NONDESTRUCTIVE TESTING FOR SPACE SHUTTLE

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INTRODUCTION

The quest for earth-orbit shuttle by the mid 70's demands awareness of material capability and performance well beyond standard characterization. In addition to providing reliable data, candidate nondestructive testing must perform within the economics of the Space Shuttle concept. Where practical, suitable instrumentation must be developed for onboard surveillance and/or for limited operation during shuttle turnaround.

NDT considerations require tradeoffs between maintainability and design. For example, should sections of the vehicle such as the TPS be designed to be removable in total or in part for replacement with new, refurbished, or recertified material, and the removed panels subsequently tested at leisure? Or should NDT methods be designed for inplace testing? Can reliable evaluation be performed by sampling over the intended service life of the vehicle? To what extent will accessibility be required? May existing NDT technology and standard airline maintenance be utilized in formulating a meaningful master plan for reliable and, equally important, economical determination of reusability?

Company-sponsored research has been conducted at Convair in nondestructive testing of advanced materials currently under development for Space Shuttle. Methods which have been investigated to date include eddy current, high frequency ultrasonics, microwave, beta backscatter, thermal and infrared methods, acoustic emission analysis, Mossbauer spectroscopy, and techniques for handling and processing NDT data. The use of radionuclides for incorporation into a coating system to monitor TPS in service is currently under development.

The most significant barrier that must be overcome to develop confidence among potential users of NDT is agreement on the problem — what are the inspection requirements for reusability? Certainly onboard surveillance is desirable, but is it necessary considering compromises that may reduce vehicle performance? The strive for NDT sophistication is fostered by the advanced technology sought for Space Shuttle, but it is the responsibility of the designer and nondestructive investigator, as well, to temper the approach with system awareness and effective utilization of the inherent serviceability and inspectibility of the vehicle.

SUMMARY

Nondestructive testing has been used extensively at Convair to aid development of advanced materials and design for Space Shuttle. In early work, considerable attention has been given to thermal protection systems, and in particular to coated metal refractories, deployment of which is desirable to meet the economic objectives of the shuttle concept. Additionally, nondestructive testing has been used to assist the development of candidate backup material such as carbon-carbon composites and ablatives. The requirements for NDT of structure, tankage, and insulation are currently under investigation. While suitable methods for most applications are available to predict initial performance, further development is required to extend these methods to measure reusability.

The NDT considerations for shuttle may be divided into three general areas: (1) thermal damage, i.e., oxidation, properties degradation, local distortion; (2) fatigue damage, i.e., cycled loads — thermal, mechanical, acoustical; and (3) structural damage, other than fatigue, i.e., damage due to subcritical defects, accidents, and corrosion. On the exterior of the vehicle, the major areas of concern are leading edges and areas subject to repeated loads. For example, areas aft of flyback engines and forward of the rocket engines, including the entire aft section and stabilizers will be susceptible to sonic fatigue. Transducer arrays operating as passive detectors in critical attachment areas have been considered for inflight monitoring of crack initiation and propagation in these areas. While it is too early to determine the need for onboard sensing, the requirements for such a concept must be examined to perform tradeoffs necessary for the selection of materials and inspection approach.

In few instances are the inspection requirements independent of materials selection. However, in several cases the approach for a particular material requires no major development affecting shuttle turnaround. For example, the performance of ablative materials can generally be characterized. Suitable NDT prior to installation can be employed to guarantee satisfactory performance. If such materials are selected, postflight evaluation will not be required since the materials are not reusable.

While thermal insulation may not be required between the tankage and TPS for the booster, it is currently planned for the orbiter. Accordingly, the need to monitor insulation is being investigated by North American Rockwell Corporation's Space Division, prime contractor for the North American/Convair Phase B team. Detection of moisture buildup may prove to be impractical considering the volume of space and restrictions surrounding tankage and fuel lines. An alternate approach is simply to eliminate it. Accordingly, at Convair a dry nitrogen purge system for operation during tanking is currently being considered.

In addition to eliminating the need to detect moisture buildup, the purge system might also be used to carry off leak gas, either the fuel itself or helium introduced externally, to sensors located at purge outlets in the system.

Cryogenic insulation inside fuel tanks requires a bond to the tank wall. Candidate materials include rigidized foam and fiber or foam-filled honeycomb gas layer systems. Moisture buildup or gas convection may propagate or initiate disbonds, rupturing or eroding the insulation. Large defects may produce cryopumping, or ice buildup, resulting in increased weight and stress. While the insulation is accessible, at least initially, from inside the fuel tanks, it is accessible from the wrong side. Sonic or ultrasonic techniques for reliable evaluation of bond area require access to the tank wall and depend on energy transferred from the metal wall to the insulation to produce a measurable dampening. While novel techniques such as the use of piezoelectric coatings for application to such problems are currently being investigated, as yet a reliable NDT method is not available for evaluating internal insulation.

North American Rockwell Corporation's Space division is currently studying NDT methods to assess structural integrity for Space Shuttle under contract with NASA Kennedy Space Flight Center (NAS 10-7250). Emphasizing high speed methods and onboard techniques, the objective of the program is to identify nondestructive testing suitable for Space Shuttle. A second objective is to recommend necessary technology programs to meet objectives during turnaround. Techniques currently being evaluated include fiber optics, holography, in-place ultrasonics, and thermal methods. Convair is providing consultants for the program.

The use of acoustic emission analysis for in-situ NDT of structural materials is currently under investigation at Convair. Among other forms of energy, mechanical pressure or stress waves are spontaneously emitted by materials undergoing deformation. The energy arises from many sources, including shifting of unseen imperfections in the material (dislocations) and nucleation or propagation of cracks. The application of acoustic emission for in-situ life monitoring of critical structures and components and/or to assist process control will be investigated.

Problems associated with NDT of structural components cannot be identified until material and design have been decided. In the mean time, adequate inspectibility cannot be assumed. A significant tradeoff among material candidates is the need and relative ease of testing each to determine its capability for reuse flight after flight. One candidate material, coated columbium, was deemed a primary candidate for booster and orbiter leading edges, but presented difficulties in testing. While techniques had been suggested for NDT of this material, previous studies had been confined to the laboratory. Convair instituted a program to build on this early work and apply knowledge gained in the laboratory to NDT processes suitable for factory and field evaluation (Refs. 1 and 2).

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1. DeLacy, Thomas J. and Anderson, R.T., 'Nondestructive Testing of Refractory Coatings — Solutions and Problems," 16th Meeting of Refractory Composites Working Group, Seattle, Washington, 13-15 October 1969.

2. DeLacy, Thomas J. and Anderson, R.T. 'Nondestructive Testing of Composites and Refractory Coatings," 17th Meeting of Refractory Composites Working Group, Williamsburg, Virginia 16-18 June 1970.

The development of NDT methods for process control of coated refractories produced standard techniques to assist early design studies and fabrication development. An ultrasonic transmission reflection technique was shown to be satisfactory for detecting disbond in diffusion bonded base metal. The technique, which records ultrasonic energy transmitted through the test specimen to a smooth reflector as a function of bond area, is valuable for process development and inspection of bonded or brazed shield structures.

Methods to evaluate the integrity of the coating include eddy current, thermoelectric monitoring, and electron emission radiography. Eddy current testing employs an induced electric field in the substrate, which is modified by variation in the diffusion layer between the coating and substrate and/or by distance between the probe and substrate. It is used by some coating manufacturers for green state monitoring. Thermoelectric testing, which is based on a reverse thermocouple principle, is sensitive particularly to chemistry variation in the coating. This technique, which requires point by point monitoring over the entire surface of the shield, is not applicable to shuttle turnaround due to a nonconductive oxide layer developed on the surface of the coating during high temperature service.

Of the three principal NDT methods for manufacturing process control, electron emission radiography has proven most valuable. The technique employs the use of electrons ejected from the metal substrate by x-ray bombardment to image variability in the coating. While extensive use of the method has aided the development of an improved coating technique, the method requires close control. Setup time and restrictions to personnel working near the exposure area make the technique less suitable for application to shuttle turnaround.

During re-entry, the heat shield will encounter extreme temperature and pressure regions as well as mass flow, which may reduce the thickness of the coating. Spalling or other damage to the coating during landing or cool-down of the vehicle may also reduce coating thickness. Accordingly, periodic monitoring will be required to assess coating losses and/or damage that may initiate early failure.

The use of radioactive labelling (tagging) to provide inherent radiation emission properties to the coating has been under investigation at Convair. It appears that a safe quantity of radioisotope can provide a rapid means for measuring coating thickness and discernment of flaws. The tag provides two useful categories of nondestructive measurement: (1) autoradiography, which provides a very detailed and high resolution picture of the coating, and (2) direct counting, which before and after abrasion tests correlate with coating thickness and which provides a measurement of coating uniformity.

While further development is required, the indications are positive that the radioactive tag will provide a practical means for in-situ NDT of thermal shields. The radioactivity loading can be increased sufficiently to reduce autoradiography time to less than one hour per exposure with complete safety. Since many films can be exposed at one time, complete autoradiography interrogation could be carried out within a 24-hour period without interruption of required maintenance.

Based on studies using ^{147}Pm (a weak beta emitter), the thickness of the coating in a 0.05 square foot area would be measurable using a single G-M detector (3-inch diameter) to a precision of better than 1% within a 0.2-minute count. Thus, 1 square foot could be measured every 4 minutes; 300 square feet would require approximately 20 hours of measurement time. However, just as a multiplicity of areas can be simultaneously autoradiographed, a multiplicity of G-M counters would reduce the required inspection time.

Mossbauer Spectroscopy has been investigated for measuring coating service life, specifically changes in chemical bond relating to oxidation and diffusion. While the results of the tests were inconclusive, the application remains feasible. Considerable investigation would be required to apply the method outside the laboratory. Beyond the cost of material, the method requires a relatively sophisticated setup and considerable counting time. However, for its intended application, a relatively simple device is conceivable for sampling the shield in areas previously screened.

The need for further investigation will be determined by continued experience with coated metal refractories and particularly by the degree to which these systems can be characterized.

CONCLUDING REMARKS

The reliability, possibly the success, of the Space Shuttle concept will require extensive but most important, proper application of nondestructive testing. Techniques required for reusability must be economical as well as reliable. While suitable instrumentation requires development, a practical inspection plan will depend on serviceability, in particular on the amount of inspection required and, where necessary, accessibility for inspection and repair. Consideration of these requirements must be clear throughout our analysis and design approach.

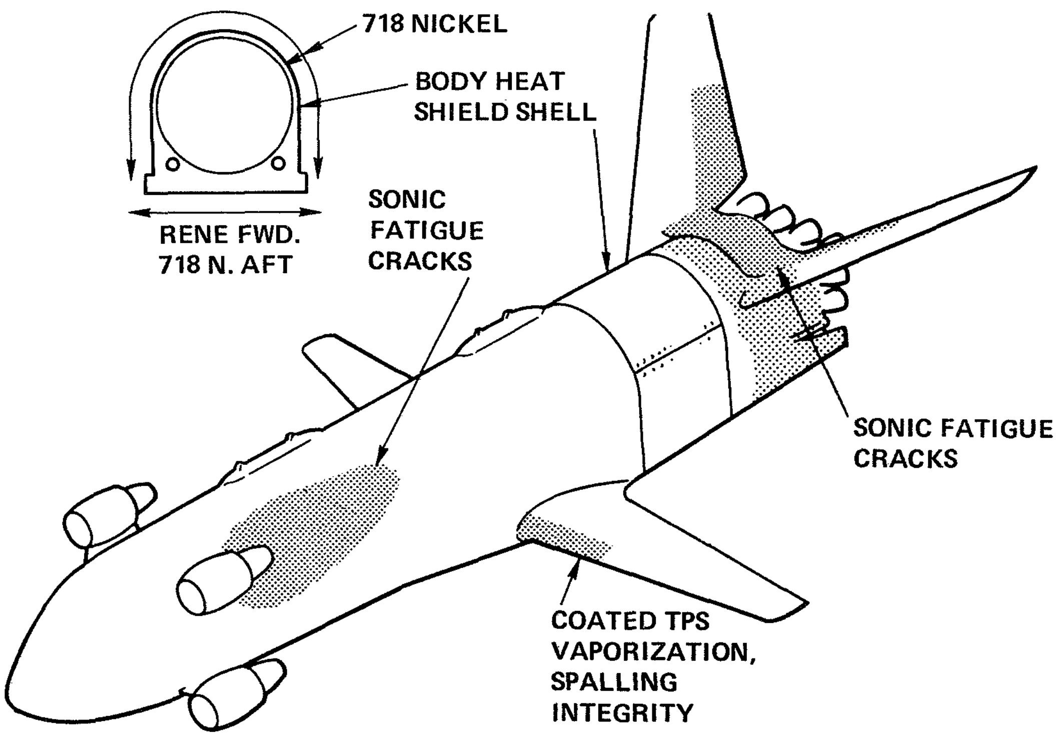
NDT REQUIREMENTS

The inspection requirements for reusability are unprecedented. NDT must be developed concurrently with materials technology and design to meet objectives for turnaround.

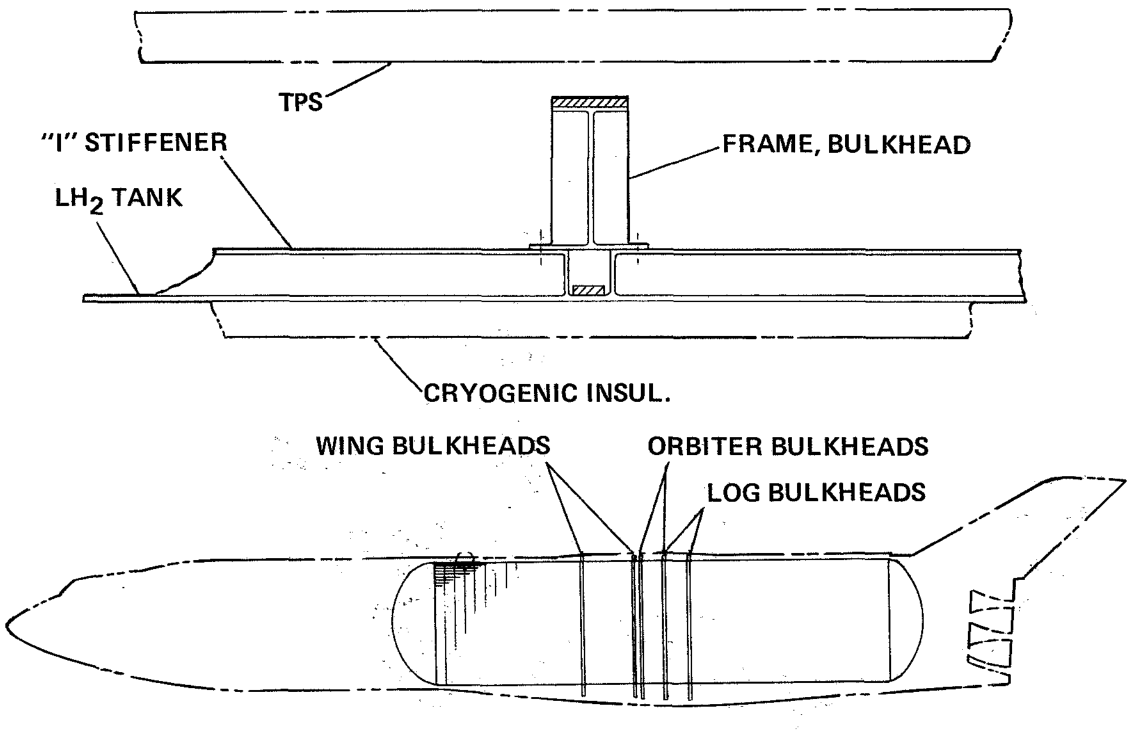
- DEVELOPMENT – CHARACTERIZATION
- IN PROCESS – MANUFACTURE (INSPECTION)
- IN SERVICE – OPERATIONS CHECKOUT

EXTERNAL NDT REQUIREMENTS

Areas susceptible to repeated loads and overheating are of major concern for reusability.

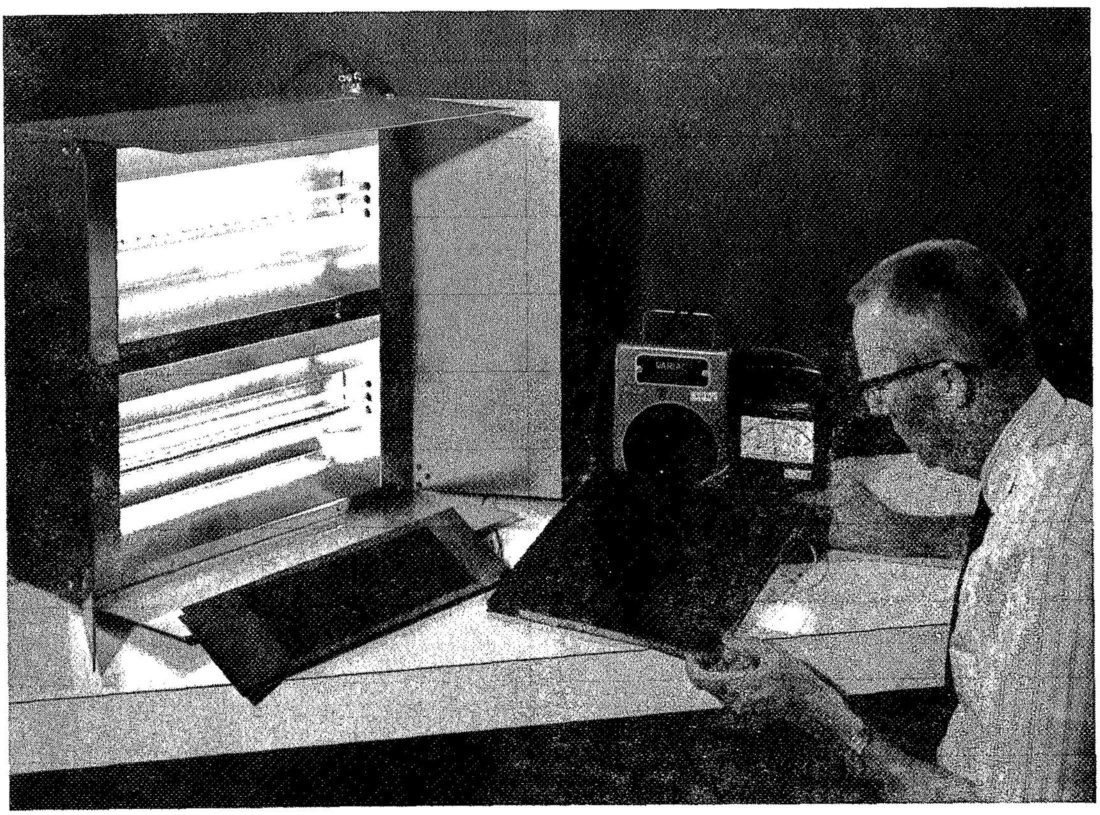


Suitable techniques have not been developed for inspection of cryogenic (internal) insulation. Inaccessibility is a major limitation.

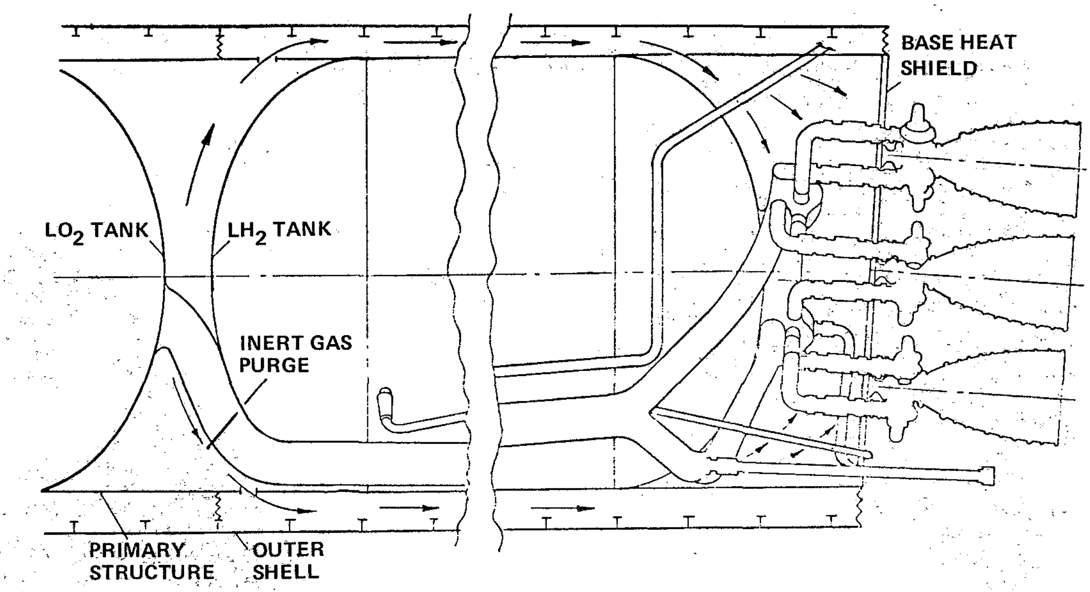


LIQUID CRYSTAL THERMOGRAPHY

Thermal techniques are currently being investigated for application to Space Shuttle by North American Rockwell Corporation's Space Division. Under contract to NASA Kennedy Spaceflight Center, NAR has begun a program to assess structural integrity for space shuttle vehicles. Convair is providing consultants to the program.

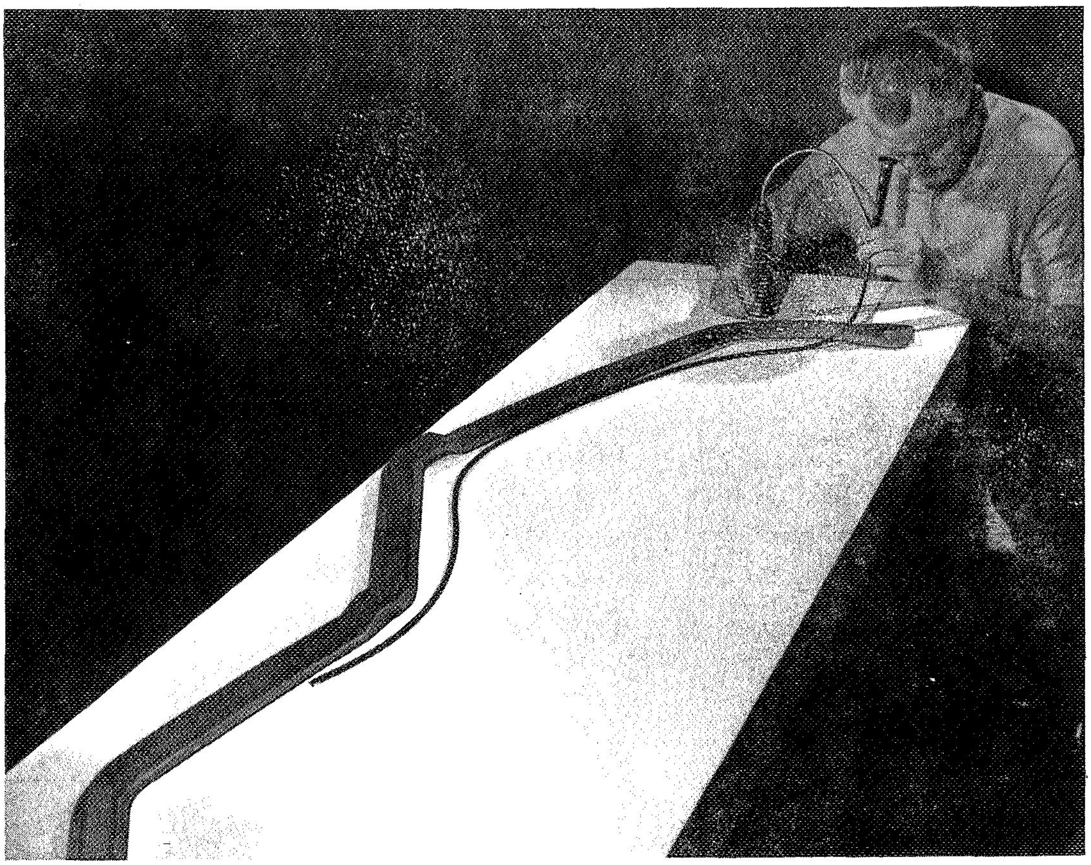


A dry nitrogen purge system is currently a principal candidate to eliminate moisture buildup in the booster. In addition to eliminating the need to detect moisture, a leak detection system for the tankage utilizing the purge manifold and outlet sensors is feasible to detect leakage prior to refueling.



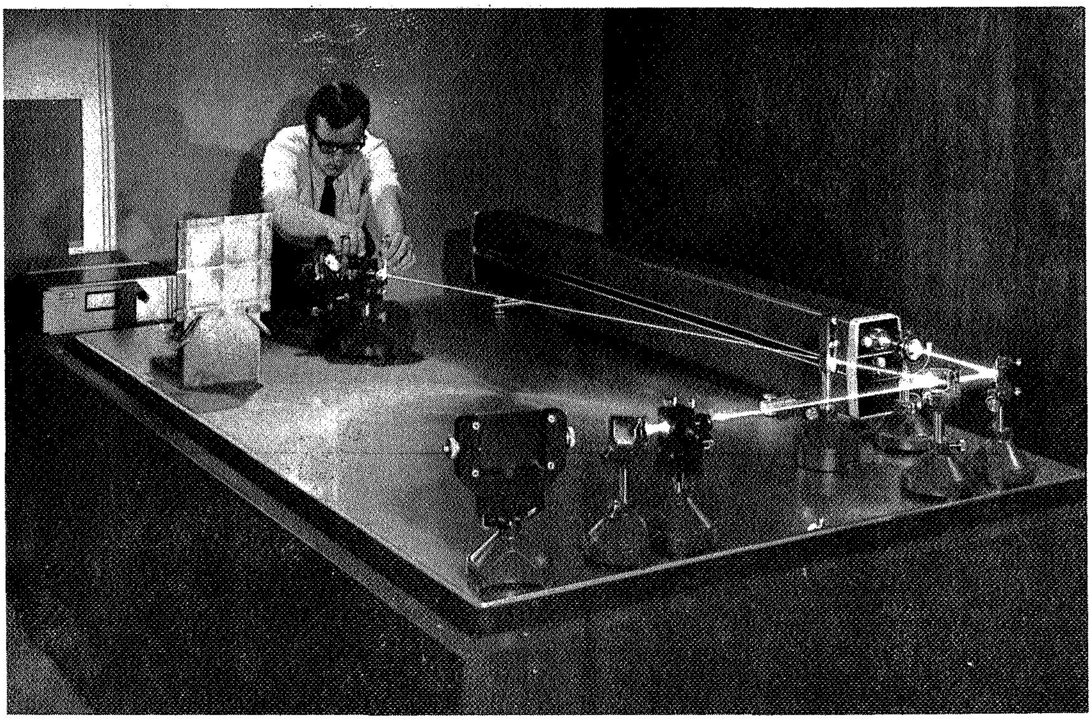
FIBER OPTICS

The use of fiber optics for remote sensing in inaccessible areas is currently under investigation at NAR. Potential applications include the detection of corrosion, cryopumping, and leakage in critical stress areas. Weight and cost factors are primary obstacles.



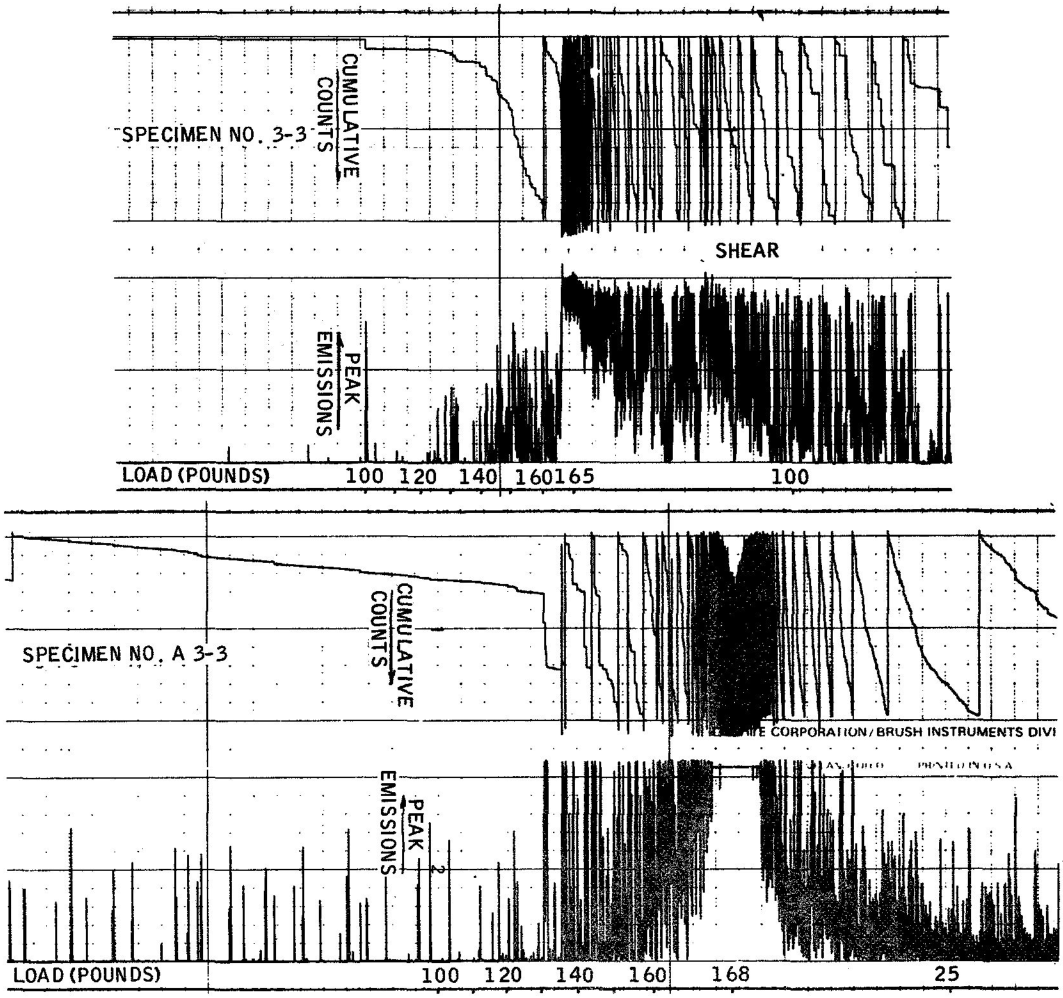
HOLOGRAPHY

The application of laser holography to assist manufacturing control is included in the NASA investigation of techniques to assess structural integrity currently in progress at NAR.

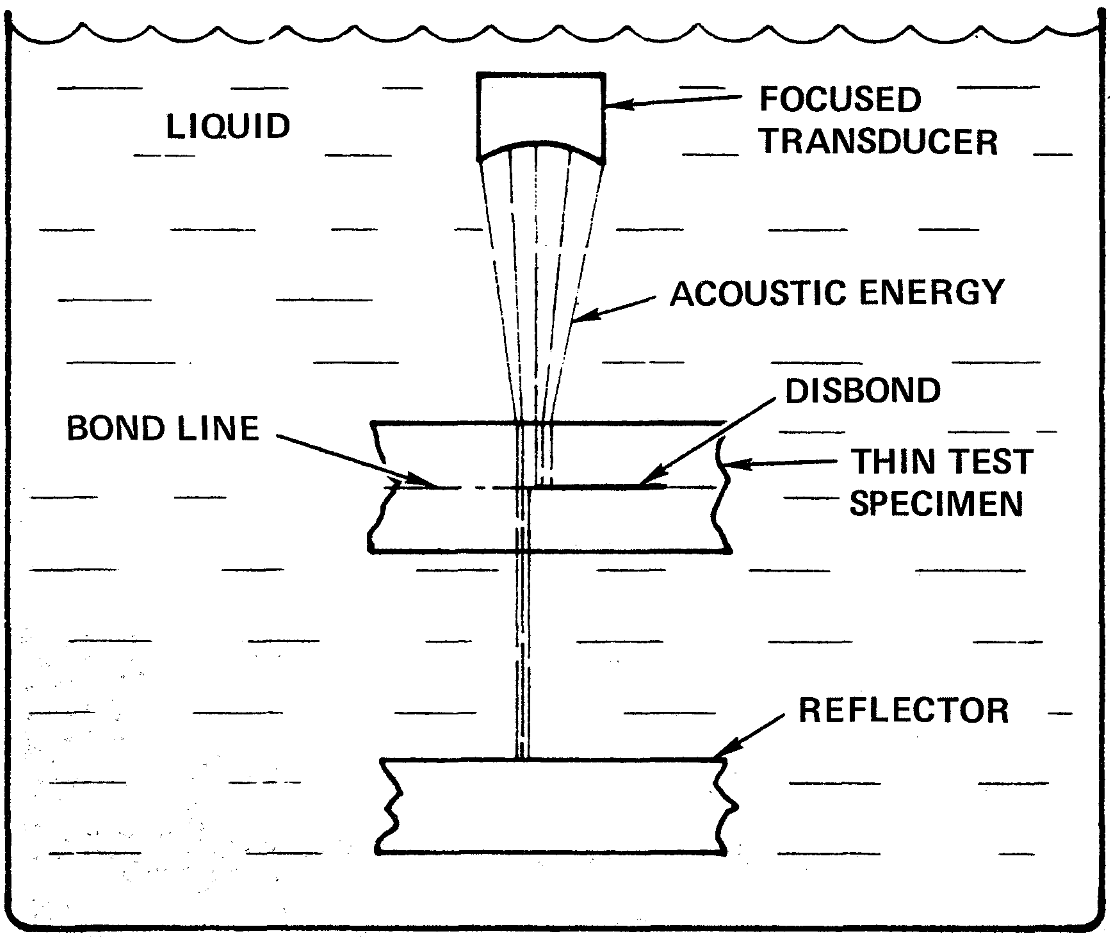


ACOUSTIC EMISSIONS FROM GRAPHITE-EPOXY FLEXURAL TEST SPECIMENS

Flexural tests on two similar fiberglass-epxoy specimens produced the load-emission results shown. Note on the lower pair of traces (specimen A3-3) that burst emissions associated with filament failures started at about 130 pounds of applied load. The upper pair of traces show fewer and lower amplitude emissions leading to fairly abrupt interlaminar shear failure. Eventhough the loads at failure were comparable in this particular example, being able to clearly predict the mode of failure is an important feature.



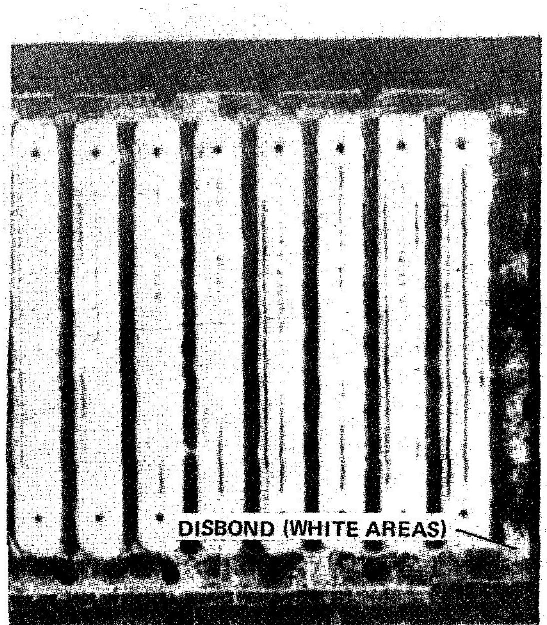
A schematic showing position of transducer, test specimen, and reflector plate for ultrasonic bond inspection of diffusion bonded or brazed shield structure is shown.



ULTRASONIC C-SCAN VS. RADIOGRAPH OF Td-Ni-Cr BRAZED HEAT SHIELD

A comparison between the radiograph showing lack of braze alloy and corresponding indications on the ultrasonic C-scan recording is evidence of the accuracy of the ultrasonic technique. Since radiography is sensitive to material change whereas ultrasonics is relatively unaffected by such change but sensitive to material interfaces, correlation between the two tests in this case should be expected. The large white strips in the center of the C-scan recording are attributable to specimen geometry.

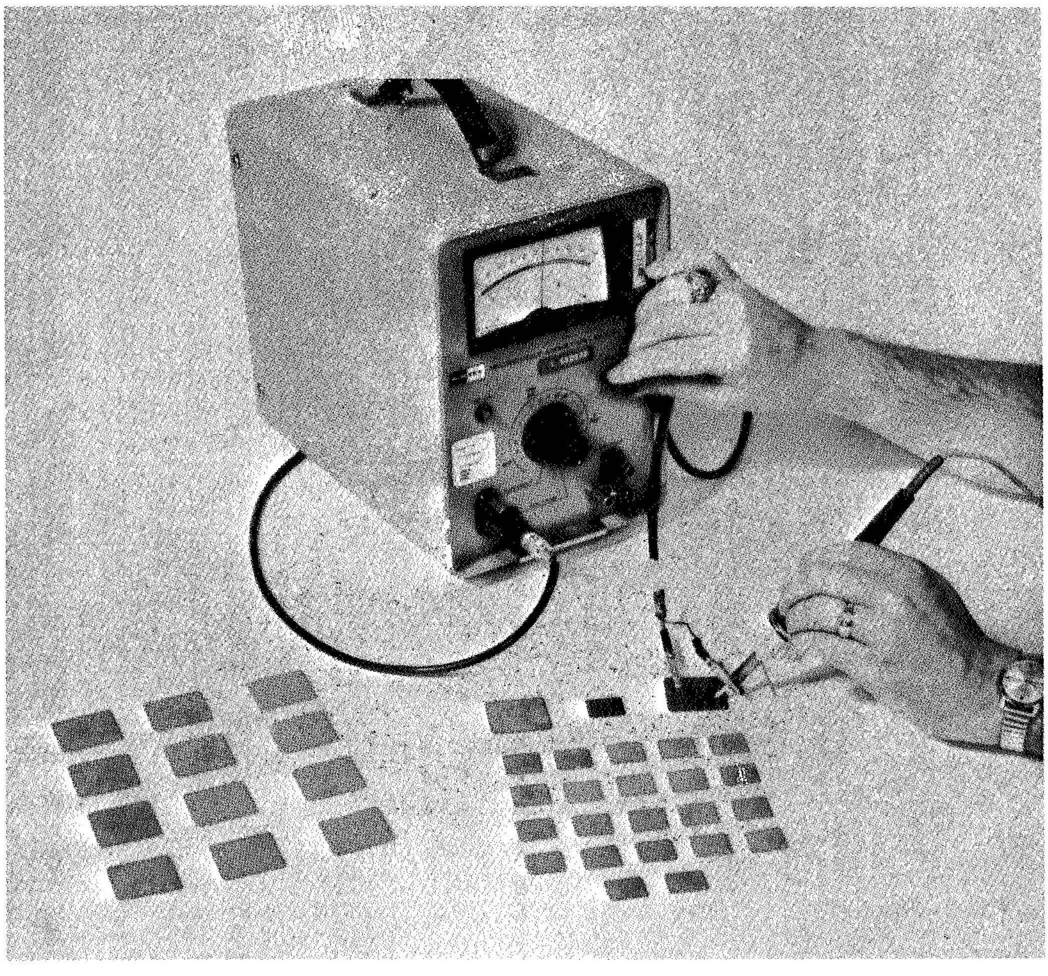
A. ULTRASONIC C-SCAN



B. RADIOGRAPH

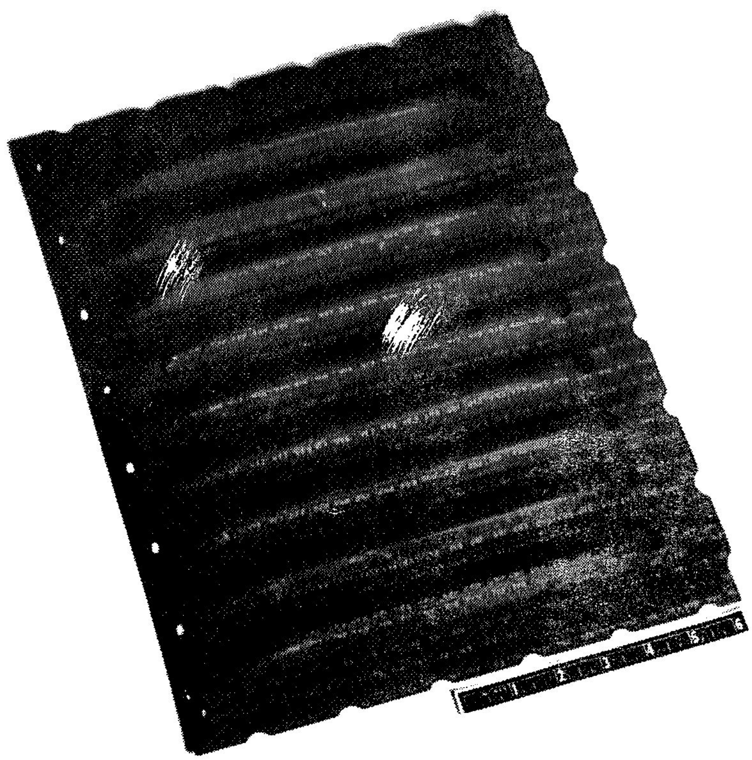
THERMOELECTRIC TEST SETUP

Setup showing reverse thermocouple principle used to detect coating variation.



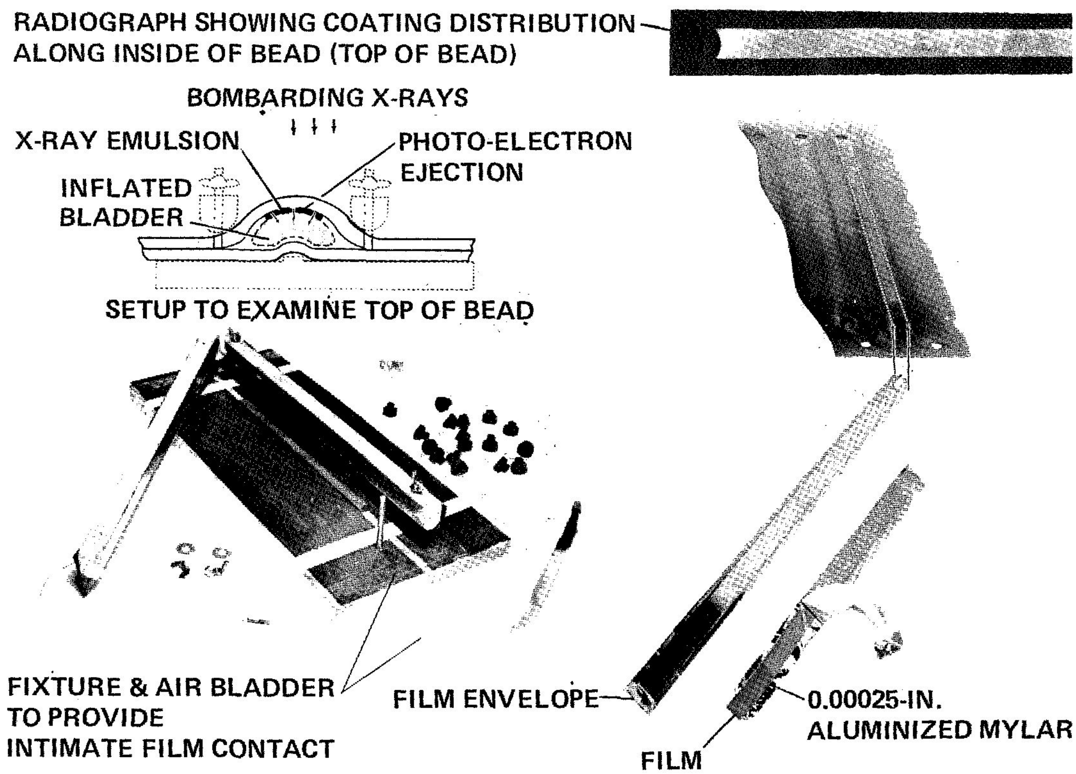
SHIELD STRUCTURE GRIDDED FOR THERMOELECTRIC TESTING

A major limitation of thermoelectric testing is the time required to adequately cover the surface of a large shield structure. A nonconductive oxide layer developed on the surface of the coating in service prevents its application during shuttle turnaround.



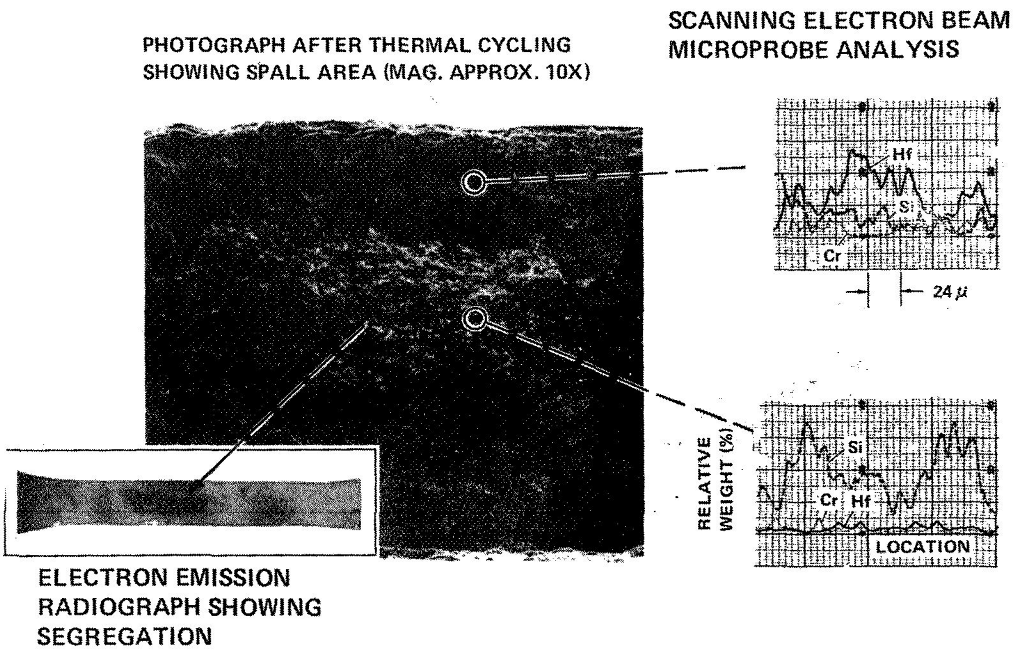
Either forward or backward emission techniques may be employed to examine the uniformity of silicide coatings on substrates such as tantalum and columbium. The technique is most effective to assist process control and to provide necessary direction for design and fabrication studies involved with coated TPS. Restrictions to maintenance personnel, inspection time, and geometry limitations make it less suitable for turnaround inspection.

TECHNIQUE FOR ELECTRON-EMISSION RADIOGRAPHY INSIDE COATING SURFACE



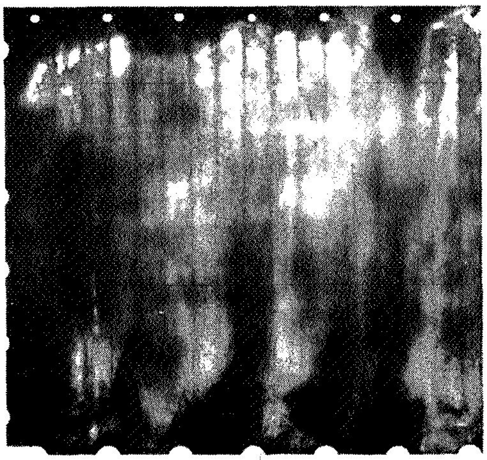
CORRELATION BETWEEN TEST RESULTS

While correlation between coating performance and the results of electron emission radiography has been observed, abrupt variation in coating chemistry frequency has no apparent effect on coating behavior. In general, however, our experience is that coatings containing significant variation fail more frequently than do coatings which contain less variation. In controlled simulated re-entry cycling of full-scale test articles (bead-stiffened panels), overall shield performance improved markedly with uniformity of the coating.

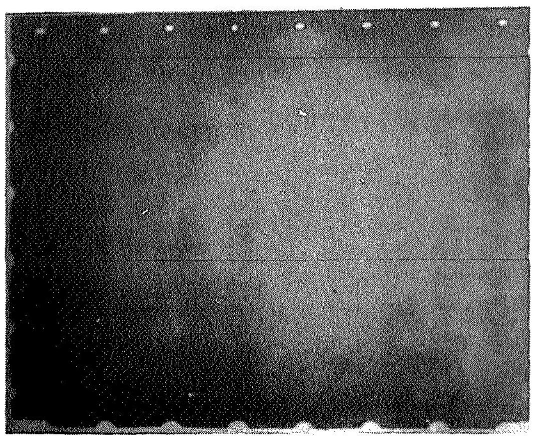


ELECTRON EMISSION RADIOGRAPHS OF COATED COLUMBIUM ALLOY HEAT SHIELDS

The electron radiographs of two columbium heat shields (12 by 18 inches) are shown. The radiographs show marked improvement in coating uniformity between early and recent applications.



EARLY COATED HEAT SHIELD

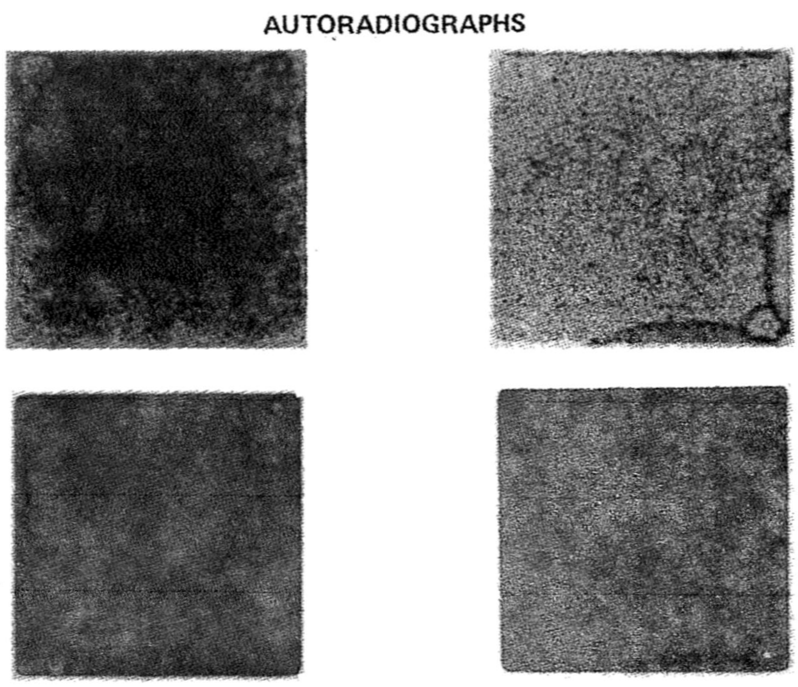


RECENTLY COATED HEAT SHIELD

AUTORADIOGRAPHS AND ELECTRON-EMISSION RADIOGRAPHS SHOWING DISTRIBUTION OF RADIOACTIVITY AND MAJOR ELEMENTS, RESPECTIVELY

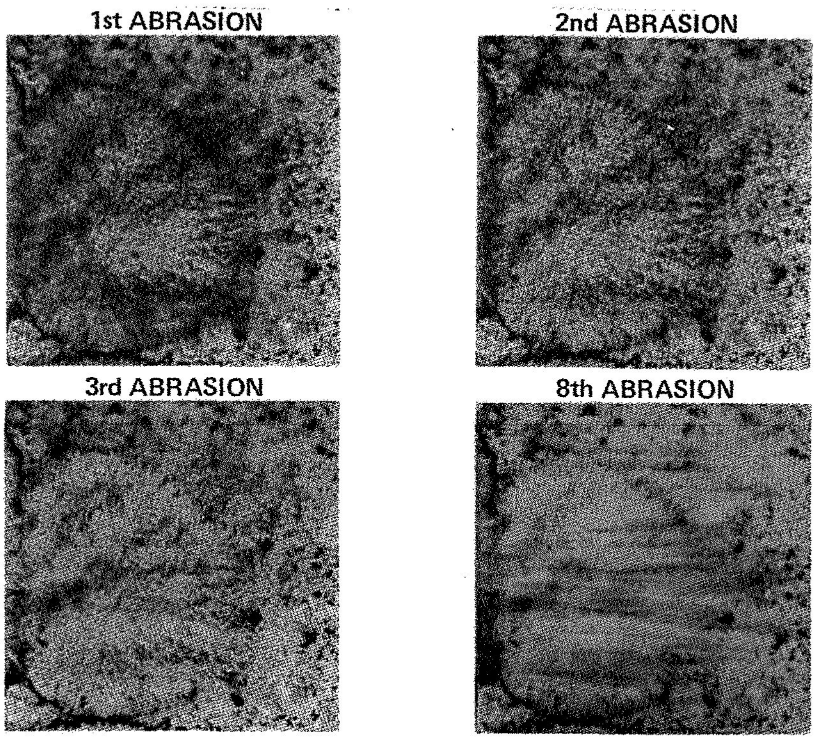
The use of low energy beta emitting isotopes in high temperature coatings is currently under investigation at Convair. The technique offers the potential of in-situ NDT of metallic or nonmetallic coated TPS. The objective is to develop a practical inspection approach that can be economically applied during shuttle turnaround.

The autoradiographs (top of figure) were produced by contact with Kodak Type T x-ray film. It is interesting to note that apparent concentrations of radioactivity are identically mirrored in the electron radiographs of the same specimens, bottom of figure. The indications on both radiographs probably report segregation of a heavy element modifier in the coating, which behaves similarly to the isotope carrier, i.e., flowing and/or chemically combining in a like manner.

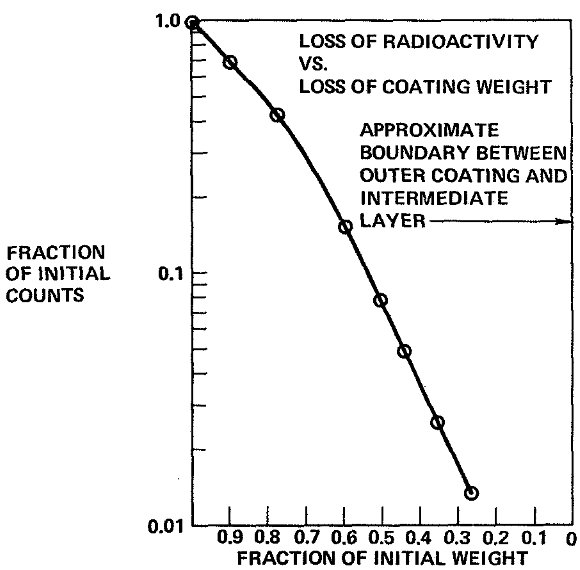


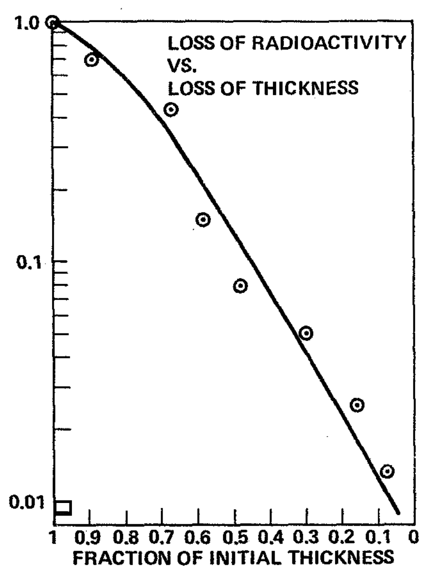
AUTORADIOGRAPHS SHOWING REMAINING RADIOACTIVITY
FOLLOWING CONTROLLED ABRASION

Autoradiography following controlled abrasion in eight equal steps (approximately 0.5 mils removed per step), shows the overall dispersion of the radioactive tag to remain essentially unchanged although the final abrasion removed essentially all radioactivity from portions of the surface. Even dispersion of the tag can be achieved with improved mixing procedures.



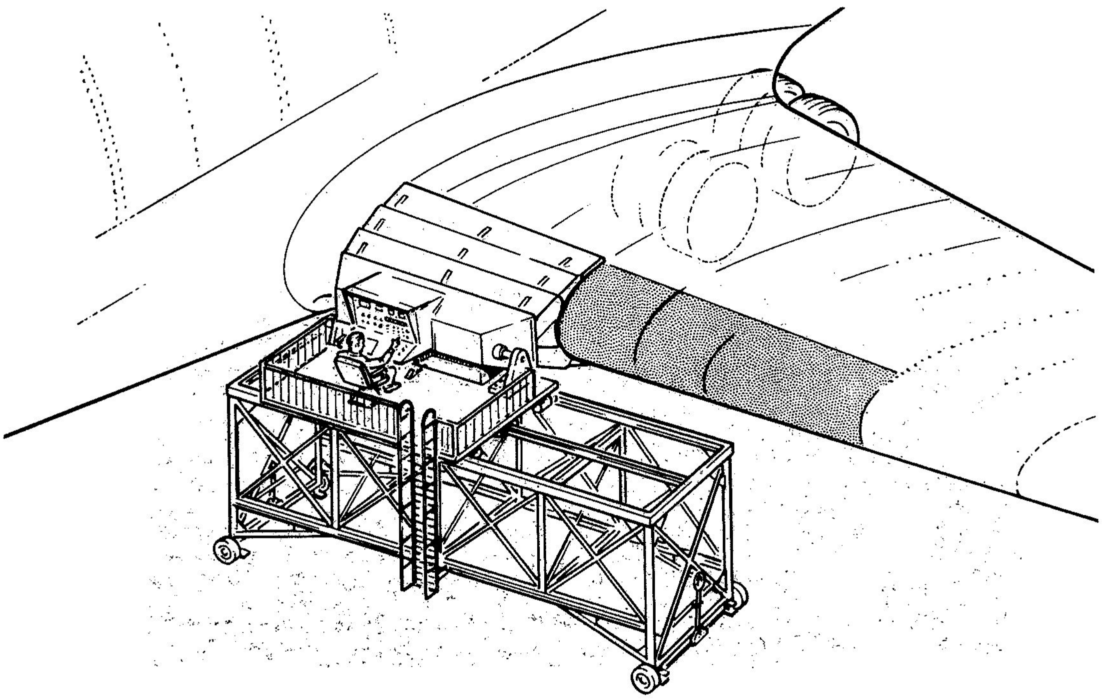
Figures 18 and 19 report changes in the initial count rate at the surface of a coating tagged with ^{147}Pm as a function of remaining coating weight and thickness. It can be noted that the level of radioactivity measured by a wide aperature (1.25-inch end window) G-M counter is a marked function of the fractional remainder of coating after abrasion.





RADIATION COUNTER

This figure shows an artist's concept of a radiation counter to measure coating thickness during shuttle turnaround inspection.



ACTUAL MOSSBAUER SIGNATURE OF VH101/Cb752 CONTAINING 57 Fe

Early investigation of Mossbauer Spectroscopy to measure coating service life was performed by Sanders, Inc. for Convair. Further study in this area will be determined by continued experience with coated metal refractories and specifically by the degree to which these systems can be characterized.