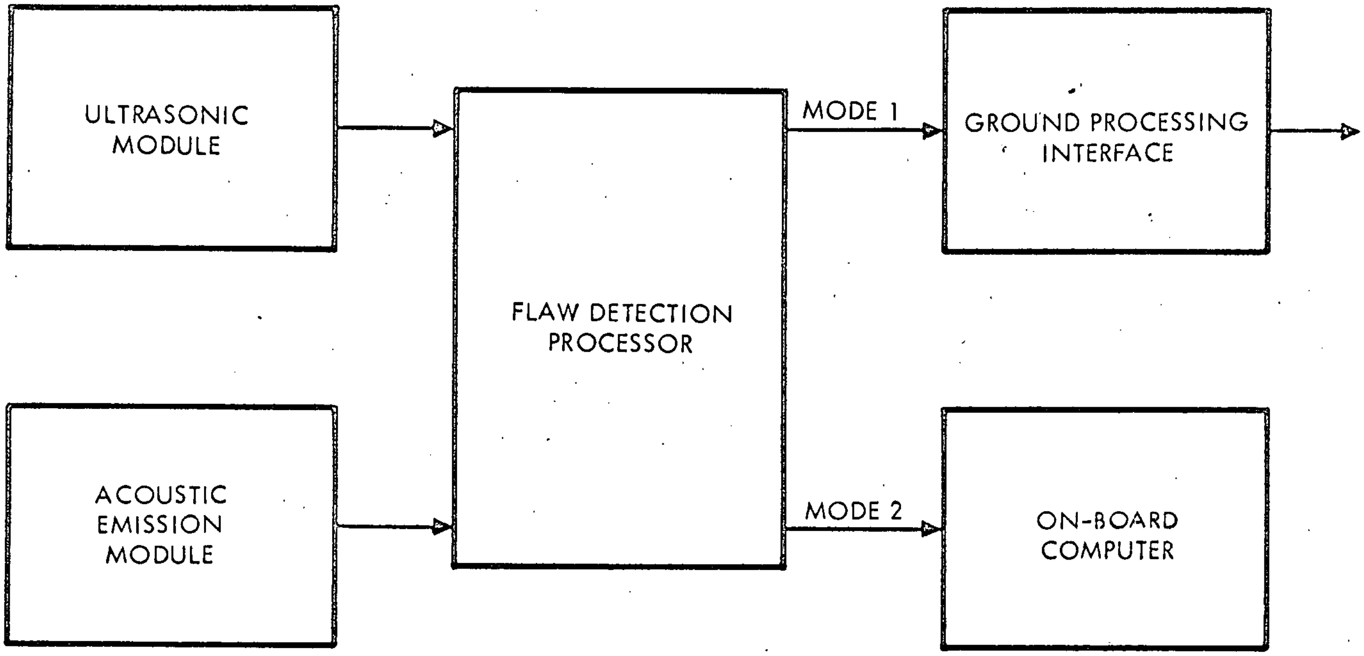


Figure 38. Acoustic Emission Recording Block Schematic

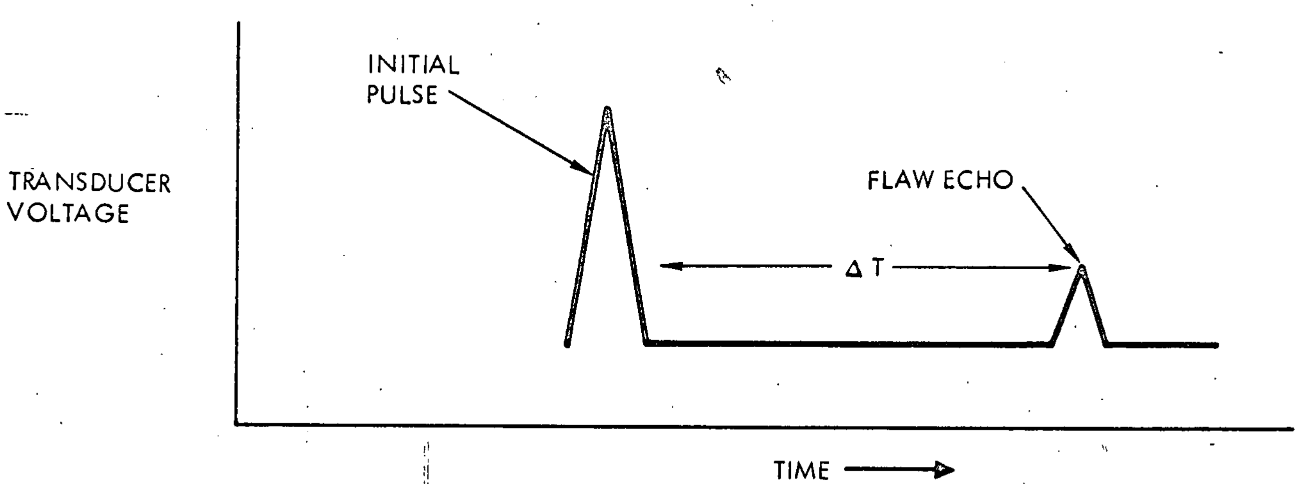


Figure 39. Ultrasonic Transducer Response

The acoustic emission module continuously records total emission from each microphone located throughout the structure. Total emission count is an indicator of maximum strain within the structure. Accurate failure predictions can be made by correlating total counts with established failure criteria. Failure predictions become more complicated, however, as structure size increases and will necessitate an increase in the total number of acoustic transducers attached to a structural member. A localized area near a transducer may be used for failure detection by limiting input cross talk between adjacent acoustic transducers. To predict failures and accurately locate the growing flaws will require statistical analysis of the continuously recorded acoustic mixture of all the transducers located on a single structural member. This analysis will remove the recurring periodic component required for flaw location using triangulation. The acoustic emission module is shown in Figure 41.

Since installation of an on-board ultrasonic system to perform structural integrity checkout is technically feasible at this time, the following discussions detail a potentially automatic on-board ultrasonic system for Shuttle use. Discussion has been limited to ultrasonic methods since acoustic emission methodology still requires research and development for its ultimate availability.

ON-BOARD ULTRASONIC TECHNIQUES

The use of on-board ultrasonic detection techniques has been demonstrated in feasibility prototype configurations. Figures 42 and 43 show the possible NDE structures configuration. The adoption of these techniques to computerized data handling deserves careful attention.

Figure 44 illustrates the principle of ultrasonic flaw detection. The ultrasonic transmitter and receiver which convert high-frequency electrical energy to high-frequency sonic energy for this application are one device or transducer. The short duration burst of sonic energy is shown traveling through the structure. If a flaw or defect is encountered, some of the energy is reflected back into the transducer. A graph of voltage across the transducer versus time is shown in Figure 39.

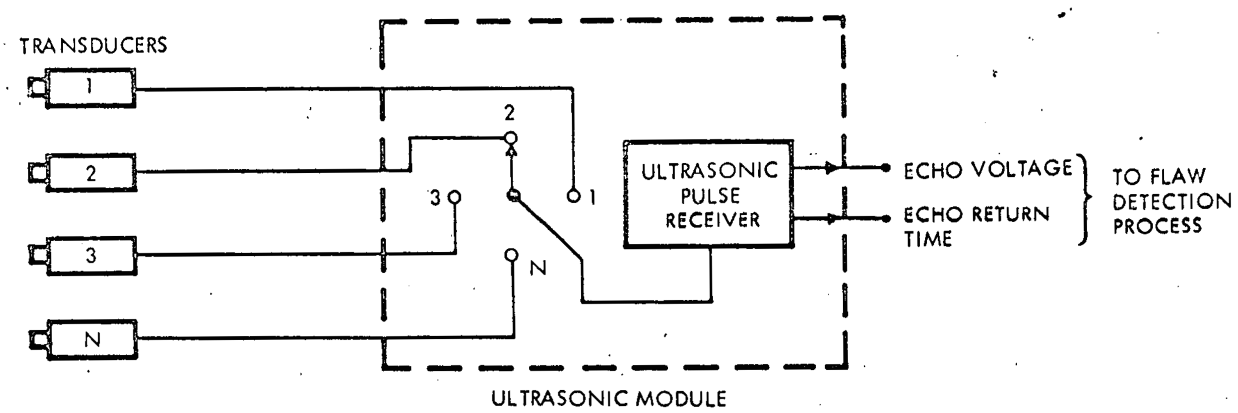


Figure 40. Multiple Transducers

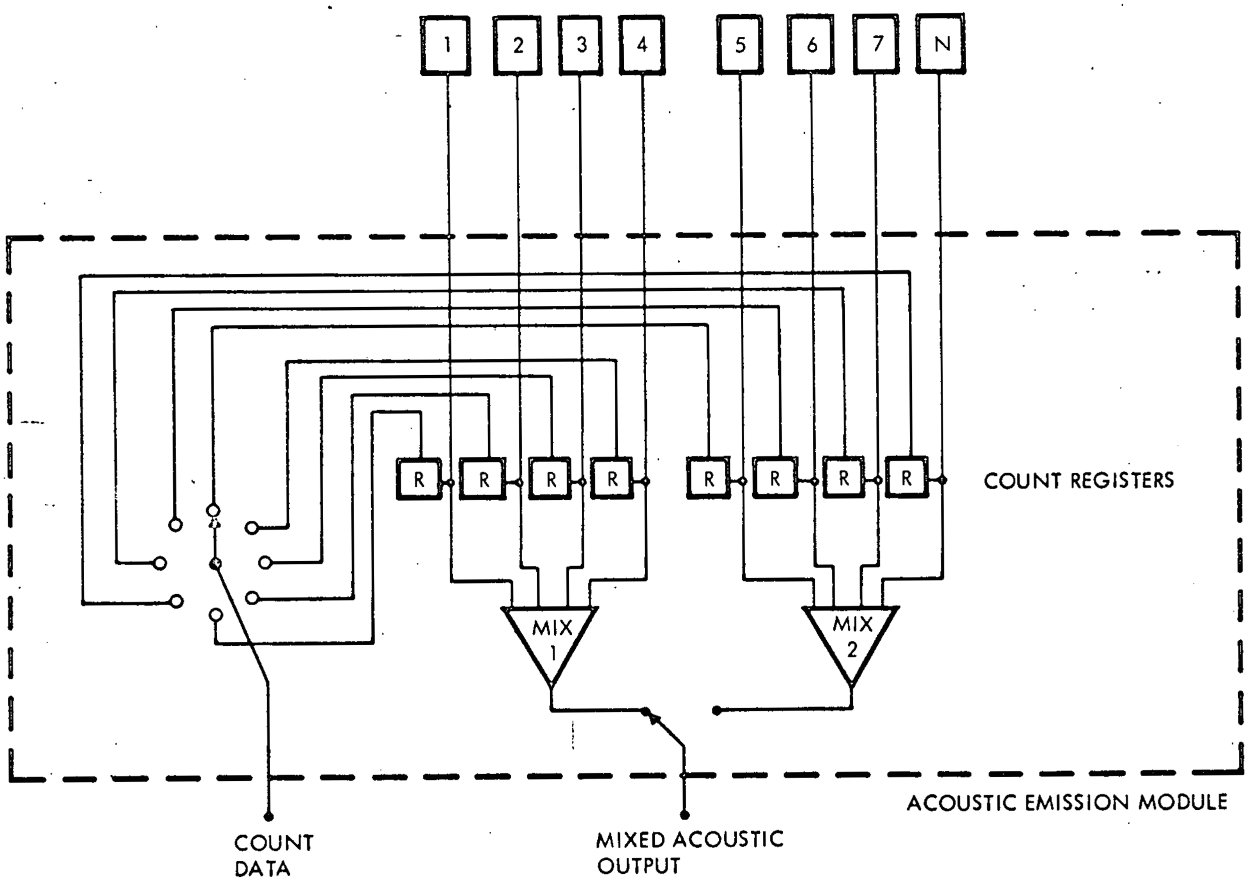
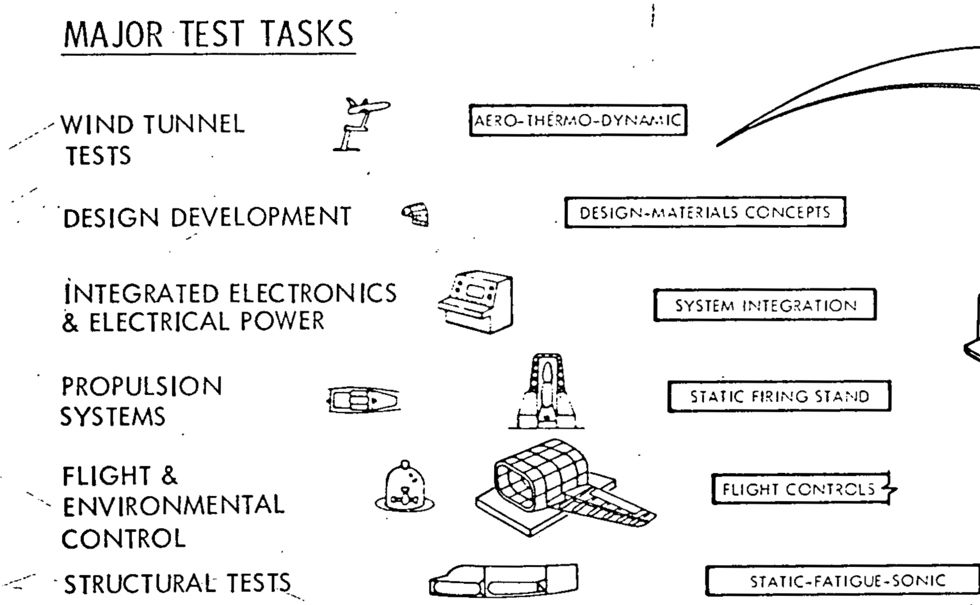


Figure 41. Acoustic Emission Module



RIGHT ILLUSTRATES A POSSIBLE APPLICATION ON SPACE SHUTTLE STRUCTURES. IN ORDER TO DIRECT SUCCESSFUL LABORATORY EFFORTS TOWARDS PRACTICAL APPLICATION, COMPLEX STRUCTURES BEING TESTED IN PHASE B SPACE SHUTTLE DEVELOPMENT WILL BE INSTRUMENTED WITH THE TECHNIQUE. ONE SUCH STRUCTURE WITH THE DESIGNATED TRANSDUCER LOCATIONS SHOWN IS PICTURED IN THE TOP. THE STRUCTURE IS USED FOR GENERAL STRUCTURES INFORMATION FOR POSSIBLY THE STABLIZER.

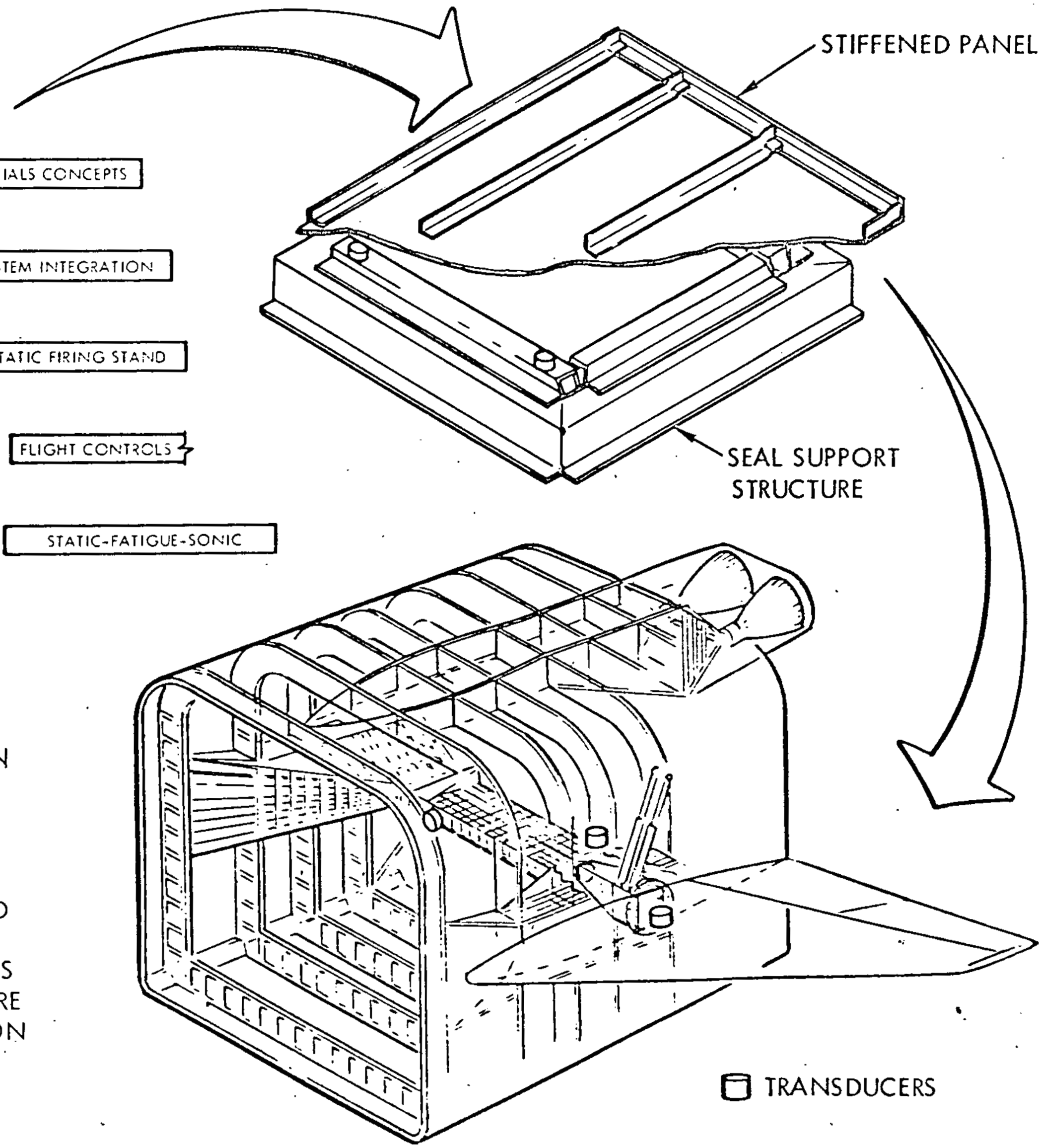
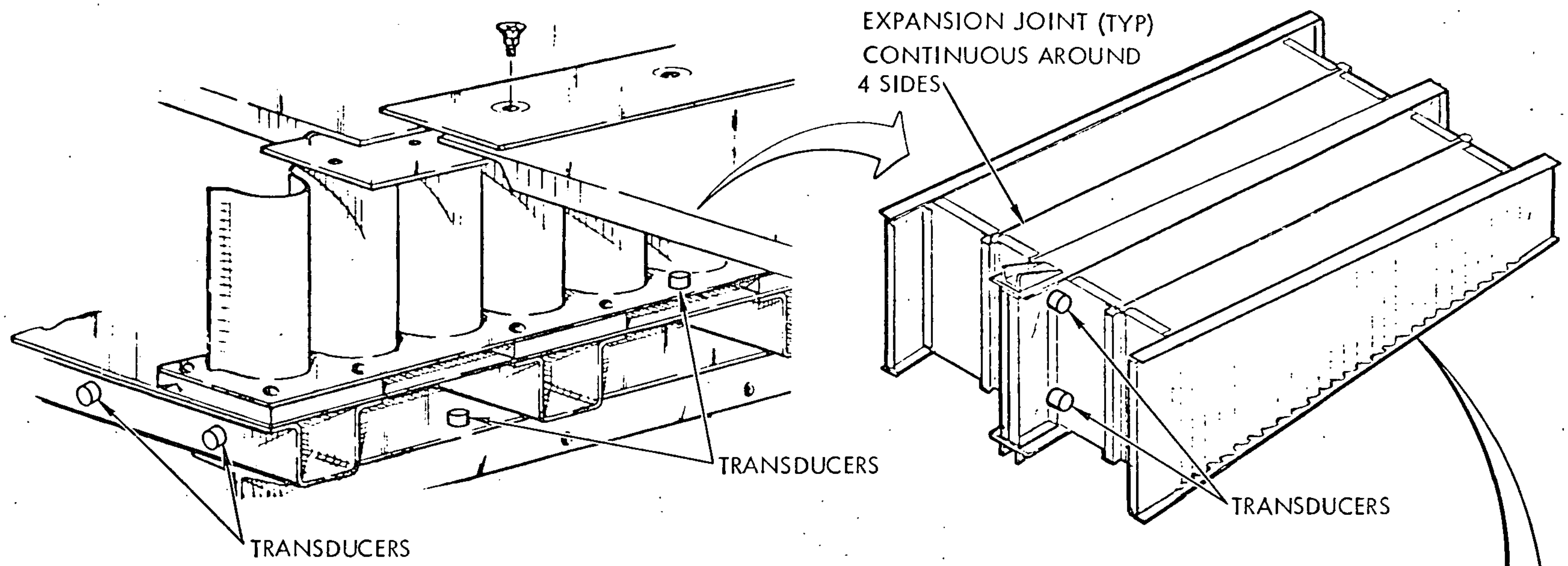


Figure 42. Prototype Ultrasonic Application—Stabilizer



RIGHT ILLUSTRATES A POSSIBLE APPLICATION ON SPACE SHUTTLE STRUCTURES. IN ORDER TO DIRECT SUCCESSFUL LABORATORY EFFORTS TOWARDS PRACTICAL APPLICATION, COMPLEX STRUCTURES BEING TESTED IN PHASE B SPACE SHUTTLE EFFORTS WILL BE INSTRUMENTED WITH THIS TECHNIQUE. ONE SUCH STRUCTURE WITH THE DESIGNATED TRANSDUCER LOCATIONS SHOWN IS PICTURED IN THE TOP. THIS STRUCTURE IS A SINE WAVE WELDMENT TEST STRUCTURE.

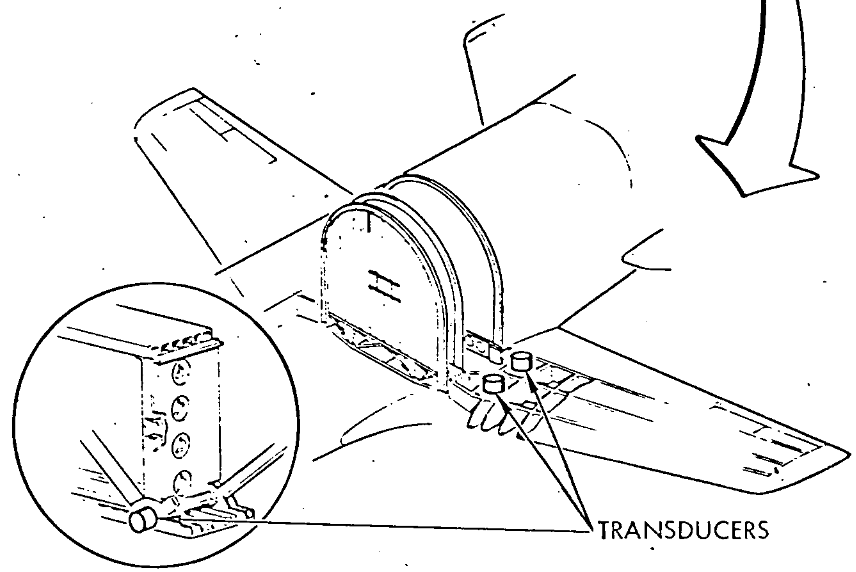


Figure 43. Prototype Ultrasonic Application—Sine Wave Weldments

Flaw location with respect to the ultrasonic transducer can be determined using the following simple formula:

$$D = V(\Delta T)/2$$

where

D = Distance from transducer along beam

V = Velocity of sound in material

ΔT = Time between initial pulse and echo

Flaw size may be approximately determined by comparing the magnitude of the returning echo voltage with a known standard.

In order to identify, locate, and evaluate a flaw or defect completely, at least two separate and simultaneous measurements, delay time and voltage, must be made. A third parameter, real time, is required to complete the definition. See Figure 45.

For a vehicle as complicated and demanding as the Space Shuttle, the time a flaw or defect occurred may have greater value for future prevention than the characteristics of the flaw itself. Continuous monitoring of the transducer is not required. A sampling interval of once every second should be more than adequate for establishment of flaw generation time. Multiple transducers can be connected to one ultrasonic processor with a commutator, as shown in Figure 40.

Each transducer is operated once per rotation of the commutator. If the commutator rotates at 100 rpm, then the sampling rate is 100 times per second. A flaw event can then be bracketed within 1/100 of a second. This time bracket can be increased or reduced by changing the commutator rotation rate.

A standard method of storing these data would be the utilization of a commutated telemetry channel. For maximum information, two commutated lugs would be required — one for echo voltage and a second for time delay. A real time clock is normally attached to a telemetry channel, and its availability is assumed. The arrangement of Figure 46 shows a typical

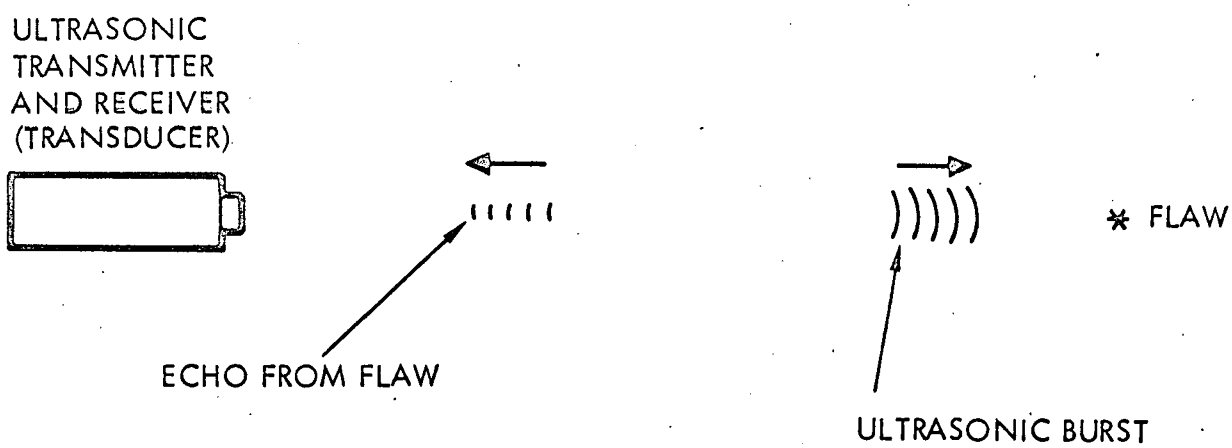


Figure 44. Pulse Echo Ultrasonics

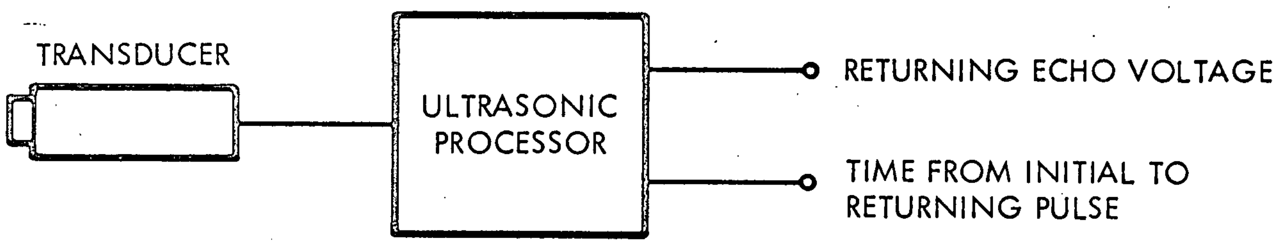


Figure 45. Ultrasonic Flaw Location

attachment of the ultrasonic processor to a commutated telemetry link. Lug 1 is tied to the real time clock with lugs 2 and 3 connected to echo voltage and delay time. Lugs 4 through 9 are connected to other telemetry inputs.

Transducer No. 2 is shown being activated by the ultrasonic processor. Echo voltage, if a flaw was detected, and the associated delay time data are stored until readout by the telemetry commutator. Lug No. 3 is currently being read. The telemetry commutator must have a complete rotation before another ultrasonic output can be made. The telemetry processor must provide synchronization signals to the ultrasonic processor to advance the transducer commutator and trigger the ultrasonic burst. Proper timing is important to ensure positioning of the transducer rotor, triggering of the ultrasonic burst, and returning echo analysis prior to telemetry readout. Output to the storage device is in time data frames. Each time data frame contains one time entry, one ultrasonic entry comprising two signals, and the various other telemetry inputs. The ultrasonic commutator is advanced one transducer for each time data frame output.

In Figure 47, two complete time data frames and a portion of a third are shown being produced by the telemetry processor. One time data frame is produced for each rotation of the telemetry commutator. An output record is produced for each position of the rotor. Nine positions are shown in the above figure for simplicity of illustration. Output is shown starting with data produced when the rotor was in the clock position or position No. 1. When the rotor was in positions 2 and 3, time delay and echo voltage data were recorded from ultrasonic transducer 1. Rotor positions 4 through 9 generated the remainder of the time data frame, making one complete rotation of the rotor. As each complete rotation advances the ultrasonic transducer commutator, flaw detection is now performed on transducer 2. The second time data frame contains clock output and ultrasonic time delay and echo voltage from transducer 2. After another complete rotor rotation, ultrasonic transducer 3 is activated. An echo voltage record is shown being written.

The area of flaw scan can be greatly increased by stepping the transducer through some angle. A step angle equal to the transducer beamwidth would provide maximum flaw scan with a minimum of steps. The ultrasonic processor would provide the stepping pulse for each scanning type transducer.

Two scanning-type and two fixed-type transducers are shown in Figure 48. Each transducer is processed in order, starting with stepping transducer No. 1. The ultrasonic processor provides a pulse through the stepping commutator to advance the scanning transducer after completion

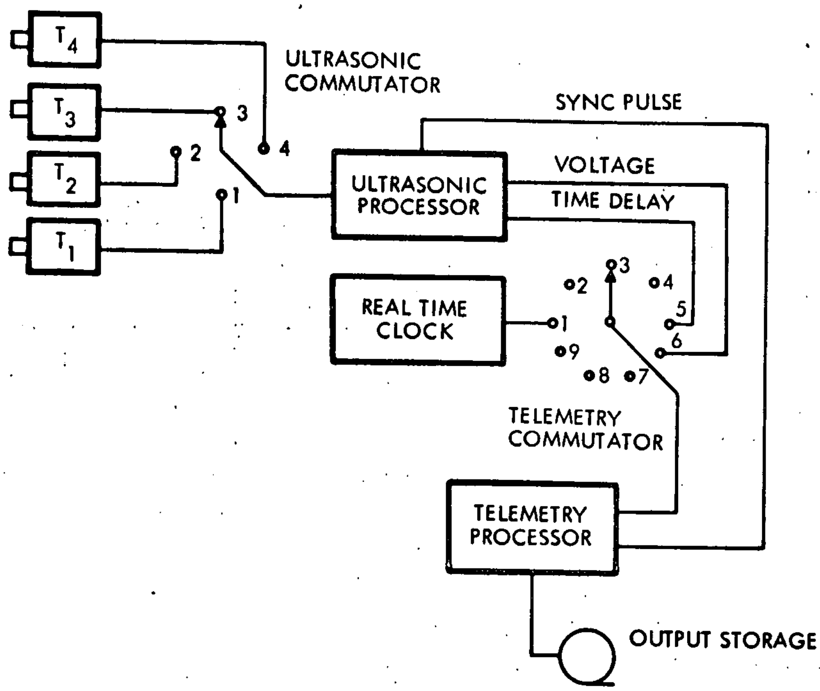


Figure 46. On-Board Ultrasonic Information Storage

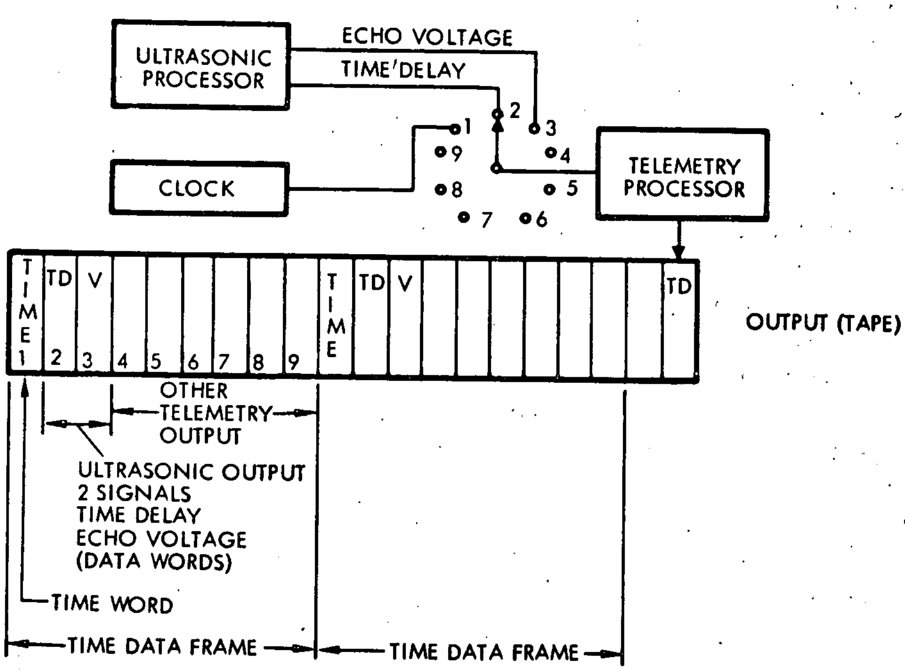


Figure 47. Ultrasonic Data Computerization

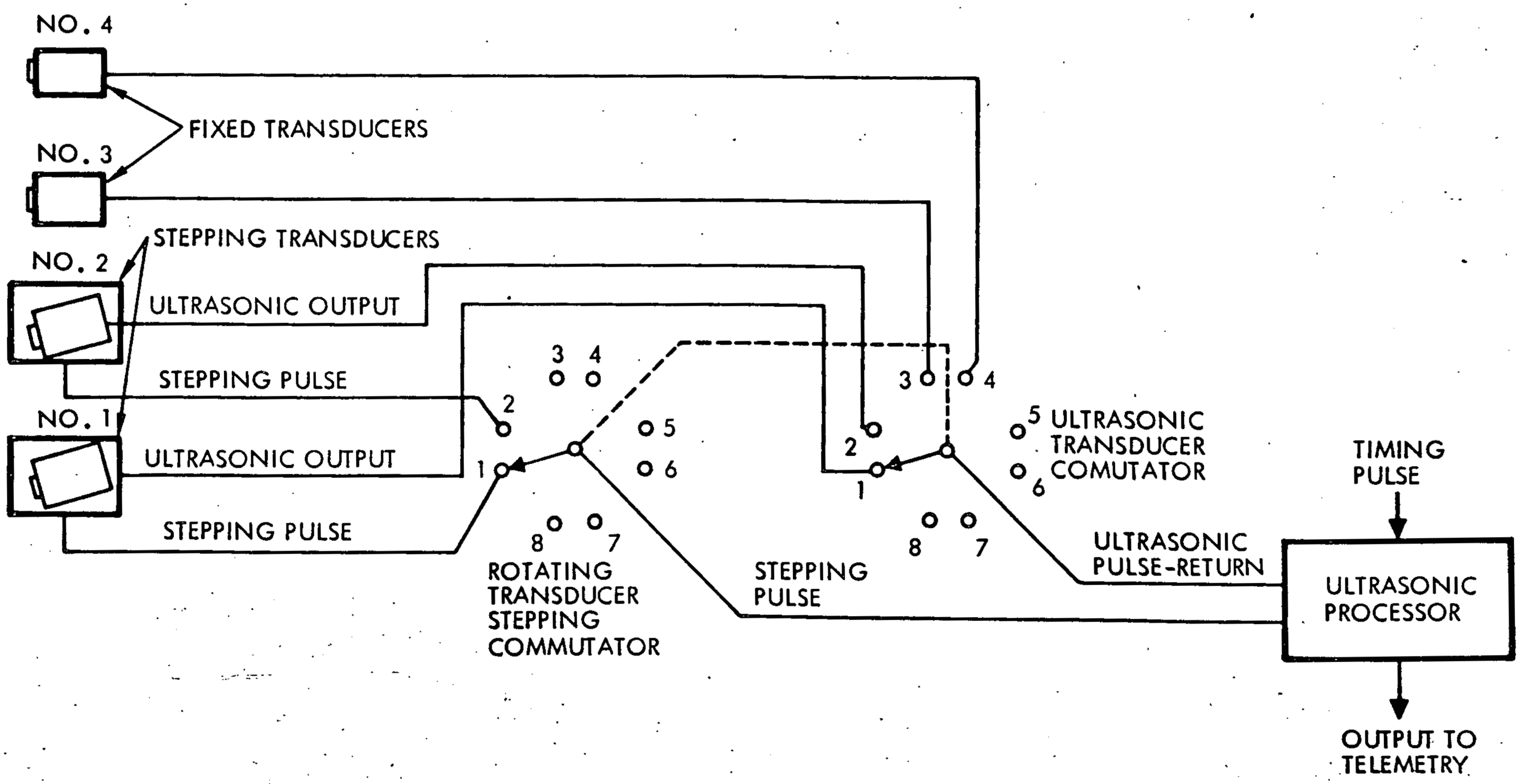


Figure 48. Transducer Stepping and Commutation

of the pulse echo analysis. Pulse echo analysis is the same for both fixed and scanning transducer types. The following flaw search is produced:

1. Output from transducer 1
   Step transducer 1

2. Output from transducer 2
   Step transducer 2

3. Output from transducer 3

4. Output from transducer 4

5. Output from transducer 1 (in new position)
   Step transducer 1

6. Etc.

The fixed transducers perform flaw search repeatedly in the same limited area while the scanning transducer sweeps a large area covering any one area far less frequently. This can be useful where time of flaw occurrence is important. A fixed transducer bounds flaw occurrence to the time data-frame generation rate (commutator rotation rate). As the scanning-type transducer searches the same area once per stepping cycle, flaw occurrence time is bounded by time data-frame rate times the step number.

The ultrasonic processor responds to structure deviations, clearance holes, flanges, welds, etc., just as efficiently as structural flaws. These deviations can easily be removed in postflight computer processing. However, methods can be incorporated to prevent their inclusion at the ultrasonic processor.

Returning echoes are time dependent and can be gated. If the time gate shuts before the echo returns from the deviation in material, no flaw signal is produced. Any flaws that lie inside the gate will be detected. Accurate adjustment of the time gate will allow detection of flaws that are between the transducer, but just short of the deviation. For the scanning transducers, a gate adjustment must be provided for each step position. This allows deviations that are well within the range of the transducer to be ignored.

These structural deviations can also be used as flaw standards. A switching network would change the gating to include echoes from deviations or built-in standards placed in noncritical areas. A typical configuration is shown in Figure 49.

The ultrasonic processor shown periodically switches from the flaw scan mode to one complete cycle of calibration. Output from the telemetry processor is a continuous stream of time data frames. Each time data frame contains one or more ultrasonic signals. These signals, in turn, cycle between individual ultrasonic transducers which periodically alternate from the flaw scanning mode to the calibration mode. This stream of data is decollated by time dependent event vectors which point to individual transducer data. Each data frame and its associated time are placed in buffer storage as the data stream is scanned. Prior to decollation, however, the flight data must be converted from analog form to digital form. This may be an integral part of the telemetry processor or a postflight operation performed immediately after landing. Decollation of the data stream operates on one time data frame placed in temporary work storage. A new data array word address is computed, which is common to both time arrays and data arrays, for each complete cycle of the ultrasonic commutator.

Array Number	1	2	3	4	5
Time Array	T_1	T_2			
Transducer 1 Array	$D_{1,1}$	$D_{1,2}$			
Transducer 2 Array	$D_{2,1}$	$D_{2,2}$			
Transducer 3 Array	$D_{3,1}$	$D_{3,2}$			
Transducer 4 Array	$D_{4,1}$	$D_{4,2}$			

Five data storage arrays are tabulated above running horizontally. These are the time array and four transducer data arrays. This example shows that four time data frames are required for one ultrasonic commutator cycle. The time array contains the time word, T_1, and transducer array 1 contains the data word, $D_{1,1}$, both from the first time data frame. The remaining data entries, $D_{2,1}$, $D_{3,1}$, and $D_{4,1}$, are from time data frames 2, 3, and 4, completing the ultrasonic commutator cycle. The cycle now starts again with time and data from frame 5 and continues until the entire stream has been scanned. This information is stored (see Figure 50) on a direct access device which allows selection of any particular transducer data with a minimum of time and computer operations.

Each transducer data is analyzed separately, using the common time array. Time delay and echo standards are compared with calibration data for each transducer to verify operation during the reentry period. Any flaws are verified with subsequent time-data pairs and the magnitude, location, and occurrence time stored.

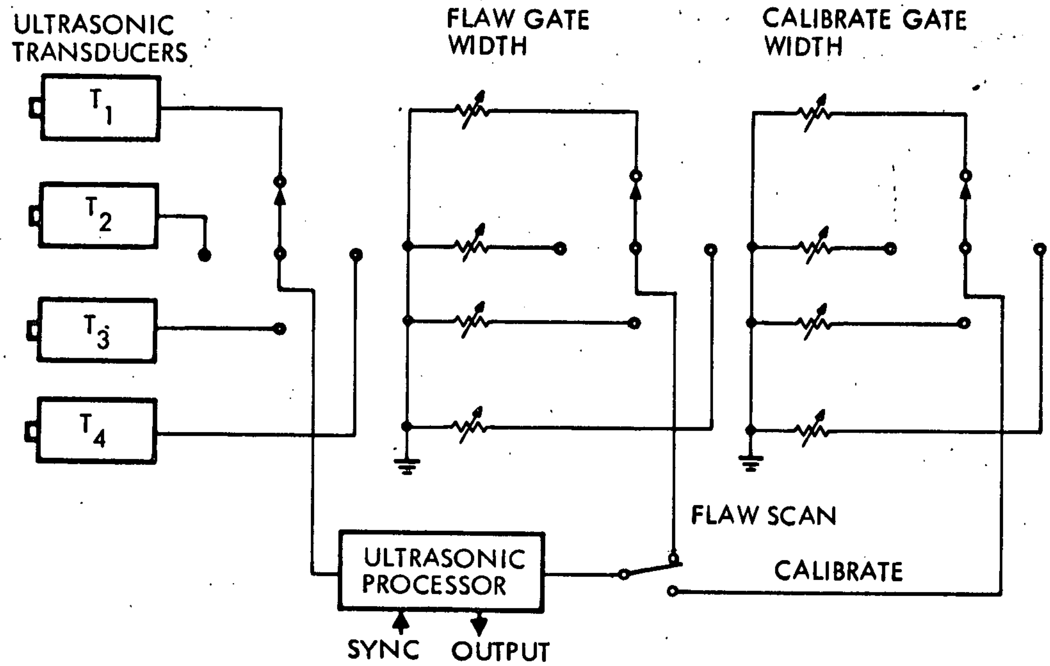


Figure 49. Switching Network

	ARRAY NUMBER				
	1	2	3	4	5
TIME ARRAY	T_1	T_2			
TRANSDUCER 1 ARRAY	$D_{1,1}$	$D_{1,2}$			
TRANSDUCER 2 ARRAY	$D_{2,1}$	$D_{2,2}$			
TRANSDUCER 3 ARRAY	$D_{3,1}$	$D_{3,2}$			
TRANSDUCER 4 ARRAY	$D_{4,1}$	$D_{4,2}$			

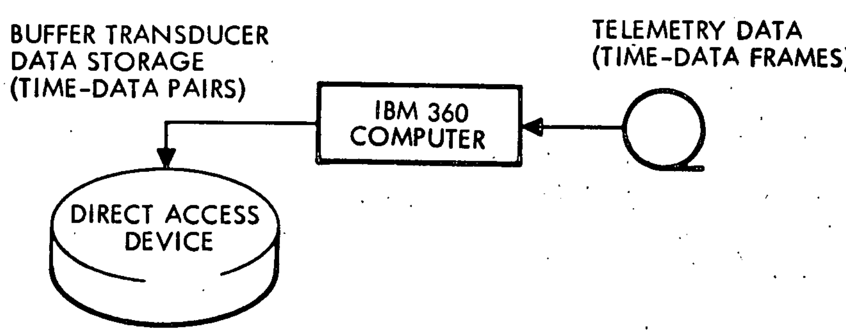


Figure 50. Data Storage

The historical data bank is scanned for identical flaws which occurred in previous flights. A list of flaws, including approximate magnitude, location, and occurrence, is printed along with all pertinent historical information. The historical data bank is then updated to include flaws from the latest flight. Hence the defect has been detected, located, and recorded. This then constitutes a complete on-board ultrasonic system. Several other operational modes are under study.

The extension of on-board structural check-out methods to the optical images of fiber optics monitoring could not be accomplished with digital methods alone. The use of optical matched filters and optical transform techniques will probably be required. Future studies should consider this approach.

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EVALUATION OF SHUTTLE NDE METHODS

Evaluation of candidate NDE techniques is specifically and irrevocably dependent on detailed requirements in terms of materials, geometry, and defect criteria. The NDE techniques which were identified for this study from the Phase I effort appear in Table 2. This table indicates the operational mode and pertinent data display information. Specific Shuttle design requirements relative to NDE are only broadly defined. Table 3 lists some of these requirements for the Shuttle Orbiter and Table 4 for the Shuttle Booster.

The NDE techniques were evaluated using the rating factor matrix approach of Table 5. Several important factors have been introduced beyond those initially considered in the general rating-factor analysis of the Phase I report. Columns have been established to rate the availability of the techniques and the present state of development. A high rating would indicate present availability or a great degree of development. Cost effectiveness factors have been introduced by rating the facility cost, operational cost, and development cost. The Phase I report considered only operational speed and applicability as indicators of cost effectiveness. The weighting matrix reflects the adverse effects of high cost by assigning a negative factor for a high rating relative to operational costs.

The effectiveness of this approach is indicated by applying simple logic during interpretation. If the applicability is high but the state of development is low, then development work is necessary. If the applicability is high but the operational speed is low, then better techniques need to be used.

This rating evaluation is based on the Shuttle requirements as defined in NR's Phase B proposal, the 90-day review briefing, and the 180-day review briefing, along with extensive interfaces with many NR Shuttle design personnel. The changing nature and the nature itself of the information available does not permit detailed NDE analysis. The rating analysis then reflects broad Shuttle operational requirements. An individual rating can be made for each specific Shuttle turnaround requirement when these detailed requirements become available. As the influence of significant general factors such as flexibility and automatability become more apparent, the relative weights assigned can be sharpened and the introduction of off-axis elements considered. The use of statistical inference (game theory) may then be appropriate. The rating factors of Table 5 indicate that on-board

Table 2. Shuttle NDE Techniques Classification

Method/Techniques	Application Possibilities				Data Output	Digital Operation			Space Shuttle Turnaround Operations Recommendation
	Inflight	On-board	Portable GSE	Facilities GSE		Available Now	Implementation Control	Implementation Readout	
Ultrasonic					Analog	-	Good	Good	Use
Bonded in-place transducers	X	X			Null analog	No	Good	Good	Develop
Compression wave					Null analog	No	Good	Good	Develop
Shear wave					Null analog	No	Good	Good	Develop
Lamb wave					Null analog	No	Good	Good	Develop
Rotating wave directors	X	X			Step analog	No	Good	Fair	Develop
Lamb wave (through)					Step analog	No	Good	Fair	Develop
Shear wave (pulse echo)					Step analog	No	Good	Fair	Develop
Compression wave (through)					Step analog	No	Good	Fair	Develop
Shear wave (through					Step analog	No	Good	Fair	Develop
Surface wave (pulse echo)					Step analog	No	Good	Fair	Develop
Portable hand scanning			X		Pulsed analog	No	Poor	Fair	Use
Permanent system				X	Pulsed analog	No	Fair	Good	Use
Spectroscopic techniques				X	Analog	No	Poor	Fair	Eliminate
Digital thickness gage			X		Digital	Yes	Good	Good	Use
Optical devices (fiber optics)					Optical	No	Good	Poor	Use (max)
Portable inspection			X		Optical	No	Poor	Poor	Use
Selected on-board devices		X			Optical	No	Fair	Poor	Develop
On-board system	X				Optical	No	Good	Fair	Analyze
Penetrating radiation					Film negative	No	Fair	Poor	Use (min)
Portable machines			X		Film negative	No	Poor	Poor	Use
X-ray machines					Film negative	No	Poor	Poor	Use
Isotope cameras					Film negative	No	Poor	Poor	Use
G-251- neutron					Film negative	No	Poor	Poor	Eliminate
X-ray cabinet					Film negative	No	-	Poor	Use (max)
Permanent facilities				X	Film negative	No	Fair	Poor	Use
Lead-lined room (X-ray)					Film negative	No	Poor	Poor	Use
Neutron reactor					Film negative	No	Fair	Poor	Develop
Tunnel concepts		X			Film negative	No	Fair	Poor	Develop
Simulated electron emission				X	Film negative	No	Poor	Poor	Analyze
Beta backscatter			X		Digital	Yes	Poor	Good	Analyze
X-ray flourescence			X	X	Counts	Maybe	Fair	Fair	Analyze
Holographic interferometry					Optical image	No	Fair	Poor	Develop
Portable on-line test			X		Optical	No	Poor	Poor	Develop
Permanent test facility				X	Optical	No	Fair	Poor	Eliminate
Special applications	X	X			Optical	No	Good	Fair	Eliminate
Penetrant						No	Poor	Poor	Use
Penetrant facilities				X	Optical	No	Poor	Poor	Use
Portable penetrants			X		Optical	No	Poor	Poor	Use (min)
Magnetic particle				X	Optical	No	Poor	Poor	Eliminate
Thermal						No	Poor	Poor	Analyze
Liquid crystal			X		Optical	No	Poor	Poor	Eliminate
Infrared scanning			X		Film positive	No	Fair	Fair	Develop
Infrared film			X		Optical	No	Poor	Poor	Eliminate
Thermal paints	X	X	X		Optical	No	Poor	Poor	Analyze
Acoustic emission						-	Good	Good	Develop
Proofing techniques				X	Digital/analog	Yes	Poor	Good	Eliminate
On-board system	X	X			Digital/analog	No	Good	Good	Develop
Signature comparison technique	X	X		X	Analog	No	Good	Good	Analyze
Portable system			X		Digital/analog	Yes	Poor	Fair	Eliminate
Hybrid computer technique	X	X			Computer-analog	No	Good	Good	Develop
Electrical/electronic									
Eddy current thickness			X		Digital/analog	Yes	Poor	Good	Use (min)
Eddy current defect			X		Analog	No	Poor	Fair	Use (min)
Eddy current material properties			X		Analog	Maybe	Poor	Good	Use (min)
RF dielectric probe			X		Analog	No	Poor	Fair	Eliminate
RF leak current probe			X		Current analog	No	Fair	Fair	Analyze
RF thickness gage			X		Analog	No	Poor	Good	Use (min)
RF voltage probe			X		Voltage analog	No	Fair	Fair	Eliminate
Microwave (scatter)				X	Analog	No	Fair	Good	Analyze

Table 3. Shuttle Orbiter NDE Requirements

Orbiter Requirements	NDE Task Sizing	Defect Criteria	NDE Method: Monitor	NDE Method: 100% Test	NDE Method: Sample Test	NDE Scheduled Time	Manpower Requirements	Schedule
Fuselage structures	12,000 ft^2 (EST)							
Wing structures								
Subsurface thermal insulation	15,000 ft^2 (EST)							
On-orbit LH_2 tankage weldments								
On-orbit LH_2 tankage thermal insulation								
On-orbit LO_2 tankage weldments								
On-orbit LO_2 tankage thermal insulation								
Boost LH_2 tank weldment	4,000 ft^2 (EST)							
Boost LH_2 tank thermal insulation								
Boost LO_2 tank weldment								
Boost LO_2 tank thermal insulation								
TPS reusable heat shield								
TPS connector								
LH_2 bisector structural truss	450 ft (EST)							
Orbitor/booster attachment structure								
Hoist attachment structure								
Wing box								
Passenger cabin attachment								
Passenger cabin thermal insulation								
Pilot cockpit high stress members								
Pilot cockpit thermal insulation								
Engine suspension truss								
Air breathing engine system (ABES)								
Electronic systems								
Fuel lines and controls								
Cargo container system								
Landing gear								
Reaction control thrusters								
Electrical generator (fuel cells)								

TO BE DETERMINED

Table 4. Shuttle Booster NDE Requirements

Booster Requirements	NDE Task Sizing	Defect Criteria	NDE Method			NDE Scheduled Time	Manpower Requirements	Schedule
			Monitor	100% Test	Sample Test			
Fuselage structures	22,400 ft^2							
Wing structures	4,500 ft^2							
Subsurface thermal insulation	28,400 ft^2 (EST)							
Boost LH_2 tank weldment	8,000 ft^2 (EST)							
Boost LH_2 tank thermal insulation	8,000 ft^2 (EST)							
Boost LO_2 tank weldment	3,500 ft^2 (EST)							
Boost LO_2 tank thermal insulation	3,500 ft^2 (EST)							
TPS reusable heat shield								
TPS connector								
Orbiter/booster attachment structure								
Hoist attachment structure								
Wing box								
Pilot cockpit high stress members								
Pilot cockpit thermal insulation								
Engine suspension truss								
Air breathing engine system (ABES)								
Electronic systems								
Fuel lines and controls								
Cargo container system								
Landing gear								
Reaction control thrusters								
Electrical generator (fuel cells)								

TO BE DETERMINED

Table 5. Candidate Rating Factor Matrix

Methods	Applicability	Availability	State Development	Development Costs	Simplicity	Flexibility	Facility Cost	Operational Cost	Operational Speed	Maintainability	Automatability	Reliability	Total Rating Points	Position
Penetrating Radiation	10 (30)	10 (30)	10	2 (-6)	5	6	7	8 (-16)	4 (8)	8	3	9	80	Overall 5
Portable machines	7 (35)	9 (27)	8	2 (-6)	5	7	6	9 (-16)	2 (4)	7	2	8	73	30
X-ray machines	8 (40)	10 (30)	10	1 (-3)	5	8	6	7 (-14)	4 (8)	8	3	9	98	11
Isotope cameras	9 (45)	8 (24)	8	3 (-9)	4	8	5	8 (-16)	3 (6)	6	3	9	83	24
Cf251 neutron	5 (25)	2 (6)	2	8 (-24)	3	4	10	10 (-20)	1 (2)	5	1	7	1	52
X-ray cabinets	9 (45)	10 (30)	10	1 (-3)	7	6	3	3 (-6)	5 (10)	9	4	10	119	4
Permanent facilities	7 (35)	10 (30)	10	2 (-6)	6	5	8	7 (-14)	5 (10)	8	2	9	87	19
Lead-lined room (X-ray)	8 (40)	9 (27)	10	2 (-6)	7	6	7	6 (-12)	6 (12)	9	2	10	98	12
Neutron reactor	6 (30)	8 (24)	9	6 (-18)	3	4	10	8 (-16)	4 (8)	6	3	7	50	42
Tunnel concepts	9 (45)	3 (9)	5	3 (-9)	5	6	5	5 (-10)	7 (14)	6	4	7	77	27
Stimulated electron emission	6 (40)	5 (15)	3	8 (-24)	2	4	8	9 (-15)	2 (4)	7	1	5	31	50
Beta backscatter	8 (40)	8 (24)	6	2 (-6)	7	6	3	6 (-12)	4 (8)	7	5	6	88	18
X-ray fluorescence	8 (40)	6 (8)	5	6 (-18)	2	5	9	8 (-16)	3 (6)	4	2	6	45	45
Electromagnetic	8 (40)	9 (27)	9	2 (-6)	8	8	3	8 (-16)	3 (6)	7	7	8	95	Overall 4
Eddy current thickness	8 (40)	10 (30)	8	1 (-3)	8	8	3	5 (-10)	4 (8)	7	9	9	111	5
Eddy current defect	9 (45)	9 (27)	7	3 (-9)	6	8	5	9 (-18)	2 (4)	6	4	6	81	26
Eddy current material properties	7 (35)	8 (24)	6	0 0	9	7	1	4 (-8)	5 (10)	9	9	10	110	6
Radio frequency (RF) dielectric probe	6 (30)	5 (15)	2	4 (-12)	8	4	3	7 (-14)	2 (4)	6	4	7	51	41
RF thickness gage	9 (45)	7 (21)	5	3 (-9)	9	6	2	6 (-12)	4 (8)	8	8	8	95	14
RF leak detection (electrical)	7 (35)	5 (15)	3	4 (-12)	6	4	4	8 (-16)	3 (6)	5	3	7	52	40
RF voltage probe	2 (10)	6 (18)	1	4 (-12)	6	3	1	8 (-16)	2 (4)	7	3	6	29	51
Microwave (scatter)	4 (20)	6 (18)	4	7 (-21)	4	2	6	3 (-6)	4 (8)	7	7	6	43	47
Ultrasonic	9 (45)	7 (21)	8	4 (-12)	8	9	4	5 (-10)	7 (14)	8	8	9	104	Overall 3
Bonded inplace transducers	8 (40)	5 (15)	7	3 (-9)	9	8	3	3 (-6)	8 (16)	8	9	8	102	9
Compression wave	8 (40)	7 (4)	8	1 (-3)	9	9	2	3 (-6)	9 (18)	9	9	9	121	3
Shear wave	6 (30)	4 (12)	6	3 (-9)	7	7	3	3 (-6)	7 (14)	8	9	8	83	23
Lamb wave	7 (35)	4 (12)	5	4 (-12)	8	8	4	4 (-8)	8 (16)	7	9	7	99	10
Rotating wave director	9 (45)	4 (12)	4	6 (-18)	7	9	5	4 (-8)	9 (18)	7	10	8	89	16
Lamb wave (through)	8 (40)	5 (15)	5	4 (-12)	7	8	6	5 (-10)	9 (18)	6	9	8	88	17
Shear wave (pulse echo)	7 (35)	4 (23)	5	6 (-18)	5	9	4	4 (-18)	9 (18)	8	10	9	90	15
Compression wave (through)	8 (40)	2 (6)	2	4 (-12)	8	8	3	3 (-6)	8 (16)	7	9	7	82	25
Shear wave (through)	5 (25)	3 (9)	2	7 (-21)	4	7	4	4 (-8)	8 (16)	7	9	7	53	39
Surface wave (through)	3 (15)	4 (12)	1	5 (-15)	5	5	5	4 (-8)	7 (14)	6	9	6	45	46
Compression wave (pulse echo)	8 (10)	5 (15)	3	5 (-15)	7	9	3	3 (-6)	10 (20)	7	10	9	96	13
Portable hand scanning	6 (30)	8 (24)	9	2 (-6)	7	9	6	7 (-14)	6 (12)	7	6	8	86	20
Permanent system	7 (35)	8 (24)	9	0 0	8	8	7	5 (-10)	7 (14)	8	9	9	107	8
Spectroscopy techniques	4 (20)	8 (18)	6	4 (-12)	4	6	7	5 (-10)	5 (10)	6	7	6	34	49
Digital thickness gages	8 (40)	9 (27)	10	0 0	10	8	3	3 (-6)	6 (12)	9	9	9	125	1
Acoustic emission	8 (40)	2 (6)	3	9 (-27)	4	7	3	2 (-4)	8 (16)	7	9	7	65	Overall 6
Proofing techniques	2 (10)	7 (21)	7	3 (-12)	6	4	4	5 (-10)	6 (12)	7	6	9	56	38
On-board systems	7 (35)	1 (3)	1	9 (-27)	3	8	3	1 (-2)	9 (18)	6	10	8	60	34
Signature comparison technique	6 (30)	1 (3)	3	7 (-21)	2	6	2	1 (-2)	8 (16)	6	9	7	57	37
Portable systems	1 (5)	2 (12)	5	5 (-15)	5	3	4	3 (-6)	7 (14)	8	8	7	42	48
Hybrid computer techniques	9 (45)	1 (3)	1	8 (-24)	3	9	3	1 (-2)	9 (18)	6	10	8	74	29
Rating Factor Multiplier	5	3	1	-3	1	1	-1	-2	2	1	2	1		

Table 5. Candidate Rating Factor Matrix (Cont)

Methods	Applicability	Availability	State Development	Development Costs	Simplicity	Flexibility	Facility Cost	Operational Cost	Operational Speed	Maintainability	Automatability	Reliability	Total Rating Points	Position
Holographic interferometry														Overall 8
Portable on-line test	7 (35)	4 (12)	7	7 (-21)	2	6	9	5 (-10)	5 (10)	5	2	7	46	35
Permanent test facility	8 (40)	4 (12)	1	4 (-12)	3	7	6	5 (-10)	5 (10)	5	2	7	59	31
Special applications	7 (35)	6 (18)	7	2 (-6)	4	6	9	5 (-10)	6 (12)	6	3	7	73	53
	3 (15)	2 (6)	1	10 (-30)	0	5	10	4 (-8)	4 (8)	2	1	8	-10	
Thermal	5 (25)	5 (15)	4	7 (-21)	6	7	6	6 (-12)	8 (16)	9	2	6	51	Overall 7
Liquid crystal	2 (10)	7 (21)	6	6 (-18)	6	8	4	5 (-10)	6 (12)	9	1	7	48	43
Infrared scanning	7 (35)	8 (24)	5	8 (-24)	5	7	8	2 (-4)	9 (18)	6	3	5	72	32
Infrared films	5 (25)	2 (6)	2	5 (-15)	6	6	3	6 (-12)	7 (14)	8	4	6	47	44
Thermal paints	4 (20)	5 (15)	4	3 (-9)	7	7	2	3 (-6)	6 (12)	9	2	7	66	33
Penetrant	8 (40)	9 (27)	9	1 (-3)	7	8	3	5 (-10)	5 (10)	10	2	8	105	Overall 2
Penetrant facilities	8 (40)	9 (27)	7	0 0	8	7	5	5 (-10)	6 (12)	10	3	9	108	7
Portable penetrants	4 (20)	10 (30)	10	0 0	6	9	1	5 (-10)	3 (6)	9	1	6	86	21
Magnetic particle	3 (15)	9 (27)	8	1 (-3)	7	6	4	4 (-8)	5 (10)	8	2	7	75	28
Optical devices (fiber optics)	10 (50)	7 (21)	8	4 (-12)	8	9	5	2 (-4)	8 (12)	8	7	9	115	Overall 1
Portable inspection	10 (50)	8 (24)	8	2 (-6)	9	10	6	2 (-4)	7 (14)	8	5	9	121	2
Selected on-board devices	9 (45)	1 (3)	2	4 (-12)	8	9	4	2 (-4)	8 (12)	8	7	8	86	22
On-board system	8 (+40)	0 (0)	0 (0)	9 (-27)	7	8	3	3 (-6)	9 (18)	6	8	7	58	36
Rating Factor Multiplier	5	3	1	-3	1	1	-1	-2	2	1	2	1		

techniques require development, that many conventional NDE techniques will be useful during turnaround, that high-speed GSE NDT techniques require development, etc. The techniques have already been described in this report. Methods to implement these techniques are presented as specifications in Appendix B.

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NONDESTRUCTIVE EVALUATION DESIGN CRITERIA

Nondestructive inspection methods appropriate for Shuttle Operations (turnaround and prelaunch) were selected from Table 2 based on the analysis presented there and detailed consideration of requirements and techniques discussed in "Applications of NDE Methods of Space Shuttle Vehicle." The data were then organized into equipment specifications which are presented in Appendix B. The rationale is summarized in Tables 6 and 7.

The specifications of Appendix B were developed from the following outline of general requirements.

On-Board Equipment Specification

1. Functional characteristics
2. Weight
3. Power requirements
4. Size
5. Method of installation
6. Checkout
7. Interconnecting requirements

Facilities Specification

1. Operability
2. Space requirements
3. Electrical requirements
4. Water and drainage requirements
5. Location requirements

Table 6. General Classification of NDE Methods

<table>
<tr><th rowspan="2">Defect Type</th><th colspan="2">Material Type</th></tr>
<tr><th>Metals</th><th>Non-metals</th></tr>
<tr><td rowspan="2">Structural Deformation</td><td>Holographic Interferometry</td><td>Moire' Gaging</td></tr>
<tr><td colspan="2">Strain and Fatigue Gages</td></tr>
<tr><td rowspan="3">Surface</td><td colspan="2">Visual Fiber Optics</td></tr>
<tr><td>Penetrants</td><td>Leak Detection</td></tr>
<tr><td colspan="2">Thermal Methods</td></tr>
<tr><td>Near Surface</td><td>Eddy Current Devices</td><td>Radio-Frequency Devices</td></tr>
<tr><td rowspan="2">Deep Defects</td><td colspan="2">Acoustic Emission</td></tr>
<tr><td>Ultrasonics</td><td>Microwave Techniques</td></tr>
<tr><td rowspan="2">Material Voids and Inclusions</td><td colspan="2">X-Ray Radiography</td></tr>
<tr><td>Gamma Radiography</td><td>Neutron Radiography</td></tr>
</table>

Table 7. NDE Methods Evaluation Survey

Methods	General Application	Condition Detected	Advantages	Disadvantages	State of Art	Recommendation
Ultrasonics						
Permanent rotating system through transmission defect detection	Honeycomb phenolic structures	Voids Unbonds	Signal loss if not working.	Need access from 2 sides alignment of quarters.	Well developed	Use as developed on limited basis line removable units.
Permanent rotating system pulse echo defect detection	Metal plates, weld, diffusion bonds.	Laminar voids or delamination.	Can time gate particular level	Alignment Limited penetration and echos compared to through transmission.	Well developed	Use as developed on limited basis. Line removable units.
Lamb wave testing defect detection	Uniformly thick metal plate or hollow square tubing.	Cracks	Long range coverage	Lower sensitivity.	Immediate	Analyze further. basic experimentation.
Rotating wave director	Metallic structure Plates Forgings Machined parts	Cracks formation	On-board technique	No commercial hardware available.	Preliminary	Develop and use.
Hand scanning	Welds. Small adhesive bonds	Unbonds Cracks.	Very flexible	Operator dependance. Slow	Well developed	Must be used, but use to minimum extent.
Spectroscopic techniques	Heavy metal stock.	Grain size	Monitors grain growth	Difficult. Outside laboratory.	Preliminary	Eliminate
Thickness micrometer	Plate, machined.	Thickness	One sided	Point-to-point coverage.	Well developed	Use as appropriate.
Bonded-in-plate transducer	Weld lines high stress metallic members.	Crack formation	On-board technique	Limited coverage.	Preliminary	Develop and use.
Acoustic Emission						
Proofing technique	Load carrying members	Incipient cracking.	Most available and developed. Acoustic emission technique.	Proof load damage.	Intermediate	Eliminate
Monitoring system	Foam, adhesive bonds, load carrying members	Incipient cracking. Internal degradation.	On-board system. High speed.	Background noise problem.	Conceptual	Analyze
Signature comparison	Foam, adhesive bonds, load carrying members.	Incipient cracking. Crack growth. Internal degradation.	On-board system. High speed.	Background noise problem.	Conceptual	Analyze
Portable system	Load carrying members.	Incipient cracking.	Ground system.	Proof load damage.	Preliminary	Eliminate
Hybrid computer	Mechanical attachment. Bonded and welded load bearing members.	Structural relaxation. Incipient cracking. Crack growth.	General indication of structural soundness.	Background noise problem. Require lifetime mounting.	Conceptual	Develop
Holographic Interferometry						
Potable system	Forge, thin-walled contoured structures, such as honeycomb, stresskin, etc.	Subsurface degradation. Voids, unbonds, structural weakness.	High speed coverage potential.	Vibration problems.	Preliminary	Develop

Table 7. NDE Methods Evaluation Survey (Cont)

Methods	General Application	Condition Detected	Advantages	Disadvantages	State of Art	Recommendation
Permanent test facility	Large, thin-walled contoured structures, such as honeycomb, stresskin, etc.	Sursurface degradation. Voids, unbonds, structural weakness.	High speed coverage potential.	Requires line removable units	Intermediate	Analyze
Special techniques	Structural members.	Structural relaxation. Structural weakness. Creep.	Monitoring internal structural, using fiber optics/vidicon monitoring.	Weight. Lack of preliminary development.	Not developed	Eliminate
Electromagnetics						
Eddy current thickness	Metal plates. Metallic or non-metallic coatings on metallic substrate.	Thickness	Simple to use.	Effect of metallic structures in near proximity. Requires standards.	Well developed	Use as appropriate.
Eddy current material properties	Metal structures.	Heat treat or alloy	Simple to use.	Limited application and need.	Well developed	Use as appropriate.
Eddy current defect	Metallic surfaces.	Crack depth	Determination of seriousness of cracks (depth).	Requires access and development of technique for each application.	Moderately developed	Develop techniques as necessary.
Radio frequency thickness	Nonmetallics on metallic base.	Proximity of metal	Simple to use.	Low sensitivity.	Moderately developed	Use as appropriate.
Radio frequency leakage current	Nonmetallic coating on metallic substrate.	Porosity of coating	Coating porosity measurement.	Slow. Lack of flexibility.	Preliminary	Eliminate
Radio frequency dielectric voltage probe	Nonmetallic coatings on metallic substrate.	Crack or discontinuity through coating	One of few techniques available for thin poreous dielectric coatings.	Lack of flexibility. High voltage hazard.	Preliminary	Eliminate
Radio frequency dielectric constant device	Nonmetallics.	Dielectric constant as effected by resin, glass, moisture, etc., content.	Measures useful properties for nonmetallics.	Possible applications are not accessible. Slow.	Preliminary	Analyze. Develop as appropriate.
Microwave (scatter)	Nonmetallics.	Voids. Cracks.	One of few techniques applicable to deep defects in nonmetallics.	Strong material and geometry dependance. Better microwave equipment needed (variable frequencies etc.)	Intermediate	Analyze
Penetrating Radiation						
Portable machines	Welds, joints, internal alignment	Material absences, spatial relationships, cracks, voids	Well established	Slow and costly	Well developed	Use with tunnels and tracks. No disassembly.
Permanent facilities	Welds, joints, internal alignment	Material absences, spatial relationships, cracks, voids	Cost-effective technique can be developed.	Requires line removable units	Well developed	Use as appropriate.
Tunnel and track concepts	Welds, joints, internal alignment	Material absences, spatial relationships, cracks, voids	On-board	Design requirement ill-defined.	Intermediate	Maximum usage.

Table 7. NDE Methods Evaluation Survey (Cont)

Methods	General Application	Condition Detected	Advantages	Disadvantages	State of Art	*Recommendation
Stimulate electron emission	Silicide coatings	Thickness, uniformity, composition	Now being used in Columbrium development programs.	Need vacuum casset and bare film touching part. 300 KV required.	Laboratory technique	Eliminate.
Beta backscatter	Surface chemistry (average atomic number)	Wall thickness Coating thickness Surface roughness Oxidation of high atomic number metals	Yields useful material properties data.	Lift-off sensitivity. Lack of adequate sensitivity. Slow point-by-point.	Intermediate	Analyze further.
X-ray fluorescence	Surface chemistry	Chrome boil out, and other specific metals. Oxygen with vacuum techniques	Yields useful material properties data.	Slow point-by-point.	Under development	Analyze further.
Isotope autoradiography	Surface chemistry	Taggable constituents	May yield useful surface properties data.	Radiation hazard. Low sensitivity.	Not developed	Analyze further.
Thermal			Multipoint coverage.	Appropriate heat sources and sinks required.	Intermediate.	
Liquid Crystal	Thermal protection system.	Surface temperature as effected by voids, cracks, etc.	Multipoint coverage reversible.	Requires surface application.	Intermediate.	Use to develop IR scanning techniques.
Infrared scanning	Thermal protection system.	Surface emittance as effected by surface emissivity, voids, cracks, etc.	High speed usable detectors to 5 microns in infrared.	Lack of flexibility in complex scanning machines, field-of-view, sensivity, etc. Operationability difficult.	IR advanced. NDE intermediate.	Use as appropriate.
Infrared film	Thermal protection system.	Surface emittance as effected by surface emissivity, voids, cracks, etc.	High speed, low cost.	Only near infrared range to about 1 micron.	Preliminary.	Eliminate
Thermal paints	Thermal protection system.	Surface temperature as effected by voids, cracks, etc.	Possible on-board usage with fiber optics.	Nonreversible. Requires surface application. Limited ranges available.	Intermediate.	Analyze further.
Penetrants						
Penetrant facility	Metallic structure.	Surface cracks.	Fast, cost-effective.	Requires line removable unit.	Well developed.	Use as necessary
Portable penetrant	Metallic structure.	Surface cracks.	Simple.	Slow. Costly. Access required.	Well developed.	Minimal usage.
Magnetic particle	Metallic structure.	Surface and near surface cracks.	Near sub-surface defects in fero-magnetic parts.	Penetrants are almost as effective and penetrants are much easier and faster to use.	Well developed.	Minimal usage.

Table 7. NDE Methods Evaluation Survey (Cont)

Methods	General Application	Condition Detected	Advantages	Disadvantages	State of Art	Recommendation
Fiber optics						
Portable inspection	Inaccessible areas.	General condition, corrosion, gross damage.	Simple.	Slow.	Well developed but improvement possible.	Use and develop.
Selected on-board devices	Inaccessible areas.	General condition, corrosion, gross damage.	Simple, easily understood and interpreted.	Need to identify selected areas. Requires design implementation.	Conceptual	Develop.
On-board system	Inaccessible areas.	General condition, corrosion, gross damage.	Well defined monitoring, flexibility, usefulness with other instrumentation; high speed.	Weight. Development costs.	Conceptual	Analyze further.

6. Lighting requirements
7. Communication requirements
8. Air conditioning and environmental control

NDE Vehicle Design Manual

1. Where to apply NDE
2. Why apply NDE
3. What NDE to apply
4. How to apply NDE

Techniques

1. Bonded in-place ultrasonic transducers
2. Rotating ultrasonic wave director
3. Lamb wave ultrasonic techniques
4. Fiber optics ports and tunnels
5. Fiber optics on-board devices
6. Fiber optics on-board system
7. Radiographic isotope tunnels
8. Radiographic film tunnels
9. On-board acoustic emission system
10. Acoustic emission signature comparison technique
11. Acoustic emission hybrid computer technique
12. On-board holographic interferometric frame
13. On-board thermal NDE techniques

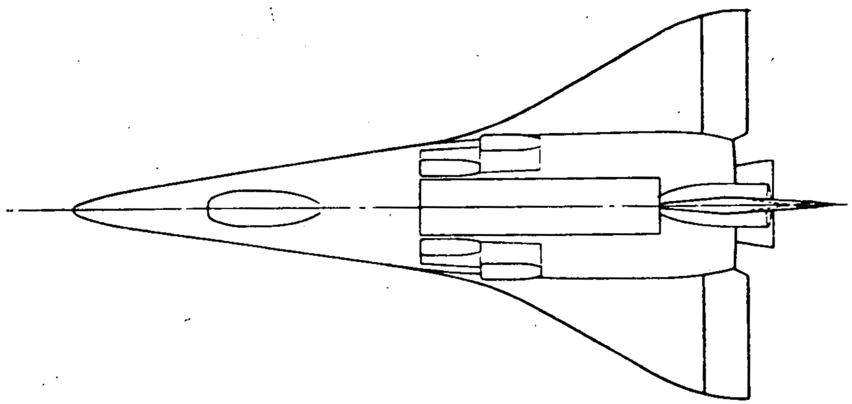
Portable Equipment Specifications

1. Function
2. Operation
3. Description
    a. Portable ultrasonic hand scanning
    b. Ultrasonic digital thickness gage
    c. Portable fiber optics methods
    d. Portable radiographic methods
    e. Portable acoustic emission system
    f. Portable holographic testing method
    g. Liquid crystal portable technique
    h. Infrared scanning
    i. Infrared film
    j. Eddy current thickness gage
    k. Eddy current defect detection
    l. Portable penetrant
    m. Portable magnetic particle
    n. Backscatter thickness gaging
    o. Nondestructive chemical analysis
    p. RF voltage probe
    q. Direct radiation counting (Geiger-Muller counter)

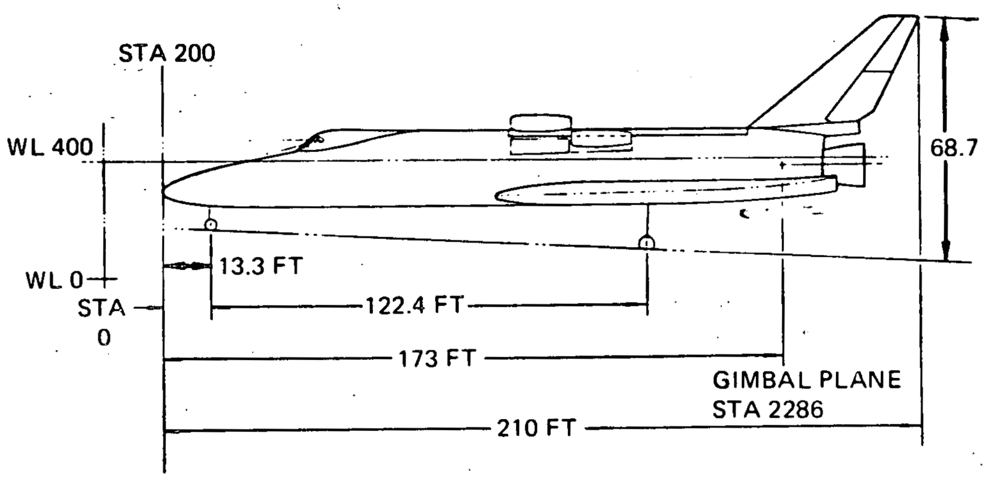
Facility Equipment Specifications

1. Function
2. Operation
3. Description
   a. Permanent ultrasonic inspection system
   b. Spectroscopic techniques
   c. Permanent radiographic facilities
   d. Cabinet radiographic facilities
   e. Acoustic emission proofing technique
   f. Hybrid computer acoustic emission
   g. Holographic interferometric test facility
   h Liquid crystal test facility
   i. Penetrant booth
   j. Magnetic particle facility
   k. Electron emission radiography
   l. Nondestructive chemical analysis
   m. RF voltage probe

Baseline Shuttle configurations considered in this study are shown in Figures 51 and 52. The surface areas for the various types of external structure are shown in Figure 53. Based on these data and inspection speed information, estimates can be made for the amount of time required to inspect the external TPS structure. Precise definition of inspection speed is difficult without well defined and established defect criteria. Based on Apollo/Saturn history and laboratory experience, general and relative inspection speed information is presented in Table 8.



GROSS WT - 935,740 LB	
CONFIG	INTEGRAL LH_2 TANK, FLOATING LO_2 TANK
AERO/ THERMAL	ENTRY L/D: 0.7 to 2.5 SUB L/D: 7.8 W/C_L S: 54 LB/FT^2
STRUCT/TPS	PRIMARY: TITANIUM TANKS: ALUMINUM HEAT SHIELD: REI
SYSTEMS	MAIN PROPULSION: 2 X 620K LB ENGINES ACPS/OMS-INTEGRATED COMMON TANKAGE ACPS-29 THRUSTERS @ 2100 LB THRUST EACH OMS-3 THRUSTERS @ 10,000 LB THRUST EACH ABES: 4 X JTF22B-2, JP FUEL
PAYLOAD	25,000 LB



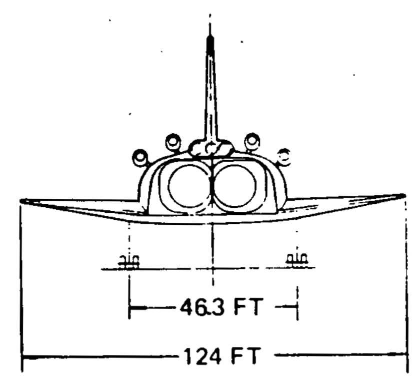
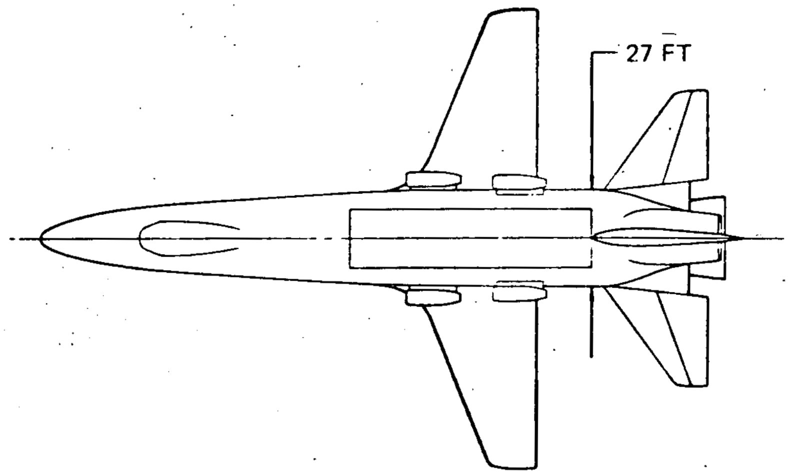


Figure 51. Long Cross-Range Orbiter Configuration



	GROSS WT = 852,984 LB
CONFIG	INTEGRAL LH_2 TANK, FLOATING LO_2 TANK
AERO/ THERMAL	ENTRY L/D: 0.56 SUB[illegible] L/D: 8.2 W/S: 51.7 LB/FT^2
STRUCT/TPS	PRIMARY: TITANIUM TANKS: ALUMINUM HEAT SHIELD: REI
SYSTEMS	MAIN PROPULSION: 2 X 574K LB ENGINES ACPS/OMS-INTEGRATED COMMON TANKAGE [illegible]CPS-29 THRUSTERS @ 2100 LB THRUST EACH O[illegible]MS-3 THRUSTERS @ 10,000 LB THRUST EACH ABES: 4 X JTF22A-2, JP FUEL
PAYLOAD	25,0[illegible] LB

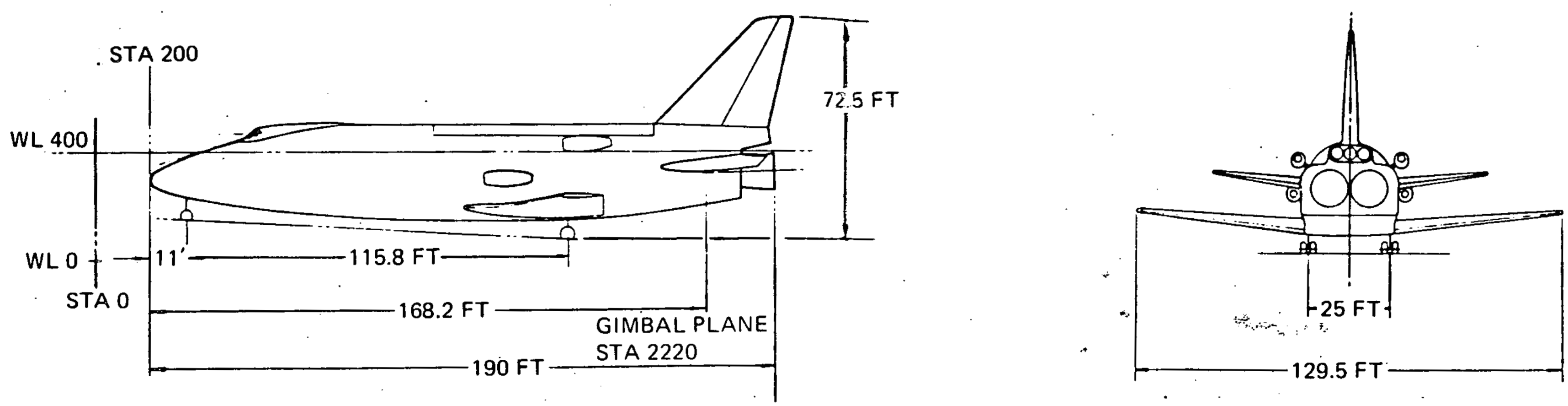
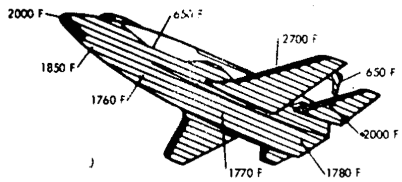
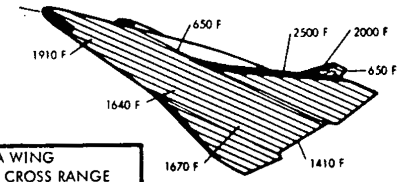


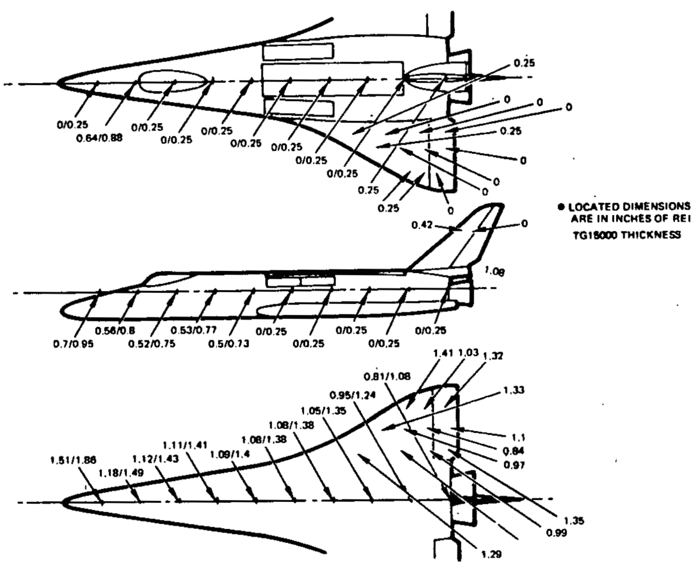
Figure 52. Short Cross-Range Orbiter Configuration





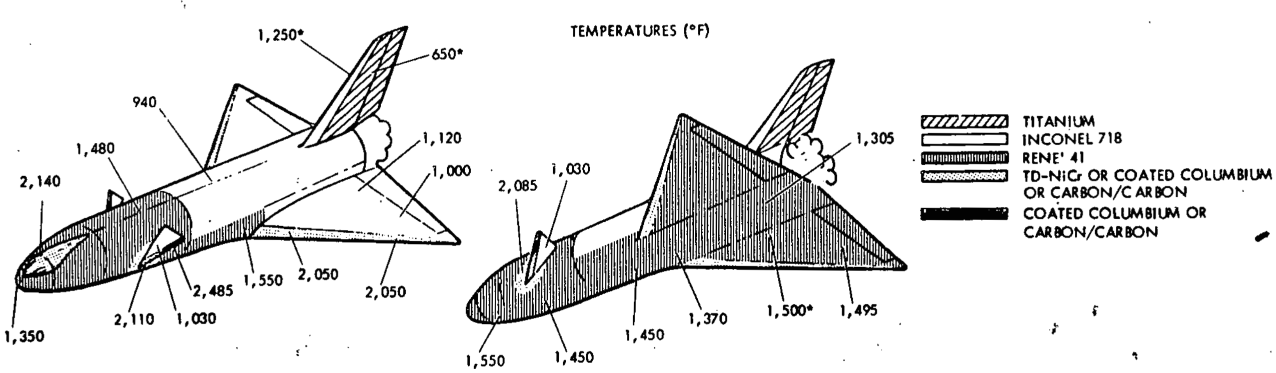
TPS MATERIAL	MAX TEMP	ST WING LOW CROSS RANGE AREA	ST WING LOW CROSS RANGE WEIGHT	DELTA WING HIGH CROSS RANGE AREA	DELTA WING HIGH CROSS RANGE WEIGHT
REI	2000°	(13,434)	(17,735)	(10,525)	(19,325)
RPP	3000°	(665)	(2,835)	(720)	(3,055)
CARRIER PANELS		(3,250)	(2,270)	(4,350)	(3,040)
INSULATION, + A&P		(16,248)	(4,430)	(15,735)	(5,685)
SUBTOTAL		-	27,270	-	31,105
H 188		54	100	-	-
INC 718		567	2,550	710	3,195

THERMAL PROTECTION SYSTEM



DELTA WING ORBITER HCR INSULATION SIZING

TEMPERATURES (°F)



*TEMPERATURE LIMITED TO VALUE SHOWN BY HEAT SINK DESIGN

BOOSTER MAXIMUM TEMPERATURE & MATERIAL DISTRIBUTION

Figure 53. Thermal Protection Systems

Table 8. General and Relative NDE Inspection Speed

Technique	*Type of Operation: Area Coverage — Facility (ft²/manhour)	Area Coverage — Portable (ft²/manhour)	Line Coverage (weld lines, etc.) — Facility (ft/manhour)	Line Coverage (weld lines, etc.) — Portable (ft/manhour)	Point Coverage (joints, etc.) — Facility (joints/manhour)	Point Coverage (joints, etc.) — Portable (joints/manhour)	On-board (inspection task 1000 cu ft)
Radiographic	3	1	5	1	3	0.5	10 hr
Ultrasonic	5	2	30	5	5	1.0	15 min
Holographic Interferometry	40	30	40	30	5-1/2	2.5	1 min
Thermographic	50	30	150	50	3.5	2	1 hr
Visual — General	300	150	200	150	50	15	3 min (fiber optics system)
Visual — Detailed	50	30	50	40	20	10	15 min (fiber optics system)

*Based on a 2-man team

CONCLUSIONS

Effort conducted to satisfy requirements of the Phase II study has included the development of 12 specifications (see Appendix B). These provide initial equipment and facility requirements for NDE systems during maintenance and turnaround of the Shuttle. Four of these specifications provide design criteria for on-board testing; eight provide design criteria for ground-support NDE facilities. In addition, a design manual must be developed if on-board NDE technology is to successfully support turnaround. The specifications providing design criteria are the products of the Phase II effort and thus form conclusions. The content of these documents has been derived from the body of the report.

In addition to these specific conclusions, the following general conclusions are presented.

NDE TECHNOLOGY FOR IMMEDIATE APPLICATION

NDE technology ready for immediate application to the Shuttle for on-board and GSE use includes:

On-Board

1. Fiber optics - selected on-board devices
2. Radiography - isotope and film tunnel concepts

GSE

1. Ultrasonics - portable hand scanning devices
2. Ultrasonics - permanent laboratory facilities
3. Ultrasonics - digital thickness gages
4. Fiber optics - portable devices
5. Radiography - portable machines
6. Radiography - permanent laboratory facilities

7. Radiography - cabinet machines

8. Electromagnetics - eddy current thickness devices

9. Electromagnetics - eddy current materials properties determination

10. Penetrants - permanent inspection facilities

11. Penetrants - portable systems

NDE TECHNOLOGY FOR APPLICATIONS DEVELOPMENT

The following NDE technologies will be ready with applications development programs established to determine the limits of applicability:

On-Board

1. Ultrasonics - bonded in-place transducers
2. Ultrasonics - rotating wave directors
3. Fiber optics - on-board systems

GSE

1. Radiography - neutron radiographic facilities
2. Radiography - beta backscatter techniques
3. Radiography - stimulated emission
4. Radiography - X-ray fluorescence
5. Electromagnetics - eddy current defect detection
6. Electromagnetics - microwaves
7. Electromagnetics - RF thickness gages
8. Acoustic emission - proof loading technology
9. Holography - permanent laboratory facilities

10. Thermography - liquid crystal techniques

11. Thermography - infrared scanning

12. Thermography - infrared film

NDE TECHNOLOGY FOR RESEARCH AND DEVELOPMENT

NDE technology which will require a great deal of research and development for both the technique itself and its application to the Space Shuttle is listed below.

On-Board

1. Acoustic emission - on-board system
2. Acoustic emission - signature comparison methods
3. Acoustic emission - hybrid computer techniques

GSE

1. Electromagnetics - RF voltage probes
2. Electromagnetics - RF dielectric probes
3. Electromagnetics - RF leakage probes
4. Holography - portable on-line systems
5. Electromagnetics - thermoelectric methods
6. Radiography - direct radiation counting

RECOMMENDATIONS

Nondestructive evaluation methodology as discussed and evaluated in this study will provide operational personnel for the Space Shuttle vehicle substantial help in achieving a two-week turnaround capability. All NDE systems and techniques should be implemented as Shuttle structural-integrity checkout devices within the constraints of their individual specifications. It is therefore recommended that the essential requirements from the specifications appended to this report be included in any NASA statement of work for ultimate Phase C/D proposals from industry.

It is also recommended that a follow-on program be conducted to further develop the technologies listed as requiring further development. This program should be conducted to develop detail requirements for NDE technology to support the Space Shuttle design effort. It will be the objective of this follow-on program to further develop, establish feasibility, design prototypes, and prepare specific specifications for the identified NDE technologies.

As the Space Shuttle design becomes firm, revisions of the specifications in Appendix B will yield more definitive requirements for Space Shuttle operations. Implementation of the on-board concepts and designed-in inspectability for the Space Shuttle will require design manuals. It is recommended that a design manual incorporating the requirements of the specifications and extending these requirements be initiated. The design manual will function as a source of specific design information for the inclusion of on-board NDE methods into the Shuttle vehicles. Design manual data would include access requirements, installation techniques (such as bonding or attaching methods for transducers), power, and weight information. In addition, specific techniques and methods to be employed in utilizing other on-board systems, such as computers, display equipment, data bases, etc., would be included.

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APPENDIX A

RELATED LABORATORY EFFORT

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APPENDIX A. RELATED LABORATORY EFFORT

To aid in the engineering assessment of NDE techniques for Space Shuttle application, limited laboratory testing was employed. The materials tested were representative of those being proposed for the Space Shuttle program. The configuration of the test specimens was typical of those designed for engineering tests and manufacturing development studies. In order to provide realistic test data, special emphasis was placed on securing from Shuttle engineering and manufacturing groups engaged in Phase B work, actual defective test structures. In that this study contract provided for only limited testing, only four of the twelve technologies studied had any significant laboratory effort expended on them. They were holographic interferometry, ultrasonics, thermography, and acoustic emission. These technologies were selected over the other eight because it was felt that more development effort was required for these methods. With the exception of ultrasonic NDE, the selected methods are embryonic in development and not fully exploited from a practical standpoint.

Development efforts to establish cost effective NDE technology for Space Shuttle operations studied at NR/SD emphasize high-speed methods and on-board techniques. Holographic NDE is being evaluated as a manufacturing inspection system and for TPS inspection during maintenance and overhaul. Figure A-1 shows the laboratory system which is being used to develop holographic equipment parameters and requirements. Acoustic emission equipment shown in Figure A-2 is being evaluated for its ability to detect metal fatigue and adhesive delamination. Although acoustic emission techniques are primarily a laboratory research tool, the feasibility of using emission proof-loading techniques for nondestructive inspection has been recognized by many investigators. The possibility of applying acoustic emission monitoring during flight has received close examination by SD investigators.

Liquid crystal thermography will possibly find application in the Shuttle program where the lower thermal conductivity of titanium, cobalt, and nickel alloys allows greater flexibility in their application. Preliminary laboratory evaluation work will define the usefulness of this thermal NDE technique for Space Shuttle structures.

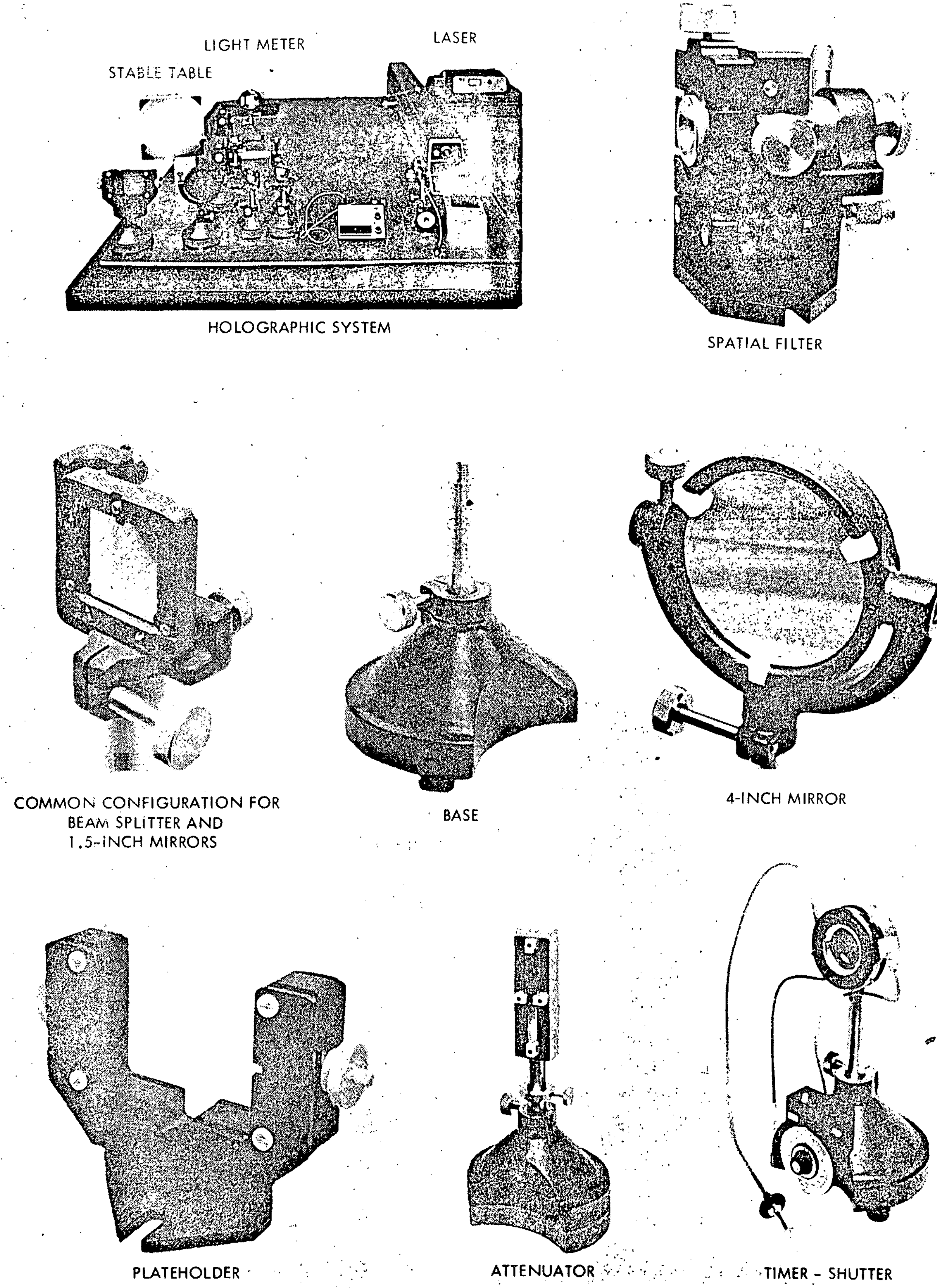


Figure A-1. Laboratory Holography System

Ultrasonic NDE was performed on selected Space Shuttle test specimens to determine its basic capability for the detection of defects peculiar to those structures. Laboratory testing was limited to conventional C-scan presentations using longitudinal waves.

HOLOGRAPHIC INTERFEROMETRY

The primary objective of this laboratory study was to establish feasibility data. Since the installation of a holography facility, a wide variety of materials have been examined. Table A-1 details these results. Many different arrangements of optical components are possible, with the primary constraint being to maintain the same length in the object and reference beam. The plan view of a typical optical component arrangement is shown in Figure A-3. Five methods of proof loading specimens for holographic examination are generally recognized. (Se : Table A-2.) The majority of test structures examined thus far have been subjected to a thermal loading technique using a heat gun. Generally, the test specimen is thermally excited with hot air for a few seconds, with the surface temperature rise being normally less than 15 degrees Fahrenheit. As shown in Figure A-4 prior to loading, a uniform fringe pattern is normally present. The holographic interferograms show a broad and a narrow band fringe pattern on a Haynes 188 brazed panel. The two white spots are braze material and not holographic artifacts. The typical pattern caused by dust on the optical components is indicated by the arrow and must not be confused with defect indications. The loading or thermal stress level is quite low, and interpretation of fringe wiggles is questionable. Although appearing as parallel lines, the fringes are part of the circular bulls-eye pattern. In the dormant or rest condition, the parallel lines are little disturbed. Figure A-5 shows the holographic interferogram of a Haynes 188 Shuttle thermal protection system test structure after loading. This panel measured 18 by 39 inches and was a brazed, corrugated structure. The facing sheet thickness is 20 mils and has 1-inch-wide shallow stamped corrugations with brazed z-section ribs as stiffeners between the corrugations. The fine fringed pattern is typical of that which first appears after thermal loading.

This pattern may be manipulated over the surface using the object or reference beam mirrors. Because spherical wavefronts are universally used in holography, a bulls-eye pattern is always present in the image plane as shown by the arrow in this interferogram. A defect indication associated with the large white braze spot appears real. However, ultrasonic testing shows it is not an unbond, and it is presumed to be associated with some other type of material abnormality. By accurately adjusting either the object or reference mirror, the fringes may be broadened as the center of the bulls-eye pattern is approached or made fine as the fringe-coherence resolution limits are approached on the edge of the circles in the

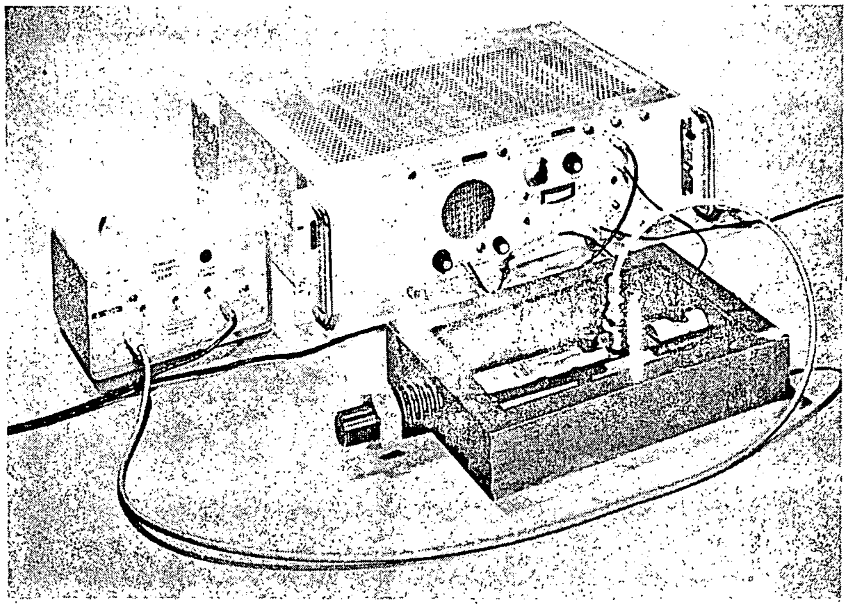


Figure A-2. Laboratory Acoustic Emission Equipment

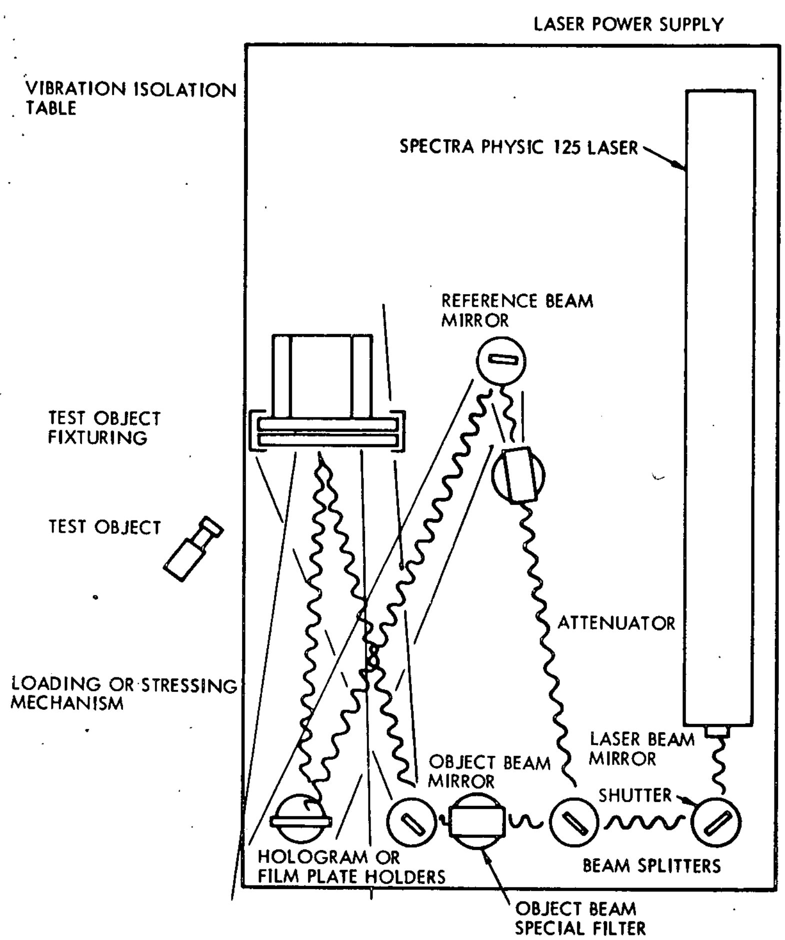


Figure A-3. Useful Holographic Optical Component Arrangement

Table A-1. Results of Cursory Holographic Examinations

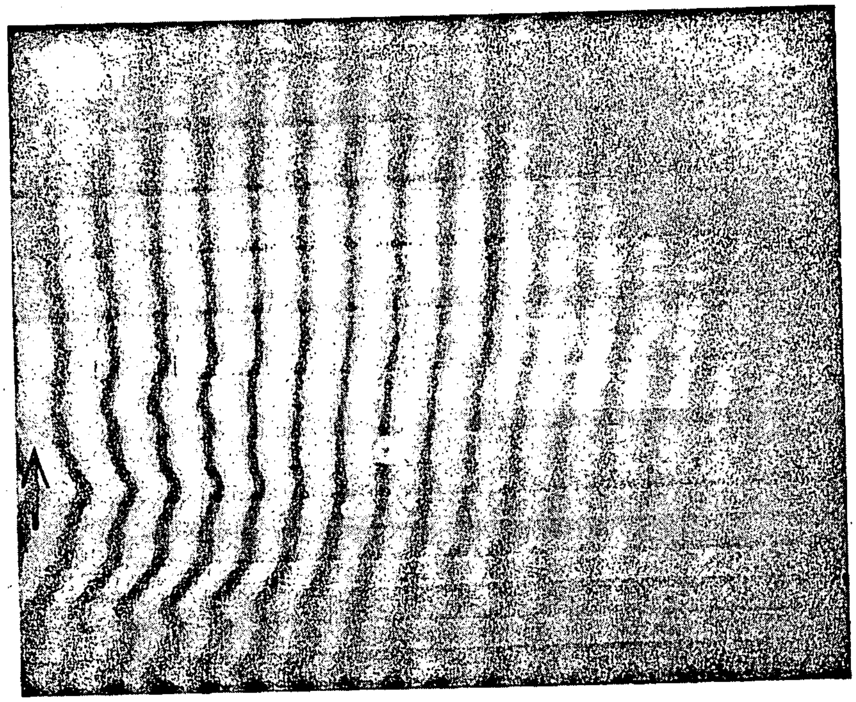
Material	Important Holographic Material Parameters	Defect	Results
Honeycomb Phenolic core Phenolic facing	Adhesively bonded, 15-mil thick facing	Unbond	1/2-inch defects resolvable.
Honeycomb Phenolic core Aluminum facing	Adhesively bonded, 15-mil thick facing	Unbond	1/2-inch defects resolvable.
Honeycomb Aluminum core Phenolic facing	Adhesively bonded, 15-mil thick facing	Unbond	1/2-inch defect resolvable.
Honeycomb Aluminum core Aluminum facing	Adhesively bonded, 15-mil thick facing	Unbond	1/2-inch defect resolvable.
Boron aluminum composite	20-mil thick	Delamination	Gross defects only.
Cork-on-foam	Adhesively bonded, 1/4-inch cork	Unbond	4-inch defects detectable with difficulty.
Brazed Haynes 188 heat shield structure	20-mil thick facing, "Z" ribs	Unbond	Interesting results. Interpretation development needed.
Hot-shot honeycomb panels	Titanium diffusion formed	Unbond, etc., none present	Weakness in formed section evident.
Stresskin panel	Titanium diffusion-bonded, 53-mil thick facing	Unbonds, no known defects present	Standards needed.
Columbium diffusion bonded tee panels	20-mil thick facing	Unbond	Interesting results. Interpretation work necessary.
Step wedge facing sheet honeycomb	Al core Ti facing, adhesively bonded	Unbond	1/4-inch defects resolvable under 1/16-inch face sheet thickness.

Table A-2. Holographic Loading Techniques

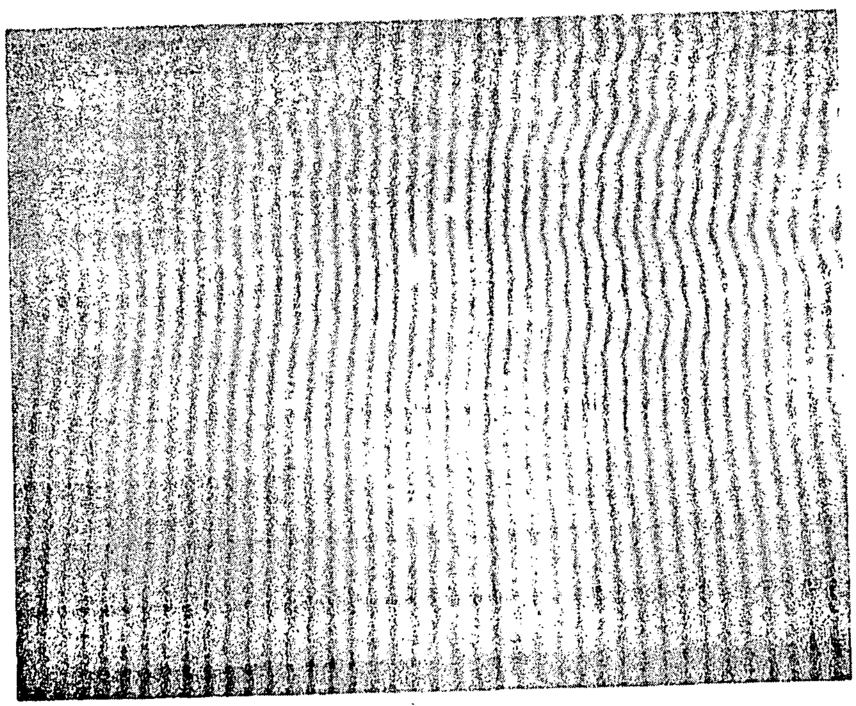
Method	Description	Advantages	Disadvantages
Mechanical	Applying a force with a weight, vise clamp, etc.	Simple, good control	Limited application
Thermal	Heating or cooling of test specimen	Simply, broadly applicable	Poor control, heat distortion.
Vibration	Using a shaker, piezoelectric, etc. transducer to setup, resonant vibration modes	With pulsed or high power CW no vibration isolation is necessary	Resonant conditions in test specimen too erratic and specific.
Pressurizing	Applying either a vacuum or pressure to all or part of test specimen	Good penetration	Excessive setup time and specific tooling needed.
Shock	Hitting part with a hammer or dropping it making a double exposure	Unique and unusual effects are often uncovered	Pulsed technique only at present.

bulls-eye. The pattern normally disappears on application of the thermal load; then after a short wait (typically 20 seconds), a fine bulls-eye fringe pattern appears on the surface. Over the subsequent time period, the fringes broaden out to cover the whole surface and to eventually settle down to the original pattern observed prior to loading. Defects such as unbonds in honeycomb which cause irregularities in this fringe pattern are shown in Figure A-6.

Figure A-6 shows interferogram "A" on a 1-foot-square adhesively bonded honeycomb panel with a 4- by 6-inch array of various sizes and types of unbonds. The aluminum facing sheet was a step plate varying from 1/8-inch thick to 15-mil thick. The titanium core gives a good thermal coefficient of expansion mismatch, and voids are readily detected. An ultrasonic C-scan of the panel verified defect location. In the C-scan, defect size is readily apparent while holographic interferometric interpretation of size is complex and involved. However, the C-scan would require



Broad Fringe Pattern



Narrow Fringe Pattern

Figure A-4. Holographic Interferometric Image

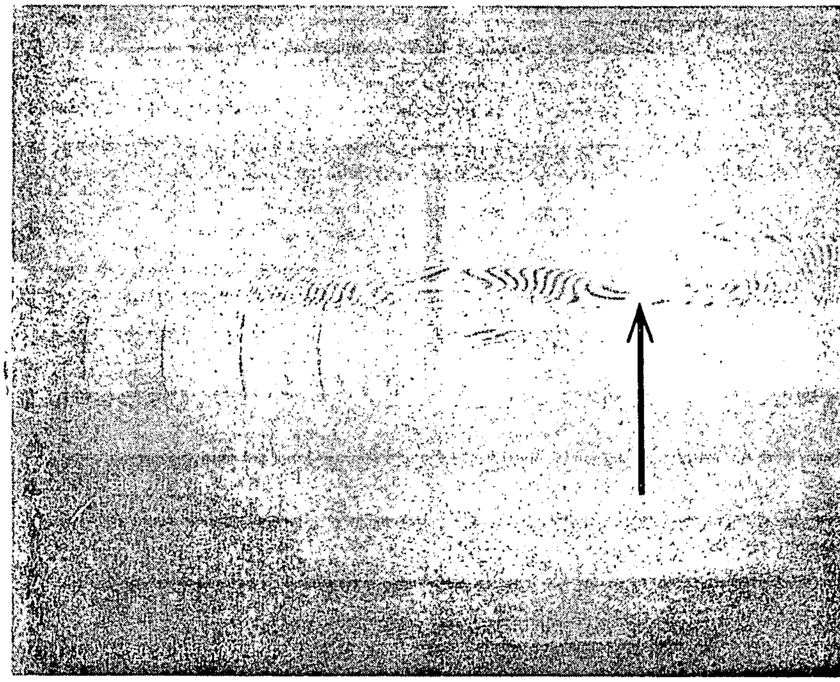


Figure A-5. Holographic Interferometric Pattern After Thermal Loading

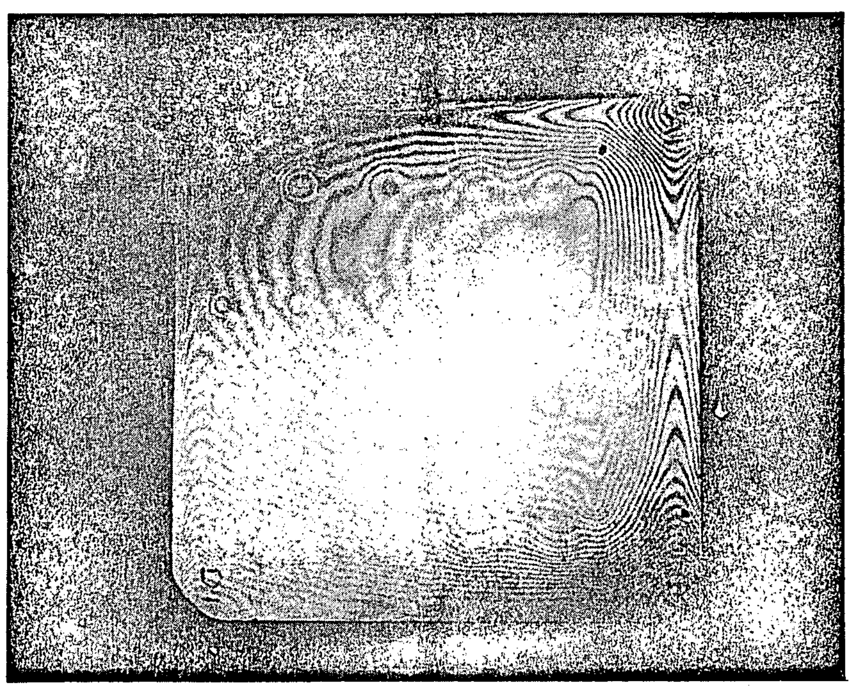


Figure A-6. Holographic Interferogram "A" of Honeycomb Panel about 50 minutes of actual testing while the holographic interferogram can be shot in a few minutes.

Figure A-7 shows interferogram "B" of the same panel under a different set of loading conditions. Defects not apparent in Figure A-6 are vividly brought out here. The variety and nature of the loading variables and wide latitudes in the holographic system variables represent a formidable "techniques search" to uncover proper operating conditions. The kinds and types of defects which can be found depend on the defect depth, stiffness of the material's structures, and the type and method of loading, among other factors.

It is believed that the greatest usefulness of the present holographic studies for the Space Shuttle will be derived from the continued examination of manufacturing development specimens and engineering test specimens. This is reflected in the holographic photographs presented in this report, the majority of which are photographs of Shuttle development test specimens. At the same time, it is important to discover where holographic nondestructive testing is applicable and how to apply this method. Pursuant to these aims, controlled panels with controlled defects are examined to determine resolution, ease of operation, best operating techniques, operating cost, etc. At present, these studies are only in preliminary phases.

Figure A-8 shows a holographic interferogram of a phenolic-facing-sheet adhesively bonded honeycomb. Defect indications are indicated by the arrows and correspond to built-in unbonds. The nature of the bulls-eye pattern is readily evident. It is normally much more difficult to photograph the fringe pattern than visually see the fringes, and this photograph illustrates several of the difficulties. A bright, reflective spectral peak is evident as a white area. In the more severe condition, this can completely wash out the dark fringe pattern. The illumination is quite nonuniform across the object. Although this nonuniformity is often photographically difficult to handle, it rarely gives a problem with visual investigation. Exposure times of a few seconds (typical) often result in a blurred image since, under the transient thermal loading conditions, the pattern is continually changing especially during the high-stress levels encountered immediately after applying the thermal load. Although these photographic problems have been a nuisance, nothing has been encountered which could not eventually be resolved.

Holding fixtures and methods of attachment are important considerations which also must be understood in interpreting such fringe patterns. Figure A-9 shows an array of several structures. This have proven to be a useful laboratory approach. Panel X is a diffusion-bonded columbium rib structure with three ribs. Panel Y is a 4-by-6-inch boron aluminum panel

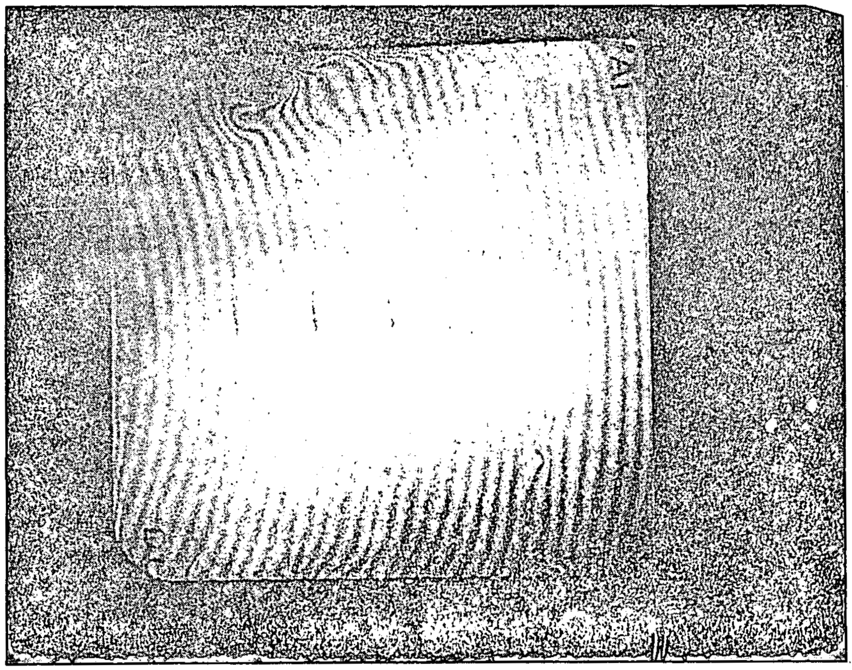


Figure A-7. Holographic Interferogram "B" of Honeycomb Panel

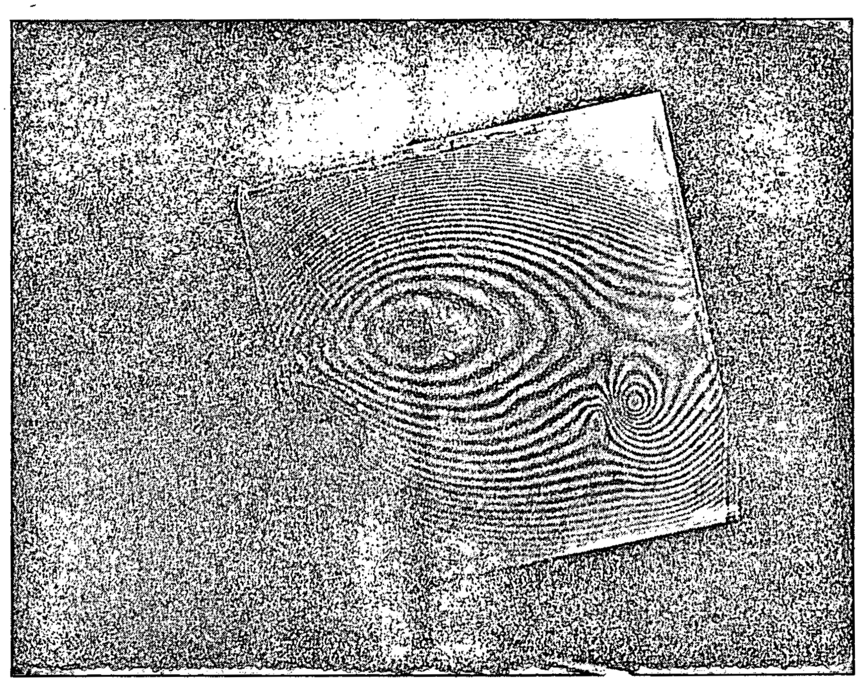


Figure A-8. Holographic Interferogram of Phenolic Honeycomb with several defects readily evident. The background fringe pattern shows on the angle block Z to which everything has been clamped. The optical adjustments were such that the fringe pattern was lost on the ceramic block W. However, the fringe pattern could be developed on this block by readjusting.

At present, as a nondestructive inspection tool, holographic interferometry seems best applied to large, thin-skinned, contoured structures. Noted, however, that the fringes are half-wavelength spaced and that great amounts of quantitative data about surface displacements are available. Other investigations have shown the feasibility of not only obtaining on-axis movement but also in-plane displacements. The usefulness of such techniques for fatigue, creep, and strain analysis studies deserves careful consideration.

ULTRASONICS

One of the candidate thermal protection systems (TPS) studied for possible application on the Space Shuttle is the alloy Haynes 188 as base material with diffusion bonding as the presently selected attachment process. Manufacturing engineering effort has produced many laboratory test structures constructed from this alloy and joined by diffusion bonding. These specimens were constructed for testing during the trade studies pursued to determine the baseline TPS for the SD Shuttle candidate. During these trade studies, ultrasonic NDE was conducted to determine the feasibility of utilizing this technology to determine the integrity of the diffusion bond. The results of this effort are directly applicable to the satisfaction of the objectives of this study. The basic purpose of the ultrasonic examination, once feasibility was established, was correlation with destructive testing to show the absence or presence of disbonds and delaminations in the diffusion bond.

A double box test panel overlapped in the middle, as shown in Figure A-10, was positioned in a laboratory ultrasonic bond inspection system equipped with C-scan or plan-view recording capabilities, utilizing longitudinal waves. The interface of the diffusion zone was held at 90 degrees to the face of the transducer. A C-scan was made using through-transmission reflector principles. The attenuation or absence of signal detected by the transceiver is shown by the white areas of the recording as pictured in Figure A-11.

After the ultrasonic recordings were made, the test panel was sectioned and divided into six separate pieces shown (see Figure A-11) as 2A, 2B, 2C, 2D, 2E, and 2F. The two narrow sections 2B and 2D were mounted, polished, and photographed. The two 75X macrospecimens indicate partial

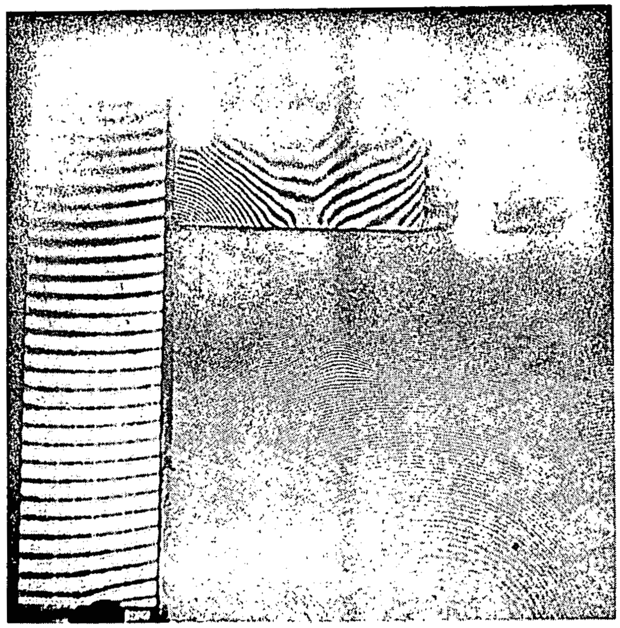


Figure A-9. Holographic Interferometric
Test Specimen Array

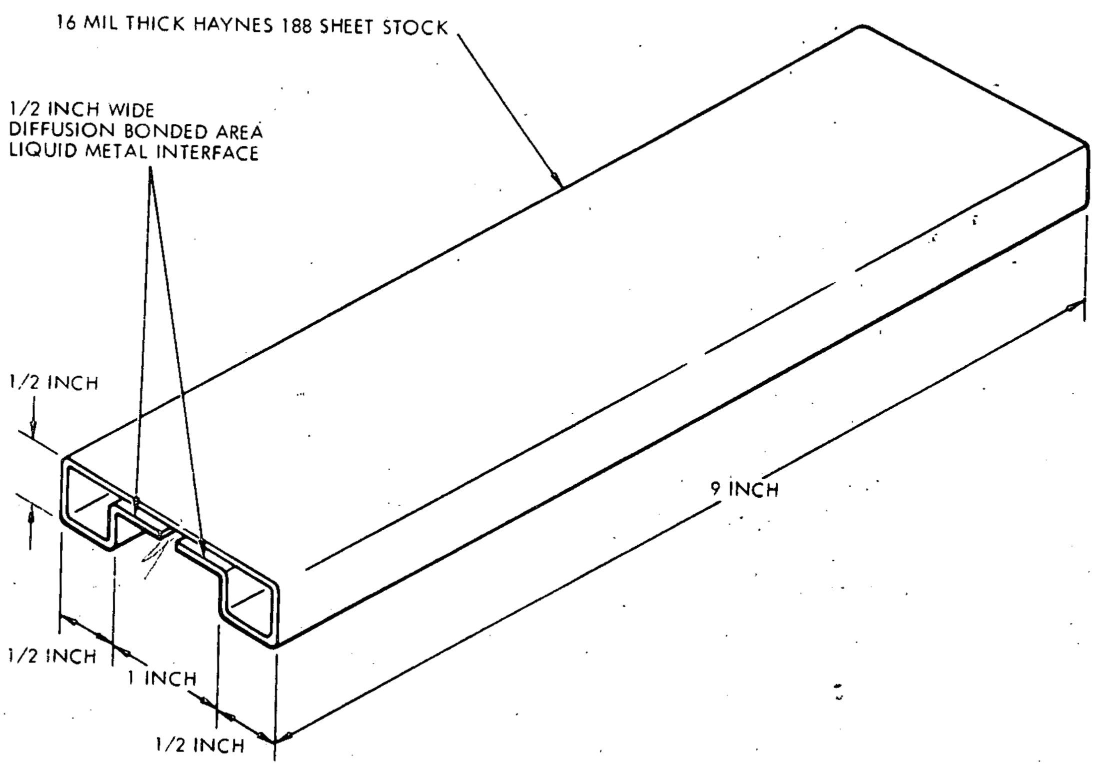
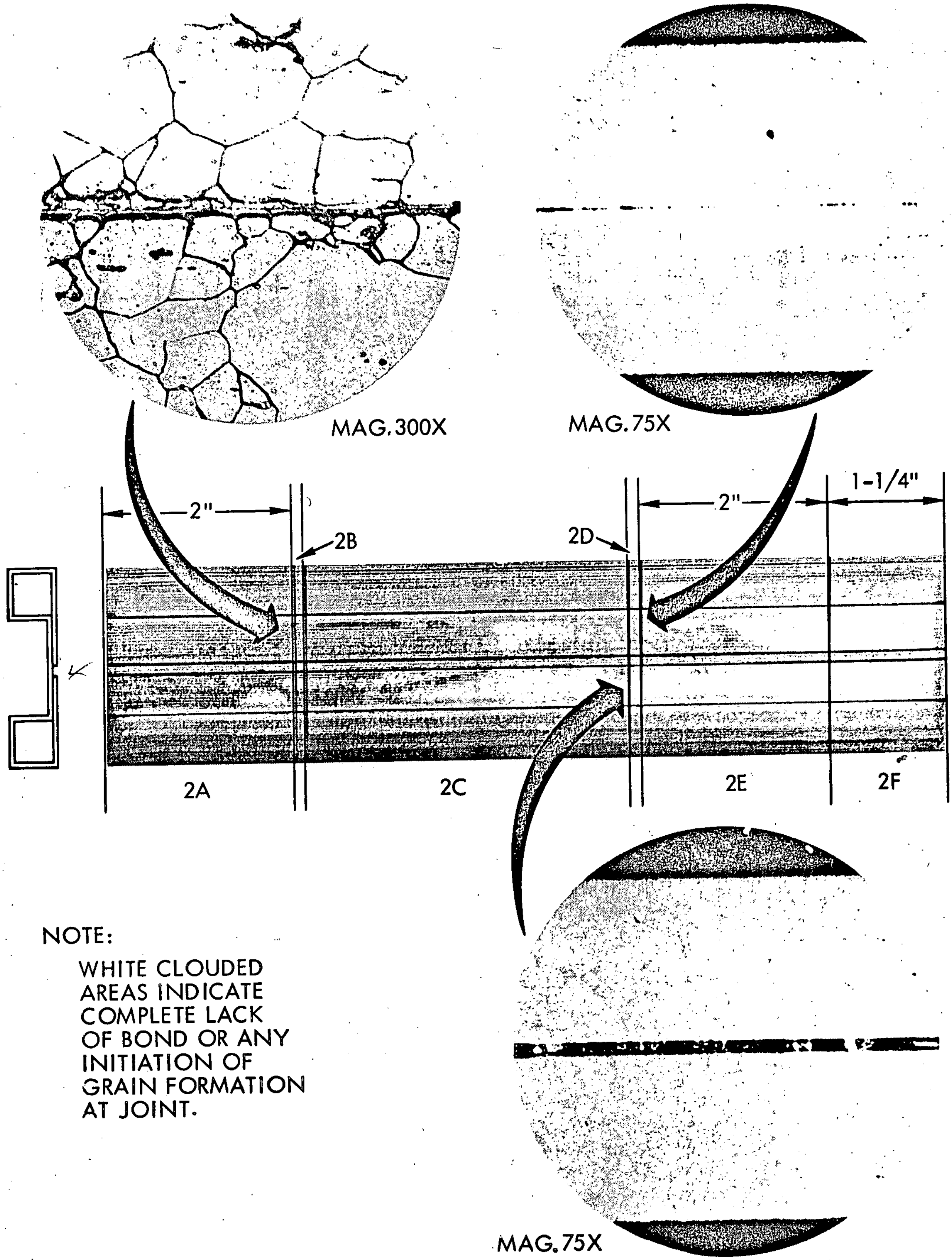


Figure A-10. Double Box Test Panel



NOTE:
WHITE CLOUDED AREAS INDICATE COMPLETE LACK OF BOND OR ANY INITIATION OF GRAIN FORMATION AT JOINT.

Figure A-11. Ultrasonic/Micrographic Analysis contact and complete separation respectively from top to bottom. This correlates well with the comparable ultrasonic recorded results. The 300X microspecimen 2B shows the diffusion zone with grain boundaries extending through the zone. This bond condition, although less than optimum, does correlate with the ultrasonic recorded results which are indicated as dark areas upon the C-scan recording.

At the ultrasonic sensitivity established for this nondestructive evaluation, the defective areas are readily apparent. The good to optimum areas, although shown as good, cannot be evaluated as to the degree of acceptability that they possess. The fussion zone, when complete, allows sound to propagate across the boundary without too much opposition to the zone impedance. However, the ultrasonic sensitivity can be adjusted to a level that is sensitive to the more subtle changes of a zone boundary impedance, provided reference standards can be established for control. Many times it is more difficult to fabricate the standards for accurate reference control than it is to detect the subtle inconsistencies. For this reason, it is an advantage to be able to evaluate test specimens nondestructively and destructively at the design stage. Feedback information of defect analysis related to future hardware will provide baseline information for acceptance standards. Fabrication of reliable acceptance standards with realistic defect sizes will help to optimize the NDE process to be used on Shuttle hardware.

ACOUSTIC EMISSION

Since internal cracking and delamination from substrates of foam-type insulation of pressure vessels will be a source of concern during Shuttle operations and maintenance, acoustic emission NDE was tested as a candidate method for rapid assessment. Preliminary tests were conducted using acoustic emission to monitor spray-on foam insulation (SOFI) used as test pressure vessel substrates. Initial tests indicated that there would be good transmission of sound through the foam although the transducer was mounted on the base metal. SOFI is a closed-cell material with entrapping air pockets; consequently it is an excellent thermal insulation.

After selective gain adjustments were made, extraneous motor and hydraulic pump noise were effectively eliminated from the acoustic signal. The SOFI-insulated test specimen was then placed in a tension tester with the transducer attached to the test specimen as shown in Figure A-12. A slowly increasing load (0 to 170 pounds) was applied to the test specimen. A definite precursor of imminent fracture was obtained eight minutes prior to failure through the cross section. Figure A-13 is a photograph of the plot obtained during the test. Explanation of the events are shown on the charts.

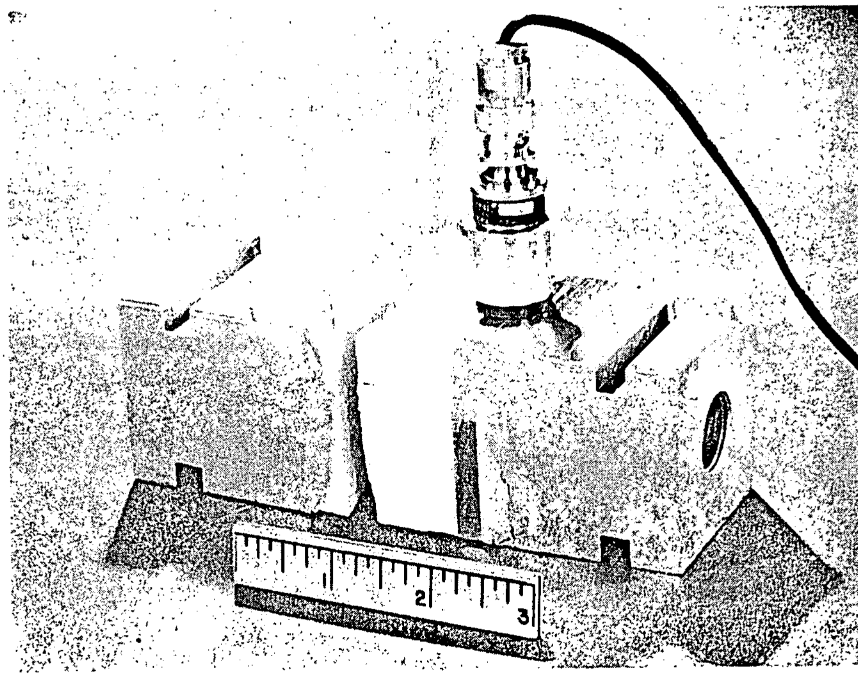


Figure A-12. Acoustic Emission Testing of SOFI Specimen

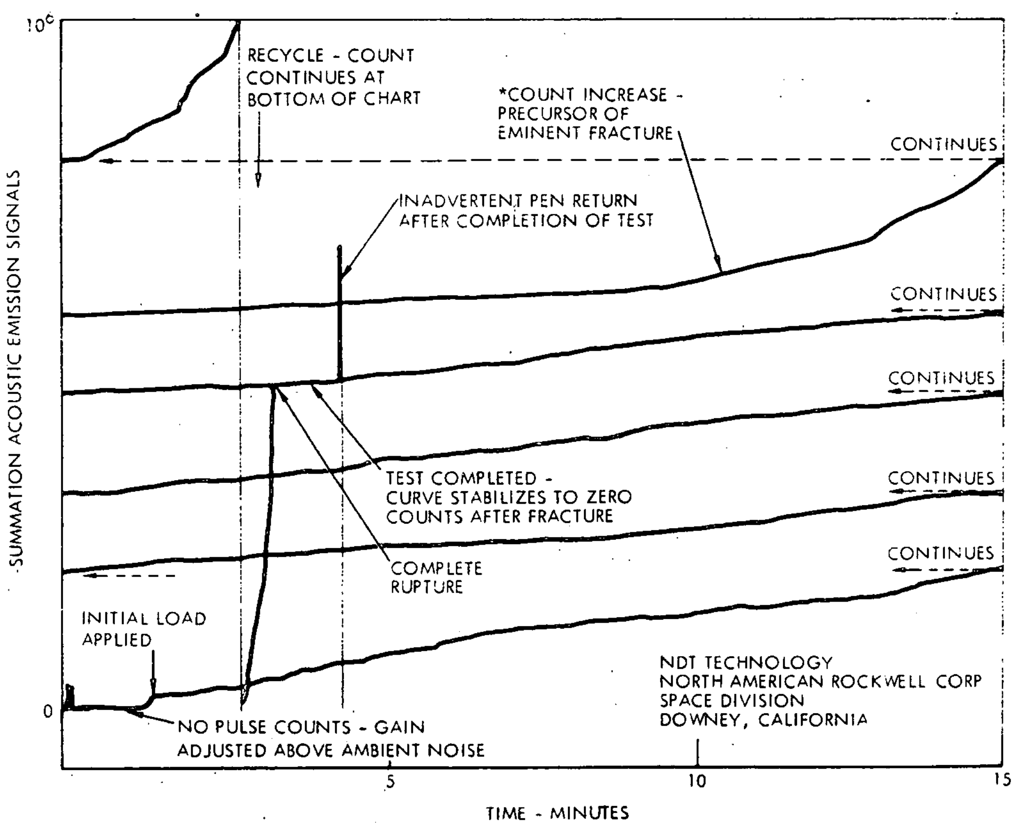


Figure A-13. Acoustic Emission Test Plot—SOFI Specimen

Three significant observations can be made from the work performed so far. The first is that it is possible to separate and ultimately eliminate ambient noise from information signals during testing. This was illustrated by the success in removing the noise of the motors and pumps of the tester during test. The ultimate goal in this area would be to develop acoustic emission methodology to operate if necessary during a high noise-level environment such as launch or landing. The second observation that can be made from this test is that it will be possible to successfully monitor foam insulation for early indications of failure. SOFI concepts are being proposed for the Shuttle vehicle and will be used most probably in insulating hydrogen storage and pressure containers. Acoustic emission will provide information during flight or on the ground which can be used as an indication of the quality of a specific structure.

THERMOGRAPHY

Cholesteric liquid crystals were evaluated as detection systems during the thermography evaluation. Several liquid crystal manufacturers were contacted in order to obtain information regarding their products. Table A-3 lists the organizations contacted and the major liquid crystal compounds they produce.

All the manufacturers basically offer materials in the bulk form with approximately equal temperature and sensitivity ranges. Although the bulk material can be encapsulated by the user, NCR offers their liquid crystals already encapsulated on either paper or mylar.

One of the primary problems with the use of liquid crystals as an NDE tool is that of providing an even application of thermal energy into the specimen being evaluated. Information on various heating methods was obtained from several suppliers (see Table A-4) so that different systems could be evaluated to locate the optimum methods for heating.

In conjunction with the manufacturers' information obtained from the literature search, many known applications and techniques for the use of liquid crystals as an NDE method were disclosed. All applications were basically similar in that they used bulk liquid crystals with infrared heat sources. No routine production usage of liquid crystals as a NDE method was known or anticipated by the users contacted.

A series of initial tests were conducted on a set of phenolic-aluminum-honeycomb test panels for familiarization as to materials and application techniques. The test panels consisted of one-half phenolic core and one-half

Table A-3. Liquid Crystal Manufacturers and Products

Manufacturer	Material Description
Vari-Light Corp. 9790 Conklin Road Cincinnati, Ohio 45242 513/714-6330	Bulk material 51 to 132 C, wide range
Pressure Chemical Co. 3419-25 Smallman St. Pittsburgh, Pa. 15201 412/682-5882	Bulk material -7 to 68 C, narrow ranges
Liquid Crystal Industries 460 Brown Ave. Turtle Creek, Pa. 15145 412/823-1500	Bulk material Zero to 154 C, narrow ranges Sheet form, memory-type crystal
Westinghouse Electric Corp Research and Development Center Pittsburgh, Pa. 15235 412/242-1500	Bulk material -3 to 106 C, narrow ranges
Distillation Product Industries Division of Eastman Kodak Co. 343 State St. Rochester, New York 14603	Bulk material 10 to 200 C, wide range
Capsule Products Division National Cash Register Co. Main and K Streets Dayton, Ohio 45409 513/449-2697	Slurry or encapsulated form 30 to 37 C, wide or narrow range
Peninsular Chemresearch Box 1466 Gainesville, Fla. 32601 904/376-7522	Typical types by chemical name and formula, bulk material
Frinton Laboratories Box 301 South Vineland, N. J. 08360 609/692-6902	Typical types by chemical name and formula, bulk material

Table A-4. Heating System Suppliers and Products

Suppliers	Product Description
Thermal Systems, Inc. 13920 S. Broadway Los Angeles, Calif. 90061	Heating blankets, printed circuit heaters, custom built to requirements
George W. Leseman Co., Inc. 1251 W. Redondo Beach Gardena, Calif.	IR heating units
Fostoria Corp. 1200 North Main St. Fostoria, Ohio	IR heating units
Biscot Manufacturing Co. P. O. Box 628 Columbus, Ohio 43216	Heating blankets, heating tapes, heating jackets
Wall Manufacturing P. O. Box 3349 Kinston, N. Carolina 28501	Small point hot air guns

aluminum core, with face sheets of 0.020-, 0.040-, 0.062-, 0.080-, and 0.100-inch aluminum corresponding with 2-, 4-, 6-, 8-, and 10-ply phenolic face sheets on the opposite side. Each panel contained four sets of face sheets to core adhesive cutout voids of 1/4 inch, 1/2 inch, 1 inch, and 2 inches, with two sets of voids on either side of the panel. All the tests were conducted with the liquid crystals on the phenolic face sheet, which was designated as the top surface. The results of these tests with respect to defect size and location in relation to face sheet thickness and heating technique are shown in Table A-5.

The following conclusions were made as a result of these initial familiarization tests:

1. Top and bottom surface heating can be utilized for the location of top surface defects.

Table A-5. Void Size Detectable by Heat Method

Panel Face Sheet Dimension	Heating Method		
	Heat From Top Surface	Heat From Bottom Surface	Oven Heat Air Gun Cool-Top
0.020-inch 2-ply	1/4-inch top 1/4-inch bottom	1/4-inch top 1/2-inch bottom	1/2-inch bottom
0.040-inch 4-ply	1/4-inch top	1/4-inch top 1/2-inch bottom	1/4-inch top
0.062-inch 6-ply	1/4-inch top 1/2-inch bottom	1/4-inch top 1/2-inch bottom	1/2-inch top
0.080-inch 8-ply	1/4-inch top 1/2-inch bottom	1/4-inch top 1/2-inch bottom	1/2-inch top
0.100-inch 10-ply	1/4-inch top 1-inch bottom	1/4-inch top 1/2-inch bottom	1/2-inch top

2. Increased bottom surface defect detectability can be obtained from bottom surface heating.

3. Increased sensitivity and defect definition can be obtained by thermal pumping techniques, such as back surface heating and front surface cooling.

4. Even coating thickness is required when utilizing bulk liquid crystals.

5. Vacuum hold-down of encapsulated liquid crystals is required to eliminate uneven surface contact, which can cause false indications.

6. Encapsulated liquid crystals possess longer life, increased color brightness, and freedom from atmospheric contamination when compared to the bulk liquid crystals.

Typical results of liquid crystal thermography on the phenolic aluminum panels can be seen in Figure A-14. The photograph was taken of a test on a 0.020-inch aluminum face sheet and 2-ply phenolic face sheet honeycomb panel, which had encapsulated liquid crystal in the 35 to 36 C temperature

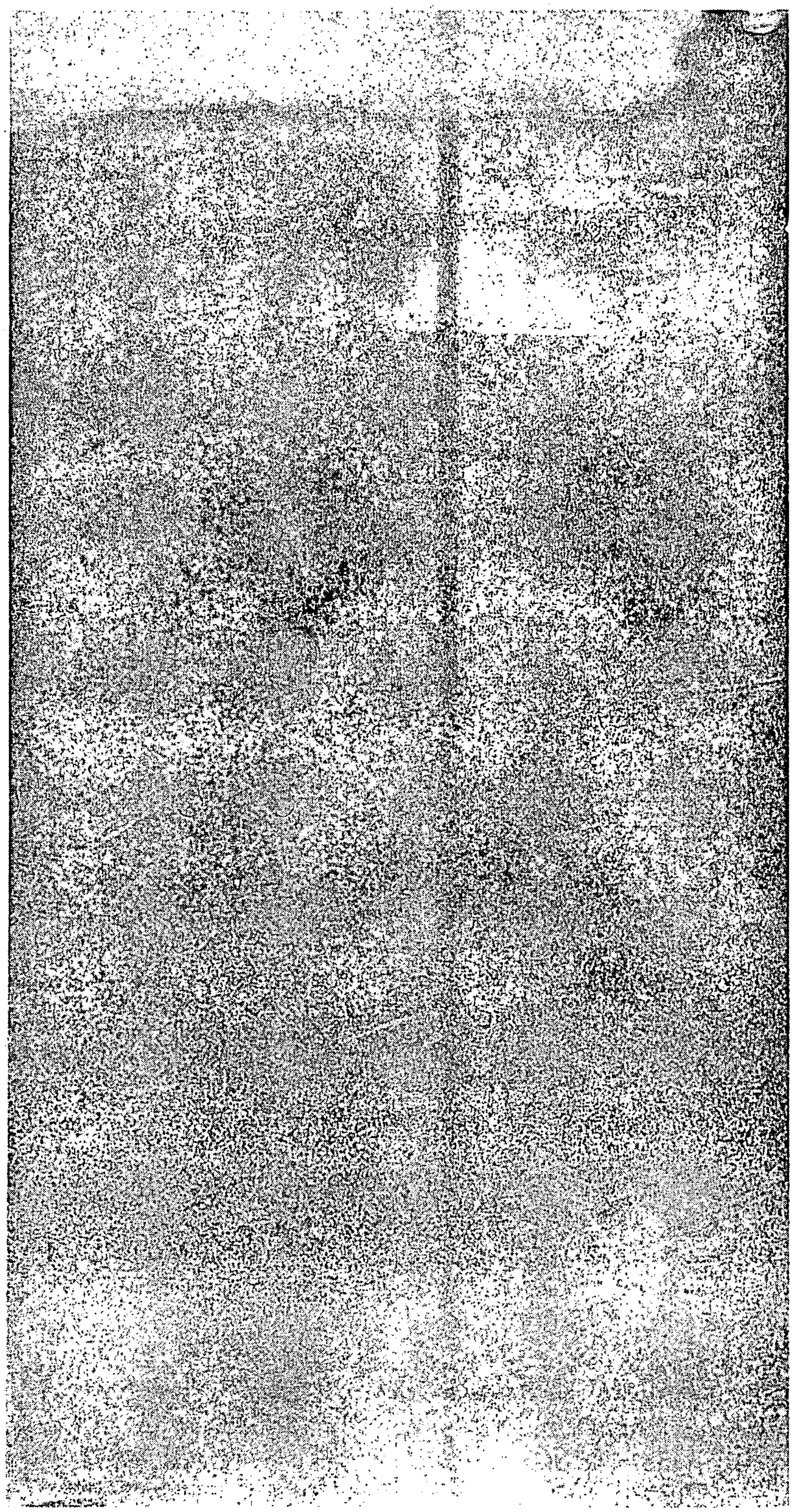


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Figure A-14. Bondline Voids/Liquid Crystal Thermography sensitivity range bonded to the phenolic face sheet. A quartz lamp IR heater, 12 inches from the rear surface, and an input voltage of 120 volts were used as the heat source. The photograph in Figure A-14 was taken during the early portion of the color transformation. Voids of 2 inches, 1 inch, 1/2 inch, and 1/4 inch can be seen at the edge of the panel.

Upon completion of the initial familiarization tests, several types of candidate Shuttle configuration test specimens were used to evaluate various liquid crystal thermographic techniques. The test procedure and results are detailed in the following sections.

Diffusion-Bonded Columbium Panel

A tee configuration diffusion-bonded columbium panel with known disbonds in the center tee was evaluated using liquid crystal thermography. Encapsulated liquid crystals with a 35 to 36 C color transformation range were bonded to the panel top face sheet. A quartz lamp IR heater, using one lamp at 130 volts, was placed 12 inches from the rear surface as the thermal source. The disbond could be detected as a result of its slower color change in response to thermal energy being transmitted up the tee leg to the top face sheet. The results of this test are shown in Figure A-15.

Brazed Haynes 188 Panel

A brazed Haynes 188 hot structure test panel was used to determine if liquid crystal thermography could locate small unbrazed areas, which had previously been located with ultrasonic C-scan techniques. Because of the surface configuration of the panel, a bulk liquid crystal was utilized. The surface of the panel was coated with an ultra-flat black paint and a 35 to 37 C color transformation range crystal was applied by spraying. Thermal inputs were provided by a quartz lamp IR heater at various distances from the panel surfaces. Four quartz lamps were energized at various voltages in three heating techniques (front surface heat, back surface heat, and back surface heat in conjunction with front surface cooling). In addition, two 1000-watt photographic lights were used from the front surface for a slow heat input. None of these small braze voids could be seen.

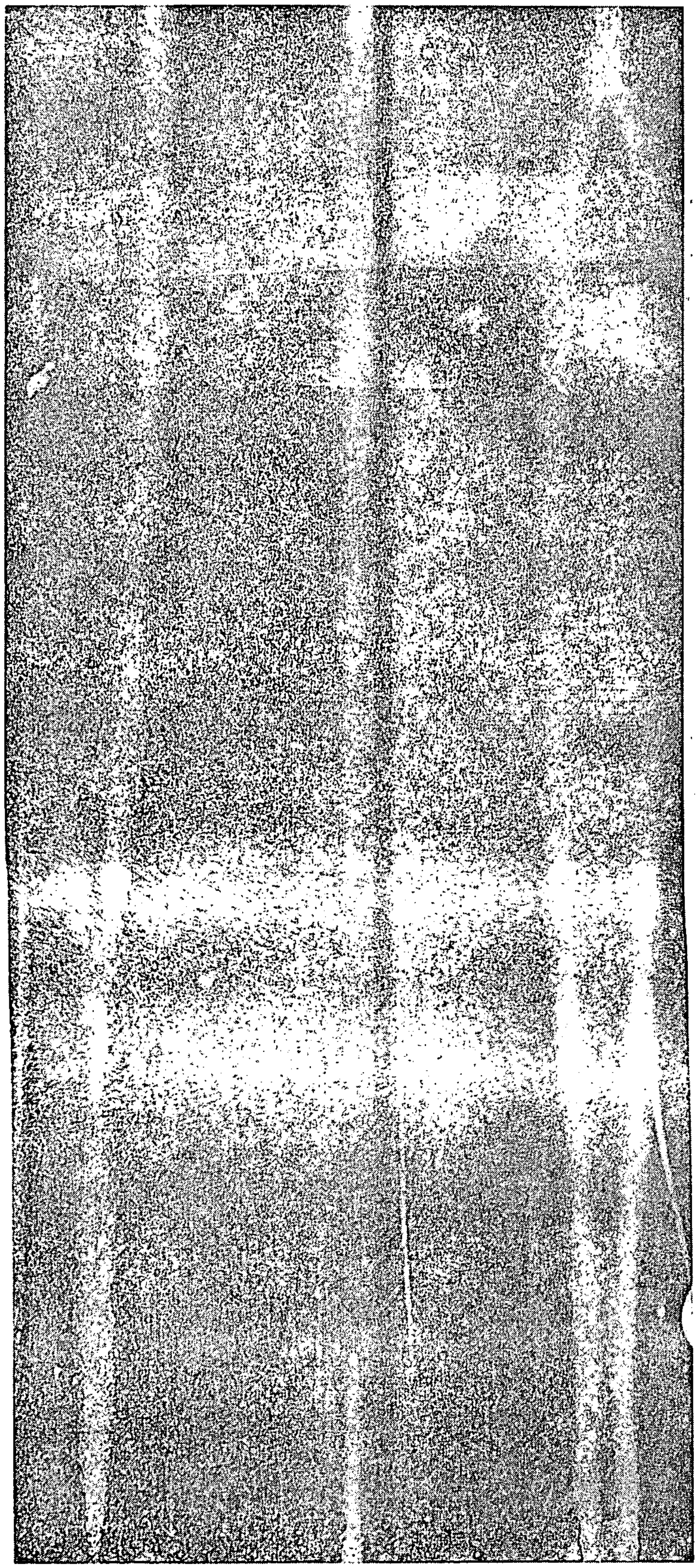

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Figure A-15. Liquid Crystal Thermography of Diffusion Bonded Panel

APPENDIX B

SPECIFICATIONS

APPENDIX B. SPECIFICATIONS

NDE hardware and predevelopment specifications have been generated to satisfy design criteria requirements of the contract. Following the format of NP500-1, detailed specifications for the 12 NDE methods follow.

1. On-board optical NDE methods
2. On-board ultrasonic NDE methods
3. On-board radiographic NDE methods
4. On-board acoustic emission NDE methods
5. Radiographic facility
6. Ultrasonic ground support
7. Electromagnetic NDE techniques
8. Penetrant facility
9. Holographic interferometric facility
10. Acoustic emission ground support
11. Thermographic NDE facility
12. Fiber optics for ground support

Liberal use has been made of the designations EST (estimated) and TBD (to be determined). This reflects both labor and state of the art limitations inherent in this study. As the Space Shuttle design becomes firm, revisions of these specifications will yield more realistic and definitive requirements.

SPECIFICATION SSV-NDE-FO-OB

ON-BOARD FIBER OPTICS SYSTEM

1.0 SCOPE

This specification defines the performance and design requirements for the on-board optical nondestructive test system for the Space Shuttle structural integrity checkout system and establishes requirements for its design, development and test and is the single authoritative document stating the program technical requirements. All elements and contract end items of the on-board fiber optic system shall conform with the requirements specified herein.

The on-board fiber optics system includes those devices listed as follows:

1. Fiber optic devices

2. Boroscopes

3. Remote area surveillance devices

4. Optically aided visual inspection devices.

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. The on-board optical NDE system shall allow visual access and surveillance of all load-bearing structural member and critical

functional units which are not readily accessible and shall be one of the following:

a. Type I. Access ports and tracks shall be provided to permit visual access to critical Shuttle structures and functional components. This system shall involve minimal usage of on-board optical components. The tracks and tunnels shall be compatible with commercially available optical NDE equipment.

b. Type II. Optical systems including both the flexible and rigid types shall be provided to permit visual observation of inaccessible critical Shuttle structures and functional components. This system shall not involve usage of the on-board digital data bus, computer, or other Shuttle functional electronics.

c. Type III. Provisions for incorporation of optical systems including the possibility of an on-board closed circuit vidicon system shall be provided to permit visual observation of inaccessible critical Shuttle structures and functional components during the flight test program. The digital data bus shall be used to control and direct this optical system and an RF data bus shall be used to transmit images to a monitor which permits viewing by the Shuttle flight crew.

2. Rigid devices shall be used in preference to flexible ones.

3. The tunnels and tracks for the Type I system shall meet the following requirements:

a. Minimum diameter to clear optical device - 5/8 inch (EST)

b. Maximum distance to structure being viewed - 18 feet (EST)

4. The on-board optical components of the Type II and Type III systems shall meet one of the following requirements:

a. Maximum length - 6 feet (EST)
Minimum diameter - 1/4 inch (EST)
Maximum weight per foot of length - 3 grams (EST)
Rigid type minimum resolution - TBD
Flexible type minimum resolution - TBD

b. Maximum length - 12 feet (EST)
Minimum diameter - 1/2 inch (EST)
Maximum weight per foot of length - 10 grams (EST)
Flexible type minimum resolution - TBD
Rigid type minimum resolution - TBD

c. Maximum length - 18 feet (EST)
Minimum diameter - 5/8 inch (EST)
Maximum weight per foot of length - 12 grams (EST)
Flexible type minimum resolution - TBD
Rigid type minimum resolution - TBD

5. The vidicon optical imaging system shall meet the following:

   a. Standard raster scans shall be used. Object resolution shall be controlled by the field of view and object distance for the attached optical scope.

   b. The vidicon camera shall have access to an RF data bus as controlled by the digital data bus.

   c. The vidicon camera shall be capable of being switched to a maximum of 10 (EST) different optical channels.

   d. The number of vidicon optical centers shall be between 4 and 10 (EST)

6. All Shuttle structures shall be optically resolvable to the extent of one of the following:

   a. Gross damage - 1/4 inch or greater displacement (EST)

   b. Minor damage - 0.1 inches or greater displacement (EST)

   c. Major crack 0.050 inches or greater (EST)

   d. Minor crack 5 mil or greater crack discernible

7. Viewing accessories of the following capability shall be attachable to the far end of the scope:

   a. Direct vision forward

      Field of view - (a) 60 degrees to 70 degrees and/or (b) less than 10 degrees (EST)

b. Foroblique

Viewing angle - 45 degrees (EST)
Field of view - (a) 60 degrees to 70 degrees and/or (b) less than 10 degrees (EST)

c. Right angle

Viewing angle - 9 degrees (EST)
Field of view - (a) 60 degrees to 70 degrees and/or (b) less than 10 degrees (EST)

d. Retrospective

Viewing angle - 175 degrees (EST)
Field of view - 45 degrees to 50 degrees (EST)

8. The light sources used with fiber optics devices shall be one of the following:

a. Integral to scope attached to viewing end
Light intensity at exit - TBD

Wattage - 500 watts (EST)

b. Integral to scope attached to viewing end strobe type.

Light intensity exit - TBD
Strobe type - TBD
High intensity - TBD

c. Independent of scope, has own non-coherent light pipe train or has light source at end of inserted bundle

Minimum length - 18 feet (EST)
Maximum diameter - 1/4 inch (EST)
Light intensity - TBD
Wattage - TBD

9. The Type I system shall be supported by ground optical systems including appropriate fiber optics, rigid optics devices, etc., from a fiber optics crib operation. The Type II and Type III optical systems shall require minimal ground support equipment. These on-board optical systems shall be used by ground support crews to visually inspect inaccessible Shuttle vehicle areas.

10. Trained inspection personnel shall be capable of using the optical systems with the aid of an operating handbook which shall be originated and maintained by optical laboratory personnel.

3.1.2 Program Definition

The on-board optical system shall consist of part or all of the following subsystems:

1. Optical access tunnels
2. Optical entry ports
3. Optical transfer lines
4. Vidicon optical information access module
5. Optical lighting system
6. Radiofrequency data bus
7. Optical digital data bus interface
8. Optical/computer interface equipment
9. Data display/optical monitoring system interface equipment
10. Optical system/auxiliary power interface equipment
11. Communications/optical monitoring interface equipment

3.1.3 Operability

1. The on-board fiber optic system shall be designed for a performance life compatible with other on-board checkout systems (TBD).
2. Environmental standards which all on-board optics hardware shall be designed to withstand are as follows:

   a. Terrestrial

   Protected in "hangar" type atmosphere (TBD)

b. Space

Class I Environmentally controlled electronic bay

Temperature 40 - 120 degrees fahrenheit (EST)
Pressure 0.1 to 1.1 atm (EST) (TBD)

Class II On Protected Non-Environmentally Controlled Shuttle Vehicle Hardware (TBD)

3.2 Program Design and Construction Standards

1. The onboard optical equipment shall be to the greatest possible extent ruggedized commercial hardware.

2. The design and construction standards for the on-board optical equipment shall be consistent with the intended use and expected environmental conditions.

3.3 Requirements for Functional Area (TBD)

4.0 QUALITY ASSURANCE

4.1 Phase I Integrated Project Test Requirements

1. Developmental and qualification testing of this equipment shall be performed on test structures appropriately configured to represent typical Shuttle materials and structures. Such tests shall consist of functional demonstration of the fiber optics system

2. Demonstration of the on-board optical NDE system shall be accomplished on an engineering flight test Shuttle vehicle used in the horizontal flight test program.

SPECIFICATION SSV-NDE-ULT-OB

ON-BOARD ULTRASONIC NONDESTRUCTIVE EVALUATION SYSTEM

1.0 SCOPE

This specification defines the performance and design requirements for the on-board ultrasonic evaluation system for the Space Shuttle integrity checkout system and establishes requirements for its design, development, and test and is the single authoritative document stating the program technical requirements. All elements and contract end items of the ultrasonic system shall conform to the requirements specified herein. The on-board ultrasonic nondestructive evaluation (NDE) system is composed of the following elements.

1. Bonded in-place transducers
2. Bonded scanning transducers
3. Rotating ultrasonic wave directors
4. On-board Lamb wave ultrasonic evaluation
5. On-board ultrasonic phased arrays

The requirements contained in this specification shall be compatible with those for the launch/turnaround facility with respect to ultrasonic support and maintenance.

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. The on-board ultrasonic NDE system shall provide indications of defect origination (especially cracks) in selected critical metallic structures on the Space Shuttle Orbiter and Booster.

2. The on-board ultrasonic system shall be one of the following types:

   a. Appropriate ultrasonic transducers and sensors shall be built into the Shuttle vehicle and connected to external ports in the wheel wells, cargo bay, electronic bay, etc. By connecting appropriate ground support equipment, defects in the monitored structures shall be detectable.

   b. The on-board ultrasonic NDE system shall provide a method to record defect indications during flight for analysis upon landing at the launch/turnaround facility.

   c. The on-board ultrasonic NDE system shall meet all the requirements of (a) and (b) above. In addition, for selected structural elements, the on-board ultrasonic system shall provide in-flight indications of defect origination (especially cracks) to the Shuttle flight team on a scheduled sampling basis (once per 1/2 hour EST).

   d. The on-board ultrasonic NDE system shall have provisions for being directed and used by either the Shuttle flight team or by ground stations via telemetry.

3. The ultrasonic transducers shall be secured to appropriate Shuttle structures and be one of the following:

   a. Bonded in-place transducers: crystal piezoelectric chip

      $d_{33} = 3.7 \times 10^{-10}$ meter/volt minumum (EST)

      $d_{31} = -1.7 \times 10^{-10}$ meter/volt maximum (EST)

      $d_{15} = 5.8 \times 10^{-10}$ meter/volt minimum (EST)

g_{33} = 24.8 x 10^{-3} (volt/meter)/Newton minimum (EST)

g_{31} = 11.4 x 10^{-3} (volt/meter)/Newton maximum (EST)

g_{15} = 38.0 x 10^{-3} (volt/meter)/Newton minimum (EST)

Mechanical Q = (TBD)

Resonant frequency 1.0 or 2.25 or 5 MHz (Est)

Size

(1) Angle 45 degrees shear (EST)

1/2 inches by 3/4 inches maximum
3/4 inches high max. (EST)

(2) Compression flat

3/4 inches diameter maximum
1/8 inches max. height (EST)

Weight

(1) Angle

25 grams maximum (EST)

(2) Compression

4 grams maximum (EST)

Connector - microminiature microdot (EST)

b. Rotating ultrasonic wave director

(Scan mode only)

Crystal - piezoelectric chip

d_{33} - 3.7 x 10^{-10} meter/volt minimum (EST)

g_{33} - 24.8 x 10^{-3} (volt/meter)/Newton minimum (EST)

Mechanical Q - 75 maximum (EST)

Frequency - 2.25 MHz (EST)

Type of drive for movement (TBD)

Transducer angle:

(1) Critical angle for Lamb wave propagation in material to which it is attached (TBD).

(2) Shear wave angle for propagation in material to which it is attached (TBD).

(3) Surface wave angle

Weight - 6 ounces or less (EST)

Size - 2 inch diameter maximum; 1-1/2 inch high (EST)

Operation - to transmit or receive only

c. Rotating ultrasonic wave director (signature comparison mode)

Crystal - piezoelectric chip

d_{33} - 3.7 x 10^{-10} meter/volt minimum (EST)

g_{33} - 24.8 x 10^{-3} (volt/meter)/Newton minimum (EST)

Mechanical Q - 75 maximum (EST)

Frequency - 1, 2.25, or 5 MHz (EST)

Electric motor drive (EST)

Preamplifier attached (TBD)

Disc recorder (TBD)

Angle - adjustable

Weight - 12 ounces or less (EST)

Size - 2-1/2 inch diameter maximum (EST)
- 2-1/2 inch high maximum (EST)

d. Rotating ultrasonic wave director (pulse echo mode)

Same as (b) above. In addition, two isolated chips shall be present in rotating head to allow pulse-echo type operation.

4. The sensitivity of the on-board ultrasonic systems shall conform to one of the following categories:

a. Short-range pulse echo to detect 0.060 inch hole 18 inches from detector (EST).

b. Shear wave pulse and receive pair to detect 60-mil hole 36 inches from detectors on centers (72 inches) (EST).

c. Lamb Wave pulse and receive pair to detect 1/8 inch hole 24 feet from detector on center (EST).

d. Surface Wave (TBD)

5. The pulser-receivers used to activate the sensor-transducer system shall conform to the following requirements:

a. Operating frequencies: 1, 2.25, and 5 MHz (EST)

b. Pulse repetition rate:

50, 125, 250, 500, 1250, 2500, or 5000 pulses per second (EST)

c. No vidicon display - real time signal data will be converted to digital format and computer analyzed.

d. Output voltage:

1 kv minimum at 1 amp (EST)

e. Output power: 15 to 25 watts (EST)

f. Pulse rise time: less than 9 nanosecond (EST)

g. Pulse fall time: less than 12 nanosecond (EST)

h. Size: 8-1/2 inches by 8-1/2 inches by 11 inches maximum (EST)

i. Weight: 10 pound maximum (EST)

6. On-board ultrasonic wiring and switching network (TBD)

3.1.2 Program Definition

1. The ultrasonic ground support laboratory shall be capable of repairing and maintaining on-board and at-site ultrasonic checkout gear by ordering replacement components and parts from the approved suppliers.

2. The on-board ultrasonic system shall be capable of fully automated operation with appropriate connection of supporting ground support equipment. Computer analysis programs shall be generated where necessary to analyze and interpret system response.

3.1.3 Operability

1. The on-board ultrasonic NDE system shall be designed for a performance life compatible with other on-board checkout systems (TBD).

3.2 Program Design and Construction Standards

1. The on-board ultrasonic equipment shall be ruggedized commercial hardware as far as is possible.

2. The design and construction standards for the on-board ultrasonic equipment shall be consistent with the intended use and expected environmental conditions.

3. All transducers of the same type shall be interchangeable. Transducer design shall be specified in a more complete manner in lower level specifications.

3.3 Requirements for Functional Area (TBD)

4.0 QUALITY ASSURANCE

4.1 Phase 1 Integrated Project Test Requirements

4.1.1 Development and Qualification Testing

Development and qualification testing shall be performed on test structures appropriately configured to represent typical Shuttle materials and structures. Such tests shall consist of two types:

Type I - functional demonstration of transducer design

Type II - functional demonstration of ultrasonic interfacing equipment configured to simulate ultrasonic on-board interfacing concepts

4.1.2 Demonstration

Demonstration of the on-board ultrasonic NDE system shall be accomplished on an engineering flight test Shuttle vehicle used in the horizontal flight test program.

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SPECIFICATION SSV-NDE-PRT-OB

ON-BOARD RADIOGRAPHIC TUNNELS AND TRACKS

1.0 SCOPE

This specification defines the performance and design requirements for on-board radiographic tunnels for the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test and is the single authoritative document stating the program technical requirements. All elements and contract end items of the on-board radiographic system shall conform with the requirements specified herein.

On-board radiographic tunnels detail those NDE requirements which are generally recognized as follows:

1. Isotope tunnels
2. Film tunnels
3. Radiographic access ports

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

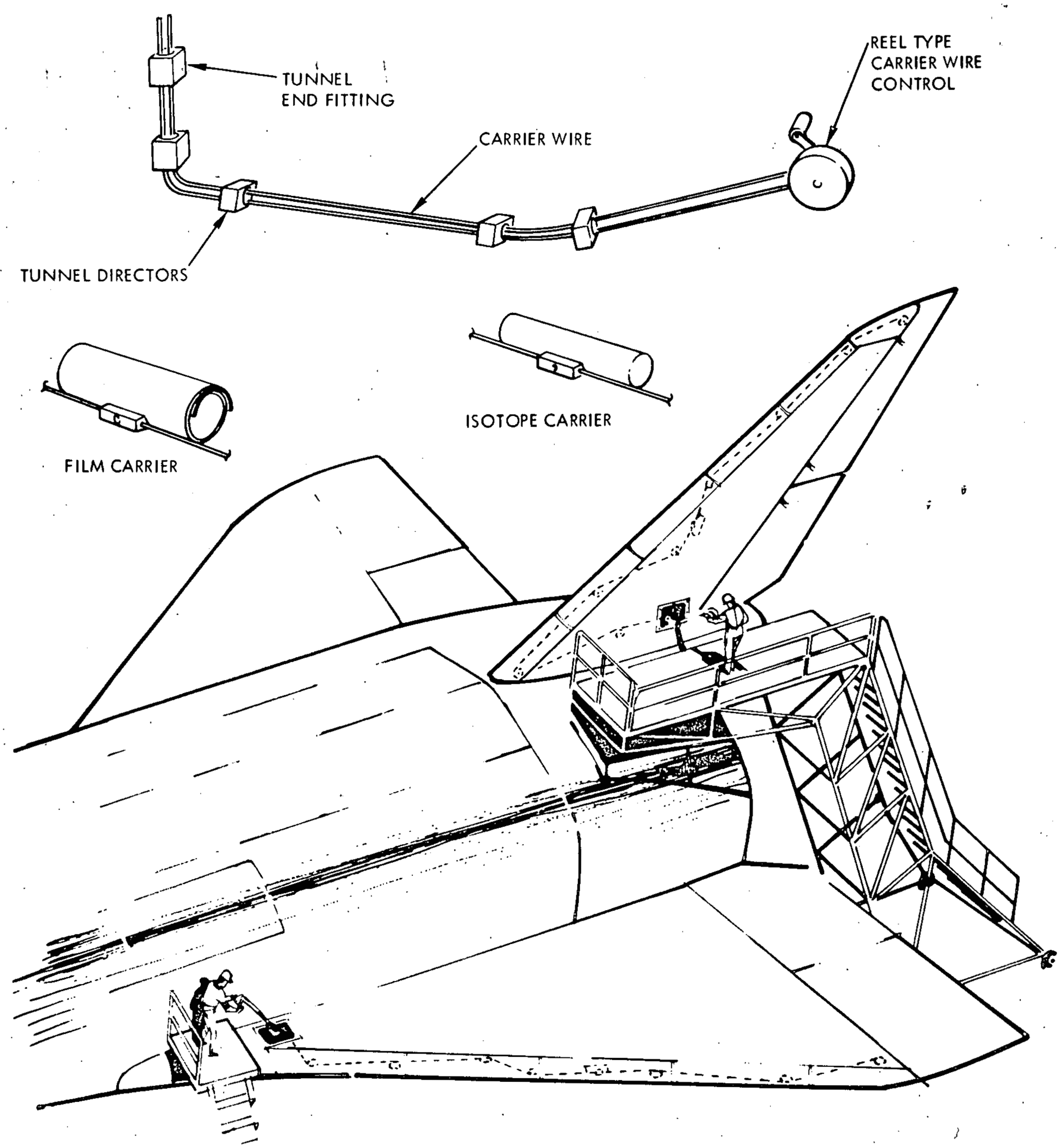
3.1 Performance

3.1.1 Characteristics

1. The on-board radiographic tunnel system shall provide tunnels and/or tracks for inserting and removing film and/or isotope camera ends into selected areas of the Space Shuttle vehicle in order to obtain radiographs of selected critical structures on the Shuttle vehicle.

2. The on-board radiographic tunnel systems shall be hand operated and self-contained with respect to moving and locating the film or isotope within the Shuttle vehicle.

3. The hardware necessary to attach the tunnel system shall be of one standard configuration and universally used. Overall tunnel hardware configuration concepts are as shown.



Tunnel Hardware Configuration Concepts

4. Specific on-board radiographic hardware requirements are as follows:

   a. Carrier wire

      Maximum Length - TBD

      Weight - TBD

      Support requirement - 500 grams min. (EST)

      Tunnel directors - 2 to 3 foot centers or as necessary (EST) to follow contour

      Minimum clearance above wire - TBD

   b. Tunnel directors

      Maximum size - 1/2 inch cube (EST)

      Maximum weight - 2.0 grams (EST)

   c. Carrier cartridge

      Application - film or isotope

      Maximum size folded - 3/4 inch high (EST)
      12 inches long (EST)
      2 inches wide (EST)

      Unfolded clearance - 2 inches height (EST)
      8 inches wide (EST)
      12 inches long (EST)

      Maximum allowable weight - 50 grams (EST)

   d. Tunnel end fittings

      Movement - reel type

      Maximum size - 1 inch wide (EST)
      1/2 inch high (EST)
      1-1/2 inches long (EST)

      Weight - 15 grams maximum (EST)

5. The isotope camera used with the on-board isotope tunnel system shall meet the following requirements:

   a. Source - Americium 241, 1 curie (EST)

   b. Tube end - attachable to tunnel isotope carrier

   c. Tube length - 30 feet (EST)

6. The X-ray machine used with the on-board film tunnel system shall meet the following requirements:

   a. Voltage - 150 kv or 100 kv min (EST)

   b. Shielding - TBD

   c. Maximum jacking height - 0 to 8 feet (EST)

   d. Maximum weight - 25 pounds (EST)

7. All equipment and operations shall meet state and federal radiological requirements as applicable.

8. The system shall be designed such that all maintenance and repair activities may be performed at the turnaround site.

9. Personnel and training - Personnel authorized to operate the radiographic system shall be trained in radiological safety by a radiological safety officer who shall originate and coordinate such activities. Laboratory personnel shall be responsible for operating and maintaining the on-board radiographic system. This group shall be the same as the group responsible for on-site radiographic NDE.

3.1.2 Program Definition (TBD)

3.1.3 Operability

1. The on-board radiographic system shall be designed for a performance life compatible with other on-board checkout systems.

2. The radiographic NDE ground support team shall maintain the on-board radiographic hardware.

3. Safety - Radiological safety standards per the USA AEC Code of Federal Regulation Title 10 and applicable state codes shall be adhered to.

3.2 Program Design and Construction Standards

The design and construction standards for the on-board radiographic equipment shall be consistent with the intended use and expected environmental conditions.

4.0 QUALITY ASSURANCE

4.1 Phase I Integrated Project Test Requirements

1. Developmental and qualification testing shall be performed on test structures appropriately configured to represent typical Shuttle materials and structures. Such tests shall consist of functional demonstration of tunnel design.

2. Formal qualification of the on-board radiographic NDE system shall be accomplished on an engineering flight test Shuttle vehicle during the horizontal flight test program.

SPECIFICATION SSV-NDE-AE-OB

ON-BOARD ACOUSTIC EMISSION SYSTEM

1.0 SCOPE

This specification defines the performance and design requirements for the on-board acoustic emission for the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test and is the single authoritative document stating the program technical requirements. All elements and contract end items of the on-board acoustic emission system shall conform with the requirements specified herein.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. This system shall provide a means of detecting incipient structural failure of selected critical structures.

2. The launch/turnaround site shall have supporting facilities which are compatible with and complementary to the requirements which have been established in this specification.

3. The acoustic emission monitoring system shall be one of the following:

   a. The acoustic emission system shall provide a flight record of all NDE indications, the severity of the indications, which probe gave the indication, and at what point in the flight that indication occurred. Analysis of the acoustic emission flight record shall be accomplished at the launch/turnaround site.

b. The acoustic emission system shall meet all the requirements of (a) above. In addition, in-flight monitoring by the system shall be provided to allow scheduled cursory monitoring with the status telemetered to ground stations and/or displayed for flight crew observation during the flight test program.

c. The acoustic emission system shall meet all the requirements of (b) above. During flight test, there shall be provisions for an in-flight access system to allow determination of the sensor location and the sensor indication history for the flight in progress upon command from either ground stations, on an unscheduled telemeter command basis, or a flight crew command.

4. Sensor transducers shall be of the high sensitivity piezoelectric type as follows:

<u>sensitivity</u> - 200 millivolt per 32.4 pounds/sec^2 of force (EST)

<u>resonant frequency</u> - TBD

<u>frequency range</u> - 0 to 0.5 MHz minimum (EST)

<u>size</u> - 0.5-inch diameter maximum; 0.375-inch high maximum (EST)

<u>weight</u> - 4 grams maximum (EST)

<u>operating temperature range</u> -

Type I 50 degrees to 300 degrees F (EST)

Type II 50 degrees to 700 degrees F (EST)

Type III 400 degrees to 300 degrees F (EST)

<u>connector</u> -- microminiature microdot

5. The preamplifiers for the acoustic emission system shall be of the high gain - low noise type as follows:

<u>gain</u> - 40 db minimum (EST)

<u>noise</u> - 5-microvolt noise equivalent maximum peak to peak (EST)

<u>size</u> - 0.05 cubic feet maximum, 4 inches by 5 inches by 3 inches (EST)

<u>weight</u> - 8 ounces maximum (EST)

<u>frequency range</u> - to 300 kHz minimum (EST)

6. The amplifier-filter-accumulator electronic package shall be as follows:

<u>gain</u> - to 120 db minimum (EST)

<u>noise</u> - 50 microvolt noise equivalent maximum (EST)

<u>bandwidth</u> - adjustable to:

a. 50 to 100 kHz (EST)

b. 50 to 200 kHz (EST)

c. 50 to 300 kHz (EST)

<u>output signals</u> - 0 to 10 volts nominal (EST)

<u>input power</u> - 5 watts maximum (EST)

<u>weight</u> - 12 pounds maximum (EST)

<u>size</u> - 6 by 8 by 15 inches maximum (EST)

<u>operation</u> - digital

The acoustic emission switching and wiring network shall be as follows: TBD

7. The on-board acoustic emission monitoring system shall be completely automatic and self-contained. A ground support acoustic emission laboratory shall maintain, repair, and evaluate the on-board acoustic emission system.

3.1.2 Program Definition

1. The on-board acoustic emission system shall consist of the following elements:

a. Transducers

b. Preamplifiers

c. Amplifier/accumulator/filter drawer

d. Switching and wiring network

e. Acoustic emission/digital data bus interface

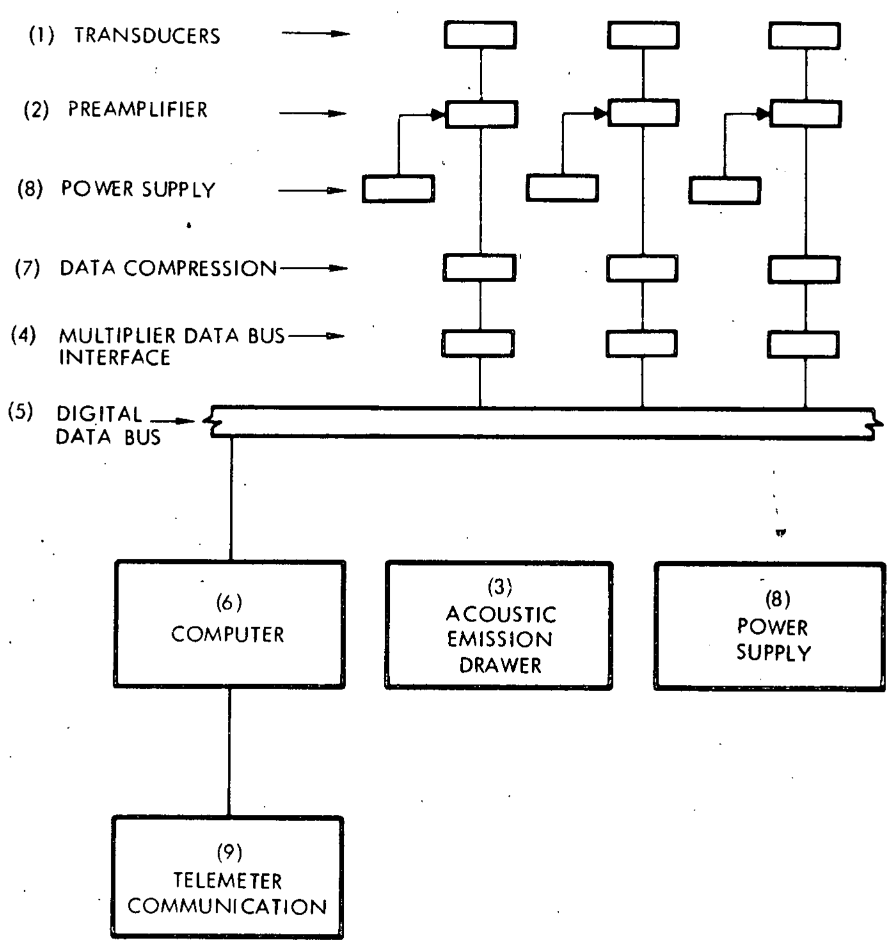
f. Acoustic emission/computer interface

g. Acoustic emission data compression

h. Acoustic emission/power supply interface

i. Acoustic emission/telemeter, communication interface

2. The on-board acoustic emission NDE system shall be functionally operative as shown



On-Board Acoustic Emission NDE System

3.1.3 Operability

1. The on-board acoustic emission system shall be designed for a performance life compatible with other on-board checkout systems (TBD).

2. The system shall be designed to be as maintenance free as possible.

3. Environmental conditions for the on-board acoustic emission system shall be as follows:

   sensor temperature - 40 degrees to 700 degrees F (EST)

   pressure - 0 to 15 pounds per square inch absolute (EST)

   electronics temperature - 60 degrees to 120 degrees F (EST)

   pressure - 5 to 15 pounds per square inch absolute (EST)

3.2 Program Design and Construction Standards

The on-board ultrasonic equipment shall be to the greatest extent possible rugged commercial hardware.

The design and construction standards for the on-board ultrasonic equipment shall be consistent with the intended use and expected environmental conditions.

All transducers of the same type shall be interchangeable. Transducer design shall be specified in a more complete manner in a lower level document.

4.0 QUALITY ASSURANCE

4.1 Phase I Integrated Project Test Requirements

1. Developmental and qualification testing shall be performed on test structures appropriately configured to represent typical Shuttle materials and structures. Such tests shall consist of two types:

   a. Functional demonstration (TBD)

   b. Functional demonstration of acoustic emission interfacing equipment configured to simulate acoustic emission on-board interfacing concepts.

2. Demonstration of the on-board acoustic emission NDE system shall be accomplished on an engineering flight test Shuttle vehicle used in the horizontal flight test program.

SPECIFICATION SSV-NDE-PR-GSE

RADIOGRAPHIC GROUND SUPPORT FOR TURNAROUND/ LAUNCH OPERATIONS

1.0 SCOPE

This specification defines the performance and design requirements for radiography in the Space Shuttle structural integrity checkout system and establishes requirements for its design, development and test and is the single authoritative document stating the program technical requirements. All elements and contract end items of radiographic ground support shall conform with the requirements specified herein.

Radiographic ground support for turnaround/launch operations details those NDE requirements designated as follows:

1. Conventional or X-ray radiography
2. Isotope radiography
3. Stimulated electron emission radiography
4. Beta backscatter measurements
5. Neutron radiography
6. Tagged autoradiography

The requirements listed in this specification include those necessary for ground support during turnaround and launch, and presume the existence of compatible and complementary on-board NDE requirements in the specification of the orbiter and booster design.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specification, standards, drawings, bulletins, and other publications are to be determined (TBD).

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. Radiographic ground support operations shall be responsible for and support the following functions:

    a. Radiographic inspection for proper location and for damage of inaccessible structures and functional units using the on-board access tunnels and radiographic tracks and in conjunction with appropriate X-ray machines, isotope cameras, and supporting equipment as specified herein.

    b. Radiographic inspection of line-removable units for internal flaws.

    c. Determination of the uniformity, thickness, and composition of changes in the surface of refractory metals due to oxidation or surface metal segregation using X-ray fluorescence, beta back-scatter, stimulated electron emissions, and/or tagged isotope auto-radiographic techniques and/or direct counting techniques.

    d. Repair and maintenance of on-board radiographic tunnels.

2. The radiographic support operation shall be capable of detecting the following type defects and conditions:

    a. Misalignment and displacement of structures and components of 1/8 inch, minimum (EST). Components shall be designated radiographically resolvable when the particular component or part thereof is shown to give a 5 percent or greater radiation attenuation change (between source and film locations) for the specified radiation (type and wavelength) relative to the total radiation attenuation along the source-to-film path. The total radiation attenuation shall be between 20 percent (EST) and 80 percent (EST) of unattenuated radiation with the same source and source-to-film distance calculation. Attenuation coefficients (in percent) shall be calculated from the following table where:

$$100\ I/I_o\ (\text{percent}) = e^{-\mu_1 \ell_1}\ e^{-\mu_2 \ell_2}\ e^{-\mu_3 \ell_3} \cdots e^{-\mu_i \ell_i} \cdots$$

and μ_i is the linear attenuation coefficient of the ith element and ℓ_i is the path length.

Source	Attenuation Coefficient				
	6Aℓ-4V Titanium	2219 Aluminum	Reinforced Pyrolyzed Plastic	Silicide Coated Columbium	etc.
150-v X-ray Be Window			TO BE DETERMINED		
300-v X-ray					
Thermal Neutrons					
Gamma Rays Ytterbium					
Gamma Rays Iridium					
Gamma Rays Americium					

b. Foreign material and corrosion when the foreign material or corrosion is shown to give 2 percent (EST) or greater radiation attenuation change.

c. Changes in the average surface layer (3 mils thickness, EST) atomic number of 3 or greater (EST).

d. Variations in amount of braze, liquid interface diffusion bonding, or adhesive material which results in a 2 percent (EST) or greater change in the radiation attenuation.

3. Fifty kilovolt X-ray machines shall meet the following requirements:

   a. Power input 115 volts, 60 Hz, 10 amps maximum (EST)

   b. Output capable of 10 milliamps at 50 kv (EST)

   c. Maximum head size
      weight: 9 pounds (EST)
      size: 3-inch diameter (EST)
      7-inch long (EST)

   d. Beryllium window with 1.8-mm focal spot size (EST)

   e. Minimum "tube to generator" cord length 50 feet (EST)

   f. Collimators and tube shields necessary to limit and direct the radiation in a 10 degree (EST) field of view shall be supplied.

4. One-hundred-and-fifty-kilovolt X-ray machines shall meet the following requirements:

   a. Power input 110 volt to 120 volt, 60 Hz, 25 amp maximum (EST)

   b. Output capable of 10 milliamps at 150 kv (EST)

   c. Maximum head size
      Weight: 20 pounds (EST)
      Size: 6-inches diameter by 18-inches long maximum (EST)

   d. Beryllium window with 1.5-mm focal spot size (EST)

   e. Minimum "tube to generator" cord length 30 feet (EST)

   f. Collimators and tube shields necessary to limit and direct the radiation in a 10 degree (EST) field of view shall be supplied.

5. Four-hundred-kilovolt X-ray machines shall meet the following requirements:

   a. Power input 220 volts, 60 Hz, 1 phase, maximum amperage TBD (EST).

b. Output capable of 10 milliamps at 400 kv minimum (EST).

c. Jigging and crane facilities for positioning head for use in lead-lined room shall be provided.

d. Lead-lined room approximately 20 feet by 20 feet shall be provided to allow safe operation of the 400-kv X-ray machine.

e. Maximum focal spot size shall be 4.0 mm (EST).

6. Isotope cameras of the following types shall meet the following requirements:

a. Isotope cameras (EST):

Type	Source Intensity	Half Life	Pellet Size	Pellet Focal Spot Size	Source Energy
Americium 241	50 millicuries and 200 millicuries (EST)	460 years	1/2 inch dia max (EST)	TBD	60 kv
Ytterbium 169	2 1/2 curies	32 days	TBD	2 mm	75 kv
Iridium 192	TBD	75 days	TBD	TBD	600 kv
Thulium 170	TBD	127 days	TBD	TBD	TBD

b. When the source is stored in the isotope camera, the total radiation intensity shall meet appropriate safety standards 5 millirems/hr at the surface (EST).

c. All cameras shall have an insert length of 3 to 30 feet (EST), with a maximum diameter of 5/8 inch (EST).

7. The neutron radiation source shall be of the reactor type with facilitized operation to meet the following requirements:

a. Minimum thermal neutron intensity level over a 2 foot by 2 foot (EST) window shall be $2x10^{+7}$ neutron/cm^2 per second (EST) at the film plane.

b. The gamma radiation intensity shall be less than 10 percent of neutron radiation intensity (EST).

c. The ratio between the maximum window diameter and the window to film plane shall be 6/1 minimum (EST).

d. Appropriate collimators, imaging screens, etc., shall be provided.

8. Portable beta-backscatter equipment shall meet the following requirements.

a. The sources listed in the following table shall be provided (EST):

Source	Beta Energy	Half Life	Radiation Intensity
Carbon 14	0.16 Mev	5600 years	TBD
Promethium 147	0.22 Mev	2.6 years	TBD
Thallium 204	0.77 Mev	3.5 years	TBD
Strontium/ Yttrium 90	2.18 Mev	19 years	TBD

b. Three-place digital readout shall be provided, with provision for directly inputting count value to the supporting computer terminals.

c. The device shall be capable of operating on 110 volts, 60 volts or as a self-contained battery-operated unit. Rechargeable batteries shall be used with recharging capability built into the unit for operation from the 110 volt, 60 Hz power outlets.

d. The devices shall be capable of providing accumulated counts over the following time intervals: 10 second, 1/2 minute, 1 minute, 5 minutes (EST).

e. The detector/source head shall be capable of portable operation on surfaces (TBD) and have a maximum weight of 5 pounds (EST).

9. X-ray fluorescence equipment shall meet the following requirements:

   a. The output shall be in digital format.

   b. The detectors shall be of the cryogenic lithium type (EST).

   c. Minimum detection limits are (TBD).

10. The automatic film developer and processor equipment shall meet the following requirements:

    a. Process film sizes up to 20-inch width (EST).

    b. Variable speed up to 30 inches of film per minute (EST).

    c. Maximum time to process film 5 minutes (EST).

    d. Operate on a 115 volt, 60 Hz power outlet.

11. A radiographic interpretation room shall be provided to meet the following requirements:

    a. High intensity lights (250-watts minimum (EST)) with 12-inch to 1-inch (EST) windows shall be provided for viewing radiographs.

    b. Appropriate radiographic standards shall be available (TBD).

    c. Light intensity levels shall be (TBD).

12. Logistics. The radiographic operations shall be operated from a shop-type facility. Laboratory personnel shall be responsible for establishing operating procedures, interpretating radiographs, and maintaining radiographic equipment.

13. Personnel and training. Only properly trained and certified operators shall be designated radiographic inspectors. Laboratory personnel shall have had appropriate training courses and experience and shall be responsible for the radiographic operations.

14. All radiographic equipment and facilities shall conform to all applicable local, state, and federal safety standards. Personnel shall be trained in radiation safety as required by the above safety standards and shall conduct radiographic operations accordingly.

3.1.2 Program Definition

1. The radiographic facilities shall be provided from appropriate commercial sources on an individual unit basis. Requirements for specialized test facilities requiring extensive construction or unusual building facilities shall be restricted to the neutron radiographic equipment and the lead-lined room for the 400-kv x-ray machine.

2. The radiographic facility shall consist of the following major components:

   a. Interpretation room

   b. Radiation machines

   c. Lead-lined room

   d. Film-processing facilities

   e. Neutron facility

3.1.3 Operability

The equipment shall be designed for a ten-year operation life.

3.2 Program Design and Construction Standards

1. All radiographic equipment with the exception of the neutron equipment shall be procured as single elements from appropriate commercial sources. The neutron facility shall be constructed by one general contractor who shall be responsible for meeting all intended operational and equipment requirements.

2. Construction standards (TBD)

4.0 QUALITY ASSURANCE

1. Detailed test plans shall be generated to provide for functional demonstration of equipment requirements as specified in Section 3.0 of this specification. These plans shall take into account past historical development of the equipment in the sense that functionally accepted practices need not be demonstrated while recently developed concepts and hardware must be proven. Simulated Shuttle test structures and test standards shall be used to demonstrate functionality where deemed necessary, as follows: (TBD).

2. A periodic maintenance and calibration schedule and operation shall be established and maintained to assure operational functionality of the test equipment.

   a. Maintenance and calibration schedules shall be based on defect trend data. Initial maintenance and calibration schedules are as recommended below: (TBD).

   b. Detailed test requirements for the equipment shall be primarily based on functional operation rather than on equipmental parameters.

   c. Preventive maintenance procedures shall be emphasized while calibration operations shall be minimized.

SPECIFICATION SSV-NDE-PEN-GSE

PENETRANT NONDESTRUCTIVE EVALUATION TECHNIQUES FOR GROUND SUPPORT DURING LAUNCH/TURNAROUND SHUTTLE OPERATIONS

1.0 SCOPE

This specification defines the performance and design requirements for the penetrant facility for the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test. This specification is the single authoritative document stating the program technical requirements. All elements and contract end items for the penetrant facility shall conform with the requirements specified herein. Penetrant ground support for turnaround/launch operations details those nondestructive testing requirements generally recognized as dye penetrant and magnetic particle methods.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. The penetrant ground support operation shall provide indications of surface cracking in appropriate structures of the Space Shuttle Orbiter and Booster. These structures shall be primarily metallic line removable units (LRU) where surface cracking is anticipated or suspected. Ground support penetrant operations shall primarily be accomplished as a facility operation as opposed to portable operations. Portable penetrant methods shall be available on an unscheduled basis only.

2. The penetrant techniques shall be capable of detecting the following types of surface cracks:

   a. Machined metallic structure cracks 0.006 inch minimum depth.

   b. Nonmachined metallic structure cracks 0.015 inch minimum depth.

   c. Nonmetallic, smooth, nonporous structure cracks 0.005 inch minimum depth.

   d. Nonmetallic, nonsmooth, nonporous, structure cracks 0.025 inch minimum depth.

   e. Penetrant methods shall not be used on porous structures such as polyurethane foam, etc.

3. The penetrant used on Space Shuttle hardware shall be one of the following types:

   I Low sensitivity, water washable

   II High sensitivity, water washable

   III LO_2 compatible

   All penetrants shall be of the fluorescent type.

4. The penetrant facility shall meet the following requirements:

   a. The operation shall be a tank and basket type of operation. Six tanks 60 inches by 40 inches by 36 inches deep shall be provided, two of which will be water spray tanks (EST).

   b. A darkened area 12 feet by 6 feet wide with appropriate work tables shall be provided for interpretation of inspection results.

5. Ultraviolet lamps shall be used to illuminate the fluorescent penetrant. The lamps shall be no more than 18 inches from the specimen being examined. The ultraviolet lamps shall meet the following requirements:

   a. Input power: 110 volts, 60 Hz

b. Minimum ultraviolet intensity (TBD)

c. Maximum light intensity outside ultraviolet range (TBD)

6. Portable magnetic particle equipment shall meet the following requirements: MIL-M-6867B.

7. The permanent magnetic particle machine shall meet the following requirements: MIL-M-6867B.

8. Appropriate demagnetization equipment shall be provided to meet the following requirements: MIL-M-6867B.

9. The penetrant ground support facility shall be operated from a shop facility. Laboratory personnel shall be responsible for establishing operating procedures and interpretation aids and developing new techniques. Penetrant shop operators shall be responsible for performing penetrant inspection and interpretation.

10. Operating booklets and detailed instructional manuals shall be generated to allow performance of penetrant operations by inspectors with minimal experience and training.

3.1.2 Program Definition

The primary purpose of the penetrant ground support operation shall be to provide a dye penetrant inspection facility for processing line removable units. Portable operations shall be minimal and performed on an unscheduled basis. Magnetic particle inspection operations shall be applicable to appropriate ferromagnetic materials where near subsurface cracking is suspected. For ferromagnetic materials where surface cracking is suspected, appropriate penetrant inspection operations shall be employed.

The penetrant facilities shall be procured as a single element composed of the following three major components:

Penetrant line
Interpretation room
Magnetic particle facility

3.1.3 Operability

The penetrant nondestructive evaluation system shall be designed to operate for ten years with minimal maintenance.

3.2 Program Design and Construction Standards

The penetrant facility shall be constructed by one general contractor who shall be responsible for meeting all intended operational and equipment requirements.

Construction standards are to be determined.

3.3 Requirements for Functional Areas

To be determined.

4.0 QUALITY ASSURANCE

1. Detailed test plans shall be generated to provide for functional demonstration of equipment requirements, as specified in Section 3.0 of this specification. These plans shall take into account the historical development of the equipment in the same sense that accepted functional practices need not be demonstrated but recently developed concepts and hardware must be proven. Simulated Shuttle test structures and test standards shall be used to demonstrate functionality, where deemed necessary, as follows: (TBD).

2. A periodic maintenance and calibration operation shall be scheduled and maintained to assure operational functionality of the test equipment.

3. Maintenance and calibration schedules shall be based on defective trend data. Recommended initial maintenance and calibration schedules are as follows: (TBD).

4. Detailed test requirements for the equipment shall be primarily based on functional operation rather than equipment parameters.

5. Preventive maintenance procedures shall be emphasized, and calibration operations shall be minimized.

SPECIFICATION SSV-NDE-HIT-GSE

HOLOGRAPHIC INTERFEROMETRIC TEST FACILITY FOR GROUND SUPPORT DURING LAUNCH/TURNAROUND SHUTTLE OPERATIONS

1.0 SCOPE

This specification defines the performance and design requirements for the holographic interferometric test facility of the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test. This specification is the single authoritative document stating the program technical requirements. All elements and contract end items of the Space Shuttle structural integrity checkout system for holographic interferometry shall conform with the requirements specified herein. The requirements contained in this specification detail those requirements necessary for high-speed inspection of thin-walled outer thermal protective system (TPS) structure and inspection for the attachment of the TPS for the Orbiter and Booster Space Shuttle vehicles.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. The holographic interferometric test facility shall consist of a laboratory room with vibration isolation/interpretation facilities and a portable rail track/holographic interferometric cart for deploying the holographic system around the space vehicle.

2. The holographic interferometric system shall be capable of exposing 50 square feet minimum (EST) of Shuttle vehicle outer skin in one exposure at a minimum rate of 120 square feet per hour (EST).

3. Holographic interferometric interpretation shall be a separate operation located in the holographic interferometric facilities room. A pair of matched, twin (or double) reference beam systems shall be employed. The holographic system shall be capable of the following:

   a. Operation at the ambient vibration level around the space vehicles at the turnaround site (double-exposure mode).

   b. Operation on a vibration-free isolation table in the holographic facilities room (real-time mode).

4. The holographic interferometric system shall be capable of giving useful images with exposure times in the 0.1 to 10 millisecond range.

5. The laser used in the holographic interferometric system shall meet the following requirements:

   a. Single-mode, continuous-wave operation: Argon burst output (EST).

   b. Minimum operational output power: 500 milliwatts (EST).

   c. Coherence length: 36 inches minimum (EST).

   d. Cavity length: 6 feet maximum.

   e. Light output in visible band: (TBD)

6. The optical components used in the holographic interferometric system shall meet the following requirements:

   a. Large Fresnel types of plastic lenses 5 feet in diameter (EST) shall be used to condense object beam light to give exposure in the 0.1 to 10 millisecond speed range.

   b. A double reference beam shall be used with an optical zoom type of lens in one leg to facilitate observations of deflections between 200 microinches and 1 inch.

   c. The beam splitter shall be of the continuous variable ratio type to facilitate maximum employment of available laser light.

d. The object and reference mirror shall be large enough, 4 inches (EST), to not limit the projected image area and shall be capable of fine adjustment on three axes: X linear, Y linear, and Z rotational (Z along optical axis).

e. All optical surfaces shall be 1/4 wave or better finish.

f. The film plate holder shall be capable of in-place development, 35-mm roll film exposure operation, or real-time external plate development (replaceable for real-time holography).

g. The optical component arrangement shall be as illustrated: (TBD).

7. The portable holographic inteferometric cart shall meet the following requirements:

a. Maximum weight: 5000 pounds (EST).

b. Maximum size: 8 feet by 6 feet by 10 feet high (EST).

c. Applicable requirements of items 1 through 7 of this paragraph.

8. The holographic interferometric ground support facility shall be operated from a laboratory facility. This laboratory shall be responsible for maintaining the holographic equipment, establishing operating procedures, and interpreting the holographic interferograms. Shop operation of the portable holographic interferometric cart shall be accomplished by trained inspection personnel following appropriate operating procedures. All development work and interpretation shall be done by laboratory personnel in laboratory facilities.

9. Personnel and training: Operating booklets and detailed instructional manuals shall be generated to allow operation by operators with minimal experience and training.

Laboratory personnel shall have had appropriate training courses and shall be responsible for the holographic inspection operation and the maintenance of systems and applications specifications.

3.1.2 Program Definition

The holographic interferometric facility shall be procured as a single element composed of the following three major components:

1. Laboratory room adjacent to operational area to allow storage and operation of the holographic cart either on or off a vibration-free isolation table.

2. Portable holographic interferometric cart.

3. Rail track system platform and jacking capability for directing the cart to any portion of either Booster or Orbiter Shuttle vehicle, to within 10 feet minimum (EST). This system shall allow control and operation by an inspector on the platform.

The functional interface between ground support operations shall be as illustrated: (TBD)

3.1.3 Operability

The holographic interferometric system shall be designed to operate for ten years with minimal maintenance.

3.2 Program Design and Construction Standards

The holographic interferometric system shall be constructed by contractors who shall be responsible for meeting all intended operational and equipment requirements.

Construction standards are to be determined.

4.0 QUALITY ASSURANCE

Detailed test plans shall be generated to provide for functional demonstration of equipment requirements, as specified in Section 3.0 of this specification. These plans take into account the historical development of the equipment in the sense that accepted functional practices need not be demonstrated but recently developed concepts and hardware must be proven. Simulated Shuttle test structures and test standards shall be used to demonstrate functionality, where it is necessary, as follows: (TBD)

A periodic maintenance and calibration schedule shall be scheduled and maintained to assure operational functionality of the test equipment.

1. Maintenance and calibration schedules shall be based on defect trend data. Recommended initial maintenance and calibration schedules are as follows: (TBD)

2. Detailed test requirements for the equipment shall be primarily based on functional operation rather than equipment parameters.

3. Preventive maintenance procedures shall be emphasized, and calibration operations shall be minimized.

SPECIFICATION SSV-NDE-IR-GSE

THERMOGRAPHIC NONDESTRUCTIVE EVALUATION GROUND SUPPORT TEST FACILITY

1.0 SCOPE

This specification defines the performance and design requirements for the thermographic nondestructive test facility of the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test. This specification is the single authoritative document stating the program technical requirements. All elements and contract end items of the thermographic nondestructive test facility shall conform with the requirements specified herein.

"Thermographic Nondestructive Test Ground Support" details those nondestructive testing requirements that are generally recognized as follows:

1. Liquid crystal NDT
2. Infrared NDT
3. Thermal NDT

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. The thermal nondestructive evaluation ground support devices shall provide surface temperature and/or emittance characteristics over appropriate Shuttle structures.

2. Variations in surface temperature as small as 0.2 F (EST) shall be detectable over the temperature range, zero to 500 F.

3. Liquid crystal film sheets shall meet the following requirements:

   a. Temperature ranges: TBD

   b. Sheet size: 24 inches by 36 inches minimum

   c. Reusable adhesive backing

   d. Black background part of film sheet

   e. Liquid crystal encapsulated type with 1/10 to 1/4 inch cell size

4. Thermal indicating paints shall meet the following requirements:

   a. Temperature of color change: 104, 554, 1184, 1832 F, and others (TBD)

   b. Nonreversible color change

   c. Brush application

5. Infrared scanning camera shall meet the following requirements:

   a. Liquid nitrogen cooled - indium antimonide detector shall be specified for operation to 350 F (EST); lead sulfide detector shall be specified for operation above 350 F (EST).

   b. Field-of-view: 60 by 60 degrees and 12 by 12 degrees (EST)

   c. Real-time operation, 16 frame-per-second minimum (EST)

   d. Range of focus: 4 feet to infinity (EST)

   e. Raster scan 100 lines per frame EST minimum, 100 elements per line EST minimum.

   f. Input power requirements 115 volt, 60 Hz, 3 amps maximum (EST)

   g. Object temperature level zero to 500 F

h. Thermal sensitivity 0.2 F minimum

i. Seven-tone gray scale shall be displayed as part of video image.

6. Appropriate thermal laboratory supporting equipment shall be provided to include:

   a. Silicon grease thermal couplant

   b. Heat guns

   c. Small spray paint gun

   d. Thermocouples and potentiometers

   e. Ovens and temperature-controlled baths

   f. Finch thermal conductivity hot plate

   g. Color portrait camera

   h. Appropriate heat sources and sinks

7. Logistics: The thermographic ground support operation shall be operated from a laboratory facility. Laboratory personnel shall be responsible for maintaining the thermographic equipment, establishing operating procedures, interpreting the thermographic images and profiles, and performing thermographic NDE inspection operations in the shop facility.

8. Personnel and training: Laboratory personnel shall have had appropriate training courses and shall be responsible for the thermographic inspection operation, maintenance of systems, and maintaining application specifications.

3.1.2 Program Definition

The thermographic laboratory facility shall consist of the following major elements:

1. Thermal sensing materials and equipment (including infrared camera)

2. Thermal sources and heat sinks

3. Camera and other data recording equipment

4. Thermal image standards and interpretation standards

3.1.3 Operability

The thermographic test facility shall be designed for a ten-year operational life.

3.2 Program Design and Construction Standards

All thermographic equipment shall be procured from appropriate commercial sources.

3.3 Requirements for Functional Areas

A thermographic NDE laboratory operation adjacent to vehicle turnaround inspection facility shall be responsible for the equipment and its usage (400 ft^2 (EST)).

4.0 QUALITY ASSURANCE

1. Detailed test plans shall be generated to provide for functional demonstration of equipment requirements as specified in Section 3.0 of this specification. These plans shall take into account past historical development of the equipment in the sense that functional accepted practices need not be demonstrated while recently developed concepts and hardware must be proven.

2. Simulated Shuttle test structures and test standards shall be used to demonstrate functionability where deemed necessary, as follows: (TBD)

3. A periodic maintenance and calibration schedule and operation shall be established and maintained to assure operational functionality of the test equipment.

4. Maintenance and calibration schedules shall be based on defective trend data. Initial maintenance and calibration schedules are as follows: (TBD)

5. Detailed test requirements for the equipment shall be primarily based on functional operation rather than equipmental parameters.

6. Preventive maintenance procedures shall be emphasized while calibration operations shall be minimized.

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SPECIFICATION SSV-NDE-FO-GSE

OPTICAL NONDESTRUCTIVE GROUND SUPPORT DURING LAUNCH/TURNAROUND OPERATIONS

1.0 SCOPE

This specification defines the performance and design requirements for optical nondestructive test ground support for the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test. It is the single authoritative document stating the program technical requirements. All elements and contract end items of the optical NDE system shall conform with the requirements specified herein.

"Optical Nondestructive Ground Support During Launch/Turnaround Operations" details those nondestructive testing requirements that are generally recognized as follows:

Fiber optics devices

Boroscopes

Endoscopes

Optically aided visual inspections

The requirements as detailed herein are complementary to compatible requirements in the design specifications for the orbiter and booster. They principally relate to assembly and location of entry ports. It is the intent of this specification to set forth equipment requirements that are compatible with existing commercial hardware yet meet specific detailed Space Shuttle requirements.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. Optical nondestructive test ground support devices shall provide visual access where required, to all Shuttle vehicle structures not accessible by visual inspection techniques.

2. Damage or defects occurring in Shuttle structures shall be resolvable with the fiber optic device as described by one of the following four categories:

   a. Gross damage, 1/4 inch or greater displacement

   b. Minor damage, 0.100 inches or greater displacement

   c. Major crack, 0.025 inches or greater

   d. Minor crack, 0.005 inches or greater

3. Appropriate ground support will be maintained for utilization and maintenance of the on-board fiber optics systems.

4. Rigid optics devices will be used in preference to flexible fiber optics devices. Rigid optic devices shall be one of the following:

   a. Minimum length: 24 inches

      Maximum diameter: must be able to clear 0.1-inch diameter hole

      Maximum light transmission loss: 40% (EST)

      Light source type: No. 1

   b. Minimum length: 3 feet

      Maximum overall length: 5 feet

      Maximum diameter: must be able to clear 0.25-inch diameter hole

      Maximum light transmission loss: 45% (EST)

      Light source type: No. 2 or No. 3

c. Minimum length: 6 feet

Maximum length: 7 feet

Maximum diameter: must be able to clear 0.375-inch diameter hole

Maximum light transmission loss: 65 percent (EST)

Light source type: No. 3

d. Minimum working length: 12 feet

Maximum overall length: 13 feet

Maximum diameter: must be able to clear 0.5-inch diameter hole

Maximum light transmission loss: 80 percent (EST)

Light source type: No. 3

5. This scope will be capable of being disassembled into sections approximately two to three feet in length each.

6. The flexible fiber optics devices shall be one of the following:

a. Minimum working length: 6 feet

Maximum overall length: 7 feet

Maximum individual fiber diameter: (TBD)

Maximum diameter: must be able to clear 0.25-inch diameter hole

Minimum bending radius: must be able to pass 2-inch radii

Maximum light transmission loss: 60 percent (EST)

Resolution type: (TBD)

Light source type: No. 1 or No. 2

b. Minimum working length: 10 feet

Maximum overall length: 12 feet

Maximum individual fiber diameter: (TBD)

Maximum diameter: must be able to clear 0.375-inch diameter hole

Minimum bending radius: must be able to pass 3.5-inch radius

Maximum light transmission loss: (TBD)

Resolution type: (TBD)

Light source: No. 2

Data collection type: No. 1 or No. 2

c. Minimum working length: 18 feet

Maximum overall length: 18 feet

Maximum individual fiber diameter; must be able to clear 0.5-inch diameter hole

Maximum bending radius: must be able to pass 5-inch radius

Maximum light transmission loss: (TBD)

Resolution type: (TBD)

Light source: No. 3

Data collection type: No. 1

7. The light sources used with fiber optics devices shall be one of the following:

a. Integral to scope attached to viewing end:

Light intensity exit: (TBD)

Wattage: 500

b. Integral to scope attached to viewing end:

Light intensity exit: (TBD)

Wattage: (TBD)

Strobe type: high intensity

c. Independent of scope, has own non-coherent light pipe train or has light source at end of inserted bundle:

Minimum length: 18 feet

Maximum diameter: 1/4 inch

Light intensity: (TBD)

Wattage: (TBD)

8. The data collecting method shall be one of the following:

a. To be viewed with the unaided eye, focus accessories required.

b. Provisions for a camera attachment shall be provided with the general camera parameters as follows: The camera shall be of a high quality motion picture type with provisions for single-shot exposure. The image as received at the viewing end of the scope shall fill the film frame. Image quality losses through the camera shall be negligible. Camera weight shall be less than 5 pounds.

c. Provisions for a closed circuit television attachment shall be provided with general requirement as follows:

(1) Total vidicon weight as used by the inspector shall be 25 pounds maximum.

(2) Centralized monitoring, data interpretation, and data storage shall be employed.

(3) The facilities vidicon system shall be compatible with on-board vidicon systems and interface shall be provided.

(4) Conventional 525 raster scan shall be employed. High resolution shall be achievable by changing the field-of-view, light intensity, and object distance.

9. Viewing accessories shall be attachable to the far end of the scope and shall be one of the following:

a. Direct vision forward: field-of-view, 60 to 70 degrees

b. Foroblique:

Viewing angle: 45 degrees

Field-of-view: 60 to 70 degrees and less than 10 degrees

c. Right angle:

Viewing angle: 90 degrees

Field-of-view: 60 to 70 degrees

d. Retrospective:

Viewing angle: 175 degrees

Field-of-view: 45 to 50 degrees

The optical NDE GSE system shall be controlled from a crib operation. Repair of the optical devices and support of the on-board optical system shall be maintained by a small laboratory function.

Operating books and detailed instructional manuals shall be generated to allow use by operators with minimal experience and training. Inspection personnel shall have appropriate training and shall be responsible for both maintenance and repair of optical devices, generation of instructional data, and establishment of new techniques.

3.2 Program Design and Construction Standard

The best available commercial off-the-shelf devices shall be used.

3.3 Requirement for Functional Area

The devices shall be used in enclosed hanger areas.

1. Standard 60 Hz, 110 ac voltage shall be available.

2. Not less than 20 devices shall be required (EST) with interchangeable accessories and cameras.

3. The devices shall be usable with little or no training. General operational instructions shall be attached to devices.

4. A centralized crib, repair, and maintenance center shall be responsible for the devices and their usage.

4.0 QUALITY ASSURANCE

Detailed test plans shall be generated to provide for functional demonstration of equipment requirements, as specified in Section 3.0 of this specification. These plans shall take into account the historical development of the equipment in the sense that accepted functional practices need not be demonstrated while recently developed concepts and hardware must be proven.

Simulated Shuttle test structures and test standards shall be used to demonstrate functionality, where it is necessary, as follows: (TBD)

A periodic maintenance and calibration operation shall be scheduled and maintained to assure operational functionality of the test equipment. Maintenance and calibration schedules shall be based on defective trend data. Initial maintenance and calibration schedules are recommended as follows: (TBD)

Detailed test requirements for the equipment shall be primarily based on functional operation rather than equipmental parameters.

Preventive maintenance procedures shall be emphasized while calibration operations shall be minimized.

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SPECIFICATION SSV-NDE-ULT-GSE

ULTRASONIC GROUND SUPPORT FOR TURNAROUND/LAUNCH OPERATION

1.0 SCOPE

This specification defines the performance and design requirements for ultrasonic nondestructive evaluation ground support for turnaround/launch operations in the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test. It is the single authoritative document stating the program technical requirements. All elements and contract end items of the ultrasonic ground support system shall conform with the requirements specified herein.

"Ultrasonic Ground Support for Turnaround/Launch Operations" details those nondestructive testing requirements which are generally recognized as follows:

1. Digital ultrasonic thickness gaging
2. Portable ultrasonic inspection
3. Permanent pulse-echo/through transmission facility
4. On-board ultrasonic support

The requirements contained in this specification are those necessary for ground support during turnaround and launch and presumes the existence of compatible and complementary requirements for on-board nondestructive evaluation in the specification of the Orbiter and Booster design.

It is the intent of this specification to basically set forth equipment requirements that are compatible with existing commercial hardware yet meet specific and detailed Space Shuttle requirements.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

The ultrasonic ground support operation shall support the following functions:

1. Portable ultrasonic inspection functions. (Portable NDE techniques will be utilized to minimum extent.)
2. Ultrasonic technique development and analysis as confined to the laboratory area.
3. Direction and interpretation of on-board ultrasonic systems utilization, primarily during turnaround operations. (Flight records will be computer analyzed.)

The ultrasonic support operation shall be capable of detecting the following type defects and conditions:

1. Metallic cracks 0.050 inch, minimum dimension
2. Nonmetallic cracking (high density plastic: 2.4 g/cc or greater (EST)). 0.100 inch, minimum dimension
3. Nonmetallic cracking/void formation: (low density plastics 2.4 g/cc or less (EST)P). 1.0 inch, minimum dimension
4. Adhesive unbonds metal-to-metal: 1/2 inch, minimum dimension
5. Brazed unbonds: 1/4 inch, minimum dimension
6. Honeycomb, Stresskin structures, 4 times cell size, minimum dimension
7. Metallic thickness: 0.016 inches minimum
8. Weld bead defects (especially electron beam) 15 percent of weld bead width minimum

Equipment operations characteristics shall be as follows:

1. A laboratory ultrasonic water tank and recording system shall be provided with the following requirements:

   a. Minimum tank size: 50 inches by 40 inches by 24 inches deep with a minimum tank capacity of 150 gallons (EST)

   b. Scan speeds: adjustable from 0.1 to 200 ft/min (EST)

   c. Raster speed: adjustable from 0.01 to 5 inch/min (EST)

   d. Minimum "C" Scan Width: 30 inches (EST)

   e. "C" Scan recording: adjustable from 4 to 1, to 1 to 10 times actual size; and shall have a seven-tone gray scale recording capability. Provisions for a strip gray scale record on the "C" scan shall also be possible.

2. Appropriate transducers and electronic cables, etc., shall be provided (TBD).

3. A high energy pulser shall be provided with the following requirements:

   a. Frequency: adjustable from 5 KHz to 10 MHz

   b. Pulse repetition rate: 3 to 100,000 pulses per second

   c. Voltage: 0 to 2000 volts at 10 A

   d. Output power: 0 to 20 kw

   e. Input power: 650 watts from 115V to 60 Hz maximum

4. Digital ultrasonic thickness gages shall be available with the following capabilities:

   a. Operation: pulse echo

   b. Accuracy: ±0.0001 inch minimum

      For metallic thickness range: from 0.010 to 1 inch

   c. Readout: 3 digit minimum

Ultrasonic laboratory personnel shall be responsible for maintaining, repairing, and providing operational procedures for all ultrasonic systems and equipment. These operations shall be accomplished by ordering appropriate components and equipment from commercial sources.

Trained and certified inspection personnel shall be capable of operating the ultrasonic systems with the aid of an operating handbook.

3.1.2 Program Definition

The primary purpose of the ultrasonic ground support operation shall be to complement on-board ultrasonic testing. Portable ultrasonic inspection operations shall be minimal and shall be on an unscheduled basis. Appropriate on-board monitoring techniques shall be applied to critical and troublesome Shuttle structures and Shuttle components. Modification work, as contrasted with repair and check operation, shall be supported by the ultrasonic laboratory using techniques and procedures equivalent to those techniques used in the original manufacture.

The ultrasonic test equipment shall be procured from appropriate commercial sources on an individual unit basis. No specialized test facility requiring extensive construction or unusual building facilities shall be required.

3.1.3 Operability

1. The laboratory equipment shall be designed to have an expected life of 10 years.

2. All ultrasonic systems shall be maintained and repaired or repair directed by laboratory personnel by ordering components, modules, or replacement equipment, etc., from appropriate commercial sources.

3. The ultrasonic laboratory test equipment shall be operated in a laboratory environment with the following environmental conditions:

   a. Temperature: 65 to 85 F

   b. Humidity: 20 to 50 percent relative humidity (EST)

   c. Pressure: 14.7 ± 1.5 psia (EST)

3.2 Program Design and Construction Standards

No specific construction standard shall be imposed.

3.3 Requirements for Functional Areas

The ultrasonic laboratory shall occupy a maximum of 400 square feet (EST) and shall be a conventional room which will be equipped by responsible engineering personnel.

4.0 QUALITY ASSURANCE

1. Simulated Shuttle test structures and test standards shall be used to demonstrate functionality where deemed necessary, as follows: (TBD).

2. A periodic maintenance and calibration schedule and operation shall be established and maintained to assure operational functionality of the test equipment.

    a. Maintenance and calibration schedules shall be based on defect trend data. Initial maintenance and calibration schedules are recommended as follows: (TBD).

    b. Detailed test requirements for the equipment shall be primarily based on functional operation rather than equipment parameters.

    c. Preventive maintenance procedures shall be emphasized while calibration operations shall be minimized.

SPECIFICATION SSV-NDE-EM-GSE

ELECTROMAGNETIC NONDESTRUCTIVE EVALUATION TECHNIQUES FOR GROUND SUPPORT DURING LAUNCH/TURNAROUND OPERATIONS

1.0 SCOPE

This specification defines the performance and design requirements for electromagnetic nondestructive test techniques for the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test. It is the single authoritative document stating the program technical requirements. All elements and contract end items of electromagnetic nondestructive test operations shall conform with the requirements specified herein.

"Electromagnetic Nondestructive Evaluation Techniques for Ground Support During Turnaround/Launch Operations" defines those nondestructive test requirements that are normally recognized as follows:

1. Portable eddy current flaw detection
2. Portable eddy current thickness gaging
3. Portable eddy current material identification
4. Microwave (scatter)
5. Thermo-electric testing
6. Radio frequency voltage probe
7. Radio frequency thickness gaging

It is the intent of this specification to set forth basic equipment requirements that are compatible with existing commercial hardware.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. Portable eddy current equipment shall be capable of measuring metal thickness from one side in the thickness range of 0.0001 to 0.020 inches.

2. Portable eddy current thickness measuring equipment shall meet the following requirements:

   a. Power input: 115 volts 60 Hz, 80 watts maximum

   b. Frequency: 50 KHz to 5 MHz variable

   c. Drift: less than 1.6×10^{-6} ohm/cm on silver
      less than 3×10^{-3} ohm/cm on graphite

   d. Resistivity resolution: 10^{-8} ohm/cm minimum

   e. Sample time: 1 millisecond maximum

   f. Probe coils: (TBD)

3. Portable eddy current flaw detection equipment shall be capable of detecting and measuring surface cracks and flaws in metallic structure.

4. Portable eddy current flaw detection equipment shall meet the following requirements:

   a. Power input: 112 volts 60 Hz, 1 amp maximum (EST)

   b. Frequency 1 to 4 MHz (EST)

   c. Sensitivity: 15 percent accuracy for crack depths

   d. Probe coil: (TBD)

5. Portable eddy current equipment shall be capable of determining electrical conductivity between one to 107 percent IACS (based on copper 100 percent), in order to determine heat treat for specified alloy or alloy when heat treat is known.

6. Portable eddy current material properties equipment shall meet the following requirements:

   a. Power input: self contained rechargeable batteries

   b. Frequency: low range (TBD)
      high range (TBD)

   c. Sensitivity: minimum one percent change in IACS (EST)

   d. Probe coil: (TBD)

7. Appropriate eddy current probes shall be developed for specialized applications dependent on test geometry and material and defect criteria. Eddy current equipment manuals shall specify required electrical properties of the test coil to include allowable probe resistances and inductances.

8. Appropriate supporting devices and probe holders shall be developed for specialized applications dependent on test geometry and materials and accessibility.

9. Radio frequency thickness equipment shall be capable of measuring the thickness of nonmetallic materials on metallic substrates in the thickness range of 0 to 5 inches (EST) with an accuracy of 0.1 inch. Nonmetallic materials to be mea ured must have dielectric constants between 1 and 40 (EST) and an electrical resistivity greater than 10^6 microhm cm (EST).

10. Microwave defect detection equipment shall be capable of detecting 1/2 inch square by 0.050 inch void type flaws in nonmetallic materials with dielectric constants and electrical resistivities as described in Item 9.

11. Electromagnetic nondestructive evaluation ground support operations shall be conducted from appropriate facilities as follows:

Laboratory	Tool Crib
Eddy current defect	Eddy current thickness
RF voltage probe	Eddy current material
Microwave (scatter)	RF thickness

12. Electromagnetic nondestrictive evaluation personnel shall be responsible for maintaining, repairing, and providing operational procedures for all electromagnetic systems and equipment. These operations shall be accomplished by ordering appropriate components and equipment from commercial sources.

13. Trained and certified inspection personnel shall be capable of operating the electromagnetic nondestructive evaluation equipment with the aid of an operating handbook.

3.1.2 Program Definition

The primary purpose of the electromagnetic nondestructive evaluation operation shall be to provide appropriate portable equipment to allow measurement and detection of pertinent material properties, such as thickness, cracks, etc. These portable electromagnetic techniques shall be used to a minimal extent on an unscheduled basis. Facility operation shall be established where necessary for use on line removable units.

Shuttle structure modification work, as contrasted with repair and check operation, shall be supported by the electromagnetic NDE laboratory using techniques and procedures equivalent to those techniques used in the original manufacture.

The electromagnetic NDE equipment shall be procured from appropriate commercial sources. No specialized test facility requiring extensive construction or unusual building facilities shall be required.

3.1.3 Operability

1. The laboratory equipment shall be designed to have an expected life of 10 years.

2. All electromagnetic NDE systems shall be maintained and repaired or repair directed by laboratory personnel by ordering componenets, modules, or replacement equipment, etc., from appropriate commercial sources.

3. The electromagnetic NDE laboratory test equipment shall be operated in a laboratory environment with the following environmental conditions:

   a. Temperature: 50 to 120 F

   b. Humidity: 0 to 50 percent relative humidity (EST)

   c. Pressure: 14.7 ±1.5 psia (EST)

3.2 Program Design and Construction Standards

No specific construction standard shall be imposed.

3.3 Requirements for Functional Areas

The electromagnetic NDE laboratory shall occupy a maximum of 400 square feet (EST) and shall be a conventional room which will be equipped by responsible engineering personnel.

4.0 QUALITY ASSURANCE

1. Simulated Shuttle test structures and test standards shall be used to demonstrate functionality where deemed necessary, as follows: (TBD).

2. A periodic maintenance and calibration operation shall be scheduled and maintained to assure operational functionality of the test equipment.

   a. Maintenance and calibration schedules shall be based on defect trend data. Initial maintenance and calibration schedules are recommended as follows: (TBD).

   b. Detailed test requirements for the equipment shall be primarily based on functional operation rather than equipment parameters.

   c. Preventive maintenance procedures shall be emphasized while calibration operations shall be minimized.

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SPECIFICATION SSV-NDE-AE-GSE

ACOUSTIC EMISSION GROUND SUPPORT AT LAUNCH/TURNAROUND FACILITY

1.0 SCOPE

This specification defines the performance and design requirements for acoustic emission support for the Space Shuttle structural integrity checkout system and establishes requirements for its design, development, and test. It is the single authoritative document stating the program technical requirements. All elements and contract end items of the acoustic emission system shall conform with the requirements specified herein.

The details contained in this specification are for those requirements necessary for ground support during turnaround and launch. The requirements presume the existence of compatible and complementary evaluation in the specification of the orbiter and booster design.

The requirements contained in this specification detail the necessary and sufficient facilities to support an on-board acoustic emission nondestructive evaluation presuming the existence of appropriate computer and computer support facilities.

It is the intent of this specification to set forth basic equipment requirements that are compatible with existing commercial hardware.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification. Specifications, standards, drawings, bulletins, and other publications are to be determined.

3.0 REQUIREMENTS

3.1 Performance

3.1.1 Characteristics

1. Ground support operations for acoustic emission testing shall be limited to those laboratory functions necessary to complement the on-board acoustic emission system.

2. The ground support operations personnel for acoustic emission testing shall be capable of activating and operating the on-board acoustic emission system.

3. The ground support acoustic emission laboratory shall have equipment and personnel necessary to simulate background noise encountered in launch, reentry, and operation of air-breathing engines.

4. At least two complete acoustic emission systems equivalent to, or better than, the on-board system shall be provided.

5. Tensile test hardware shall be provided.

6. Necessary electronic equipment shall be provided to support a typical electronics laboratory operation.

7. A time-shared computer terminal shall be provided.

8. Audio and ultrasonic spectrum analysis equipment and recording capabilities shall be provided.

9. Appropriate means to measure (on site) sonic intensities and simulate sonic distribution shall be provided.

10. For personnel and training, operating booklets and detailed instructional manuals shall be generated to allow maintenance and repair by operators with minimal experience and training. Laboratory personnel shall have had appropriate training courses and shall be responsible for all acoustic emission testing operations, maintenance of systems and maintaining applications specifications.

11. Appropriate computer programs shall be generated to analyze and interpret acoustic emission flight record and in-flight data.

3.1.2 Program Definition

Acoustic emission test equipment shall be procured from appropriate commercial sources. No specialized test facility requiring extensive construction or unusual building facilities shall be required.

Acoustic emission monitoring techniques shall be developed as a primary Space Shuttle structural integrity monitoring system in conjunction with fiber optics, holographic interferometry, and conventional NDE techniques. On-board ultrasonic systems shall serve as a back-up technique.

3.1.3 Operability

Laboratory equipment to support acoustic emission nondestructive evaluation technology shall be designed to operate for 10 years with minimal maintenance.

The acoustic emission laboratory test equipment shall be operated in a laboratory environment with the following environmental conditions:

1. Temperature: 65 to 85 F
2. Humidity: 20 to 50 percent relative humidity (EST)
3. Pressure: 14.7 ±1.5 psia (EST)

3.2 Program Design and Construction Standards

To be determined.

3.3 Requirements for Functional Areas

The acoustic emission laboratory shall occupy a maximum of 800 square feet (EST) and shall be a conventional room equipped to support acoustic emission technology.

4.0 QUALITY ASSURANCE

Simulated Shuttle test structures and test standards shall be used to demonstrate functionality where deemed necessary, as follows: (TBD)

A periodic maintenance and calibration operation shall be scheduled and maintained to assure operational functionality of the test equipment.

1. Maintenance and calibration schedules shall be based on defect trend data. Initial maintenance and calibration schedules are recommended as follows: (TBD)
2. Detailed test requirements for the equipment shall be primarily based on functional operation rather than equipmental parameters.
3. Preventive maintenance procedures shall be emphasized while calibration operations shall be minimized.