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NONDESTRUCTIVE TESTING FOR EVALUATION OF STRENGTH OF BONDED MATERIALS (METALLIC)

National Aeronautics and
Space Administration

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A DIVISION OF LOCKHEED AIRCRAFT CORPORATION
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1 September 1966

To: Director, George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama 35812

Attention: PR-RC

From: Proficiency Development Laboratory
Department 58-11, Zone 401
Lockheed-Georgia Company
Marietta, Georgia 30060

Subject: Bibliographic List, Contract NAS8-20627

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STRENGTH OF BONDED MATERIALS (METALLIC)

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NONDESTRUCTIVE TESTING FOR EVALUATION OF
STRENGTH OF BONDED MATERIALS (METALLIC)

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28 February 1967

TO: Director, George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama 35812

Attention: PR-RC

FROM: Proficiency Development Laboratory
Department 58-11, Zone 401
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No. 70 Dave, J. S., and Dewar, M. J. S.: J. Chem. Soc. 1955, 4305. "The Effect of Structure on the Transition Temperatures of Mixed Liquid Crystals." The transition temperatures of binary systems in which one equipment can form liquid crystals were determined.

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No. 81 Dreyer, J. F.: U. S. Patent 2,524,286. This invention relates to oriented films and the method of making them. More particularly the invention relates to light-polarizing films of dyes, to composite and laminated films, to products embodying such films and to methods of making and using such films.

No. 82 Dreyer, J. F.: U. S. Patent 2,544,659. This invention relates to dichroic (including pleochroic) materials having oriented molecular arrangement adapted for polarizing light and to materials readily convertible thereinto; and also to products and devices comprising such materials and to methods for the formation thereof.

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No. 477 Fergason, J. H., "Liquid Crystals", Scientific American, August 1964. This report gives a brief history of liquid crystals. It discusses their molecular structure, chemical composition, optical behaviour, and reactions to thermal changes. The characteristics of the three groups of liquid crystals, nematic, smectic and cholesteric, are explained.

No. 478 Sabourin, L., "Nondestructive Testing of Bonded Structures with Liquid Crystals," Structural Adhesive Bonding Conference, 15-16 March 1966, NASA/MSFC. A brief discussion is given of liquid crystal cholesterol esters, with emphasis on their optical characteristics as they respond to thermal environment changes that produce variations in color. The advantages of these materials as temperature indicators are speed of response, reversibility, and reproducibility. In order to visualize the colors associated with these materials it is necessary to paint liquid crystals over a dark background of the part to be tested. Approximately one gram of these mixtures will cover one square foot to a thickness of about ten microns. Applications include checking for bond defects, checking electronic circuits for hot spots, and rivet checks in structures where they have to be insulated from dissimilar metals.

No. 479 Woodmansee, W. E., "Cholesteric Liquid Crystals and Their Application to Thermal Nondestructive Testing," Society for Nondestructive Testing Annual Meeting, Detroit, 1965. A description of the unique properties of cholesteric liquid crystals and applications involving their use in visualization of small thermal gradients are shown. Mixtures of liquid crystals which respond to thermal changes of liquid crystals or less by reflecting different colors of visible light are discussed. Various nondestructive testing methods of inspection using liquid crystals are shown.

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No. 481 Brown, G. H., "Liquid Crystals," Industrial Research, May 1966. This article by Dr. Brown gives a basic background of liquid crystals describes their properties, different types of structures, and how they are formed. Their optical characteristics are discussed in depth. The possibility of developments in the field of liquid crystals being used in living systems is introduced. A bright future is predicted for the use of liquid crystals in industry and medical science.

No. 482 Jones, C. H., Fergason, J. L., Asars, J. A., et al, "Investigation of Large Area Display Screen Using Liquid Crystals," Final Report, 1 June 1964 - 4 June 1965, RADC-TR-65-274. This report describes the properties of temperature-sensitive cholesteric liquid crystals that are pertinent to their applications in large area displays. An experimental 10 in. X 12 in. display panel was built to demonstrate the color, resolution and time constant capabilities of liquid crystals. Five different methods for obtaining dynamic thermal patterns in response to video signals are described. The application will dictate which method should be used for any given display problem. Considerable experimental work has been carried out on those methods which appear to be of most practical usefulness.

These abstracts were excerpted from abstract indices and other sources available in the field.

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PDL-7

THE APPLICATION OF LIQUID CRYSTALS FOR THERMOGRAPHIC TESTING OF BONDED STRUCTURES

By

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for

Marshall Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

This report describes the equipment and procedures developed for applying, testing and photographically recording the results of thermographic tests using a liquid crystal heat sensitive coating that changes color with minute temperature gradients, caused by discontinuities, in the substrate structure.

A total of 290 square feet of bonded honeycomb and laminated metallic and non-metallic structural panels was tested in an analysis of technique capability. The test specimens with built-in flaws, were fabricated by NASA and represent 52 variations of materals and construction types used in aerospace structural composites. Special instrumentation was developed for a simple method of quantitatively evaluating liquid crystal mixtures. The data acquired is presented in tabular form and describes the type and size of flaws that can be detected with the portable nondestructive thermal analysis equipment supplied to NASA.

The technique was proven to be feasible in applications that would otherwise require more complex and costly infrared systems. The information included can be extrapolated to provide baseline data for the determination of the feasibility of specific infrared, as well as liquid crystal applications. A sample color photograph is included typifying the 180 photographs, depicting test results, which were supplied to NASA.

FOREWORD

This report was prepared by the Proficiency Development Laboratory, Lockheed-Georgia Company, Marietta, Georgia, under NASA Contract NAS8-20627, "Nondestructive Testing for Evaluation of Strength of Bonded Materials." The work was administered under the direction of the Quality Assurance Branch, Quality Engineering Department.

Program Management at Lockheed was under the general direction of Mr. O. L. Fletcher and Mr. Lawrence A. Wilson. Mr. Sherman E. Cohen was the Senior Engineer responsible for the technical aspects of the program and Mr. Robert D. Harris performed the laboratory tests. Mr. James B. Beal served as contract technical supervisor for NASA/MSFC.

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THE APPLICATION OF LIQUID CRYSTALS FOR THERMOGRAPHIC TESTING OF BONDED STRUCTURES

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1 - INTRODUCTION

History

Liquid crystals have been experimentally used for contact thermographic analyses of electronic components and adhesively bonded aircraft structural materials since 1963. A literature survey was conducted and information concerning the theory and applications of liquid crystals was reviewed and abstracted. No information was found that could be extrapolated to provide data for the evaluation of liquid crystals for nondestructive testing (NDT) of bonded structures.

Temperature sensitive phosphor coatings and paints, coalescing fluids, thermocouples, infrared radiometers, infrared sensitive photographic films, and the Evapograph system have had varying degrees of success in contact and non-contact thermal testing.

This report describes the techniques and equipment developed by experimentation for the optimal application of liquid crystals in thermal testing of bonded structures.

Purpose

On 30 June 1966 the National Aeronautics and Space Administration awarded Lockheed-Georgia Company a contract for the purpose of developing testing techniques and equipment resulting in a self-contained portable liquid crystal thermal analysis system with photographic equipment to permanently record the results of tests. In addition, 180 photographs depicting the results achieved with the actual system on 35 different test panel types were supplied to NASA. These panels were fabricated by NASA with specific built-in defects typifying anomalies resulting from fabrication process deviations and in-service incurred defects. The conditions under which the test panels were inspected were not unusual and can be replicated as described under the section on Procedures For Use.

Report Contents

The major significance of this development effort is the proof offered of method feasibility for specific applications. System effectiveness is dependent upon the particular construction of the bonded honeycomb panel or laminate to be inspected and the size, type and location of the defect. The 35 NASA test panels consisted of 52 construction and material variations in combinations representing a wide range of thermal characteristics. A total of 290 square feet of test panel area was inspected. The defects detected were tabulated and keyed to photographs to provide baseline data for the determination of method capability and specific utilization. Special instrumentation for calibration and quality checking of liquid crystals is also described.

Brief Description of Liquid Crystals

The phenomena exhibited by liquid crystalline substances have been known since 1888 (Ref 1). The most common name of the material, liquid crystals, seems to be paradoxical. However, since these materials are fluid and also birefringent (an optical property of solid crystals) the name is descriptive.

Until quite recently most activities related to liquid crystals have not been in nondestructive testing, but in basic research. The properties of liquid crystals produce immediate, in situ, thermal images in a pattern of colors which respond rapidly to minute changes in substrate surface temperatures. Infrared radiometers accomplish a similar end result but require complex equipment.

A complete understanding of the abstruse theoretical explanations of the behavior of liquid crystals is not necessary for their practical application. However, an understanding of what this material does and what it can detect is necessary for its full exploitation as an inspection tool.

The liquid crystals used in thermographic testing are cholesteric mixtures and are derived from organic compounds found in biological systems. Solvents such as chloroform and petroleum ether are used in liquid crystal mixtures commercially available and prepared ready to apply. These mixtures are clear and have approximately the same mechanical properties as the solvents used. If this type of liquid crystal mixture is applied to a surface, the solvents evaporate and the resultant coating is a thin, greasy layer of liquid crystals which remains clear, below the transition temperature and above it. Transition or melting point temperatures can be obtained that range from 20°F to 150°F by variations in chemical compounding.

The color changes seen between melting points and the color seen at a specific temperature is caused by a scattering of incident light within the coating. The wavelength which predominates is dependent upon the viewing angle, the angle of incident illumination, and the index of refraction of the liquid crystals. Figure 1 depicts the appearance of a relatively cold discontinuity that would be caused by an inclusion acting as a heat sink.

The most important property of liquid crystals is that with a change in temperature this index of refraction changes and is reversible accordingly. This optical activity is most often explained by describing the geometry of the molecular layers which rotate in a highly ordered manner, a discrete amount for a specific temperature (Ref. 2). With increasing temperatures the liquid crystals first appear colorless and with a response time on the order of 0.1 seconds, change to red, then to yellow, green, blue, violet, and colorless again within a span of 1.5 Fahrenheit degrees. In order to see these colors, a black background is required since the liquid crystals always remain transparent and do not absorb, but reflect light (Ref. 3).

2 - PORTABLE NONDESTRUCTIVE TESTING UNIT AND EQUIPMENT

General Description

The radiant heating unit with transformer power supply and a storage bench is mounted on casters. Two spray guns, a heat gun, and photographic equipment with accessories are stored in the bench. Two electronic flash units are mounted above the heating unit on adjustable arms. An air filter with a pressure regulator is mounted on the heating unit structure for use when spraying the liquid crystals and when using the air gun to cool test panels.

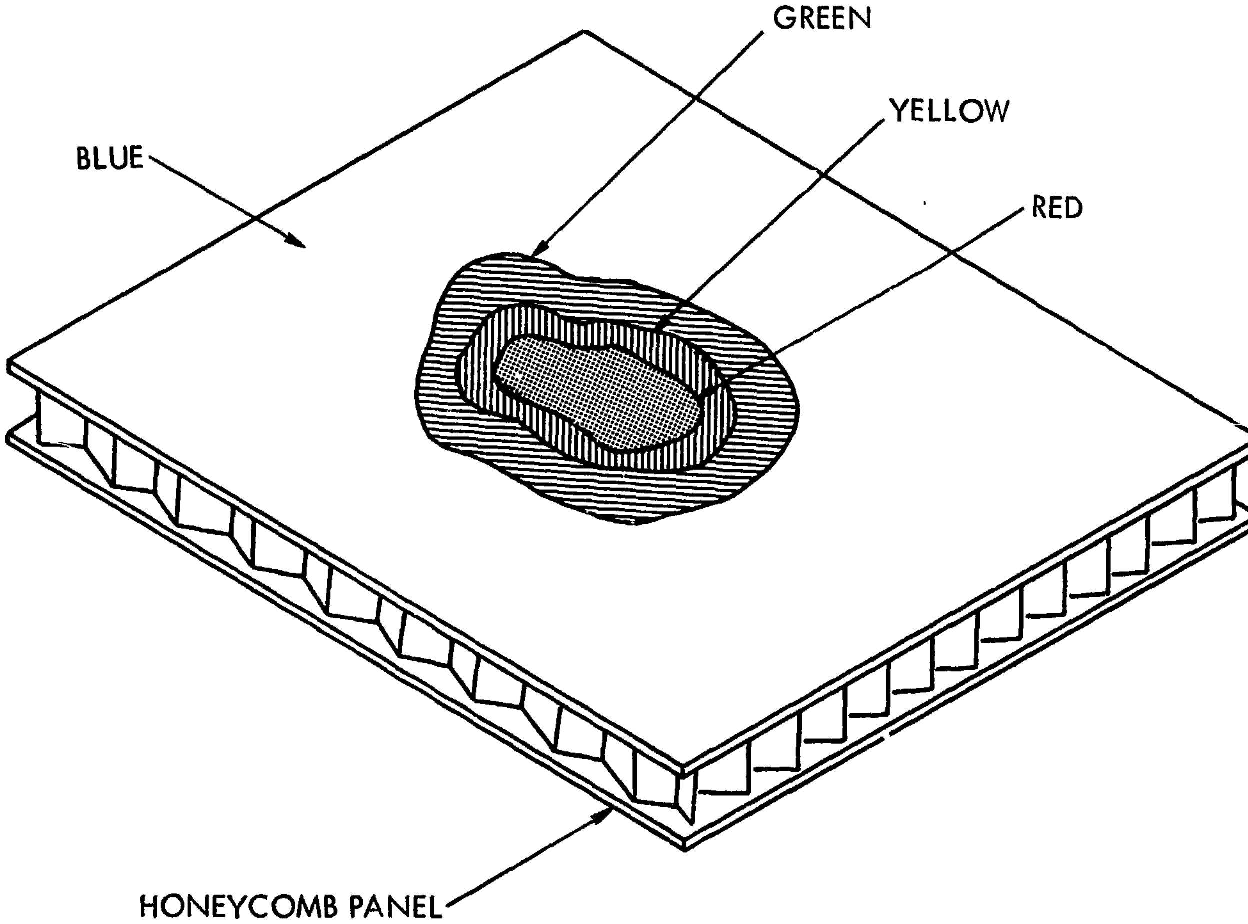

FIGURE 1 - APPEARANCE OF COLD SPOT THERMAL IMAGE UNDER TEST CONDITIONS

Figure 2 shows a front view of the portable NDT unit. The heating unit has sixteen specular gold plated reflectors. Overall dimensions of the reflectors are 44 by 44 inches. The entire bank of lamps can be raised or lowered 38 inches vertically, and can be pivoted on its supporting points. The top and bottom sections are hinged to permit contouring to the job. Four section switches are provided to control each horizontal section individually. A fused master switch is provided and also a toggle switch. The toggle switch is located adjacent to the transformer. The transformer allows adjustment of rate of heat input. The lamps are incandescent 300 watt, 130 volt, frosted. Power requirements are 240 volts AC, 60 cycle, single phase, 3 wire, 20 Amps. Figure 3 shows a left side view of the equipment as set up for testing. The final lamp configuration was chosen after experimenting with various types of reflector flood lamps and infrared lamps in an adjustable framework. The heating unit is also used to illuminate the test panel during the heating cycle. Final verification of heating and lighting conditions was accomplished by using a panel coated with liquid crystals.

The final configuration with 300 W incandescent lamps was found to have the most even heat distribution. With a test panel in position, 20 to 30 inches from the heating unit, as shown in Figure 3, the surface will reach the liquid crystal transition temperature of 95°F in approximately 50 seconds.

Photographic Equipment

The photographic recording system is comprised of a 4 x 5 Graflex Crown Graphic camera with a 90 MM Super Angulon f/8 lens, a Polaroid Land 4 x 5 film holder and two Honeywell Strobonar 600 electronic flash units. Type 58 Polaroid Polacolor film is used exclusively in this system, since it offers the advantage of eliminating the dark room.

First attempts at photographing the liquid crystal display were problematical. The source of illumination must be positioned so that the angle of incidence does not produce specular reflection. Polarizing filters were tried but were unsatisfactory when used to view the test panel directly and when used at the camera because of the attendant reduction in available light. Polaroid color film was designed and color-balanced for daylight (6250°K) exposure. It is relatively slow, having an ASA film speed of seventy-five without color balancing filters and a speed rating of twelve with filters. The use of filters necessitates longer exposures or high intensity illumination. With longer exposures, approaching one-tenth of a second, yellow color is increased in density and film speed is lost. To compensate for yellow density at longer exposures, blue filtration is recommended, which leads to a still lower effective film speed. In addition, the lenses normally used with the 4 x 5 inch format cameras are slow, usually f/8. Lamps of the correct Kelvin color temperature could have been incorporated in the heating unit (which is also used for illumination during visual inspection) except for undesirable reflections which interfere with the photography.

Photographic flood lamps and a combination of two color correcting filters were used in attempts to balance the Kelvin color temperature of the lights to the Polacolor film. Since the filters reduced the effective speed of the film to ASA 12, the photofloods had to be close to the liquid crystal coated surface. Because of the relatively low operating temperature of the liquid crystals used, the high heat of the photoflood lamps created an uneven heat input resulting in false color patterns. Because of the optical nature of liquid crystals, exposures are on the order of four times longer than colored surfaces having the same illumination.

Two Honeywell Strobonar electronic flash units mounted as shown in Figure 2 eliminated the need for filters and did not heat the test panel. This arrangement was used to test the panels supplied by NASA for evaluating liquid crystals. The only drawback is that just prior to taking the photograph the heating unit must be shut off to prevent reflections on the panel.

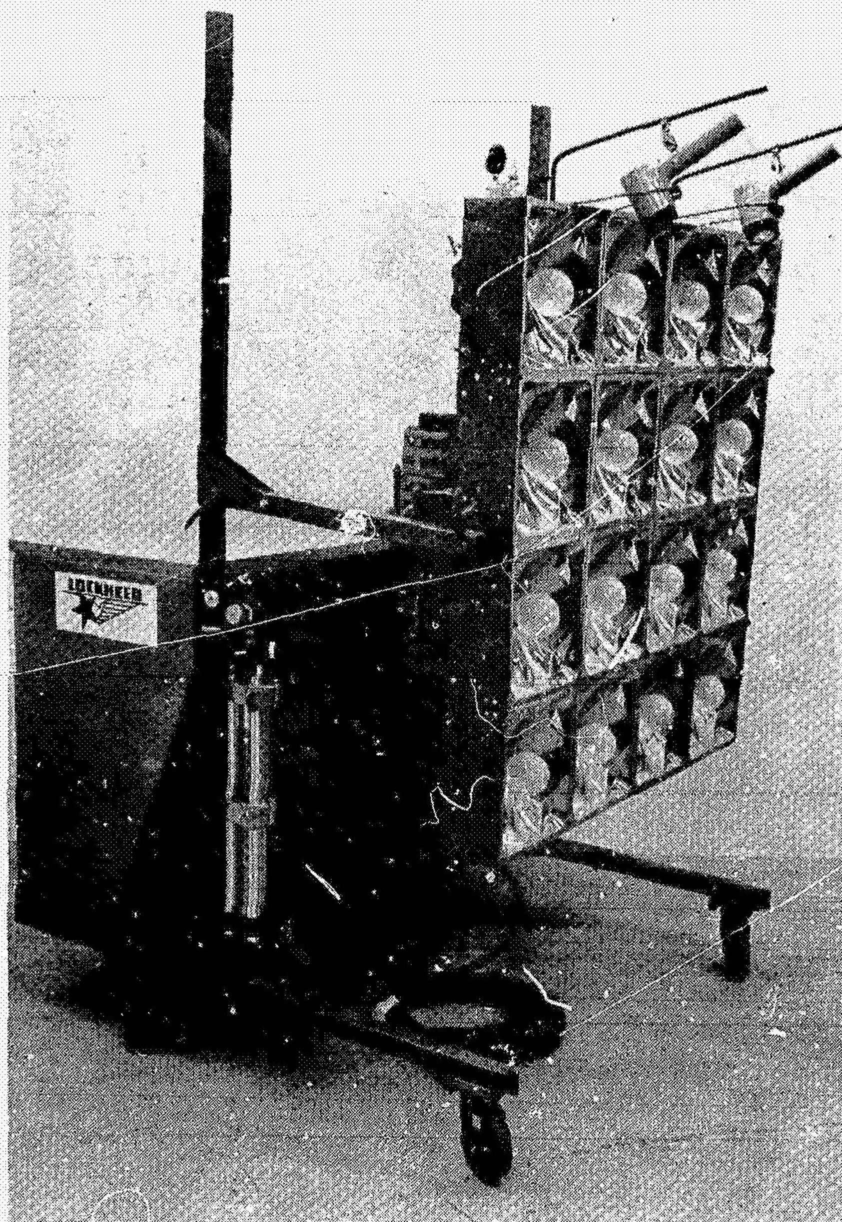

FIGURE 2 - PORTABLE NDT UNIT - FRONT VIEW

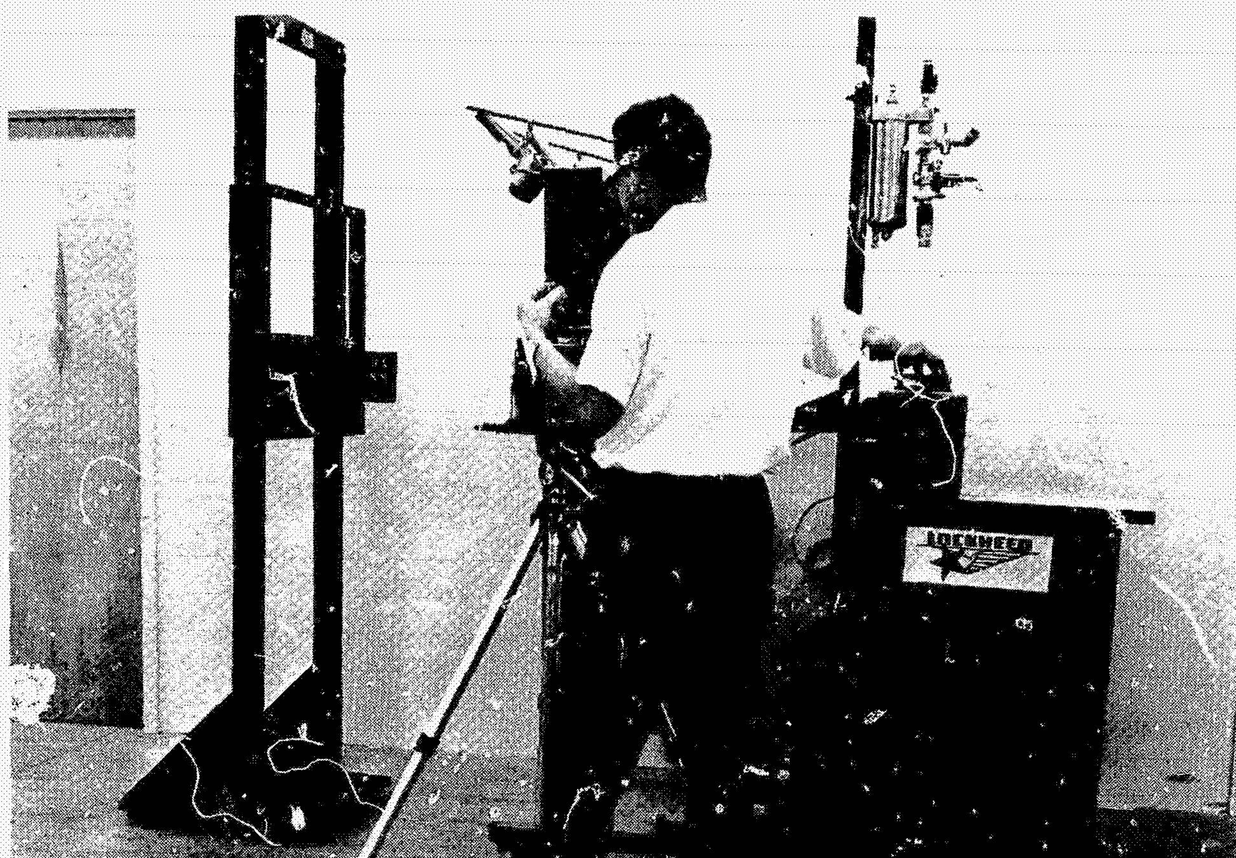

FIGURE 3 - EQUIPMENT ARRANGEMENT - LEFT SIDE VIEW

Spray Equipment

Small scale tests using a Binks Wren airbrush were conducted and proved to be satisfactory on areas no larger than 4 x 4 inches. This is due to the small spray pattern and the necessity of applying the coating in as few spray passes as possible. If the liquid crystal mixture is allowed to dry between successive coats a very noticeable irregular pattern results and coating thickness is not uniform. The spray equipment used for applying the liquid crystals and background paint was a Binks Company model 15 spray gun with a number 78 fluid nozzle and a number 78S air nozzle. An airless spray system was evaluated in an effort to obtain more economical coverage but was unsatisfactory. The results of this evaluation are discussed in the section on Miscellaneous Observations.

Background Paint

The black background paint used was Pelikan 17 black waterproof drawing ink manufactured by Gunther Wagner, Germany. A Binks model 15 spray gun is used with a number 78 fluid nozzle and a number 78S air nozzle. The spraying technique used is conventional except for warming of the panel to 95°F - 100°F between successive light coats until the surface is entirely covered. A hot air gun (Model No. 500A Ray Clad Tubes, Inc, Redwood City, California) is used for this purpose.

The black background paint must meet several requirements to be compatible with liquid crystals and the object to be tested. The paint must not be affected by, or react with, the solvents (ketone and petroleum ether) used in the liquid crystals. Since liquid crystals are sensitive to contamination, a lacquer or cellulose nitrate paint cannot be used. Various mixtures of polyvinyl alcohol, detergent and carbon black were experimented with but were not as suitable as the Pelikan ink. The surface texture of the paint is an important consideration. A rough, absorbent background paint is undesirable because poor coverage with liquid crystals will be obtained. If the surface has a high gloss it will permit specular reflection (as in a mirror) and defeat the intended purpose of the paint. The surface texture of the Pelikan ink has proven to be very satisfactory. It can be removed with warm, soapy water and, if it is necessary to remove only the liquid crystal coating (prior to respraying) acetone or ketone may be applied with a soft cloth, leaving the background coating intact. Some difficulty was encountered in removing the ink from rough surfaces of fiberglass panels.

3 - PROCEDURES FOR USE

Preliminary Preparation of Test Panel

Prior to coating, the surface of the test panel is degreased with methyl ethyl ketone or acetone. If the surface to be coated is already painted it can be cleaned with Stoddard Solvent, Federal Specification P-D-680, Type I. Most commonly used exterior aircraft paints are not affected by this solvent.

Application of Background Paint

The Pelikan ink is used without dilution. The air filter is used with a Binks model 15 spray gun. The pressure is adjusted to 30-35 PSIG. The needle valve is adjusted to give a fine even spray. The spray gun is held 8 to 10 inches from the surface.

Just before the first coat is applied the panel surface should be heated to 95° F - 100° F. The heat gun is used to speed drying between successive coats and aid adhesion. The finishing coat is the lightest coat applied and should be as light as possible. About 100 ml will cover four square feet. The time required to cover four square feet is 10 minutes. The spray gun and nozzle must be thoroughly cleaned by spraying hot water through it as soon after use as possible.

Application of Liquid Crystal Coating

The most important step in the inspection procedure is the proper application of the liquid crystals. With proper attention given to spraying technique and careful adjustment of pressure and needle valve settings, 85 milliliters of liquid crystals can provide an adequate coating thickness on a 2 x 2 foot panel. Pressure should be approximately 12 PSIG. The recommended coating thickness is 10 microns (.0004 inches). Rough surfaces such as fiberglass require considerably more. Coating thickness is judged by eye and is adequate if the surface of the panel appears glossy when viewed obliquely. The coating should not be allowed to dry between successive coats. Preliminary adjustments of the spray gun can be made by spraying methyl ethyl ketone in order to conserve liquid crystals. The gun should be dried with air before filling with liquid crystals. The time required to spray a 2 x 2 foot panel is 3 minutes.

The coated panel must be handled with care. Smearing and surface contamination with dust must be prevented. If the coating is accidently smeared it is possible to repair it, to some extent, by careful brushing with a clean camel hair brush in one direction.

Arrangement of Equipment

The equipment is arranged as shown in Figure 3. The inspection heating area is approximately 2 x 2 feet. The camera should be placed as shown unless the configuration of the part to be inspected does not permit an adequate view of the test area. The test area should be centered in front of the heating unit which is raised, lowered or tilted by loosening the clamps on the supporting structure. The heating unit should be from 20 to 30 inches from the test area. This distance is not critical as any required change in heat flux can be accomplished by adjusting the transformer. If a larger than 2 x 2 foot panel is to be inspected it must be done in sections.

The electronic flash units are aimed at the center of the test area. Prior to testing, the camera is positioned and focused by removing the Polaroid back and viewing through the ground glass.

Test Conditions

Because of the thermal sensitivity of liquid crystals, ambient drafts must be minimized. Slotted steel angle and polyethylene film were used to build an enclosure to shield panels during inspection. The enclosure was 12 x 8 x 10 feet high. This provided a simple, effective solution that is adaptable to various inspection situations requiring the elimination of drafts and dust.

The tests were conducted at an average ambient temperature of 72° F. Overhead fluorescent room lighting did not interfere with visual inspection or photography.

4 - TEST PROCEDURE

Inspection

The procedure for testing all types of panels was the same except for variations in the rate of heat input. The time required to reach transition temperature is mainly dependent upon rate of heat input, the overall specific heat, thermal diffusivity, thermal conductivity, shape and the initial temperature of the panel. Because the test panels were not cooled from the opposite side, the process is one of unsteady state heat conduction. The time required to bring the panels up to the transition point of 95° F, of the liquid crystals used, ranged from 45 to 60 seconds depending on panel type.

To begin testing, the inspector turns the transformer up to full power and stands behind the camera viewing the panel. Several attempts are usually required to gain experience on each type of panel since different types of construction have a marked effect on heat transfer characteristics. In addition, different types of discontinuities will appear at varying stages of heat-up.

The panel is cycled through the transition temperatures several times and defects that can be visually detected are noted. It was found that in some fiberglass and titanium panels, a reduction in heat input immediately after the appearance of a thermal image, aided in image retention by delaying the eventual thermal equilibrium across the surface of the panel. The air gun is used as required to save time in cooling the panel down to initial temperature between heating cycles, and to induce a thermal gradient across some types of discontinuities.

After the inspector gains familiarity with the thermal image that is to be recorded, the heating unit lamps are shut off with the toggle switch just as the image reappears and the camera shutter cable release is pressed. This is repeated and photographs are taken at as many time intervals as required to record the defects. Individual defects were not photographed since more information can be obtained if the detectable defects are viewed as part of an entire panel area. In this way, cold and relatively hot spots can be differentiated and related to flaw types. In some cases, defects could be seen but could not be photographed. In other cases defects could be detected more readily by inspection of the photograph than by observing a rapidly changing transient color pattern on the actual panel. A typical color photograph of a test panel taken with the equipment is shown in Figure 4.

5 - TEST RESULTS

Explanation of Tables

Not all types of bonded honeycomb or laminated panels are suitable for testing with liquid crystals. The objective of the tests performed was to determine the composition of panels and the type and size of defects which are within the capabilities of the technique. The data acquired in testing the 35 NASA test panels is presented in tabular form.

Table II describes the material, identifies the face sheets of each panel and keys each panel to Table V, "Defects Detected."

Table II also references figures describing construction details of the panels. Table II locates and describes the defects. Table V identifies each defect detected and the serial

FIGURE 4 - TEST PHOTOGRAPH SHOWING DELAMINATION (ROW 1),
LACK OF ADHESIVE (ROW 2)

number of the photograph in which the defect appears. Only the detectable defects are listed in Table V. If a photograph number is not listed, the defect was observed visually but could not be photographed. Photographs supplied to NASA are similar to the sample shown in Figure 4. The coordinates of defect locations listed in Table V refer to the abscissa and ordinate markers appearing in the photographs and figures describing each test panel. Near side (NS) and far side (FS) refers to both the location of defects in the panels and is also used in designating panel surfaces. This nomenclature was taken from the NASA drawings of the panels.

6 - DISCUSSION

Series I Panels

This series of panels consisted of aluminum alloy 7075-T6 face sheets ranging in thickness from 0.030 to 0.063 inch, and hex cell phenolic honeycomb core 1.00 inch thick. The smallest defects found were 0.50 inch adhesive voids with .050 inch thick face sheets, and 1.00 inch defects with 0.063 face sheets. Crushed core was the most difficult defect to detect since the HRP core does not conduct heat to an extent that makes lack of contact with the face sheet result in a detectable surface temperature gradient. Inclusions simulated by 0.0005 inch thick teflon inserts could be detected if larger than 0.50 inch in diameter. A core splice was also discovered.

This type honeycomb panel was the most difficult in which to find defects.

Series II Panels

This series consisted of 7075-T6 aluminum alloy face sheets ranging in thickness from 0.030 inch to 0.063 inch, and aluminum honeycomb core 0.930 inch thick. From Table V, the smallest lack of adhesive defect detected was 0.50 inch in diameter, the smallest inclusion was 1.25 inches in diameter and the smallest crushed core defect detected was 0.75 inch in diameter. In the case of 0.030 inch thick face sheets, a 0.25 inch diameter crushed core defect was detected. Some 0.50 inch diameter delaminations simulated by the insertion of precured adhesive could be found in .030 inch thick face sheets but in thicker face sheet thicknesses delaminations could not be found if smaller than 1.00 inch in diameter.

Series III Panels

This series of honeycomb panels had fiberglass face sheets ranging in thickness from 0.012 inch to 0.050 inch. The core was fiberglass honeycomb with 3/16" cells. Adhesive voids as small as 0.25 inch in diameter could be detected in face sheet thicknesses up to and including 0.050 inch. These fiberglass panels were found to be very suitable in construction for liquid crystal testing. Core splices were found in panels with face sheets as thick as 0.50 inch. It was found that the thermal image could be retained for 5 to 7 seconds by reducing the heat input as the image first appeared and balancing the "heat in - heat out" with the transformer controlling the heating unit.

Series IV and V Laminated Panels

Series IV panels consisted of 7075-T6 aluminum alloy laminates with sheet thicknesses ranging from 0.020 to 0.063 inch. Various combinations were tested.

Series V panels were fiberglass to fiberglass laminates bonded in several combinations of sheet thicknesses ranging from 0.012 to 0.050 inch.

In both series IV and V laminates the minimum size of a particular defect detectable was dependent upon the thickness ratio of the sheets. In some cases 0.25 inch diameter adhesive cutouts and simulated bond line porosity could be detected and photographed in the fiberglass laminates. The aluminum laminates were not as suitable as the fiberglass for liquid crystal testing. Best results were obtained when the side coated, heated and viewed was thin and bonded to a relatively thick sheet which acted as a heat sink.

It was observed that in some laminates the cutouts in the adhesive flowed in the bonding process and the actual defects were smaller by 20 to 30 percent, than intended. This was most apparent in the fiberglass laminates.

Titanium Honeycomb Panels and Laminates Series I T_i, II T_i, III T_i

Titanium face sheets were used in combination with aluminum and HRP honeycomb core.

Good results were obtained with all of the titanium panels. The best results were with aluminum core honeycomb and 0.025 inch thick titanium face sheets. In this panel the core was plainly visible. In the titanium laminates small imperfections in the shape and reduction in size of the built-in defects were apparent, and verified by ultrasonic C-scan.

Panel No. 1, Curved Honeycomb

This panel (Ref. Fig. 10) was the largest panel tested. It was included as a test panel to gain information on the effects of curvature on heating and the time required for inspection. The large size of the panel made it necessary to test the panel in eight separate sections. The 60 inch curvature caused reflections that interferred with visual observation and photography. The curvature did not adversely affect the eveness of heating. Only the convex side was inspected. As shown in Figure 10 and the photographs, core splices were detected and appeared as cold lines.

The time required to apply the background paint was 65 minutes. The time required to apply the liquid crystals was approximately 15 minutes. Inspection was difficult because the panel had to be moved to eight different positions and the heating unit was raised once. Inspection required 60 minutes. Two men were required to reposition the panel prior to the inspection of each section, because of the weight and size of the panel.

Panels C-1 and C-2

These two panels were identical in construction and are described in Figure 11. The honeycomb phenolic core was injected with oil simulating leakage. Since the core was perforated, the oil spread throughout the panel.

Photographs were taken at various stages of heat-up. Fifty percent of the panel area appeared randomly non-homogenous.

Panel P-1

This panel is described in Figure 12. Teflon inclusions, simulated adhesive porosity, and adhesive voids were located between fiberglass face sheet plies and between the core and face sheets.

Face sheets were 7 ply fiberglass 0.50 inches thick. The exterior surfaces were rough and as shown in photographs 256 and 257, reflections were caused by the curvature of the panel.

Removal of the background paint was difficult and remained in the rough surface. Core spices were found. Other defects could be found only in the outer two plies.

Water Detection Capability

Panel X-1 shown in Figure 13 was injected with incremental amounts of water to determine detection limits. Holes were drilled and a measured amount of water was injected as tabulated in Table VI. The holes were sealed to prevent leakage but during the heating of the panel some water was lost. The face sheets were aluminum 0.020 inches thick. Table VI lists the amount of water injected and detected by radiography and liquid crystals.

This test was repeated because the sealing compound interferred with the interpretation of the radiographs and also because of uncertainty as to the distribution of water in adjacent cells.

A face sheet was removed from an aluminum honeycomb panel and one 3/16 inch cell was injected with 0.10 cubic centimeters of water. This was the minimum amount of water detectable through an 0.020 inch thick aluminum face sheet with the panel vertical. In real situations water entrainment would occur in far greater volume.

7 - FEASIBILITY STUDY TO DEVELOP A ONE-COAT SYSTEM

A short study to determine if the black background coating could be eliminated or combined with the liquid crystals was performed.

A black self-adhering vinyl plastic sheet 0.004 inches thick, manufactured by Arnel Plastron, Inc., New York, was applied to an aluminum bonded honeycomb panel over an area in which water had been injected to test the relative effectiveness of the plastic and the ink background coating. The mass of water in the panel was approximately one inch in diameter and one-half inch in depth. The plastic sheet reduced the thermal gradient to an extent that makes this particular plastic sheet impractical. A 0.0025 inch thick Mylar sheet coated on the side contacting the panel was sprayed with a flat black lacquer. The Mylar was then coated on the opposite side with liquid crystals and applied to the panel. This method was satisfactory except for lack of intimate contact between the Mylar and the panel. In addition, the film of liquid crystals was too easily smeared by handling of the film.

The most suitable method for obtaining a one-coat system at the present time, suggests that the liquid crystals be encapsulated in a gelatin material through a special process developed by the National Cash Register Company, Dayton, Ohio. This experimental process yields individual coated spheres of liquid crystals approximately 30 microns in diameter. This material is then mixed with a polyvinyl alcohol binder resulting in a sprayable slurry. This slurry can be applied to a Mylar polyester film previously painted black on the opposite side. A flat lacquer could be used. The Mylar should be thin enough to be conformal to the substrate. The intimate contact necessary for thermal coupling could be maintained by electrostatic force. This system would eliminate spraying except in the production of the coated film.

Samples of encapsulated liquid crystals sprayed on Mylar have been examined and are durable enough to withstand handling. This type of film is reuseable allowing the extra cost involved in encapsulation to be offset by saving time in testing and the savings realized by repeated use of the same liquid crystals.

8 - EVALUATION OF LIQUID CRYSTALS

Liquid Crystal Calibrator

The need became apparent, during the earlier part of the development effort, for a means of determining the operating temperature span (sensitivity) of different samples of liquid crystals from various suppliers.

The instrumentation shown schematically in Figure 5 and Figure 6 was designed for this purpose. The actual arrangement of equipment is shown in Figure 7. The microscope is not necessary but simplifies maintaining the angle of observation.

This device was designed to maintain a specific surface temperature with precise control. The accuracy of the instrumentation is $\pm$ 0.5°F. The sensitivity is $\pm$ 0.15°F. Absolute accuracy of the actual operating temperature of the liquid crystals and the calibrator is of secondary importance. Since this testing technique involves the human eye as a detector, brilliance, a complete spectral color range as well as thermal sensitivity are factors of prime importance.

Heating or cooling the calibrator is achieved by controlling the amount and polarity of D.C. current applied to the thermoelectric solid state device* which utilizes the Peltier effect. Temperatures from 20°F to 212°F can be obtained.

In operation, the 2 x 2 inch test area (Ref. Figure 5) is sprayed with the ink and one or two drops of liquid crystals is applied with a syringe. An even coating can be obtained by dragging the needle across the surface during application. The volatile solvent is driven off by warming the surface to about 100°F prior to testing. The calibrator power supply is adjusted and the surface temperature and color is recorded when steady state temperature conditions are established at any desired color. The angles of viewing and incident illumination were kept constant at 90° and 30° respectively, in the same plane, during observations.

Sensitivity of Liquid Crystals

The liquid crystal calibrator was used to obtain temperature data on liquid crystal samples from three suppliers. Table I summarizes the test results.

Liquid crystals batch number 5A was the most brilliant of the samples tested and was used for the majority of panel evaluation tests. Infrared spectroanalysis showed no significant difference between samples.

Since the most useable color range of liquid crystals is red, yellow and green, it was decided to specify sensitivity as the temperature range occuring from the first visually perceptible red color to the first perceptible blue color. The color changes through blue and violet do not have enough contrast and secondly, some suppliers state temperature span as the entire range of colors and others only to blue.

Sensitivity of the Eye as a Detector

A test to determine the minimum temperature change detectable by visually observing the smallest perceptable change in color saturation of a liquid crystal film was performed. As in any visual inspection method, the eye is the "detector" and is sometimes a very limiting factor.

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*Model No. 433 thermoelectric module, Jepson Thermoelectrics, Inc. Chicago, Illinois

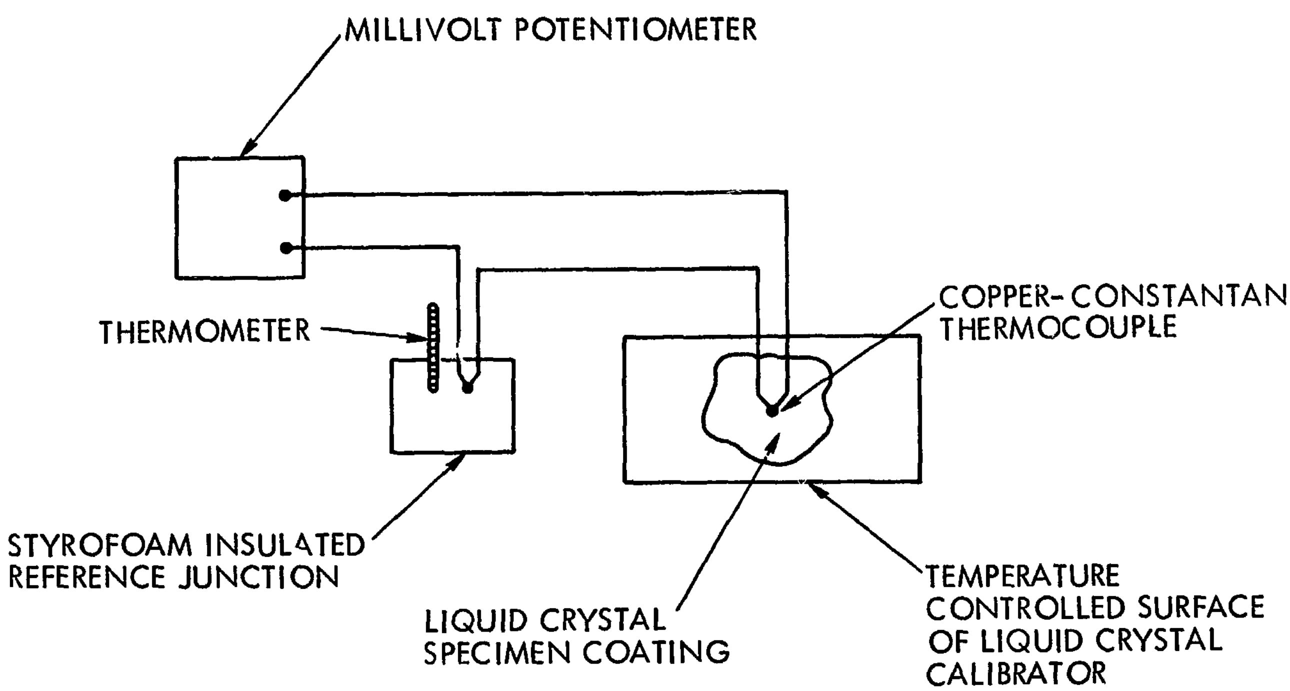

FIGURE 5 - LIQUID CRYSTAL CALIBRATOR INSTRUMENTATION SCHEMATIC

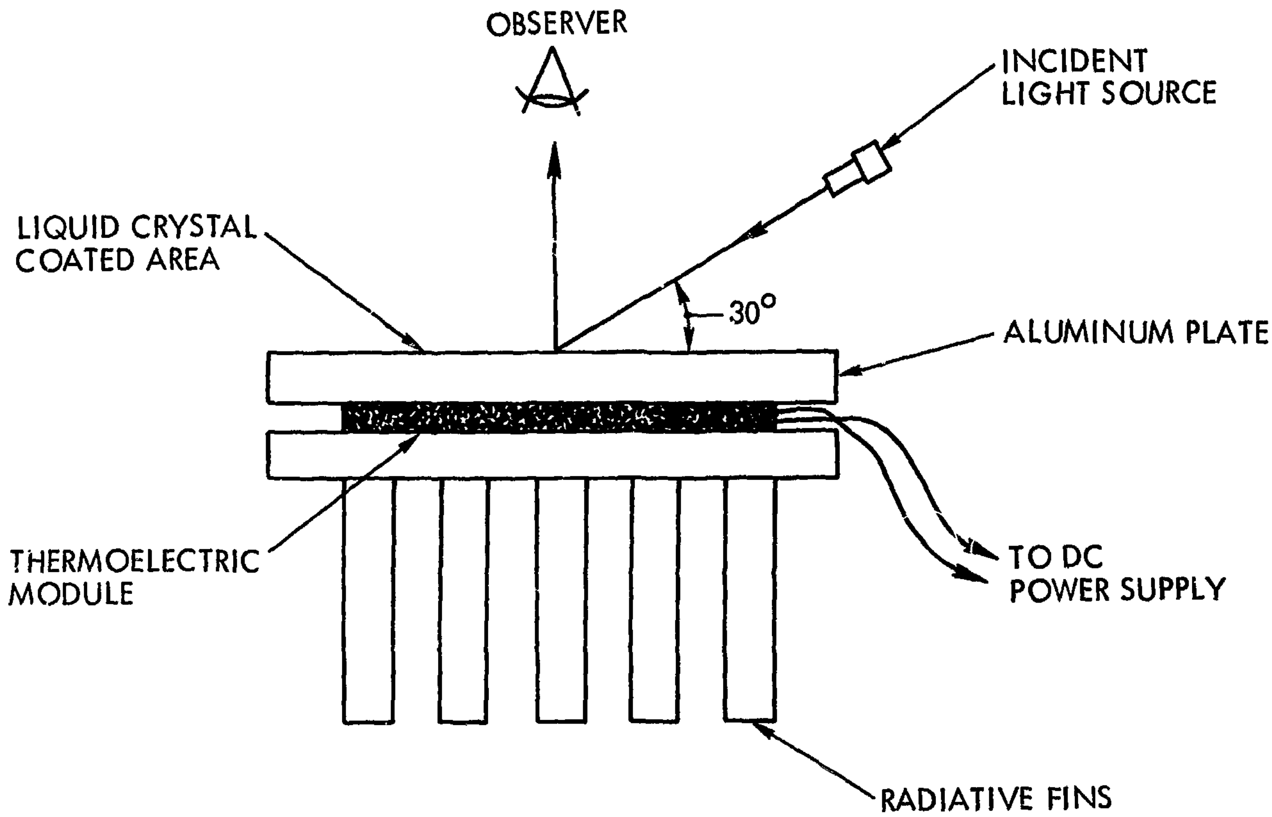

FIGURE 6 - SIDE VIEW OF LIQUID CRYSTAL CALIBRATOR

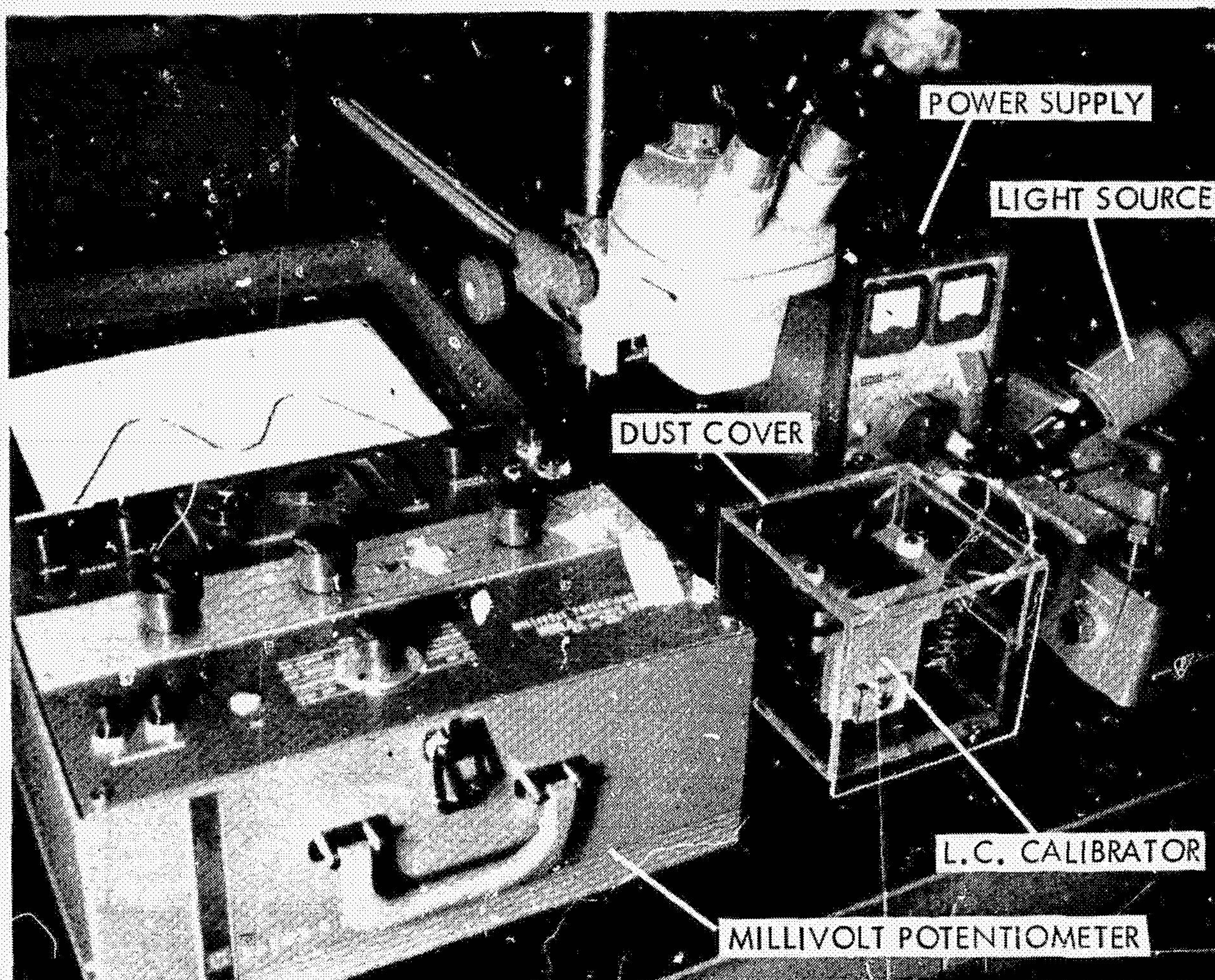

FIGURE 7 - LIQUID CRYSTAL CALIBRATOR INSTRUMENTATION

TABLE I - LIQUID CRYSTALS TEMPERATURE DATA

L. C. Batch Number (b)	Temperature Range (°F)		Temperature Span (°F)
	Red	Blue	
1A (a)	101.81	103.78	1.97
2A	89.43	91.22	1.79
3A	94.09	95.83	1.74
4A (a)	101.26	103.22	1.96
5A (a)	92.22	93.65	1.43
6A	91.39	92.82	1.43
1B	88.65	91.04	2.39
2B	88.39	90.83	2.44
1C	92.09	94.74	2.65
2C	64.32	66.09	1.77
3C	87.22	89.30	2.08
4C	87.35	89.30	1.95

(a) Used to inspect test panels

(b) See appendix for identification of liquid crystal suppliers

A sample from liquid crystal batch number 5A was used (Ref. Table I) for this test on the liquid crystal calibrator. The surface temperature was adjusted for a nominal color and stabilized. The temperature was then changed until a color change was observed. The temperature differential is the sensitivity. This procedure was conducted for red, green and blue. The averaged results of tests for all colors, indicates that 0.28 Fahrenheit degrees is the smallest temperature change that can be reliably detected by the eye using this particular liquid crystal mixture. Since the spectral response curve of the human eye peaks sharply at a wavelength of 550 millimicrons, optimum visibility is of defects appearing orange, yellow or green.

9 - CHOICE OF LIQUID CRYSTAL OPERATING TEMPERATURE

The chosen nominal operating temperature of the liquid crystals to be used in the test was 95° F. This has proven to be a practical operating temperature when the ambient temperature is between 68° F and 79°F. Liquid crystal mixtures can be obtained that operate below room temperature and can be used to advantage when both sides of a panel are accessible and the side opposite the coated side can be cooled to 32° F or lower. Under these conditions the thermal gradient through the panel is enhanced and a minimum of cooling capacity is required since the temperature required at the coated surface is reduced.

The choice of liquid crystal operating temperature for a particular thermal test depends on the heat transfer characteristics of the test article and every condition need not be analyzed in detail, since it is a simple matter of respraying with a different mixture if the first choice is not optimum. In fact, one of the advantages of liquid crystals is that it can perform thermodynamic heat transfer analyses and provide a direct image for immediate interpretation.

10 - PREREQUISITES FOR DEFECT DETECTION

Types of Defects Detectable

In bonded honeycomb panels and bonded laminated panels delaminations, crushed core, adhesive porosity, adhesive voids, inclusions and water can be detected if a surface temperature gradient of at least 0.28° F is induced by the discontinuity. The minimum size of a defect that can be detected is dependent on panel construction and can best be determined by actual tests.

Effects of Panel Construction

Panels which have relatively heavy foil core, a thick far side (the side opposite the heated and coated face sheet) face sheet and thin near side face sheet are the most suitable for liquid crystal testing.

A thick far side face sheet adds to the effective thermal mass of the core and acts as a thermal flywheel. If conditions permit, the farside can be cooled during testing to enhance its value as a heat sink. The most difficult panels to test are those composed of fiberglass core or other materials that have similar coefficients of heat conduction, and an aluminum face sheet on the side to be inspected.

The thermal conductivity of the face sheets is of prime importance. The titanium test panels (Ti-5Al-2.5Sn Alloy) had a coefficient of thermal conductivity of 0.19*. The aluminum test panels (7075-T6 Alloy) had a coefficient of thermal conductivity of 0.29.

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*$CAL/CM^2/^{o}C/SEC$

The titanium panels were found to be the most suitable for testing and the aluminum panels were least suitable.

The thermal conductivity of common aluminum alloys is between 0.29 and 0.46, and for titanium alloys between 0.19 and 0.43. It is apparent that particular alloys have a definite effect on test results.

11 - SHELF LIFE OF LIQUID CRYSTALS

No information could be found in an extensive literature survey to determine shelf life. Samples of liquid crystals have been stored for sixteen months in a brown bottle in a dark cabinet at 73° F with no adverse effects. It is known, however, that liquid crystals are subject to oxidation and should be shielded from ultraviolet light.

Some panels were left coated for several days and then re-inspected. Some brilliance was lost but this is of little consequence unless photographs are required for permanent record and in that case, inspection should follow coating as soon as possible.

12 - COST

Present material costs have been reduced to approximately $2.00 per square foot. This is a reduction of $5.50 per square foot in about three years. The reduction in price was a result of negotiations between Lockheed and a chemical supplier and was based on a 10 liter quantity.

13 - RECLAMATION OF LIQUID CRYSTALS

It is possible to remove coatings of liquid crystals for re-use. However, the economic practicality remains to be proven. A 2 x 2 foot panel was experimented with to ascertain feasibility of coating removal. The coating was completely removed in a few minutes by merely pouring acetone over the panel and collecting. The acetone was evaporated and the residue was observed to be optically active. Re-use would require filtration and the addition of solvents.

14 - CORROSION TEST ON ALUMINUM AND TITANIUM

A corrosion test was performed at 72° F ambient temperature and 60% relative humidity. Specimens of bare 6AL-4V titanium alloy sheet and bare 7075-T6 aluminum alloy sheet were polished to a mirror finish and coated with liquid crystals, with and without the Pelikan ink background coating.

No corrosion was evident after 193 hours. Specimens were inspected using 30 power magnification.

15 - SAFETY CONSIDERATIONS

Storage of Liquid Crystals

Liquid crystals should be stored in brown glass laboratory bottles at normal room temperature. The cap should not contain rubber or other materials that are attacked by petroleum ether in order to prevent contamination. Only clean glass should be used to transfer liquid crystals.

Spraying Liquid Crystals

Safety precautions should be observed since liquid crystal mixtures contain highly flammable petroleum ether. The spray gun cup should contain no more than 100 milliliters of liquid crystals. This is an adequate supply for covering 4 square feet.

Spraying should be done in a well ventilated area away from any source of ignition.

While spraying liquid crystals it is recommended that a Mine Safety Appliances Co. catalog number 10-85556 Custom Comfo chemical cartridge respirator be used with a catalog number 10-44135 cartridge. It is also advisable to use the respirator while spraying the Pelikan ink to prevent irritation to the nasal passages.

16 - MISCELLANEOUS OBSERVATIONS

Airless Spray System Test

An airless spray system was experimented with in an attempt to reduce overspray and obtain greater coverage and economy with liquid crystals. The equipment used was an Alemite Model 707 pump (Stewart-Warner Model 327138-2) with a model 323740-1 spray gun.

In this type system the material to be sprayed is pumped at high pressure through an orifice in the spray gun. Atomization is external. Orifices used were a 0.009 inch diameter, 40° spray angle and a 0.013 inch diameter, 50° spray angle. This system operates at a 26:1 pressure ratio. Inlet pressure to the pump was regulated at 50 PSIG. The pressure at the orifice was approximately 1,300 PSIG.

The system was used to spray a 2 x 2 foot panel with liquid crystals having a transition temperature of 89.6°F. The resultant coating had a mottled appearance with irregular areas of yellow, green, red and blue. These colors were retained on the panel at an ambient temperature of 68°F, well below the normal transition temperature. The panel could be cycled through the range of colors above and below 68°F but retained the original mottled appearance. A 1:1 ratio photograph, serial number 48, is included in the test photographs.

This condition would mask any defect being investigated. The characteristics of the liquid crystals are changed radically by this high pressure, high velocity system. Extremely fast usage and poor control of the spray are also drawbacks in the use of this type of spray equipment when used with low viscosity fluids. Approximately 80 milliliters were used to coat the panel. The conventional spray equipment yielded the same coverage.

Retained Thermal Image

Using an ice bath behind an aluminum honeycomb panel thermal images of the honeycomb core have been retained for long periods of time by controlling the heat input to the coated side until, by trial and error, thermal equilibrium is achieved.

Using this method with liquid crystals having a 68°F transition temperature, an aluminum honeycomb panel with 0.020 inch thick face sheets was tested. It was noticed that if the cold source is of sufficient mass and if the coated surface temperature is reduced rapidly enough, the thermal image will remain at temperatures well below the transition temperature. The extremely rapid cooling of the liquid crystals causes an increase in viscosity of the coating before rotation of molecular layers can occur. Locked in position, the liquid crystals scatter the incident light in the same manner that the image was originally formed at the much higher temperature. This effect was repeatable and could have been retained indefinitely except for the formation of condensate frost.

17 - CONCLUSIONS

Thermographic testing of bonded structures with liquid crystals is entirely feasible and can offer certain advantages over other thermographic testing techniques.

The course of this program resulted in useable data acquired from large scale testing of a wide variety of bonded panels. These data may be extrapolated to provide information relevant to infrared applications as well as liquid crystal applications.

The equipment and techniques developed do not require highly trained personnel. Ambient conditions, thermal heat transfer characteristics of the test article and cost must be taken into consideration for each specific production inspection application.

Although the present cost of materials is $2.00 per square foot, the equipment used for testing and recording results is far less expensive than infrared systems.

Interpretation of defects is straight forward and does not require matching flaw locations with test results since the thermal image is visualized directly on the panel.

The disadvantages of this technique are mainly the limitations imposed by the necessity of spraying the liquid crystals directly on the test article.

The development of liquid crystal applications resulted from aerospace technology but has also yielded practical benefits in other areas. Detection of tumors and restrictions in blood circulation are biological applications in which liquid crystals are being used today to compliment x-ray and infrared diagnostic methods.

18 - RECOMMENDATIONS

The sensitivity of liquid crystals is a major factor in obtaining optimum utilization of the technique. Prior to use, the liquid crystal calibrator or other instrumentation, should be a required prerequisite for quality assurance of liquid crystals.

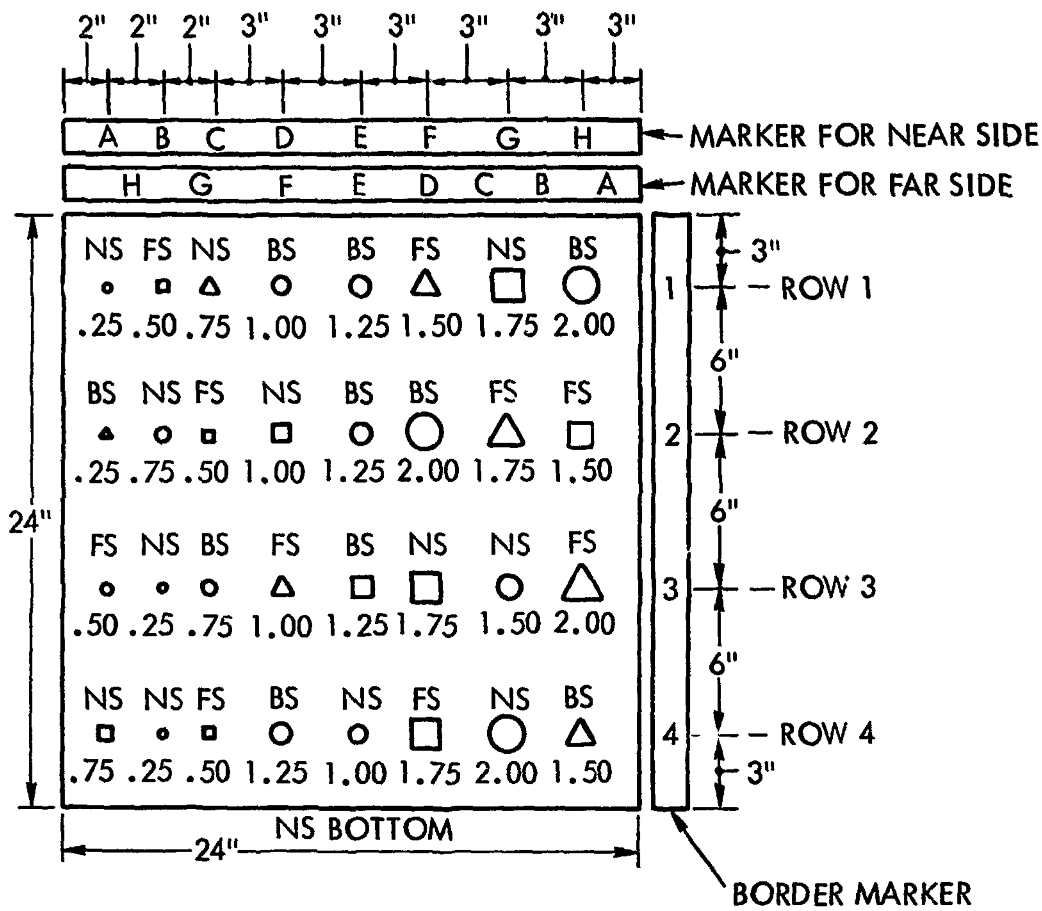
It is also recommended that after a sample part has been fabricated with built-in defects and tested with liquid crystals, for capability determinations, that the bonded panel be disassembled to prove that the actual defect was as intended.

There would be many more practical uses to which liquid crystals and the test methods discussed could be adapted if the spraying procedure could be eliminated and some means of using a removable, coated film (as described in Section 7) were perfected. In some applications a non-contact method is mandatory.

The following suggestions are presented as areas for further investigation.

1. Liquid crystals of greater sensitivity.
2. A means of fixing the liquid crystal image.
3. A strippable background coating.

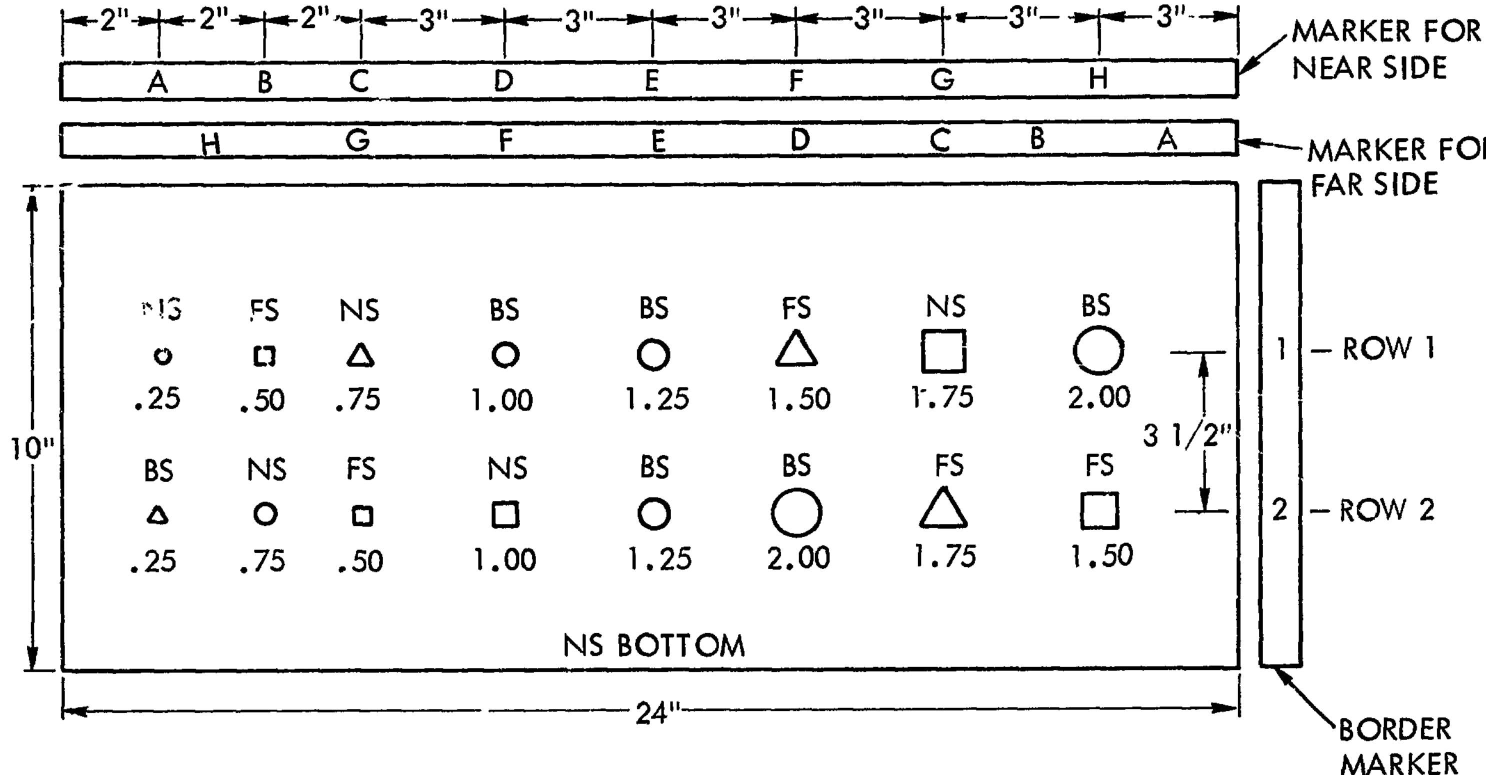
Proficiency Development Laboratory
Lockheed-Georgia Company
Marietta, Georgia, July 24, 1967



SYMBOL NOTATION:

NS - NEAR SIDE
FS - FAR SIDE
BS - BOTH SIDES
NS, FS, BS APPLY TO TYPE I, II, III PANELS ONLY
∘ .25 - CIRCULAR FLAW, .25" DIA.
□ .50 - SQUARE FLAW, .50" SIDES
△ .75 - TRIANGULAR FLAW, .75" LEGS WITH EQUAL ANGLES

FIGURE 8 - LOCATION OF BUILT-IN DEFECTS - PANEL TYPES I, II, III, IV, V



SYMBOL NOTATION:

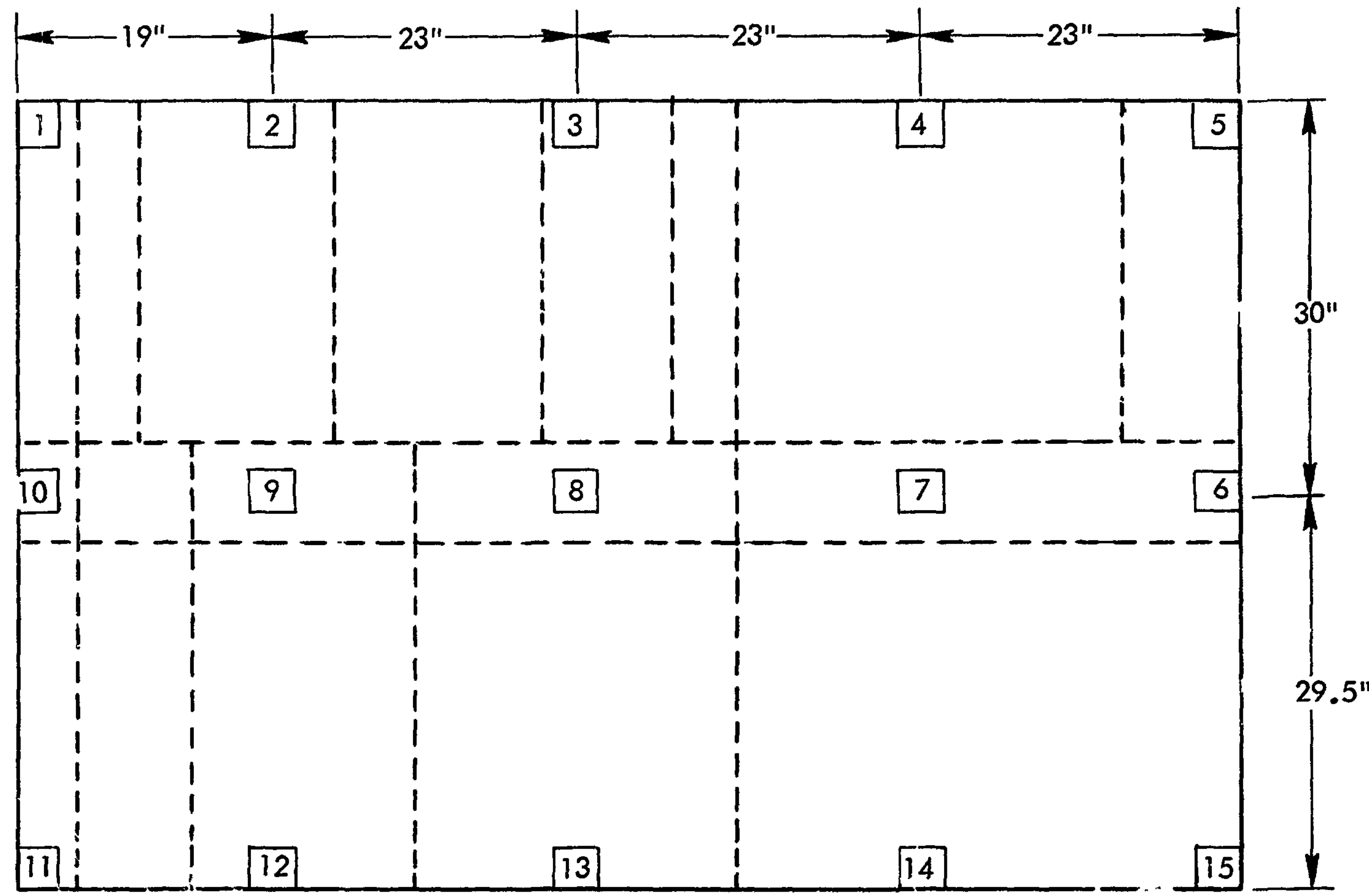
NS - NEAR SIDE
FS - FAR SIDE
BS - BOTH SIDES
NS, FS, BS APPLY ONLY TO TYPE I Ti & III Ti HONEYCOMB PANELS

○ .25 - CIRCULAR FLAW, .25" DIA.

□ .50 - SQUARE FLAW, .50" SIDES

△ .75 - TRIANGULAR FLAW, .75" LEGS WITH EQUAL ANGLES

FIGURE 9 - LOCATION OF BUILT-IN DEFECTS - TITANIUM PANELS IATi, IBTi, IIATi, IIBTi, IIIATi, IIIBTi



PANEL NO. 1 LOOKING AT CONVEX SIDE
DASHED LINES REPRESENT INTERNAL CORE SPLICES APPEARING AS COLD LINES
THE NUMBERS IDENTIFY AREAS OF THE PANEL APPEARING IN THE PHOTOGRAPHS

FIGURE 10 - PANEL NO. 1 - CORE SPLICES LOCATED

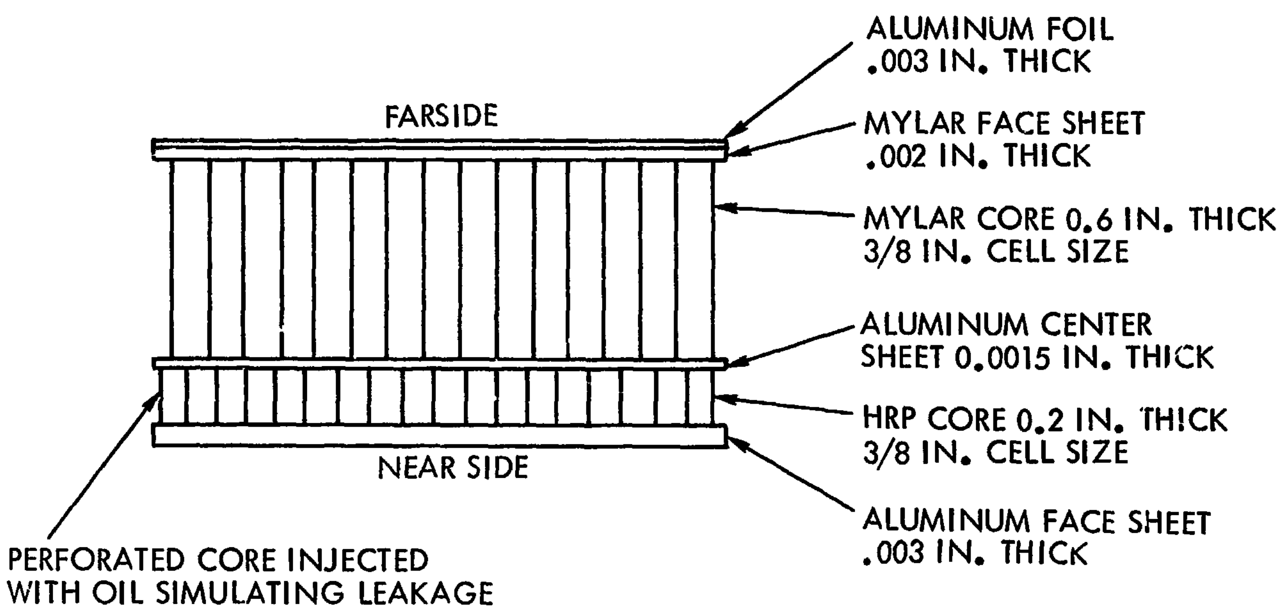


FIGURE 11 - CROSS SECTION VIEW OF PANELS C-1 & C-2

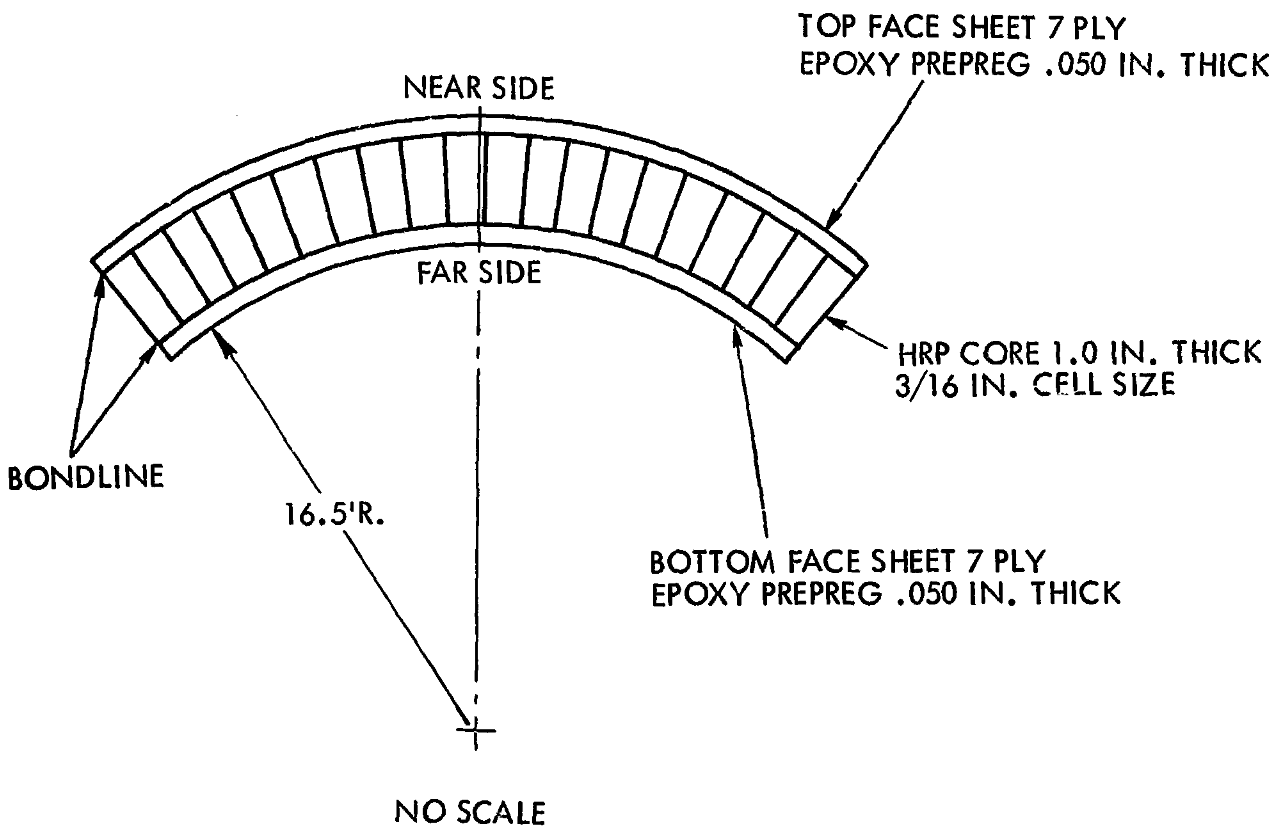
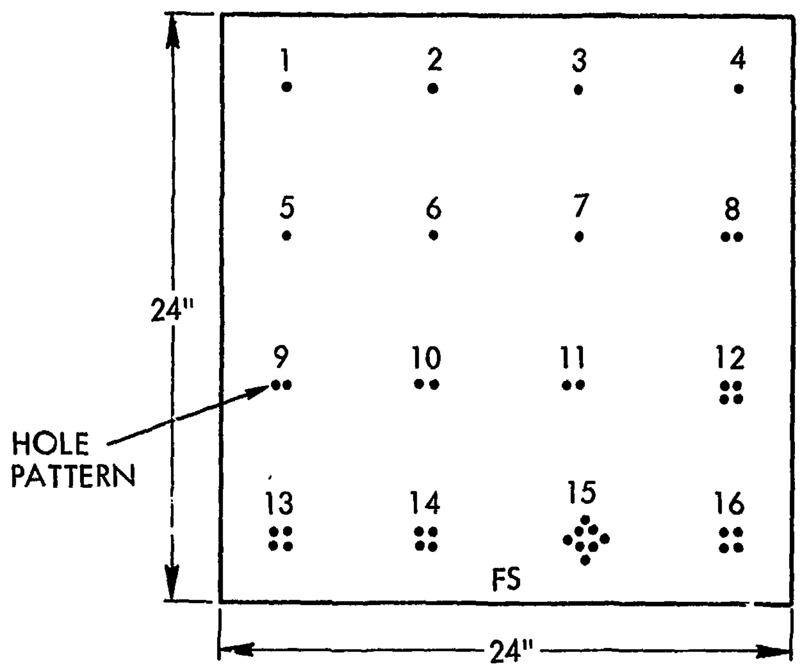


FIGURE 12 - CROSS SECTION OF PANEL P-1



DESCRIPTION:

1/64 IN. HOLES DRILLED IN FAR SIDE FACE SHEET AND INJECTED WITH WATER (SEE TABLE VI). HOLES SEALED WITH RTV RUBBER SEALANT. FACE SHEETS 0.020 INCH THICK ALUMINUM.

FIGURE 13 - PANEL X-1, LOCATION OF ENTRAPPED WATER

TABLE II - DESCRIPTION OF TEST PANELS

Construction	Face Sheet Thickness (In) Near Side	Far Side	Panel Number	Fig. No.	Table V Defects Detected - Pg. No.
Aluminum 7075-T6 Face Sheets HRP Core 1" Thick 3/16" Cell Size. 24" x 24" Honeycomb Sandwich	.030 .050 .063 .030 .063 .050	.030 .050 .063 .050 .030 .063	IA IB IC ID IE IF	8	33 33 33 33 33 33
Aluminum 7075-T6 Face Sheets. 5052 Aluminum Core, 930" Thick 3/16" Cell Size. 24" x 24" Honeycomb Sandwich	.030 .050 .063 .030 .063 .050	.030 .050 .063 .050 .030 .063	IIA IIB IIC IID IIE IIF	8	34 34 35 35 36 36
Fiberglass Face Sheets Fiber-glass Core 1" Thick 3/16" Cell Size. 24" x 24" Honeycomb Sandwich	.012 .025 .037 .050	.025 .037 .012 .050	IIIA IIIB IIIC IIID	8	36,37 37 38 38,39
Aluminum 7075-T6 Face Sheets. 24" x 24" Laminate	.030 .030 .050 .030	.050 .063 .063 .020	IVA IVB IVC IVD	8	39 39,40 40,41 41
Fiberglass to Fiberglass 24" x 24" Laminate	.012 .025 .037 .050	.025 .037 .012 .025	VA VB VC VD	8	41,42 42,43 43,44 44
Aluminum 7075-T6 Face Sheets. 5052 Aluminum Core 1/2" Thick, 1/4" Cell Size, .003" Foil. 24" x 24" Honeycomb Sandwich	.020	.012	X-1	13	47 See Table VI
Titanium Face Sheets (5Al-2.5Sn) HRP Core 1" Thick 3/16" Cell Size 10" x 24" Honeycomb Sandwich	.025 .025	.032 .032	IATi IBTi	9	44,45 45
Titanium Face Sheets (5Al-2.5Sn) 5052 Aluminum Core 1" Thick 3/16" Cell Size 10" x 24" Honeycomb Sandwich	.025 .025	.032 .032	IIIATi IIIBTi	9	46 46
Titanium Face Sheets (5Al-2.5Sn) 10" x 24" Laminate	.025 .025	.032 .032	IIATi IIBTi	9	45 45,46
Aluminum 7075-T6 Face Sheets 5052 Aluminum Core 1" Thick 3/16" Cell Size 59.5" x 88" Curved Honeycomb Sandwich	.020	.020	No. 1	10	46
Cryogenic Double Seal Insulation of Aluminum Face Sheet to HRP Core .2" Thick to Aluminum Center Sheet to Mylar Core .6" Thick to Mylar Face Sheet. 30" x 30" Honeycomb	.003 .003	.007 .007	C-1 C-2	11	46 46
7 Ply Fiberglass Face Sheets HRP Core 1" Thick 3/16" Cell Size 45" x 34" Curved Honeycomb Sandwich	.050	.050	P-1	12	See Text Page 13

TABLE III - LOCATION AND DESCRIPTION OF BUILT-IN FLAWS

Panel Type	Row 1	Row 2	Row 3	Row 4
I	Delamination	Lack of Adhesive	Crushed Core	Inclusions
II	Delamination	Lack of Adhesive	Crushed Core	Inclusions
III	Delamination	Lack of Adhesive	Crushed Core	Inclusions
IV	Delamination	Lack of Adhesive	Porosity	Inclusions
V	Delamination	Lack of Adhesive	Porosity	Inclusions
I ATi	Delamination	Lack of Adhesive		
I BTi	Crushed Core	Inclusions		
II ATi	Delamination	Lack of Adhesive		
II BTi	Porosity	Inclusions		
III ATi	Delamination	Lack of Adhesive		
III BTi	Crushed Core	Inclusions		

Delamination - Adhesive inserts, pre-cured 8 hours - (DEL)
Lack of Adhesive - Cutouts in adhesive film - (LA)
Crushed Core - 1/8" depressions in core - (CC)
Inclusions - 0.0005" teflon insert - (INC)
Porosity - Phenolic microballoons - (POR)

TABLE IV - ABBREVIATIONS USED IN TABLES

NS	Near Side
BS	Both Sides - Both Sides of Core
FS	Far Side
DEL	Delamination - Defect Simulated by Pre-cured Adhesive Insert
LA	Lack of Adhesive - Defect Simulated by Cutout in Adhesive
CC	Crushed Core - Defect Simulated by 1/8" Depression in Core
INC	Inclusions - Defect Simulated by 0.0005" Thick Teflon Insert
POR	Porosity - Defect Simulated by Inclusion of Phenolic Microballoons

TABLE V - DEFECTS DETECTED

Panel Number	Type. Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IA	1.00 LA 2.00 LA 2.00 INC	2D NS 2F BS 4G NS	NS NS NS	85 85	4A	.030 Alum. Face Sheet HRP Core
IA	2.00 LA 0.50 INC 1.25 LA 0.50 LA	2F BS 4C FS 2E BS 2C FS	FS FS FS FS	96 96	4A	.030 Alum. Face Sheet HRP Core
IB	1.75 LA 1.25 CC 2.00 INC 1.25 INC	2G NS 3E BS 4G NS 4D BS	NS NS NS NS	40	1A	.050 Alum Face Sheet HRP Core
IB	2.00 LA 0.50 LA 0.50 INC 1.00 CC	2F BS 2C FS 4C FS 3D FS	FS FS FS FS	98 98 98	4A	.050 Alum. Face Sheet HRP Core
IC	1.25 INC 2.00 INC	4D BS 4G NS	NS NS	47 47	1A	.063 Alum. Face Sheet HRP Core
IC	2.00 LA 0.50 INC	2F BS 4C FS	FS FS	101 101	4A	.063 Alum. Face Sheet HRP Core
ID	0.75 LA 1.25 CC 1.25 INC 2.00 INC 2.00 LA	2B NS 3E BS 4D BS 4G NS 2F BS	NS NS NS NS NS	50 53 53	1A	.030 Alum Face Sheet HRP Core
ID	2.00 LA 1.25 LA 0.50 LA 1.25 CC 0.50 INC	2F BS 2E BS 2C FS 3E BS 4C FS	FS FS FS FS FS	102,104 104	5A	Core Splice D to D Photo No. 104 .050 Alum. Face Sheet HRP Core
IE	1.00 LA 2.00 BS 2.00 INC	2D NS 2F BS 4G NS	NS NS NS	73	4A	.063 Alum. Face Sheet HRP Core
IE	1.25 LA 2.00 LA 1.75 LA 1.50 LA 1.25 CC 1.00 CC 0.50 INC 0.50 DEL 1.00 DEL	2E BS 2F BS 2G FS 2H FS 3E BS 3D FS 4C FS 1B FS 1D BS	FS FS FS FS FS FS FS FS FS	107,108 107,108 107,108 108 108 108	5A	Core Splice C to C Photo No. 108,109 .030 Alum. Face Sheet HRP Core
IF	1.25 LA 2.00 INC 1.25 INC	2E BS 4G NS 4D BS	NS NS NS	 56 56	1A	.050 Alum. Face Sheet HRP Core
IF	1.00 DEL 1.25 LA 2.00 LA 1.75 LA 1.50 LA 1.25 INC	1D BS 2E BS 2F BS 2G FS 2H FS 4D BS	FS FS FS FS FS FS	110 111 110 110 110 110	5A	Core Splice Horizontal At 4. Photo No. 111 .063 Alum. Face HRP Core

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IIA	1.25 DEL	1E BS	NS	82	4A	.030 Alum. Face Sheet
	1.75 DEL	1G NS	NS	80		Alum, Core
	1.00 LA	2D NS	NS	80,82		
	2.00 LA	2F BS	NS	81,82		
	1.25 LA	2E BS	NS	81,82		
	0.25 CC	3B NS	NS			
	0.75 CC	3C BS	NS	84		
	1.25 CC	3E BS	NS	81,82,84		
	1.75 CC	3F NS	NS	81,82,84		
	1.50 CC	3G NS	NS			
	2.00 INC	4G NS	NS	81,82		
	1.25 INC	4D BS	NS	84		
IIA	0.50 DEL	1B FS	FS		5A	Specular Reflection
	0.75 DEL	1C FS	FS			at 3G in Photos.
	1.00 DEL	1D BS	FS	115,117		.030 Alum. Face Sheet
	1.25 DEL	1E BS	FS	115,117		Alum. Core
	1.50 DEL	1F FS	FS	115,117		
	1.75 DEL	1G NS	FS			
	2.00 DEL	1H BS	FS	115,117		
	0.50 LA	2C FS	FS			
	1.00 LA	2D NS	FS	117		
	1.25 LA	2E BS	FS	113,115,117		
	2.00 LA	2F BS	FS	113,115		
	1.75 LA	2G FS	FS	113,115		
	1.50 LA	2H FS	FS	117		
	0.75 CC	3C BS	FS	117		
	1.00 CC	3D FS	FS	115,117		
	1.25 CC	3E BS	FS	113,115,117		
	1.75 CC	3F NS	FS	115		
	1.25 INC	4D BS	FS	117		
	1.75 INC	4F FS	FS	117		
	1.50 CC	3G NS	FS			
	2.00 CC	3H FS	FS	116,117		
IIB	1.25 LA	2E BS	NS	78	4A	
	1.00 LA	2D NS	NS	77		
	2.00 LA	2F BS	NS	77		
	1.25 CC	3E BS	NS	78,79		
	1.75 CC	3F NS	NS	78,79		
	1.50 CC	3G NS	NS	79		
	1.25 INC	4D BS	NS	79		.050 Alum. Face Sheet
	2.00 INC	4G NS	NS	78		Alum. Core
IIB	1.00 DEL	1D BS	FS	121,122	5A	Specular Reflection at
	1.25 DEL	1E BS	FS	121,122,123		2H and 3G in Photos.
	1.50 DEL	1F FS	FS	121,122		
	1.75 DEL	1G NS	FS			
	2.00 DEL	1H BS	FS			
	1.25 LA	2E BS	FS	121,122,123		
	2.00 LA	2F BS	FS	119,121,122		.050 Alum. Face Sheet
	1.75 LA	2G FS	FS	121		Alum. Core
	0.75 CC	3C BS	FS	125		
	1.00 CC	3D FS	FS	125,122,123		
	1.25 CC	3E BS	FS	121,125		
	1.75 CC	3F NS	FS	122		
	1.50 CC	3G NS	FS			

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IIB	2.00 CC	3H FS	FS	124	5A	
	1.25 INC	4D BS	FS			
	1.75 INC	4F FS	FS			.050 Alum. Face Sheet
	2.00 INC	4G NS	FS			Alum. Core
IIC	1.00 LA	2D NS	NS	62	1A	
	2.00 LA	2F BS	NS	62,63		
	1.25 CC	3E BS	NS	62,63		
	1.75 CC	3F NS	NS	62,63		
	1.25 INC	4D BS	NS	62,63		.063 Alum. Face Sheet
	2.00 INC	4G NS	NS	62,63		Alum. Core
IIC	1.00 DEL	1D BS	FS	127,128	5A	
	1.25 DEL	1E BS	FS	127,128		
	1.50 DEL	1F FS	FS	127,128		
	1.75 DEL	1G NS	FS			
	2.00 DEL	1H BS	FS	127,128		
	1.25 LA	2E BS	FS	127,128,130		
	2.00 LA	2F BS	FS	126,127,128,130		
	1.75 LA	2G FS	FS	127,128,130		.063 Alum. Face Sheet
	1.50 LA	2H FS	FS	127,128		Alum. Core
	0.75 CC	3C BS	FS	129,130		
	1.00 CC	3D FS	FS	129,130		
	1.25 CC	3E BS	FS	128,129,130		
	1.75 CC	3F NS	FS	130		
	1.50 CC	3G NS	FS			
	2.00 CC	3H FS	FS	130,131		
	0.50 DEL	1B FS	FS	130		
	1.25 INC	4D BS	FS	128		
	1.75 INC	4F FS	FS	129		
IID	1.75 DEL	1G NS	NS		4A	
	1.00 LA	2D NS	NS	89,90,91		
	1.25 LA	2E BS	NS	89,90,91		
	2.00 LA	2F BS	NS	89,90,91		
	0.75 CC	3C BS	NS			
	1.25 CC	3E BS	NS	90,91		
	1.75 CC	3F NS	NS	90,91		
	1.50 CC	3G NS	NS	91		.030 Alum. Face Sheet
	2.00 INC	4G NS	NS	90		Alum. Core
IID	1.00 DEL	1D BS	FS	140,141,142	5A	
	1.25 DEL	1E BS	FS	140,141,142		
	1.50 DEL	1F FS	FS	140,141		
	2.00 DEL	1H BS	FS	140		
	1.25 LA	2E BS	FS	139,140,141,142		
	2.00 LA	2F BS	FS	139,140,141,142		.050 Alum. Face Sheet
	1.75 LA	2G FS	FS	139,140,141,142		Alum. Core
	1.50 LA	2H FS	FS			
	0.75 CC	3C BS	FS	142		
	1.00 CC	3D FS	FS	139,141,142		
	1.25 CC	3E BS	FS	139,140,141,142		
	1.75 CC	3F NS	FS	141		
	2.00 CC	3H FS	FS	142,143		
	1.25 INC	4D BS	FS	140		
	1.75 INC	4F FS	FS	141,142		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IIE	1.25 LA	2E BS	NS	67	1A	
	2.00 LA	2F BS	NS	66		
	1.25 CC	3E BS	NS	67,68		
	1.75 CC	3F NS	NS	67,68		
	1.25 INC	4D BS	NS	67		.063 Alum. Face Sheet
	2.00 INC	4G NS	NS	66,67,68		Alum. Core
IIE	0.50 DEL	1B FS	FS		5A	Specular Reflection at
	1.00 DEL	1D BS	FS	134,135,136		2H and 3G in Photos
	1.25 DEL	1E BS	FS	135,136		
	2.00 DEL	1H BS	FS	134,136		
	1.00 LA	2D NS	FS			
	1.25 LA	2E BS	FS	132,133,134,135		
	2.00 LA	2F BS	FS	132,133,134,135		
	1.75 LA	2G FS	FS	132,133,134,135		
	1.50 LA	2H FS	FS			.030 Alum. Face Sheet
	0.75 CC	3C BS	FS	135,136		Alum. Core
	1.00 CC	3D FS	FS	134		
	1.25 CC	3E BS	FS	132,133,134,135		
	1.75 CC	3F NS	FS	135		
	1.50 CC	3G NS	FS	134,135		
	2.00 CC	3H FS	FS	135,136,137		
	1.25 INC	4D BS	FS	133		
	1.75 INC	4F FS	FS	134		
	0.50 LA	2C FS	FS	135		
	1.50 DEL	1F FS	FS	135,136		
IIF	1.00 LA	2D NS	NS	71,72	1A	
	2.00 LA	2F BS	NS	71,72		
	1.25 CC	3E BS	NS	71,72		
	1.75 CC	3F NS	NS	71,72		
	1.25 INC	4D BS	NS	72		.050 Alum. Face Sheet
	2.00 INC	4G NS	NS	71,72		Alum. Core
IIF	1.00 DEL	1D BS	FS	146,147	5A	
	1.25 DEL	1E BS	FS	146,147		
	1.50 DEL	1F FS	FS	146,147		
	2.00 DEL	1H BS	FS	146		
	0.50 LA	2C FS	FS	146		
	1.25 LA	2E BS	FS	146,147		
	2.00 LA	2F BS	FS	145,146,147		
	1.75 LA	2G FS	FS	145,146,147		
	0.75 CC	3C BS	FS	147		.063 Alum. Face Sheet
	1.00 CC	3D FS	FS	147		Alum. Core
IIF	1.75 CC	3F NS	FS	147		
	1.25 INC	4D BS	FS	145		
	1.75 INC	4F FS	FS	146		
	1.25 CC	3E BS	FS	145,146,147		
	2.00 CC	3H FS	FS	148		
IIIA	0.25 LA	2A BS	NS	151,153	5A	Core Splice 3 to 3, A
	0.75 LA	2B NS	NS	149,150,151,152,153		to A & Vertical at E to
	1.00 LA	2D NS	NS	149,150,151,152,153		3. Core Visible.
	1.25 LA	2E BS	NS	149,150,151,152,153		
	2.00 LA	2F BS	NS	149,150,151,152,153		
	0.25 CC	3B NS	NS	152		
	0.75 CC	3C BS	NS	150,151,152,153		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IIIA	1.25 CC	3E BS	NS	150,151,153	5A	
	1.75 CC	3F NS	NS	150,151,152,153		
	1.50 CC	3G NS	NS	150,151,152,153		
	1.00 DEL	1D BS	NS	151		
	1.25 DEL	1E BS	NS	151,153		
	1.75 DEL	1G NS	NS	149,153		.012 Glass Cloth Face
	2.00 DEL	1H BS	NS	153		Sheet. Fiberglass Core.
IIIA	1.00 DEL	1D BS	FS		5A	
	0.25 LA	2A BS	FS	171		
	0.50 LA	2C FS	FS	169,170		
	1.25 LA	2E BS	FS	169,170		
	2.00 LA	2F BS	FS	169,170		.025 Glass Cloth Face
	1.75 LA	2G FS	FS	169		Sheet. Fiberglass Core.
	1.50 LA	2H FS	FS	169,170		Core Splice Detected
	0.50 CC	3A FS	FS	171		Below Row 3.
	0.75 CC	3C BS	FS	170,171		Vertical to E
	1.00 CC	3D FS	FS	170		
	1.25 CC	3E BS	FS	170		
	2.00 CC	3H FS	FS	170,171		
IIIB	0.25 LA	2A BS	NS	160,161	5A	Core Splice Detected C
	0.75 LA	2B NS	NS	159,160,161		to C, Horizontal at 1,
	1.00 LA	2D NS	NS	159,160,161,162		Horizontal A to C
	1.25 LA	2E BS	NS	159,160,161,162,163		Below 4.
	2.00 LA	2F BS	NS	159,160,161,162,163		
	1.00 DEL	1D BS	NS	162		
	1.25 DEL	1E BS	NS	162		
	1.50 DEL	1F FS	NS	162		
	0.25 CC	3B NS	NS	162,163		
	0.75 CC	3C BS	NS	162,163		
	1.00 CC	3D FS	NS			
	1.25 CC	3E BS	NS	160,161,162		
	1.75 CC	3F NS	NS	161,162		
	1.50 CC	3G NS	NS	162		
	1.25 INC	4D BS	NS	161		
	1.00 INC	4E NS	NS	161		
	2.00 INC	4G NS	NS	160		.025 Glass Cloth Face
	1.75 DEL	1G NS	NS	161		Sheet. Fiberglass Core.
IIIB	1.25 DEL	1E BS	FS		5A	Core Splice Between
	1.50 DEL	1F FS	FS			D and C.
	0.25 LA	2A BS	FS	174		Horizontal at 1.
	1.25 LA	2E BS	FS	172,173,175		
	2.00 LA	2F BS	FS	172,173		
	1.75 LA	2G FS	FS	172,173		
	1.50 LA	2H FS	FS	172,173		
	0.50 LA	2C FS	FS	173,175		
	0.50 CC	3A FS	FS	175		
	0.75 CC	3C BS	FS	174,175		
	1.00 CC	3D FS	FS	175		
	1.25 CC	3E BS	FS	173,175		
	2.00 CC	3H FS	FS	175		
	1.75 INC	4F FS	FS	172,173		.037 Glass Cloth Face
	1.50 INC	4H BS	FS	174		Sheet. Fiberglass Core.

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IIIC	1.00 DEL	1D BS	NS	166, 165, 167	5A	Core Splice
	1.75 DEL	1G NS	NS	164, 165, 166		Vertical C to C
	2.00 DEL	1H BS	NS	166, 167		
	0.25 LA	2A BS	NS	165, 166, 167		
	0.75 LA	2B NS	NS	164, 165, 166, 167		
	1.00 LA	2D NS	NS	164, 165, 166, 167, 168		
	1.25 LA	2E BS	NS	164, 165, 166, 167, 168		
	2.00 LA	2F BS	NS	164, 165, 166, 167, 168		
	0.25 CC	3B NS	NS	168		.037 Glass Cloth
	0.75 CC	3C BS	NS	168		Face Sheet
	1.25 CC	3E BS	NS	165, 166, 167		Fiberglass Core
	1.75 CC	3F NS	NS	165, 166, 167, 168		
	1.50 CC	3G NS	NS	166, 167, 168		
	1.25 INC	4D BS	NS	165, 166, 167		
	1.00 INC	4E NS	NS	165, 167		
	2.00 INC	4G NS	NS	165, 167		
	1.25 DEL	1E BS	NS	166, 167		
IIIC	0.50 DEL	1B FS	FS	180	5A	Core Splice
	0.75 DEL	1C NS	FS	178		between D & C
	1.00 DEL	1D BS	FS	177, 180		
	1.25 DEL	1E BS	FS	178, 180		
	1.50 DEL	1F FS	FS	177, 178, 180		
	0.25 LA	2A BS	FS	178		
	0.50 LA	2C FS	FS	176, 177, 178, 179, 180		
	1.25 LA	2E BS	FS	176, 177, 178, 179, 180		
	2.00 LA	2F BS	FS	176, 177, 178, 179, 180		
	1.75 LA	2G FS	FS	176, 177, 178, 180		
	1.50 LA	2H FS	FS	176, 177, 178, 180		
	0.75 CC	3C BS	FS	177, 178, 179, 180		
	1.00 CC	3D FS	FS	177, 178, 179, 180		
	1.25 CC	3E BS	FS	177, 178, 179, 180		
	2.00 CC	3H FS	FS	178, 179		
	0.50 CC	3A FS	FS	179		
	0.50 INC	4C FS	FS	177, 180		.012 Glass Cloth
	1.25 INC	4D BS	FS	180		Face Sheet
	1.00 INC	4E NS	FS	178, 180		Fiberglass Core
	1.75 INC	4F FS	FS	177, 178, 180		
	1.50 INC	4H BS	FS	179		
IIID	1.75 DEL	1G NS	NS	155, 156	5A	Core Splice
	0.25 LA	2A BS	NS	157		Horizontal
	0.75 LA	2B NS	NS	155, 156, 157		above 3, Ver-
	1.00 LA	2D NS	NS	155, 156, 157		tical at F to
	1.25 LA	2E BS	NS	155, 156, 157		above 3
	2.00 LA	2F BS	NS	155, 156, 157		
	0.75 CC	3C BS	NS	157, 158		
	1.25 CC	3E BS	NS	156, 157		
	1.75 CC	3F NS	NS	156, 157, 158		
	1.50 CC	3G NS	NS	157, 158		.050 Glass Cloth
	1.00 INC	4E NS	NS	157		Face Sheet
	0.25 INC	4B NS	NS	158		Fiberglass Core
IIID	1.25 DEL	1E BS	FS	183	5A	Core Splice
	0.25 LA	2A BS	FS	184		Horizontal be-
	0.50 LA	2C FS	FS	182, 183, 184		tween 2 & 3,
	1.25 LA	2E FS	FS	182, 183, 184		Vertical to F
	2.00 LA	2F BS	FS	181, 182, 183		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IIID	1.75 LA	2G FS	FS	181, 182, 183	5A	
	1.50 LA	2H FS	FS	181, 182		
	0.50 CC	3A FS	FS	183		
	0.75 CC	3C BS	FS	183, 184		.050 Glass Cloth
	1.00 CC	3D FS	FS	182, 183, 184		Face Sheet
	1.25 CC	3E BS	FS	182, 183, 184		Fiberglass Core
	2.00 CC	3H FS	FS	183, 184		
IVA	1.00 DEL	1D	NS		5A	
	1.25 DEL	1E	NS			
	1.50 DEL	1F	NS	234		
	1.75 DEL	1G	NS	234		
	1.00 LA	2D	NS			
	1.25 LA	2E	NS			
	2.00 LA	2F	NS			
	1.75 LA	2G	NS			
	1.50 LA	2H	NS			
	0.50 POR	3A	NS			
	0.25 POR	3B	NS			
	0.75 POR	3C	NS			
	1.00 POR	3D	NS			
	1.25 POR	3E	NS	234		
	1.75 POR	3F	NS	234		
	1.50 POR	3G	NS	234		
	2.00 POR	3H	NS	234		
	0.50 INC	4C	NS			
	1.25 INC	4D	NS	234		
	1.00 INC	4E	NS	234		
	1.75 INC	4F	NS	234		
	2.00 INC	4G	NS	234		Laminate
	1.50 INC	4H	NS	234		.030 Alum. Face Sheet
IVA	1.25 INC	4D	FS	241	5A	
	1.00 INC	4E	FS	241		
	1.75 INC	4F	FS	241		
	2.00 INC	4G	FS			
	0.75 POR	3C	FS			
	1.00 POR	3D	FS	241		
	1.25 POR	3E	FS			
	1.75 POR	3F	FS			
	1.50 POR	3G	FS			
	2.00 POR	3H	FS	241		
	0.75 DEL	1C	FS			
	1.00 DEL	1D	FS			
	1.25 DEL	1E	FS			Laminate
	1.50 DEL	1F	FS			.050 Alum. Face Sheet
IVB	1.25 LA	2E	NS	235	5A	
	2.00 LA	2F	NS	235		
	0.50 INC	4C	NS	235		
	1.25 INC	4D	NS	235		
	1.00 INC	4E	NS	235		
	1.75 INC	4F	NS	235		
	2.00 INC	4G	NS	235		
	0.75 POR	3C	NS	235		
	1.00 POR	3D	NS	235		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IVB	1.25 POR	3E	NS	235		Laminate .030 Alum. Face Sheet
	1.75 POR	3F	NS	235		
	1.50 POR	3G	NS	235	5A	
	1.25 DEL	1E	NS	235		
	1.50 DEL	1F	NS			
	1.75 DEL	1G	NS			
	0.75 DEL	1C	NS			
	1.00 DEL	1D	NS			
	2.00 DEL	1H	NS			
	1.75 LA	2G	NS			
	1.50 LA	2H	NS			
	2.00 POR	3H	NS			
	1.50 INC	4H	NS	235		
	0.25 POR	3B	NS	235		
IVB	1.25 LA	2E	FS	238	5A	Laminate .063 Alum. Face Sheet
	2.00 LA	2F	FS	238		
	0.50 INC	4C	FS			
	1.25 INC	4D	FS			
	1.00 INC	4E	FS			
	1.75 INC	4F	FS			
	2.00 INC	4G	FS			
	0.75 POR	3C	FS			
	1.00 POR	3D	FS			
	1.25 POR	3E	FS			
	1.75 POR	3F	FS			
	1.50 POR	3G	FS			
	1.25 DEL	1E	FS			
	1.50 DEL	1F	FS			
	1.75 DEL	1G	FS			
IVC	0.50 INC	4C	NS		5A	Laminate .050 Alum. Face Sheet
	1.25 INC	4D	NS	236		
	1.00 INC	4E	NS	236		
	1.75 INC	4F	NS	236		
	2.00 INC	4G	NS	236		
	0.75 POR	3C	NS	236		
	1.25 POR	3E	NS	236		
	1.75 POR	3F	NS	236		
	1.50 POR	3G	NS	236		
	0.50 LA	2C	NS			
	1.00 LA	2D	NS			
	1.25 LA	2E	NS	236		
	2.00 LA	2F	NS	236		
	1.75 LA	2G	NS			
	0.75 DEL	1C	NS			
	1.00 DEL	1D	NS			
	1.25 DEL	1E	NS			
	1.50 DEL	1F	NS			
	1.75 DEL	1G	NS	236		
	0.25 POR	3B	NS	236		
	1.00 POR	3D	NS	236		
IVC	1.00 DEL	1D	FS		5A	
	1.25 DEL	1E	FS	239		
	1.50 DEL	1F	FS			
	1.75 DEL	1G	FS			

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IVC	1.25 LA	2E	FS			
	2.00 LA	2F	FS	239		
	0.25 POR	3B	FS			
	0.75 POR	3C	FS	239		
	1.00 POR	3D	FS			
	1.25 POR	3E	FS	239	5A	
	1.75 POR	3F	FS			
	1.50 POR	3G	FS			
	0.50 INC	4C	FS			
	1.25 INC	4D	FS	239		
	1.00 INC	4E	FS	239		
	1.75 INC	4F	FS	239		
	2.00 INC	4G	FS	239		Laminate .063 Alum.
	1.50 INC	4H	FS	239		Face Sheet
IVD	0.[illegible]5 POR	3C	NS			2F & 2E may have
	1.00 POR	3D	NS	237		been reduced in size
	1.25 POR	3E	NS	237		due to flow of adhe-
	1.75 POR	3F	NS	237		sive during fabrica-
	1.50 POR	3G	NS		5A	tion of panel
	2.00 LA	2F	NS	237		
	1.25 LA	2E	NS	237		Laminate .030 Alum.
	0.50 INC	4C	NS			Face Sheet
	1.25 INC	4D	NS	237		
	1.00 INC	4E	NS	237		
	1.75 INC	4F	NS	237		
	2.00 INC	4G	NS	237		
	1.75 DEL	1G	NS	237		
	1.25 DEL	1E	NS	237		
IVD	2.00 LA	2F	FS	240		
	1.25 DEL	1E	FS			
	1.50 DEL	1F	FS			
	1.75 DEL	1G	FS	240		
	2.00 DEL	1H	FS			
	0.75 POR	3C	FS	240		
	1.00 POR	3D	FS	240		
	1.25 POR	3E	FS	240		
	1.75 POR	3F	FS	240	5A	
	1.50 POR	3G	FS	240		
	2.00 POR	3H	FS	240		
	1.00 DEL	1D	FS	240		
	0.50 INC	4C	FS			
	1.25 INC	4D	FS	240		
	1.00 INC	4E	FS	240		
	1.75 INC	4F	FS	240		
	2.00 INC	4G	FS	240		Laminate .020 Alum.
	1.50 INC	4H	FS			Face Sheet
VA	0.75 INC	4A	NS	227		
	0.50 INC	4C	NS	225		
	1.25 INC	4D	NS	225, 226, 227	5A	
	1.00 INC	4E	NS	225, 227		
	1.75 INC	4F	NS	225, 227		
	2.00 INC	4G	NS	225, 226, 227		
	1.50 INC	4H	NS	225, 226, 227		
	0.25 POR	3B	NS	225, 226, 227		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
VA	0.75 POR	3C	NS	225,226,227		
	1.00 POR	3D	NS	225,226,227		
	1.25 POR	3E	NS	225,226,227	5A	
	1.75 POR	3F	NS	225,226,227		
	1.50 POR	3G	NS	225,226,227		
	2.00 POR	3H	NS	225,226,227		
	0.25 LA	2A	NS	225		
	0.75 LA	2B	NS	225,226,227		
	0.50 LA	2C	NS	225,226,227		
	1.00 LA	2D	NS	225,226,227		
	1.25 LA	2E	NS	225,226,227		
	2.00 LA	2F	NS	225,226,227		
	1.75 LA	2G	NS	225,226,227		
	1.50 LA	2H	NS	226,227		
	0.50 DEL	1B	NS			
	0.75 DEL	1C	NS			Laminate .012 Glass
	1.00 DEL	1D	NS	225,226,227		Cloth Face Sheet
	1.25 DEL	1E	NS	22[illegible].226,227		Fiberglass
	1.50 DEL	1F	NS	225,226,227		
	1.75 DEL	1G	NS	225,226,227		
	2.00 DEL	1H	NS	226,227		
VA	0.75 LA	2B	FS	213,215		
	0.50 LA	2C	FS	213,215		
	1.00 LA	2D	FS	213,215		
	1.25 LA	2E	FS	213,215		
	2.00 LA	2F	FS	213,215		
	1.75 LA	2G	FS	213,215		
	1.50 LA	2H	FS	213,215		
	0.75 POR	3C	FS	213,214		
	1.00 POR	3D	FS	214		
	1.25 POR	3E	FS	214		
	1.75 POR	3F	FS	213,214		
	1.50 POR	3G	FS	213,214	5A	
	2.00 POR	3H	FS	214		
	0.25 DEL	1A	FS	213		
	0.50 DEL	1B	FS	213,215		
	0.75 DEL	1C	FS	215		
	1.00 DEL	1D	FS	213,215		
	1.25 DEL	1E	FS	213,215		
	1.50 DEL	1F	FS	213,215		
	1.75 DEL	1G	FS	213,215		Laminate .025 Glass
	2.00 DEL	1H	FS	213,215		Cloth Face Sheet
	0.25 INC	4B	FS			
	0.50 INC	4C	FS			
	1.25 INC	4D	FS			
	1.00 INC	4E	FS			
	1.75 INC	4F	FS			
	2.00 INC	4G	FS			
	1.50 INC	4H	FS			
VB	0.75 DEL	1C	NS			
	1.00 DEL	1D	NS	228,230		
	1.25 DEL	1E	NS	228,230	5A	
	1.50 DEL	1F	NS	230		
	1.75 DEL	1G	NS	228,230		
	2.00 DEL	1H	NS	230		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
VB	1.00 LA	2D	NS			
	1.25 LA	2E	NS	228,230		
	2.00 LA	2F	NS	228,230		
	1.75 LA	2G	NS		5A	
	1.50 LA	2H	NS	228		
	0.25 POR	3B	NS			
	0.75 POR	3C	NS			
	1.00 POR	3D	NS			
	1.25 POR	3E	NS			
	1.75 POR	3F	NS	228		Laminate .025 Face Sheet Fiberglass
	1.50 POR	3G	NS	228,230		
	2.00 POR	3H	NS	230		
	0.75 INC	4A	NS	228		
	0.25 INC	4B	NS	228		
	1.25 INC	4D	NS	228,229,230		
	1.00 INC	4E	NS	223,229,230		
	1.75 INC	4F	NS	228,229,230		
	2.00 INC	4G	NS	228,229,230		
	1.50 INC	4H	NS	228		
	0.50 INC	4C	NS	228		
VB	0.50 INC	4C	FS	231,232,233	5A	Laminate .037 Fiberglass Face Sheet
	1.25 INC	4D	FS	231,232,233		
	1.00 INC	4E	FS	232,233		
	1.75 INC	4F	FS	231,232,233		
	2.00 INC	4G	FS	233		
	1.50 INC	4H	FS	231,232,233		
	0.50 DEL	1B	FS			
	0.75 DEL	1C	FS	233		
	1.00 DEL	1D	FS	233		
	1.25 DEL	1E	FS	231,232,233		
	1.50 DEL	1F	FS	231,232,233		
	1.75 DEL	1G	FS	231,232,233		
	2.00 DEL	1H	FS	231,232,233		
	1.25 LA	2E	FS	233		
	2.00 LA	2F	FS	231,232,233		
	1.75 LA	2G	FS			
	1.00 POR	3D	FS	231,232,233		
	1.25 POR	3E	FS	232,233		
	1.75 POR	3F	FS	232,233		
	1.50 POR	3G	FS			
VC	1.00 DEL	1D	NS	218	5A	L.A. Defects Smaller than 1.25 probably closed, due to adhesive flow. 2F & 2H show definite flow of adhesive 2H appears to be about 0.25 dia.
	1.25 DEL	1E	NS	218		
	1.50 DEL	1F	NS	218		
	1.75 DEL	1G	NS	218		
	2.00 DEL	1H	NS	218		
	0.75 POR	3C	NS	217		
	1.00 POR	3D	NS	217		
	1.25 POR	3E	NS	217,218		
	1.75 POR	3F	NS	217,218		
	1.50 POR	3G	NS	217,218		
	0.75 INC	4A	NS	217,218		
	0.50 INC	4C	NS			
	1.25 INC	4D	NS	216,217,218		
	1.00 INC	4E	NS	216,217,218		
	1.75 INC	4F	NS	217		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
VC	2.00 INC	4G	NS	216,217,218		Laminate
	2.00 LA	2F	NS	216,217,218	5A	.037 Fiberglass Face
	1.50 LA	2H	NS	217,218		Sheet
VC	0.75 INC	4A	FS	223,224	5A	20 - 30% reduction in
	0.50 INC	4C	FS	223		area of L.A. type de-
	1.25 INC	4D	FS	222,223,224		fects. 2H appears to
	1.00 INC	4E	FS	223,224		be about 0.25 dia.
	1.75 INC	4F	FS	223,224		
	2.00 INC	4G	FS	223,224		
	1.50 INC	4H	FS	223,224		
	1.00 LA	2D	FS	223,224		
	1.25 LA	2E	FS			
	2.00 LA	2F	FS	222,223,224		
	1.50 LA	2H	FS	223		
	0.75 DEL	1C	FS	223		
	1.00 DEL	1D	FS	223		
	1.25 DEL	1E	FS	223,224		
	1.50 DEL	1F	FS	224		
	1.75 DEL	1G	FS	223		
	2.00 DEL	1H	FS	223		
	0.50 POR	3A	FS	224		
	0.25 POR	3B	FS	224		
	0.75 POR	3C	FS	223,224		
	1.00 POR	3D	FS	223,224		
	1.25 POR	3E	FS	223,224		
	1.75 POR	3F	FS	223,224		
	1.50 POR	3G	FS	223,224		
	2.00 POR	3H	FS	223,224		
	0.75 LA	2B	FS			Laminate
	0.50 DEL	1B	FS	223,224		.012 Fiberglass Face
	1.75 LA	2G	FS	224		Sheet
VD	1.00 POR	3D	NS		5A	Laminate .050 Fiber-
	1.00 INC	4E	NS			glass Face Sheet
VD	2.00 LA	2F	FS	220	5A	
	1.75 LA	2G	FS	220		
	1.00 POR	3D	FS	221		
	1.25 POR	3E	FS	220,221		
	1.75 POR	3F	FS	220		
	1.25 INC	4D	FS	219,220,221		
	1.00 INC	4E	FS			
	1.75	INC	4F	219,220,221		
	1.50 INC	4H	FS			
	1.00 DEL	1D	FS			
	1.25 DEL	1E	FS	220		
	1.50 DEL	1F	FS	220		
	2.00 DEL	1H	FS			Laminate .025 Fiber-
	1.50 POR	3G	FS	220		glass Face Sheet
IATi	0.75 DEL	1C NS	NS	194	5A	Cold line 1.0 inch
	1.00 DEL	1D BS	NS	194		wide x 3.0 inch long
	1.25 DEL	1E BS	NS	194		vertical between 1E
	1.75 DEL	1G NS	NS	195		and 2E. Core splice
	2.00 DEL	1H BS	NS	195		vertical between
	0.75 LA	2B NS	NS	194,195		F and G.
	1.00 LA	2D NS	NS	194,195		

TABLE V - DEFECTS DETECTED (Cont'd)

Panel Number	Type Defect	Location of Defect	Side, Viewed	Photo Number	L.C. Serial Number	Comments
IATi	1.25 LA	2E BS	NS	193,194,195	5A	.025 Titanium Face Sheet HRP Core
	2.00 LA	2F BS	NS	193,194,195		
IATi	1.00 DEL	1D BS	FS	200	5A	Core splice detected vertical between F and G. .032 Titanium Face Sheet HRP Core
	1.25 DEL	1E BS	FS	200		
	1.50 DEL	1F FS	FS	200		
	2.00 DEL	1H BS	FS	199,200		
	0.50 LA	2C FS	FS	199,200		
	1.25 LA	2E BS	FS	199,200		
	2.00 LA	2F BS	FS	199,200		
	1.75 LA	2G FS	FS	199,200		
	1.50 LA	2H FS	FS	199,200		
IBTi	0.75 CC	1C NS	NS	187	5A	Core splice detected vertical between C and D. .025 Titanium Face Sheet HRP Core
	1.00 CC	1D BS	NS	185,187		
	1.25 CC	1E BS	NS	185,187		
	1.75 CC	1G NS	NS	186,187		
	2.00 CC	1H BS	NS	186,187		
	1.25 INC	2E BS	NS	185		
	2.00 INC	2F BS	NS	185		
IBTi	1.00 CC	1D BS	FS	196,197,198	5A	.032 Titanium Face Sheet HRP Core
	1.25 CC	1E BS	FS	196,197,198		
	1.50 CC	1F FS	FS	196,198		
	2.00 CC	1H BS	FS	196,197,198		
IIATi	0.25 DEL	1A	FS	209	5A	L.A. defects may have decreased in size during bonding. Laminate .032 Titanium Face Sheet
	0.50 DEL	1B	FS	208,209		
	0.75 DEL	1C	FS	208,209		
	1.00 DEL	1D	FS	207,208,209		
	1.25 DEL	1E	FS	207,208,209		
	1.50 DEL	1F	FS	207,208,209		
	1.75 DEL	1G	FS	207,208,209		
	2.00 DEL	1H	FS	207,208,209		
	0.75 LA	2B	FS	207,208		
	0.50 LA	2C	FS	207		
	1.00 LA	2D	FS	207		
	1.25 LA	2E	FS	207		
	2.00 LA	2F	FS	207,208		
	1.75 LA	2G	FS	207,208		
	1.50 LA	2H	FS	207,208		
IIBTi	0.25 POR	1A	FS	211,212	5A	Row 2 defects (inclusions) required cooling with air nozzle during heating. Panel appears to be poorly bonded all over.
	0.50 POR	1B	FS	210,211,212		
	0.75 POR	1C	FS	210,211,212		
	1.00 POR	1D	FS	210,211,212		
	1.25 POR	1E	FS	210,211,212		
	1.50 POR	1F	FS	210,211		
	1.75 POR	1G	FS	210,211,212		
	2.00 POR	1H	FS	211,212,210		
	0.75 INC	2B	FS	212		
	0.50 INC	2C	FS	210		
	1.00 INC	2D	FS	212		
	1.25 INC	2E	FS	210,211,212		
	2.00 INC	2F	FS	210,211,212		

TABLE V - DEFECTS DETECTED (Concluded)

Panel Number	Type Defect	Location of Defect	Side Viewed	Photo Number	L.C. Serial Number	Comments
IIBTi	1.75 INC	2G	FS	212	5A	Laminate .032
	1.50 INC	2H	FS			Titanium Face Sheet
IIIATi	0.25 DEL	1A NS	NS			Core Visible.
	0.75 DEL	1C NS	NS	189		One of the best type
	1.00 DEL	1D BS	NS	188,189		panels for L.C. Testing
	1.25 DEL	1E BS	NS	188,189		
	1.75 DEL	1G NS	NS	188,189		
	2.00 DEL	1H BS	NS	188,189	5A	
	0.75 LA	2B NS	NS	189		
	1.00 LA	2D NS	NS	189		
	1.25 LA	2E BS	NS	188,189		Aluminum Core .025
	2.00 LA	2F BS	NS	188,189		Titanium Face Sheet
IIIATi	0.50 DEL	1B FS	FS	203		One of the best type
	1.00 DEL	1D BS	FS	203		panels for L.C.
	1.25 DEL	1E BS	FS	202,203		Testing. Core visible.
	1.50 DEL	1F FS	FS	202,203		
	2.00 DEL	1H BS	FS	201,202,203	5A	
	0.50 LA	2C FS	FS	203		
	1.25 LA	2E BS	FS	201,202,203		
	2.00 LA	2F BS	FS	202,203		Aluminum Core .032
	1.75 LA	2G FS	FS	202,203		Titanium Face Sheet
	1.50 LA	2H FS	FS	202,203		
IIIBTi	0.25 CC	1A NS	NS	192		Core visible
	0.75 CC	1C NS	NS	191,192		One of best type panels
	1.00 CC	1D BS	NS	190,191,192	5A	for L.C. Testing
	1.25 CC	1E BS	NS	190,191,192		Aluminum Core .025
	1.75 CC	1G NS	NS	191,192		Titanium Face Sheet
	2.00 CC	1H BS	NS	191,192		
	0.75 INC	2B NS	NS	192		
	1.00 INC	2D NS	NS	191,192		
	1.25 INC	2E BS	NS	191,192		
	2.00 INC	2F BS	NS	191,192		
IIIBTi	0.50 CC	1B FS	FS	206		Core visible
	1.00 CC	1D BS	FS	205,206		One of best panel types
	1.25 CC	1E BS	FS	204,205,206		for L.C. Testing
	1.50 CC	1F FS	FS	204,205,206		
	2.00 CC	1H BS	FS	204,205,206		
	0.50 INC	2C FS	FS	206	5A	
	1.25 INC	2E BS	FS	205,206		
	2.00 INC	2F BS	FS	206		
	1.75 INC	2G FS	FS	206		Aluminum Core .032
	1.50 INC	2H FS	FS	206		Titanium Face Sheet
C-1	N/A	NS	NS			Contamination simulated
C-1	N/A	FS	FS	250,251,252		by oil injected into
C-2	N/A	NS	NS	255	5A	perforated core. 50%
C-2	N/A	FS	FS	253,254		of panel appeared
						randomly inhomogeneous
NO. 1	N/A	Convex Side	Convex Side	242,243		Internal Discontinuities
				244,245		Appearing as cold lines
				246,247	5A	were observed.
				248,249,258		See Figure 10
P-1				257,257	5A	See Text Page 12

TABLE VI - WATER DETECTED IN PANEL X-1

Hole Pattern Number	Amount of Water Injected (CC) (Note 3)	Detected By Liquid Crystals	Detected By X-ray (Note 2)
1	0.50	No	Yes 1 Cell
2	0.20	No	Yes 1 Cell
3	0.30	Yes	No
4	0.40	No	No
5	0.50	No	?
6	Note 1	Yes	Yes 1 Cell
7	0.50	Yes	Yes 1 Cell
8	0.40	Yes	Yes 1 Cell
9	Note 1	Yes	Yes 2 Cells
10	0.80	No	No Note 1
11	Note 1	Yes	Yes 1 Cell
12	1.80	Yes	Yes 1 Cell
13	2.00	Yes	Yes 1 Cell
14	2.00	Yes	Yes 2 Cells
15	4.00	Yes	Yes 4 Cells
16	0.80	Yes	Yes 2 Cells

Note 1 - Amount of water uncertain due to leakage

Note 2 - Number of cells indicate water distribution

Note 3 - Quantity of water listed is total amount entrapped in hole pattern

REFERENCES

1. Brown, G. H., and Shaw, W. G., Chemical Reviews, University of Cincinnati, Ohio, May 1957, pp 1049-1157.

2. Brown, G. H., Liquid Crystals, Industrial Research, Vol. 8, No. 5, May 1966, pp 53-58.

3. Fergason, J. H., Liquid Crystals, Scientific American, Vol. 211, No. 2, August 1964, pp 77-85.

APPENDIX

IDENTIFICATION OF LIQUID CRYSTAL SUPPLIERS

Letter Code	Cost	Supplier
A	$100/Liter	Distillation Products Industries Division of Eastman Kodak Co. Rochester, N. Y.
B	$200/Liter	Pressure Chemical Company 3419-25 Smallman Street Pittsburgh, Pa. 15201
C	$250/Liter	Westinghouse Electric Corp. Research and Development Center Pittsburgh, Pa. 15235