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ENGINEERING REPORT 8379

BIREFRINGENT COATINGS FOR NONDESTRUCTIVE TESTING OF HONEYCOMB SANDWICH STRUCTURES

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March 1966

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Engineering Development Test Laboratories Division
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[redacted]

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Control No. 1-5-30-12719 for George C. Marshall
Space Flight Center, NASA, Huntsville, Alabama

FOREWORD

This is the final report which summarizes technical findings and evaluations required by Contract NAS8-11972, Detection of Bond Defects in Honeycomb Sandwich Aluminum Panels, and covers the period of 30 June 1965 to 15 March 1966.

Contract initiation was by the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, under control number 1-5-30-12719. It was administered by Mr. H. M. Walker, R-ME-MM, of the Manufacturing Engineering Laboratory with Mr. E. L. Brown and Mr. W. A. Wilson as alternates.

The program was performed by the Engineering Development Test Laboratories Division of Lockheed-Georgia Company with D. G. Cumro of the Structural Test Laboratory Department as program manager and W. M. McGee as project leader. Other personnel and organizations who made significant contributions were: R. I. Prescott, also of the Structural Laboratory Department, and F. T. Humphrey and S. C. Porter of the Materials Laboratory Department.

ABSTRACT

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An epoxy type birefringent coating applicable using conventional paint spray type equipment was developed. The premixed coating components exhibited long pot life in large quantities, and when sprayed, cured in a short time to produce a relatively high strain-optic coefficient. The coating was evaluated for nondestructive testing of honeycomb sandwich panels having simulated face sheet bondline voids. Perforated core allowed the panels to be pressurized which produced strain discontinuities in the face sheets at void locations. These discontinuities were made visible by the birefringent coating sprayed on the face sheet. Optimal coating thicknesses for aluminum alloy face sheets up to 0.100 inch thick were determined. Coating removal evaluations were made, and results for a limited investigation of a promising polyurethane type birefringent coating are presented.

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GLOSSARY

a	Radius of unbonded circular area, inch
C	Correction factor
E_c	Coating modulus of elasticity
E_s	Skin modulus of elasticity
K	Strain-optic coefficient
n	Fringe order
P	Pressure, psig
r	Distance in a radial direction, inch
t_c	Coating thickness
t_s	Skin thickness
μ	Poisson's ratio
σ_t	Stress acting normal to a radial line, psi
σ_r	Stress acting along a radial line, psi

I - INTRODUCTION

Although plywood is known to have a date of origin around 2800 B.C., other laminar type composites have not enjoyed such an early beginning. Only in recent years has technology advanced to provide the cellular sandwich composite, more popularly known as honeycomb sandwich. Today, honeycomb sandwich applications are many and varied as evidenced by its use in airplanes, missiles, boats, trailers, furniture and even pool tables---to name only a few. Depending upon the application, honeycomb may be fabricated from a variety of materials ranging from paper to super alloys and joined by adhesives, welding or brazing. Despite the diversified applications of today, progress has been slow because of such obstacles as cost, joining and fabrication problems, and lack of adequate nondestructive testing methods. Many such obstacles have been lowered sufficiently to allow significant progress. This is true for nondestructive testing of honeycomb; however, lack of positive test methods still remains a problem.

The quality level required of honeycomb, of course, depends upon the application; and extremely high quality is demanded for applications protecting life and large investments. Defects of various types inadvertently occur during manufacture. Generally, the major defects may be classified as void areas where desired bonding of the composite constituents has not occurred. Such voids sometimes occur between the face sheet and core, at edge closures and doublers, and at core and skin splices. For honeycomb structures requiring a high quality level, these voids must be located, sized, evaluated, and possibly repaired. Direct visual detection is impossible since the voids are hidden and sealed below the composite outer layers. Consequently, indirect observations utilizing nondestructive testing methods must be relied upon for locating and sizing voids. Methods as simple as the tap of a coin to as complex and sophisticated as X-ray and ultrasonics have been evaluated and utilized in the search for voids. The success of all these methods depends to some degree on perseverance and skill of the operator as well as eliminating personal opinion in interpretation of the results. Many times the results are not sufficiently positive to eliminate conjecture.

Preliminary evaluations of strain sensitive coatings for void detection were reported by Schuerer and Simpson in Reference 1. Both brittle lacquer and birefringent coatings were employed in search of a more positive type void detection method. These evaluations were performed on honeycomb panels having perforated core and void implants between the core and face sheets. By sealing the panel edges and applying internal pressure the voids behaved as pressure loaded plates or membranes. The resulting change in face sheet stress distribution around the voids made them visible in the strain sensitive coatings applied to the face sheets. Positive detection was achieved and particularly encouraging results were obtained using birefringent coatings; however, the evaluation was preliminary in nature and considerable additional work was required before the technique could be practically applied on a large scale.

The information reported herein was obtained on a program designed to bridge the gap between the preliminary investigation discussion above and large scale application of the technique. The program was comprised of two phases. Phase I was devoted to development of a sprayable birefringent coating system having high strain-optic sensitivity. In Phase II, the coating system was evaluated on honeycomb sandwich panels containing various types of void implants for several different face sheet thicknesses up to 0.100 inch. Methods of coating removal were also studied. The investigation was limited to honeycomb panels having 7075-T6 aluminum alloy face sheets.

II - THEORY

Birefringence resulting from deformation of optically isotropic materials is by no means a modern observation since, according to history, it was first observed and reported by David Brewster in 1812. Classical photoelasticity stemmed from this early observation and a logical extension of photoelasticity, the birefringent coating technique, has occurred in recent years. The birefringent coating technique has a definite advantage over conventional photoelastic methods for many practical applications in that it allows determination of surface strains on the actual structure.

The theory utilized in general photoelastic and birefringent coating work is based on physical principles involving light transmission through optically isotropic and birefringent materials. Optically isotropic materials transmit light at the same velocity in all directions and, consequently, each material has a singular value for index of refraction. Most of these materials, however, become anisotropic or birefringent upon forced deformation due to the fact that two optical axes are formed at any point observed. These axes are orthogonal at every point, and the index of refraction of one axis is not necessarily equal to that of the other. It has been shown that the difference between indexes of refraction is proportional to the difference between the principal stresses at the point considered. Further, it has been shown that the optical axes coincide with the principal stress directions. If the indexes differ at a point, light will be transmitted faster along one axis; consequently, part of an incident light amplitude will emerge behind its complementary component.

The term "relative retardation" is used to define this phenomenon, and a polariscope is used to measure this quantity in terms of a selected wave length of light. A proportionality constant between relative retardation and principal stress difference can be determined by a simple calibration. The polariscope also allows directions of the optical axes or principal stress directions to be determined. If desired, individual values for the principal stresses can be determined by making relative retardation measurements in two different directions at each point or analytical methods can be employed which utilize the relative retardation and direction measurements.

In the birefringent coating technique the optically isotropic material is applied to the structure to be analyzed. The structure is subsequently loaded in some manner and the resulting surface strains are transmitted to the coating which then becomes birefringent. The instrument utilized to observe the birefringence is called a reflective polariscope since the observed light has reflected from the coating-structure interface. The simplest such polariscope is a circular polarizer placed directly on the coating surface. Normally, polychromatic lighting of the room is sufficient to allow observation of the distribution of principal stress differences. When using polychromatic lighting, the distribution is displayed by different colors. This method is not well suited for measurement of very small relative retardations; however, refined optical systems are available which allow accurate measurements on the order of .01 times the referenced wave length of light. More detailed information on theory of birefringence and polariscopes is in References 2 through 4.

For birefringent coatings the proportionality constant relating relative retardation to principal strain difference is termed the strain-optic coefficient. This coefficient, K, is related to the principal stress difference, $\sigma_t - \sigma_r$, by the following equation:

$$\sigma_t - \sigma_r = \frac{N\lambda \frac{E_s}{1+\mu_s}}{2t_c KC} \qquad (1)$$

The relative retardation, n, in equation (1) is the number of wave lengths of light referenced to the tint of passage. The tint of passage wave length (2.27×10^{-5} inch) is normally used for polychromatic illumination since it is very sensitive to small changes in principal stress difference and thus eliminates errors introduced by interpretation of shades of a particular color. Equation (1) indicates that for a given principal stress difference, relative retardation will increase as t_c becomes larger. This is true for plane stress conditions since the correction factor, C, which compensates for sheet reinforcement by the coating, is a linear function with coating to sheet thickness ratio. The plane stress correction factor is defined by the following equation.

$$\frac{1}{C_p} = 1 + \frac{t_c E_c}{t_s E_s} \qquad (2)$$

Equations (1) and (2) show that the actual stress difference will always be greater than that indicated by uncorrected measurements of relative retardation.

For bending, however, the correction factor is a nonlinear function with coating-to-sheet thickness ratio since a shift in neutral axis and increased section modulus must be considered. The bending correction factor is defined by the following equation.

$$\frac{1}{C}=\frac{1+\frac{E_c t_c}{E_s t_s}}{1+\frac{t_c}{t_s}}\left[4\left(1+\frac{E_c}{E_s}\left|\frac{t_c}{t_s}\right|^3\right)-\frac{3\left(1-\left|\frac{t_c}{t_s}\right|^2\frac{E_c}{E_s}\right)^2}{1+\frac{t_c E_c}{t_s E_s}}\right] \qquad (3)$$

Equations (2) and (3) were derived and verified in Reference 5. A solution of these equations is shown in Figure 1 for a particular set of conditions. The solution for bending shows a range of coating-to-sheet thickness ratios for which the correction factor is greater than one. Unlike the plane stress correction, this shows that within this range of thickness ratios the actual stress difference will always be less than that indicated by uncorrected measurements of relative retardation. In stress analysis work the coating thickness which would require no bending correction would normally be selected. For this investigation, however, the objective is to maximize void detectability rather than perform a stress analysis. Consequently, selection of the thickness ratio corresponding to the peak in the bending correction curve should produce optimal conditions. Further increases in coating thickness should be detrimental rather than beneficial. Correlations of experimental results with the above theory are presented under the Analysis section of this report.

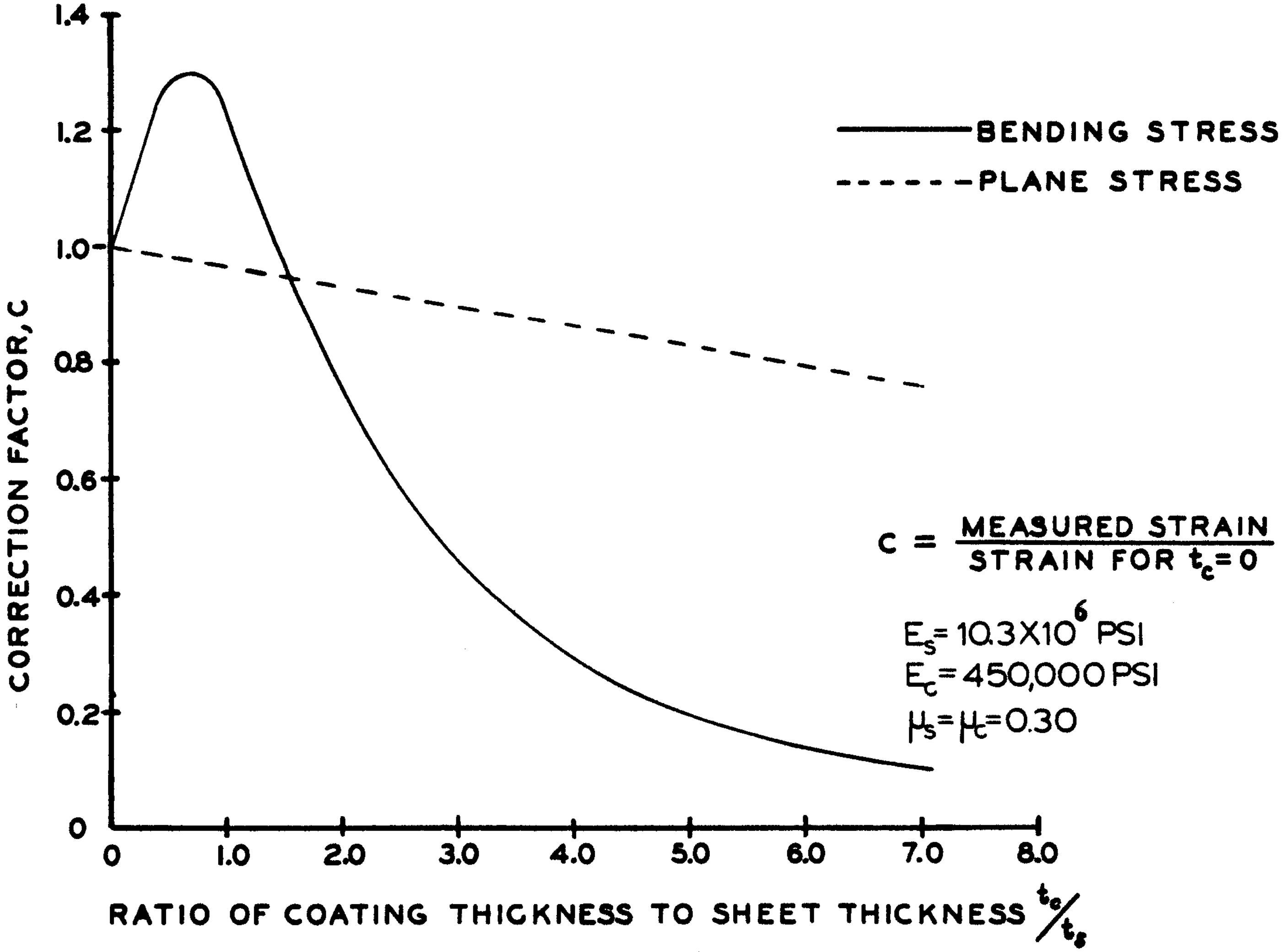


FIGURE 1: CORRECTION FACTORS FOR BIREFRINGENT COATINGS ON ALUMINUM ALLOY STRUCTURES

While the mechanical or physical theories are widely utilized in photoelastic and birefringent coating work, theories more chemical in nature have been derived. Such theories explain birefringence from a molecular standpoint, and one of the more widely accepted theories was proposed by Treloar in Reference 6. This theory states that the difference of any two principal refractive indexes is proportional to the difference of the squares of the corresponding extension ratios and is symbolized in the following manner:

$$X_1 - X_2 = \frac{(\bar{X}^2 + 2)^2}{\bar{X}} \frac{2\pi L}{45} (d_1 - d_2)(R_1^2 - R_2^2) \qquad (4)$$

Where

$X_1 - X_2$ = birefringence or difference in principal refractive indexes

$\bar{X}$ = mean refractive index

L = number of network chains per unit volume

$d_1 - d_2$ = difference in polymer chain length polarizabilities

$R_1 - R_2$ = difference in principal extension ratios (function of principal strain difference)

Molecular causes of birefringence are of interest; however, the theory defined by equation (4) was not directly utilized in the work reported herein.

III - EPOXY COATING SYSTEM DEVELOPMENT - PHASE I

Requirements - Although birefringent coatings have been utilized in practical applications for several years, the accumulated technology has primarily satisfied requirements for relatively small applications in the laboratory. Presently developed birefringent coatings are resins which cure by solvent release or by reaction with hardeners. The latter curing method has met with more success and is used quite universally for small applications in the laboratory. The need for large area coverage has existed; however, lesser technical emphasis has been placed on the associated problems.

Several possible methods are available for rapid application of birefringent coatings on large areas. Among these are two-component spray, premixed two components sprayed as one, and premixed flow coating.

In any method used it is essential that the hardener be uniformly and intimately mixed with the resin in order to produce a coating with uniform properties. Most resins are critical in this respect because hardener-to-resin ratios are quite low. Very small fluctuations in hardener proportioning and mixing ratio can produce large variations in strain-optic coefficient, and the variation existing on a coated structure cannot be easily determined. Two-component spray equipment is available from several manufacturers; however, there are definite problems associated with two-component spraying of birefringent coatings. The low hardener-to-resin ratio and coating property sensitivity to hardener content demands precise metering of the two components. Further, if metering were not a problem, the problem of intimate mixing still prevails. Proportioning and mixing is further complicated by the enormous viscosity differential between hardener and resin. Certainly, solvents can be added to the resin for lowering viscosity; however, the resin content remains the same requiring the same proportion of hardener which becomes an acute problem on a volumetric basis. Solvent additions also decrease solid content and increase coating shrinkage during cure.

Flow coating could be utilized successfully on flat horizontal surfaces, but such conditions seldom prevail in practical applications. The above discussion highlights a few of the problem areas and by no means encompasses all significant details.

From such considerations the desired characteristics of an acceptable spray coating system were established prior to initiating the investigation reported herein. The more important of these are listed below:

- Coating constituents that can be premixed and sprayed as a single component
- High hardener-to-resin ratio
- Maximum solid content
- Long pot life in large quantity mixtures
- Utilization of conventional paint spray type equipment
- Application of thick coats on vertical surface by spraying
- Short cure time after spraying at ambient temperature
- High strain-optic coefficient for cured coating
- Low modulus of elasticity for cured coating
- Stable properties after curing
- Good optical properties for fringe definition
- Removable cured coating

These twelve points were utilized as objectives in coating development since their accomplishment would provide an ideal system for large area coverage.

Screening Program Procedures - Many excellent ideas have remained dormant until technology in seemingly unrelated areas advanced and made possible their practical application. Extension of photoelasticity to the birefringent coating technique was no exception since Mesnager suggested the idea in 1930. However, the materials available to Mesnager were not suitable for use as coatings. Development of plastics in recent years, especially the epoxy family, has allowed practical application of the technique. Many and varied applications have been made during the last ten years as evidenced by publications of the Society for Experimental Stress Analysis.

The bulk of present birefringent coating technology hinges around epoxy resin systems, and in order to utilize this technology, epoxy systems were considered for this investigation. The epoxy resins are quite versatile since they can be cured in a number of different ways, and their cured properties can be varied considerably by additives. However, the effects of different curing agents and accelerators on strain-optic coefficient and optical properties were not well defined. For this reason a screening program was initiated to define these and allow selection of coating constituents and concentrations required to satisfy the previously established objectives.

The screening program was designed to determine the effects of different curing agents, resin additives and accelerators on strain-optic coefficient and optical properties. Also curing rate and small quantity pot life could be observed. Since large quantities of material were required for spraying, and evaluation of several different materials in different concentrations was anticipated, it was decided to procure the screening materials in small quantities and use a doctor knife to apply the different formulations to calibration beams. The most promising formulation would then be selected from screening program results and further modified to produce a sprayable material. This approach allowed the screening program to be performed more expediently and economically.

Calibration beams were of the configuration normally used for determining strain-optic coefficient for coatings employed in stress analysis work. They were made of 2024-T4 aluminum alloy and were one inch wide by ten inches long by 0.250 inch thick. The doctor knife and typical calibration beams are shown in Figure 2. After cleaning, the beams were

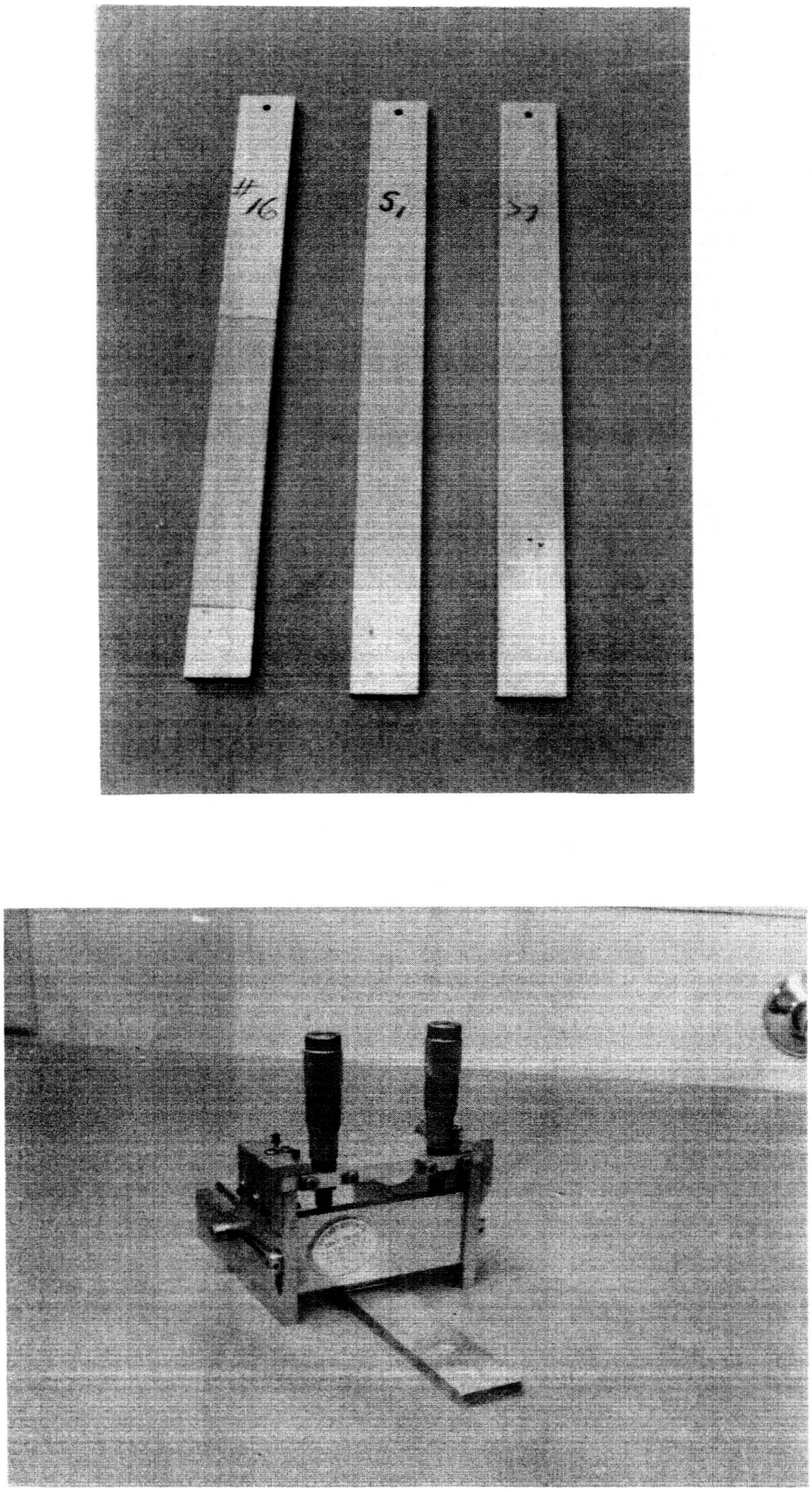


FIGURE 2: DOCTOR KNIFE AND TYPICAL CALIBRATION BEAMS UTILIZED IN SCREENING PROGRAM

taped to a flat, level surface and each was coated with a different formulation. The doctor knife was adjusted to apply a wet film thickness of 0.008 inch which represented the maximum thickness expected to be sprayable on a vertical surface without sag or run-off. Wet film coats were applied in approximate two-hour intervals until a total thickness of approximately 0.050 inch had been accumulated. This thickness was required in order to obtain an accurate strain-optic coefficient determination. Curing of the coats was at approximately 70°F, and the last coat was allowed to cure approximately 24 hours prior to performing a calibration. Prior to calibration, the cured coating thickness was determined by measuring total thickness of coating and beam and subtracting thickness of the beam. The beam was then clamped to a reaction plate at one end and dead weight loaded as a cantilever. Beam orientation was such that the coating was in tension. A Photolastic Model 030 universal reflective polariscope was then utilized to measure coating fringe order, n, at a point approximately two inches from the cantilever support. Tensile stress for the beam fiber at this point was computed using the weight applied, beam dimensions and conventional beam bending equation. The coating thickness, fringe order, stress and elastic constants for the beam material allowed solution of equation (1) in terms of strain-optic coefficient, k, and the bending correction factor, C. This factor was determined from the curve in Figure 1. Elastic constants utilized for the 2024-T4 aluminum alloy beam were 10.3×10^6 psi for modulus of elasticity and 0.30 for Poisson's ratio. While measuring relative retardation, notes relative to fringe definition and clarity were also made.

Beams having coatings exhibiting promising properties were then cured 24 hours at 120°F and again calibrated. By comparing these with the initial calibrations, it was determined if the initial 24 hour cure had been sufficient to produce stable strain-optic coefficients and optical properties. The more promising coatings surviving the elevated temperature cure were aged for 20 days at 70°F and again calibrated. During this period preliminary spray evaluations were performed using these formulations.

Coating Formulations and Evaluations - Several of the objectives are contradictory when viewed in light of present birefringent coating techniques utilized in the laboratory. For instance long pot life is not normally associated with short cure time at ambient temperature and high strain-optic coefficient. Present coatings producing high strain-optic coefficients have less than a one hour pot life when mixed in quantities of a few grams. For large area coverage a pot life of several hours is desired for one to five gallon quantities; however, a short cure time is desired when the material is sprayed. In order to accomplish this, ketimines were utilized in the screening program as the primary curing agents or hardeners. Ketimines are a recent development of the Shell Chemical Company and are formed by reaction of aliphatic polyamines and ketones. They have a very low level of reactivity with the resin in the absence of moisture; however, moisture converts the ketimine to polyamine and ketone. The ketone is released, and the polyamine functions as a reactive cross-linking agent for the resin in the same manner as conventional amine curing agents. Pure ketimines exhibit the lowest reactivity in the absence of moisture while the reactive ketimines contain free amine groups which produce an activity level between that of the pure ketimine and polyamines.

Initially EPON H-1, a reactive ketimine, was utilized as the primary curing agent in the screening program. The basic epoxy resins selected were EPON 828 and Ciba 6020 because of their known compatibility with the ketimines, and because prior experience with the resins combined with amines produced high strain-optic coefficients. The H-1 was utilized as the only curing agent in some cases, and small amounts of diethylene triamine and tri-dimethyl amino methyl phenol, DMP, were combined with the H-1 in other cases. Both of these hardeners are highly active and when used alone have a short pot life and generally produce complete cure at ambient temperature. These ingredients were added to speed gel of the coating during ketimine conversion. The DMP is often used as a co-curing agent because of its wide range of compatibility with other curing agents. Curing agent concentrations evaluated were generally within a ±25 percent range about stoichiometric.

Accelerators in the form of phenol and tricresyl phosphate were also included in some formulations. Phenol is considered a rapid accelerator because of high hydrogen activity and usually functions to decrease gel time when used with primary and secondary amines. Tricresyl phosphate, although a reactive ingredient, is more of a flexibilizer than accelerator. This flexibilizer is not generally highly compatible with epoxies; however, it was incorporated on a limited basis in hope of imparting toughness to aid in removal of the cured coating.

Limited evaluations were also made on modifications of the EPON 828. The modifying agents utilized were EPON 812, Cardolite and butyl glicidyl ether. The EPON 812 lowered viscosity as well as epoxide equivalent. The lowered viscosity was desired for spray considerations; however, the lower epoxide was expected to be accompanied by a lower strain-optic coefficient. Cardolite is a filling compound containing reactive epoxide groups that react with the curing agents in the same manner as the epoxy resins. Generally, Cardolite acts as a flexibilizer and imparts toughness as well as lowers viscosity and allows a wide range of different curing agents to be used. Butyl glicidyl ether is a reactive diluent that decreases curing agent volatilization during cure, lowers viscosity and increases pot life. These three modifiers function to produce desired properties relative to pot life, lower viscosity and toughness; however, their effect on optical properties was not known.

Twenty-three different formulations having H-1 as the primary curing agent were evaluated in the screening program. Formulations for these are shown in Table I along with strain-optic coefficients determined as described in the previous section. These results show that all three resin modifiers and tricresyl phosphate had a detrimental effect on strain-optic coefficient. Phenol additions resulted in crazing and blushing which made fringe definition practically impossible. The H-1 used alone produced low strain-optic coefficients and additions of diethylene triamine produced little improvement. Best results were obtained using H-1 and DMP in the unmodified resin. Relatively high strain-optic coefficients and good optical properties were obtained on initial calibration; however, the coefficients changed considerably after exposing the coatings to 120°F. It was also noted that formulations having the Ciba 6020 resin cured at a much faster rate than those having EPON 828.

Although the systems designated as 17 and 18 in Table I exhibited acceptable properties, a formulation exhibiting a more stable strain-optic coefficient after a 24 hour cure was desired. For this reason additional screening evaluations were made using a pure ketimine, EPON H-3, and the DMP combined with unmodified resin. Phenol was also included as an accelerator to determine its behavior when combined with the H-3. As shown in Table I, eleven different formulations were evaluated, and acceptable results were obtained for systems numbered 26, 27 and 28. Results for 26 and 28 were particularly encouraging since strain-optic coefficients changed very little as a result of the 120°F cure, and optical properties were good. At this point sufficient screening information was considered obtained, and the H-3 combined with DMP in unmodified resin was selected for modification into a sprayable material. Both EPON 828 and Ciba 6020 were utilized as base resins.

Spray Evaluations - Spray evaluations were initiated to develop spray techniques necessary to maintain the good optical properties and high strain-optic coefficient obtained for the selected formulation during screening. Initial evaluations were directed toward spraying the formulation without further modification and at a temperature of approximately 70°F. Panels of aluminum alloy sheet were sprayed. After investigating wide ranges of air pressure, air and fluid volumes, and nozzles, it was decided that the 70°F viscosity was too high to allow sufficient atomization. The resin was then heated to various temperatures between 100°F and 170°F in order to lower viscosity. Good atomization was obtained by spraying at 150°F, and the initially sprayed coating had good appearance; however, small bubbles developed in the coating as curing proceeded, and produced poor optical properties. Spraying with an airless spray gun produced the same results. Several flow control agents were added to the formulation in amounts of one to five percent by weight. The agents used were Beetle 216-8, 3M's FM-134, GE's SR82 and Monsanto's PC1244. The flow control agents retarded cure rate and did not alleviate the bubble problem. When airless spraying and flow control agents failed to eliminate the formation of bubbles, it was apparent that the problem was inherent with the ketimine. The viscosity of the coating during ketimine conversion was too high to allow the ketones to escape, and consequently the ketones remained as bubbles in the coating. Spray evaluations to this point utilized nearly 100 percent solids; however, further evaluations utilized solvent to reduce viscosity of the sprayed coating.

Methyl ethyl ketone was mixed with the formulation in various amounts and sprayed at temperatures ranging from 70°F to 125°F. Bubble-free coatings were obtained for the lower temperatures; however, little was gained at the higher temperatures because of rapid solvent flashing.

Further evaluations were limited to 70°F, and a 29 percent by weight addition of methyl ethyl ketone was found to produce a coating with good optical properties. The solvent addition, however, resulted in a reduction of wet film thickness sprayable on a vertical surface. Thixotroping agents in the form of bentonite and Cab-O-Sil in amounts of one to five percent were then investigated. Additions of bentonite produced undesirable optical properties; however, 3 percent by weight additions of Cab-O-Sil provided thixotropy required to maintain a wet film thickness of 0.006 to 0.008 inch on a vertical surface and did not significantly impair optical properties. When spraying with high fluid volume the limiting vertical surface film thickness was 0.006 inch. Of course thicker coats are applicable to horizontal surfaces; however, curing rate is a function of film thickness unless sufficient moisture for ketimine conversion is collected during spraying. Consequently, wet film thickness should be limited to approximately 0.010 inch to allow permeability to moisture if required.

Panels of aluminum alloy sheet and calibration beams were sprayed to finalize techniques. The EPON 828 and Ciba 6020 were utilized as resins in the formulation shown below.

Resin containing 3 percent Cab-O-Sil by weight -	100 parts by weight
EPON H-3 ketimine--------------------------------	40 parts by weight
Tri-dimethyl amino methyl phenol-----------------	6 parts by weight
Methyl ethyl ketone------------------------------	29 parts by weight

Satisfactory coatings were obtained using a DeVilbiss spray gun with siphon pot and a number 36 cap and nozzle. The gun was adjusted for fine spray at a line pressure of 80 psig. During spraying the nozzle was held approximately 14 inches from the panel surface, and a wet film thickness of approximately 0.0005 inch was deposited by each pass. Sufficient passes were made to produce a wet film 0.006 to 0.008 inch thick as determined using a Nordson wet film gage. The formulation utilizing Ciba 6020 cured to a tack-free condition within three hours for 80°F and 30 percent relative humidity environment. Under the same conditions the EPON 828 required an additional hour. After a 24 hour cure, strain-optic coefficients of approximately 0.08 were determined from the calibration beams. This value compared favorably with that reported in Table I for system number 26. Comparison of wet and dry film thickness measurements on calibration beams showed that a 25 to 30 percent shrinkage occurred during cure.

Pot life in small quantities had been observed during the preliminary spray evaluations and was considered acceptable. However, a one-gallon quantity of the formulation was mixed and placed in a container having insulated walls and bottom to prevent heat loss from the exothermic reaction. The top of the container was left open for exposure to moisture necessary for ketimine conversion. The container was placed in a 70°F, 30 percent relative humidity environment and observed for several hours. The material was still considered sprayable after eight hours. Ciba 6020 was utilized in the formulation for pot life evaluation since its faster cure rate was desired. Based on this evaluation, it was estimated that a five-gallon quantity in a sealed metal can would have several days pot life if refrigerated.

Having accomplished satisfactory spray techniques, cure time, strain-optic coefficient and pot life, materials for the selected formulation were procured in quantities required for Phase II. These were procured from Magnolia Plastics, Inc., Chamblee, Georgia. Since a Cowles mill was required to uniformly disperse the Cab-O-Sil in the resin, the resin was procured with the Cab-O-Sil added and was designated as Magnolia Formulation S-550.

IV - COATING SYSTEM EVALUATIONS - PHASE II

Honeycomb Test Panels - Fifty honeycomb sandwich panels containing void implants were fabricated in order to evaluate the birefringent coating system for conditions simulating the intended application. All panels had clad 7075-T6 aluminum alloy face sheets and 0.50 inch thick 6.0-1/4-30P(5052) core. Cores for the panels were purchased to the desired size of 23 inches by 23 inches, and face sheets were sheared to 25 inches by 25 inches. During fabrication the core panels were centered on the face sheets which left a one inch wide coreless perimeter. Phenolic or masonite strips were potted or bonded in this perimeter to seal the panel edges. Two opposing edge strips for each panel contained a tube to allow application and measurement of pressure. Tube locations and general honeycomb panel construction are illustrated in Figure 3. One face sheet of each panel had bondline void simulation and the thickness of that sheet was measured and recorded for the four corners. The face sheet was also serialized to define thickness and type of voids.

Prior to bonding, the face sheets were solvent cleaned with methyl ethyl ketone, alkaline cleaned for 10 minutes at 180°F in an aqueous solution containing 4 to 8 ounces per gallon Turco 4090, rinsed in water, and acid cleaned for 10 minutes at 150°F in an aqueous solution containing 22 to 26 parts by weight sulfuric acid and 3 to 6 parts by weight chromic acid. The sheets were then water rinsed, dried in forced air and bonded within four hours. Personnel handling the panel parts wore white, lint-free cotton gloves to prevent surface contamination. As detailed below, deviations from the above cleaning and handling procedures were made for three of the panels.

A Dake hydraulic bonding press was utilized for bonding all panels. With the exception of six panels, HT-424 adhesive was used and the bonding cycle was comprised of 60 to 90 minutes at 40 psi and 335°F. The six exceptions had two different adhesives as discussed below.

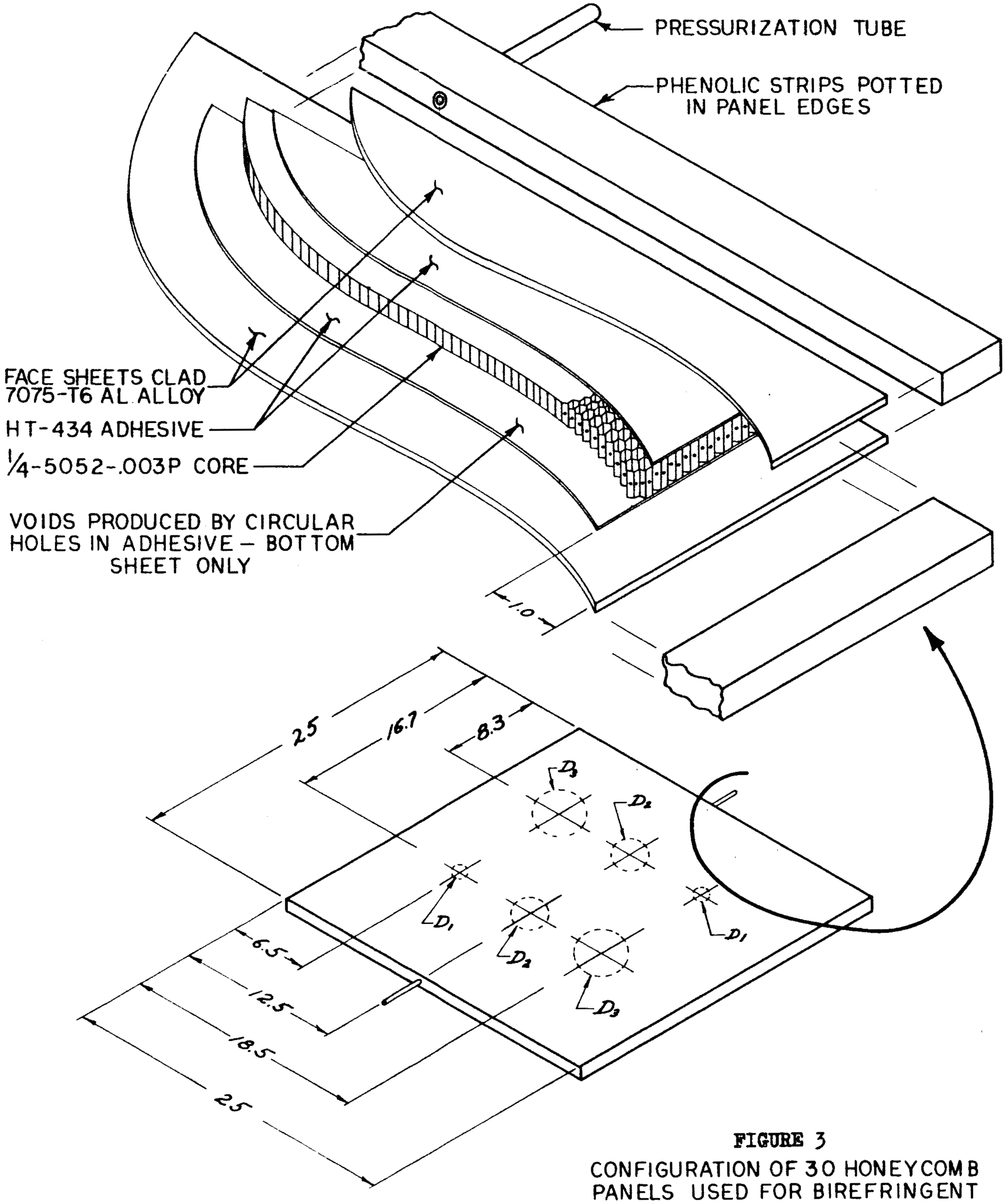


FIGURE 3

CONFIGURATION OF 30 HONEYCOMB PANELS USED FOR BIREFRINGENT COATING THICKNESS EVALUATIONS

FACE SHEET THICKNESS INCH →	0.016	0.032	0.050	0.063	0.080	0.100
VOID "D"	VOID DIAMETER-INCHES					
D_1	.50	.50	.50	1.0	1.0	1.0
D_2	1.0	1.0	1.0	2.0	2.0	2.0
D_3	2.0	2.0	2.0	3.0	3.0	3.0

Thirty of the honeycomb panels had circular bondline voids produced by cutting holes in the HT-424 adhesive. Comprising the thirty panels were five each of six different nominal face sheet thicknesses; 0.016, 0.032, 0.050, 0.063, 0.080 and 0.100 inch. Two rows of voids were cut in the adhesive for one face sheet of each panel. For the 0.016, 0.032 and 0.050 inch thick face sheets, each row had void diameters of 0.50, 1.0 and 2.0 inches. Each row for the thicker face sheets had void diameters of 1.0, 2.0 and 3.0 inches. Templates were utilized in locating and cutting voids in the adhesive in order to insure uniformity from panel to panel. Figure 3 defines the configurations of these thirty panels.

Six panels identical in configuration to those described above, except for voids, were fabricated. Three each of these six had nominal face sheet thicknesses of 0.032 and 0.063 inch. Each panel had two rows of three void implants and each void was centered as shown in Figure 3 for the thirty panels described above. One void in each row was produced by cutting a hole in the HT-424 adhesive, another was produced by placing a piece of 0.001 inch thick Teflon on the honeycomb core, and the third was produced by placing the Teflon between the adhesive and face sheet. One panel of each face sheet thickness had 0.5 inch diameter voids in one row and 1.0 inch diameter voids in the other. Another panel of each face sheet thickness had a row each of 2.0 and 3.0 inch diameter voids. Each of the remaining two panels had a row of rectangular voids 0.63 by 1.25 inches and a row 1.26 by 2.50 inches. The rectangular voids had an aspect ratio of two and areas approximately equal to the 1.0 and 2.0 inch diameter voids, respectively.

Another six panels, three each having nominal face sheet thicknesses of 0.032 and 0.063 inch, were fabricated to produce marginal bond line voids. It was desired that the voids in these panels be bonded, but the bonds have insufficient strength to sustain a relatively low pressure applied internally to the panels. Such a condition might not be detectable using conventional nondestructive test methods, but would be visible in the birefringent coating when the poor bond failed. Holes of the desired marginal bond size were cut in AF-111 adhesive and FM-1000 adhesive was placed in these holes. The panels were then bonded at 40 psi and 310°F in the Dake press. Prior to bonding, several small test specimens were prepared at different temperatures to determine the temperature at which the FM-1000 would become tacky and stick, but not flow and fillet around the cells of the core. A temperature of 310°F produced this desired condition for the small test specimens. Each of the six panels were prepared with two rows of three voids. Panels having a nominal face sheet thickness of 0.032 inch had 1.0 inch diameter voids in one row and 2.0 inch diameter in the other. The 0.063 inch thick face sheet panels had a row each of 2.0 and 3.0 inch diameter voids. Location of these voids within the panels was as previously described for other panels. After fabrication, the marginal bond voids were not detectable by the coin tap method, but were located and sized by ultrasonic inspection.

A face sheet splice having an external doubler was fabricated on one panel. The face sheets and doubler were nominally 0.032 inch thick and HT-424 adhesive was used. Four 2.0 inch diameter Teflon voids were manufactured in the face sheet bondline. Location of the voids was such that two were completely covered by both the face sheet and doubler. For the other two, the doubler edge passed diametrically over the void; consequently, half was covered by face sheet and half was covered by both face sheet and doubler. One void at each location was produced by placing Teflon on the core and one was produced by placing the Teflon on the face sheet. The face sheet, doubler and void locations for this panel are illustrated in Figure 4.

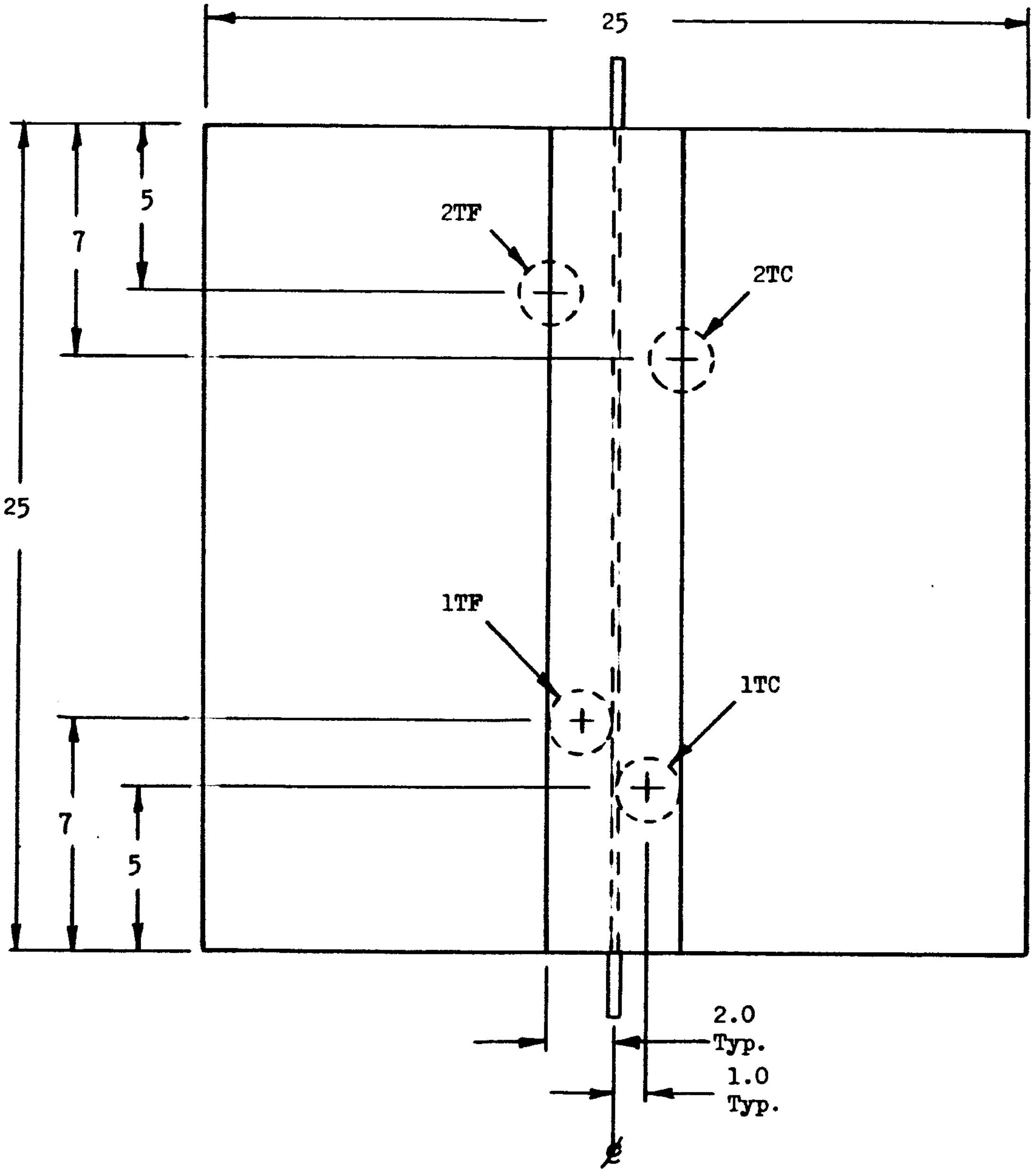


FIGURE 4: CONFIGURATION OF PANEL 32-D1 HAVING FACE SHEET SPLICE AND 2.0 INCH DIAMETER VOIDS

Four panels, two each having nominal face sheet thicknesses of 0.032 and 0.063 inch, each contained a core splice across the panel center. Core splices in one panel of each face sheet thickness were prepared using proper procedures to obtain a good splice. Two strips of 0.050 inch thick 3M-3002 adhesive were used in the splice, and the cells of the mating core panels were aligned and pressed firmly into the adhesive layers. Near one edge of the panel, a tube was inserted across the core splice to allow equal pressurization of the panel on each side of the core splice. HT-424 adhesive was used for the face sheets and bonding procedures were as previously described for other panels utilizing the HT-424. Splices in the remaining two panels were prepared in a similar manner except approximately one-half the splice length in each panel contained three strips of 0.007 inch thick FM-1000 adhesive. The splice length having FM-1000 was considered to produce a poor splice since the core gap was not filled with adhesive and the FM-1000 would flow to the core gap bottom at the bonding temperature.

The last three panels of the 50 had a nominal face sheet thickness of 0.032 inch and were fabricated using poor bonding practices. One panel, serialized 32-S1, utilized face sheets which had been cleaned 72 hours prior to bonding, and hand prints were made on the face sheets during assembly. Also, the core panel had an approximate two square inch area of crushed core tops. Face sheets for panel 32-S2 received a poor rinse after the acid bath, and an adhesive splice with a 0.25 inch gap was placed across the panel center. Panel 32-S3 also had a poor rinse after the acid bath, and the core panel was dirty. No precautions to prevent bond surface contamination were exercised during fabrication of the three panels.

After fabrication all panels except those containing marginal bond line voids were proof pressurized to the maximum pressures expected to be utilized during the void detection evaluations. Some leaks around the edge members were revealed and repaired during these pressure checks.

As previously mentioned, the thickness at each corner of the face sheets having bondline voids was measured and recorded. These measurements are recorded in Table II along with the panel serial numbers and type of void implants.

Spray Coating Honeycomb Test Panels - The honeycomb panels were sprayed in two groups, and the same coating formulation and spray procedures were used for both groups. Coating formulation and spray procedures were as defined in a previous section. The thirty panels having circular bond line voids produced by cutting holes in the HT-424 adhesive comprised the first group sprayed. As previously detailed, these thirty represented five panels each of six different face sheet thicknesses, and each panel contained two identical rows of voids. Each panel was divided into two equal areas, A and B, with each area containing a row of voids. This provided ten identical test areas for each face sheet thickness, and the birefringent coating thickness was varied approximately 0.010 inch from one area to another. Thus, ten different coating thicknesses covering an approximate range of 0.010 to 0.100 inch were provided for each of the six different face sheet thicknesses. As discussed later, evaluations of the first 30 panels provided information necessary to determine the coating thickness required to maximize void detectability for any particular face sheet thickness within the range investigated. The remaining panels, or second group, were spray coated to the optimal thickness determined for their respective face sheet thicknesses.

Immediately prior to spraying, each panel was placed in a fixture designed especially for measuring coating thickness. The fixture was comprised of two 27 by 27 by 0.5 inch thick aluminum alloy plates held parallel approximately one inch apart by spacers. The honeycomb panel to be measured was placed between the two parallel plates and pushed against reference or locator pins. The top plate had small holes which centered over the honeycomb panels at positions for which coating thickness measurements were desired. A dial indicator was then used to measure relative distance between the honeycomb panel surface and the top plate surface at each hole location. Locations of these holes with respect to the honeycomb panel voids are shown in Figure 5.

Reference measurements were made and recorded for each panel prior to spray coating. The panels were placed vertically in a forced air spray booth, and a wet coating thickness of 0.006 to 0.008 inch was applied. The panels were then placed horizontally and the coating allowed to cure approximately four hours at 80°F prior to application of a subsequent coat. This procedure was repeated until the desired coating thicknesses had been accumulated. A Nordson wet film gage was used to monitor wet film thickness, and the wet film history was recorded for each panel. The wet film history combined with the shrinkage allowance allowed prediction of cured coating thickness; however, precise thickness measurements were made using the previously described fixture and reference measurements. Each of the first group of panels sprayed required two different coating thicknesses as previously discussed. The entire face sheet was coated to the desired thinner coating thickness. One-half the area was then masked with polyethylene film, and spraying was continued on the other half. Tables III and IV contain coating thickness measurements for all panels.

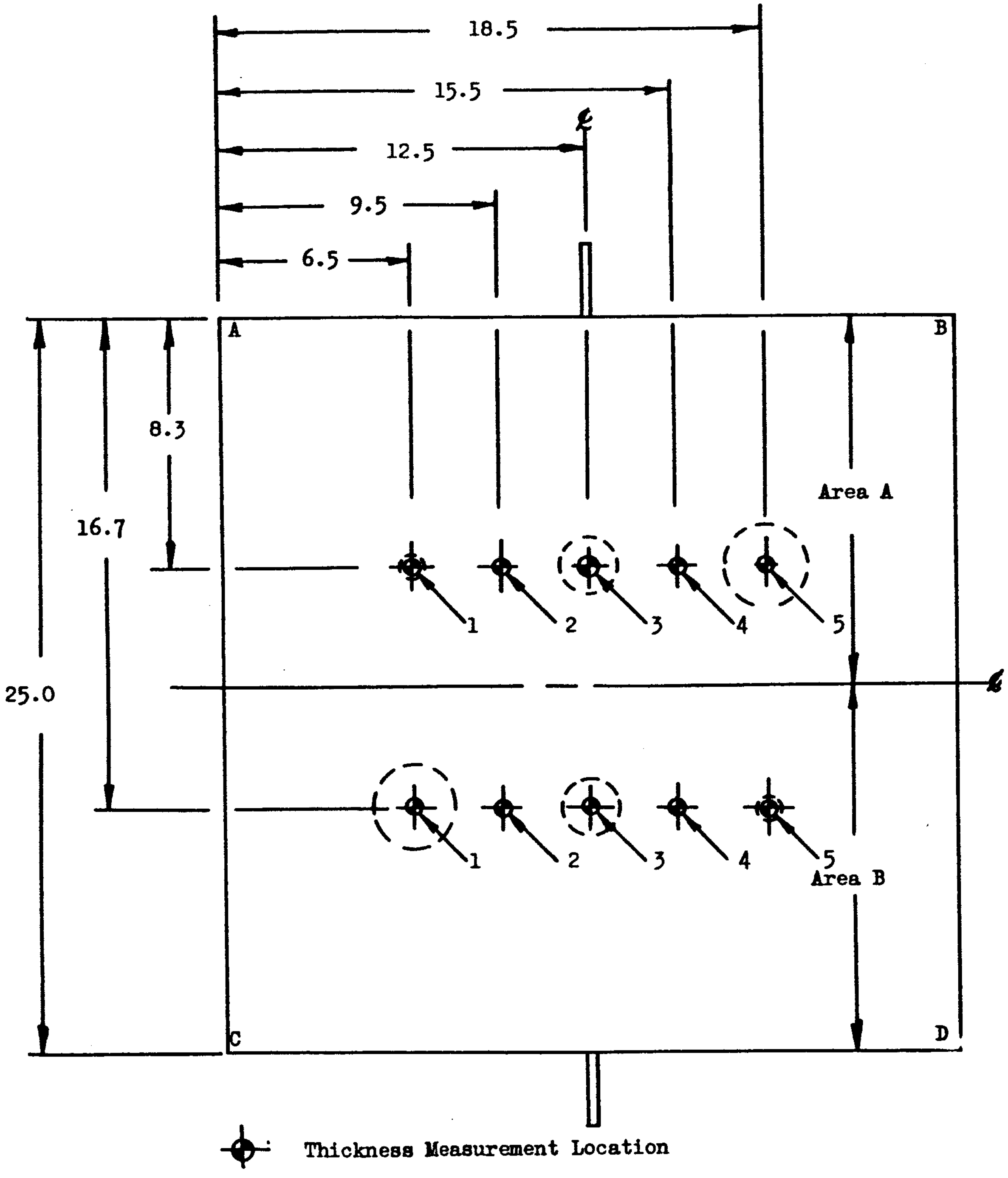


FIGURE 5: THICKNESS MEASUREMENT LOCATIONS FOR BIREFRINGENT COATINGS

Calibration beams were taped to an aluminum alloy sheet and were sprayed along with the honeycomb panels. Part of the beams were removed periodically in order to determine the strain-optic coefficient for different thicknesses of the same coating used on the panels. The last spray coat applied to the beams and panels was allowed to cure a minimum of 24 hours at 80°F before calibration or void detection evaluations were initiated.

Void Detection Evaluations - The void detection evaluations were performed by observing the birefringent coating through a Photolastic, Model 030, universal reflective polariscope while the honeycomb panel was pressurized internally with air. One of the tubes potted in the test panel edge members was connected to an air pressure gage. The other tube also had a pressure gage and was connected to the air supply through a pressure regulating valve. The polariscope was located approximately five feet in front of the panel, and the pressure regulator location was such that the operator could observe the birefringence while making changes in pressure. The photograph in Figure 6 shows this arrangement. Except for the polariscope light source, the room was in total darkness while making void detection measurements.

Prior to performing the evaluations, several methods of light conditioning and observation were investigated to determine their merit with respect to sensitivity of void detection. A sheet of circular polarizer was placed on the birefringent coating surface and observed while illuminated by a polychromatic light source. This method was found to be approximately equivalent to observations through the reflective polariscope with a circularly polarized field at normal incidence. Observations were also made by illuminating the panel surface with polarized light at various angles of incidence while observing the birefringence through a polarizer at the angle of reflection. Such observations at 45° angles made the voids detectable at pressure slightly lower than when using the

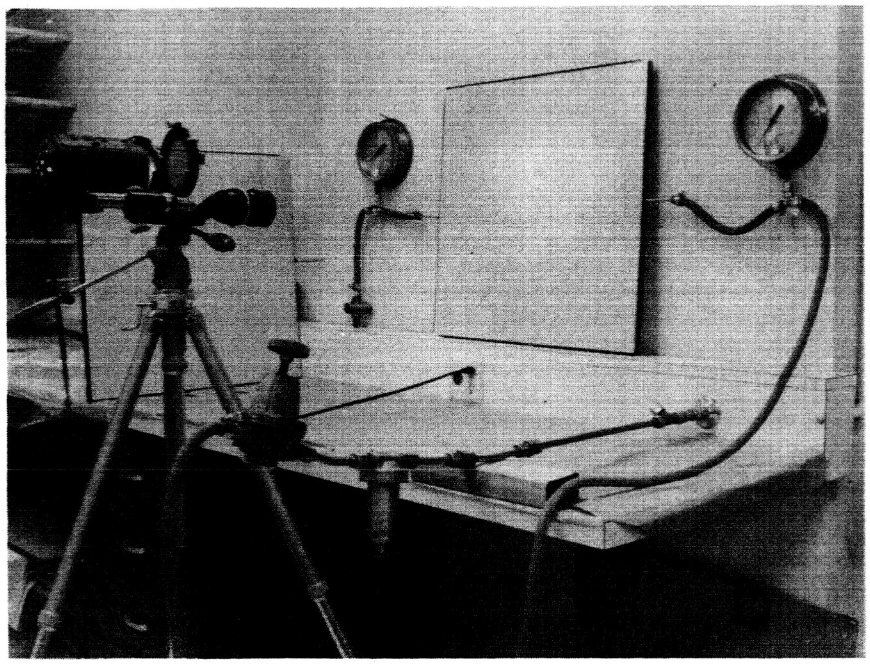


FIGURE 6: ARRANGEMENT USED FOR VOID DETECTION EVALUATIONS

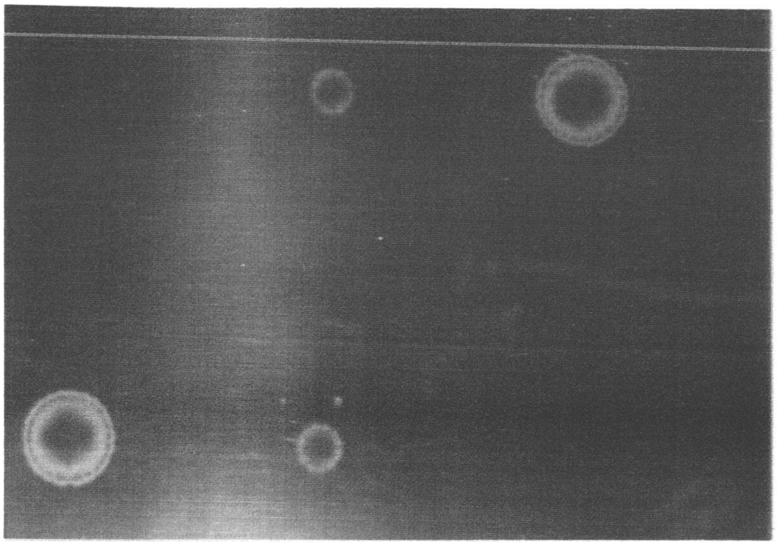
circular field at normal incidence. Greater angles produced scattering of the reflected light and poor definition of the birefringent pattern. Increased sensitivity for oblique incidence observations was expected since the light path through the coating was increased and, consequently, accumulated greater relative retardation as is shown by increasing t_c in equation (1). It should be pointed out, however, that equation (1) does not hold for stress determinations at incidence angles other than normal. The most sensitive method found utilized the reflective polariscope without quarter wave plates. The coating was illuminated at normal incidence with plane polarized light, and observations were made while rotating the analyzer or observing polarizer back and forth through an angle of 90°. This produced a mixed field of quasi-isoclinics and quasi-isochromatics that was in motion during analyzer rotation.

Upon completion of the light conditioning and observation studies, it was concluded that more uniform and reproducible results would be obtained by utilizing the reflective polariscope at normal incidence. Three different detection pressures were measured and recorded for each void in each honeycomb test panel where detection was possible within the limiting maximum pressures utilized. In most cases the fringe order at maximum pressure was also measured and recorded. One detection pressure was measured using the analyzer rotation method, and the other two were made using the circular field polariscope. One pressure, recorded when viewing the circular field, was that required to detect the void by close observation. The other pressure was that required to produce good contrast with the surrounding field which made the void easily detectable without close observation. In making these measurements, the panel pressure was slowly increased while observing the birefringent coating through the polariscope. Once void detection was accomplished for the particular condition, both pressure gages were observed to verify pressure uniformity prior to recording data. A limiting pressure of 40 psig was utilized for all honeycomb panels except those having nominal face sheet thicknesses of 0.016 and 0.032 inch. Pressures for these were limited to 20 and 30 psig, respectively.

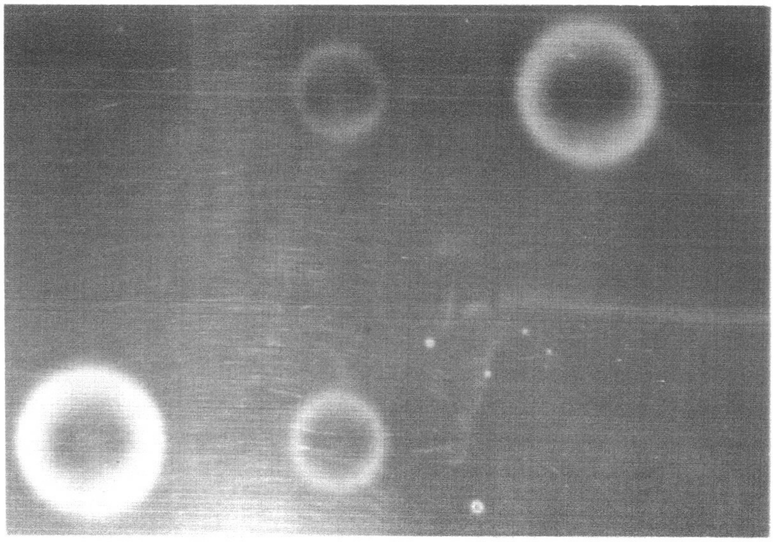
Color photographs were made of the birefringence for several of the panels during void detection evaluations. The photographs were made by placing a circular polarizer on the coating surface and illuminating with a 300-watt, 3200 K tungsten light source. Both the light source and camera were at near normal incidence to the panel. High speed Ektachrome Type B film was used. The photographic method, however, was less sensitive to void detection than the circular polariscope.

Results - Results of void detection evaluations for the 30 honeycomb sandwich panels having circular bondline voids are contained in Tables V through X. Coating thickness in these tables are average values obtained from Table III, and face sheet thicknesses are average values from Table II. The photographs in Figure 7 show the birefringence obtained at maximum pressures for panels having nominal face sheet thicknesses of 0.016 and 0.100 inch. Close observation of these photographs reveals six voids in each panel. Figure 8 shows photographs of the 0.016 inch thick face sheet panel at lower pressures.

As previously discussed, the remaining 20 panels had nominal face sheet thicknesses of either 0.032 or 0.063 inch. The coating thicknesses applied to these were approximately 0.030 and 0.060 inch, respectively, since the data in Tables VI and VIII showed that little sensitivity to void detection was gained for thicker coatings. Results for the six panels having voids produced by Teflon and adhesive cuts are in Tables XI and XII. Coating and face sheet thicknesses shown are average values from Tables II and IV. Figure 9 shows the birefringence produced at two different pressures for 2.0 and 3.0 inch diameter voids beneath the nominal 0.063 inch thick face sheet. Similar photographs for the nominal 0.032 inch thick face sheet panel are shown in Figure 10. The rectangular voids and smaller circular voids for the 0.032 inch thick face sheet are shown in Figure 11.

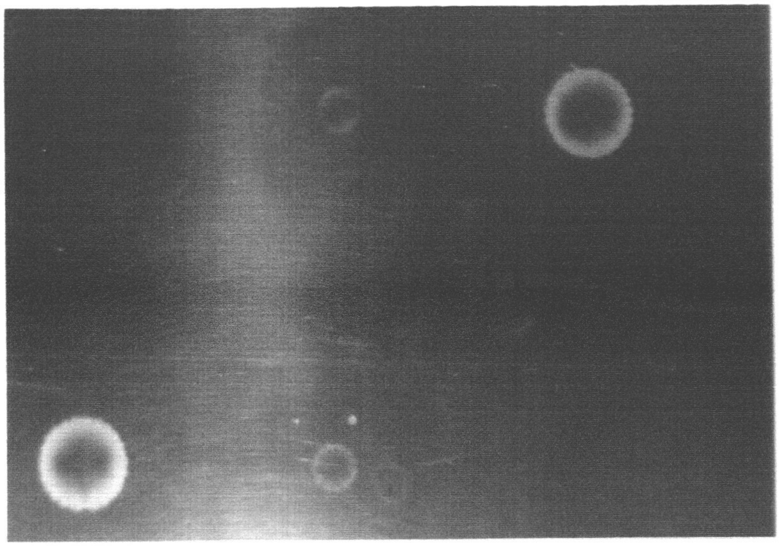


(a) Panel 16-2 Containing 0.5, 1.0 and 2.0 Inch Diameter Voids. Coating Thickness, Top = 0.029 Inch, Bottom = 0.039 Inch. Pressure = 20 psig.

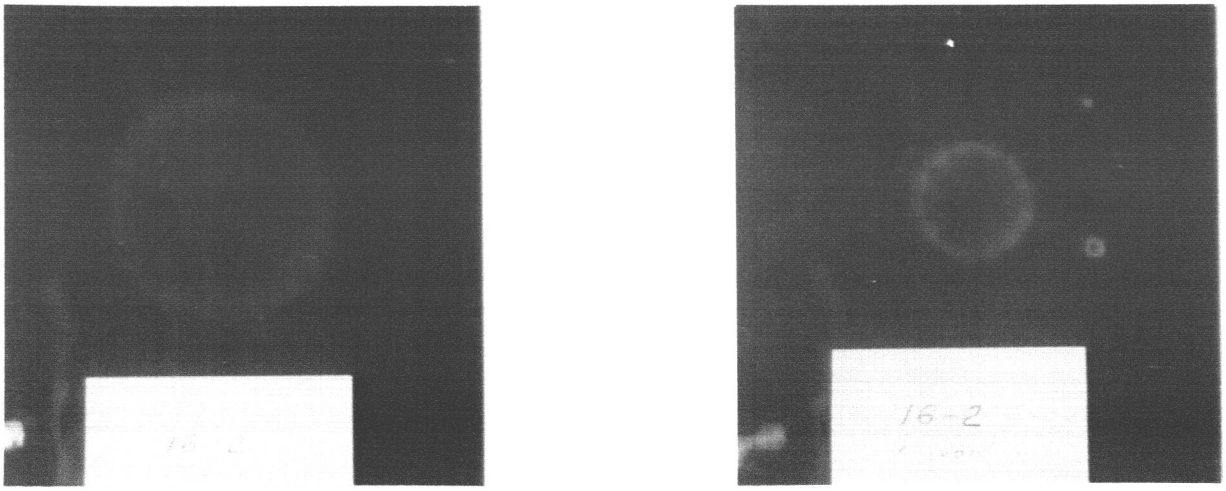


(b) Panel 100-4 Containing 1.0, 2.0 and 3.0 Inch Diameter Voids. Coating Thickness, Top = 0.068 Inch, Bottom = 0.077 Inch. Pressure = 40 psig.

FIGURE 7: PHOTOGRAPHS SHOWING BIREFRINGENCE OBTAINED FOR PANELS 16-2 AND 100-4 AT MAXIMUM PRESSURES



(a) Panel 16-2 Containing 0.5, 1.0 and 2.0 Inch Diameter Voids.
Coating Thickness, Top = 0.029 Inch, Bottom = 0.039 Inch.
Pressure = 12 psig.



(b) Panel 16-2, 2.0 Inch Diameter Void, Coating Thickness = 0.029 Inch. Pressure = 2 psig.

(c) Panel 16-2, 1.0 Inch Diameter Void, Coating Thickness = 0.029 Inch. Pressure = 4 psig.

FIGURE 8: BIREFRINGENCE OBTAINED FOR PANEL 16-2 AT DIFFERENT PRESSURES

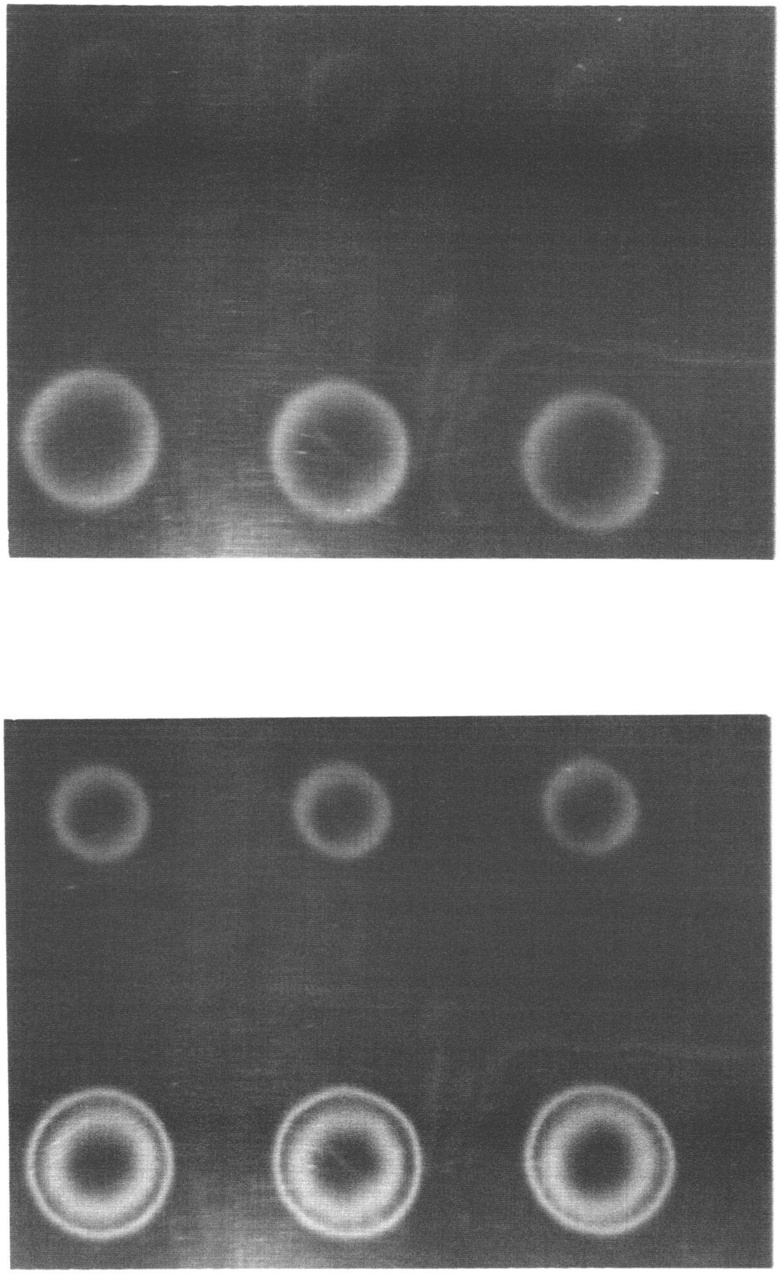


FIGURE 9: BIREFRINGENCE OBTAINED FOR 2.0 AND 3.0 INCH DIAMETER VOIDS IN PANEL 63-T2, TOP AT 10 PSIG, BOTTOM AT 40 PSIG, COATING THICKNESS = 0.063 INCH, VOID TYPES FROM LEFT TO RIGHT: TEFLON ON FACE SHEET, ADHESIVE CUT, TEFLON ON CORE

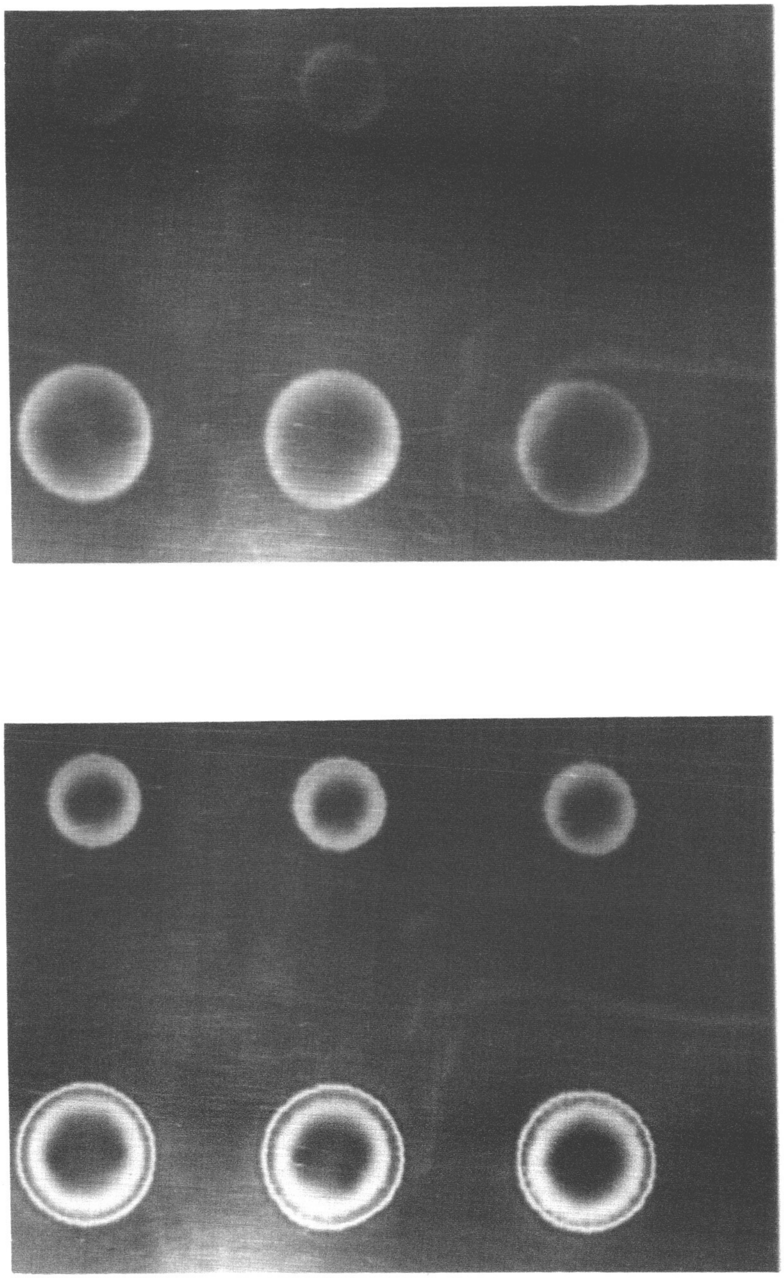
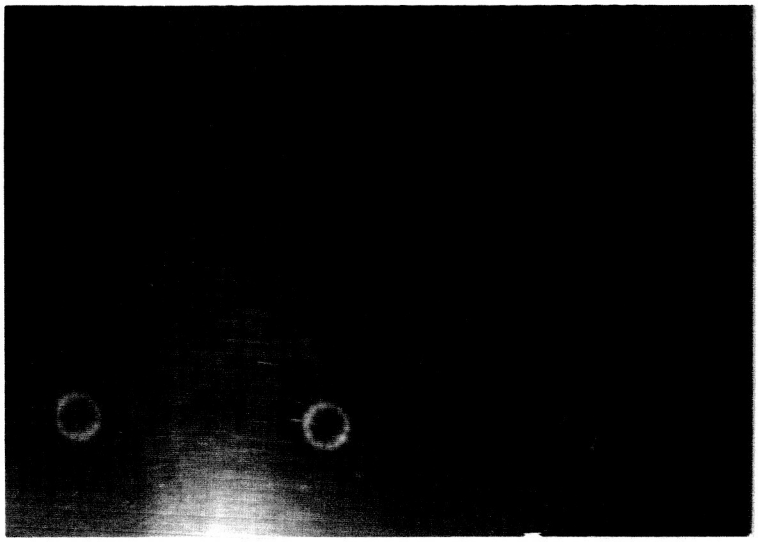
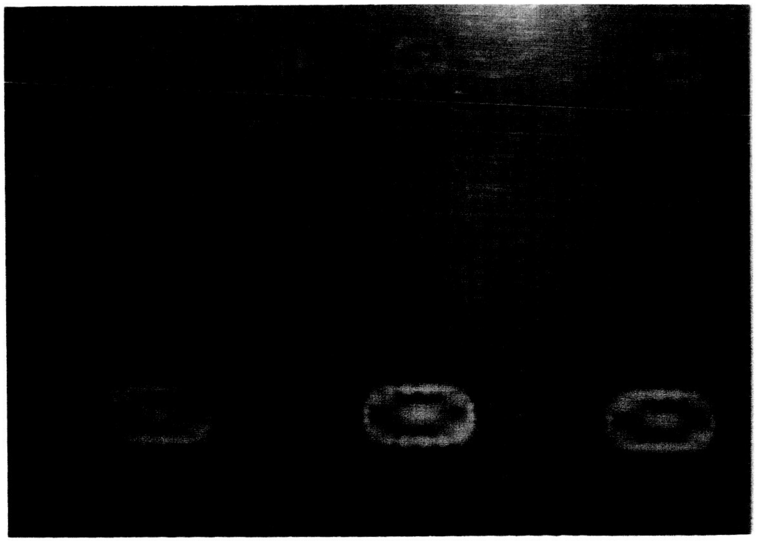


FIGURE 10: BIREFRINGENCE OBTAINED FOR 2.0 AND 3.0 INCH DIAMETER VOIDS IN PANEL 32-T2, TOP AT 4 PSIG, BOTTOM AT 30 PSIG, COATING THICKNESS = 0.035 INCH, VOID TYPES FROM LEFT TO RIGHT: TEFLON ON FACE SHEET, ADHESIVE CUT, TEFLON ON CORE



(a) 0.5 and 1.0 Inch Diameter Voids (0.5 Dia. Voids are Barely Visible), Coating Thickness = 0.033 Inch.



(b) 0.63 by 1.25 Inch and 1.26 by 2.50 Inch Rectangular Voids, Coating Thickness = 0.036 Inch

FIGURE 11: BIREFRINGENCE OBTAINED FOR PANELS 32-T1 AND 32-T3 AT 30 PSIG, VOID TYPES FROM LEFT TO RIGHT: TEFLON ON FACE SHEET, ADHESIVE CUT, TEFLON ON CORE

Two each of the marginal bond panels having nominal face sheet thicknesses of 0.063 and 0.032 inch were spray coated. These were evaluated to maximum pressures of 40 and 30 psig, respectively, and the voids were not detectable using the most sensitive method of observation. The remaining two panels were not coated since preparation procedures were identical for the six panels and the same results were expected. Even though the test specimens evaluated prior to fabricating the marginal bond panels produced a poor bond, the bonds had sufficient strength to sustain the limiting pressures without failure.

Results obtained for panel 32-D1 having the face sheet skin splice are in Table XIII.

The core splices were detectable; however, little difference in birefringent pattern was observed between the properly and improperly prepared splices. The properly prepared splice in panel 32-C1 was detectable at a pressure of 20 psig, and the tube inserted across the splice was detectable at 10 psig. A pressure of 40 psig was required to detect the properly prepared splice in panel 63-C1. The improperly prepared length of splice in panel 32-C2 was detected at 8 psig, and 30 psig was required to detect the improper splice in panel 63-C2.

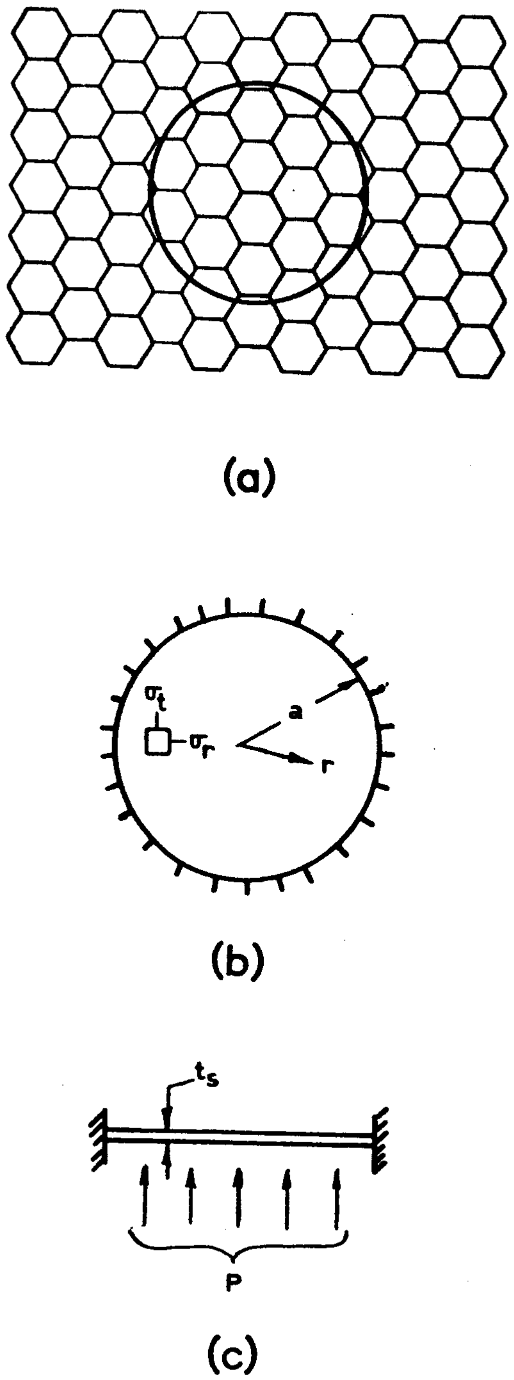
No voids were evident for the three panels prepared using poor shop practice when observed using the most sensitive method at the maximum pressure of 30 psig.

Table XIV contains strain-optic coefficients determined from calibration beams which were sprayed along with the honeycomb panels.

Analysis - The optimal coating thickness for a particular face sheet thickness can easily be determined from Tables V through X by selecting the thickness corresponding to minimum detection pressure. It would be desirable to predict the optimal coating thickness using coating and face sheet properties rather than perform such an extensive evaluation on each promising coating material that might become available in the future. For this reason an analysis was made to compare theoretical fringe order with the experimentally measured fringe orders recorded in Tables V through X for a 2.0 inch diameter void.

For this analysis an unbonded circular element of a face sheet as illustrated in Figure 12a was assumed. The element was assumed to be of constant thickness with fixed boundaries as shown in Figures 12b and 12c. When pressure is applied to one side of the element it acts as a plate in bending and the resulting stress distribution for this geometry is defined by equations (5) and (6) in Figure 12. The equations derived from Reference 7 define the stresses acting along and normal to any radial line, and for this case are the principal stresses. Figure 13 shows a general solution of these equations as well as a solution for the principal stress difference. Since birefringent coatings allow direct observation of principal stress difference, this difference solution will be of primary interest. Observation of this curve shows that no relative retardation will occur at the center of the plate, consequently the birefringent coating will always show a black spot in this area so long as the element remains elastic. Isochromatics or the locus of points having equal relative retardation will form concentric circles around the black spot and will reach a maximum at the fixed boundary. This condition is generally verified by actual birefringence observed and shown in Figures 7 through 11.

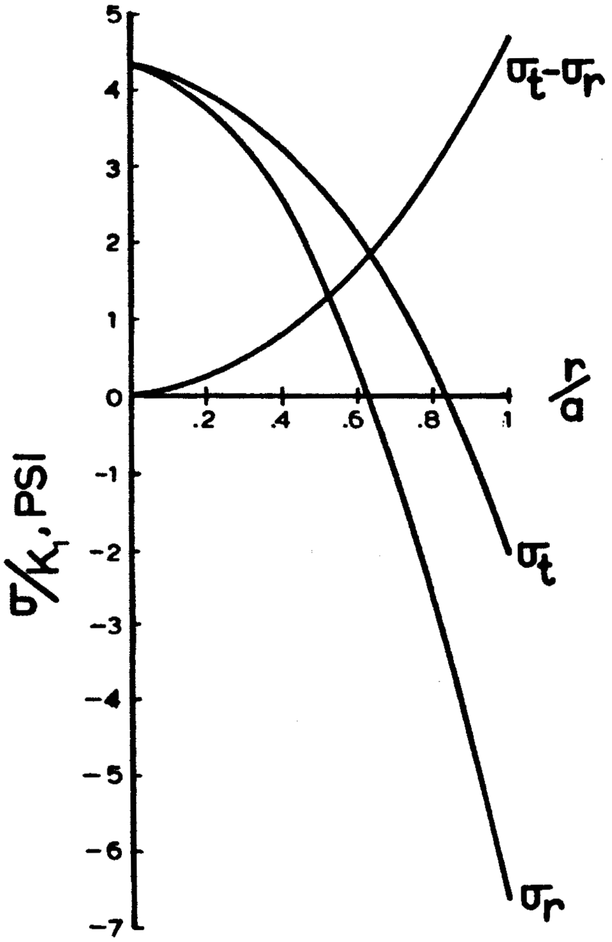
Theoretical fringe orders were determined for a 2.0 inch diameter void at the maximum pressures utilized in the experimental program for each of the six different face sheet thicknesses. Fringe orders were computed by combining equations (1), (5) and (6) and solving using several values of coating thickness for each of the six face sheet thicknesses. Bending correction factors were determined from Figure 1, and a strain-optic coefficient of 0.08 was used. These analytical results are shown in Figures 14 and 15 as curves of fringe order versus coating thickness for



$$\sigma_t = \frac{3Pma^2}{8t_s^2}\left[\left(\frac{1}{m}+3\right)\frac{r^2}{a^2} - \left(\frac{1}{m}+1\right)\right] \qquad (5)$$

$$\sigma_r = \frac{3Pma^2}{8t_s^2}\left[\left(\frac{3}{m}+1\right)\frac{r^2}{a^2} - \left(\frac{1}{m}+1\right)\right] \qquad (6)$$

FIGURE 12: ASSUMED CIRCULAR BOND VOID AND STRESS RELATIONS FOR PRESSURE LOADING



$$K_1 = \frac{3P\mu a^2}{8t^2}$$

FIGURE 13: GENERAL STRESS DISTRIBUTION SOLUTION FOR THE CIRCULAR ELEMENT IN FIGURE 12

the different face sheet thicknesses. Also shown in these figures are the experimental fringe orders from Tables V through X for the 2.0 inch diameter voids.

Good correlation was obtained for all face sheet thicknesses except the 0.014 shown in Figure 14. The poor correlation was attributed to combined bending and membrane action of the thin skin rather than just bending as assumed for the analytical curve. Data scatter in Figure 15 was attributed to small variations in coating thickness and strain-optic coefficient. Also, the bending correction utilized a coating modulus of 450,000 psi. Measurements of coating modulus for tensile loading were made using material removed from a sprayed panel. The modulus was found to be 400,000 psi. This lower modulus would shift the analytical curves up and provide better correlation for the thicker face sheets.

The correlation obtained shows that relative merit of other coatings can be assessed by analytical means providing modulus of elasticity and Poisson's ratio are known for the coating and substrate as well as strain-optic coefficient for the coating.

Coating Removal - Although general birefringent coating work normally does not require coating removal, such coatings for utilization in nondestructive testing must be removable without damaging the structure or substrate. Generally, epoxies are not attractive in light of this requirement since they are good adhesives. This is verified by the epoxy removal evaluations reported in Reference 8 which showed only limited success.

The initial removal evaluations involved application of a water soluble prime coat of polyvinyl acetate. After drying, several coats of epoxy were applied and allowed to cure. The coated sheet was then soaked in water; however, removal of the coating was not accomplished since the water was unable to penetrate and dissolve the coating-substrate interface by capillary action.

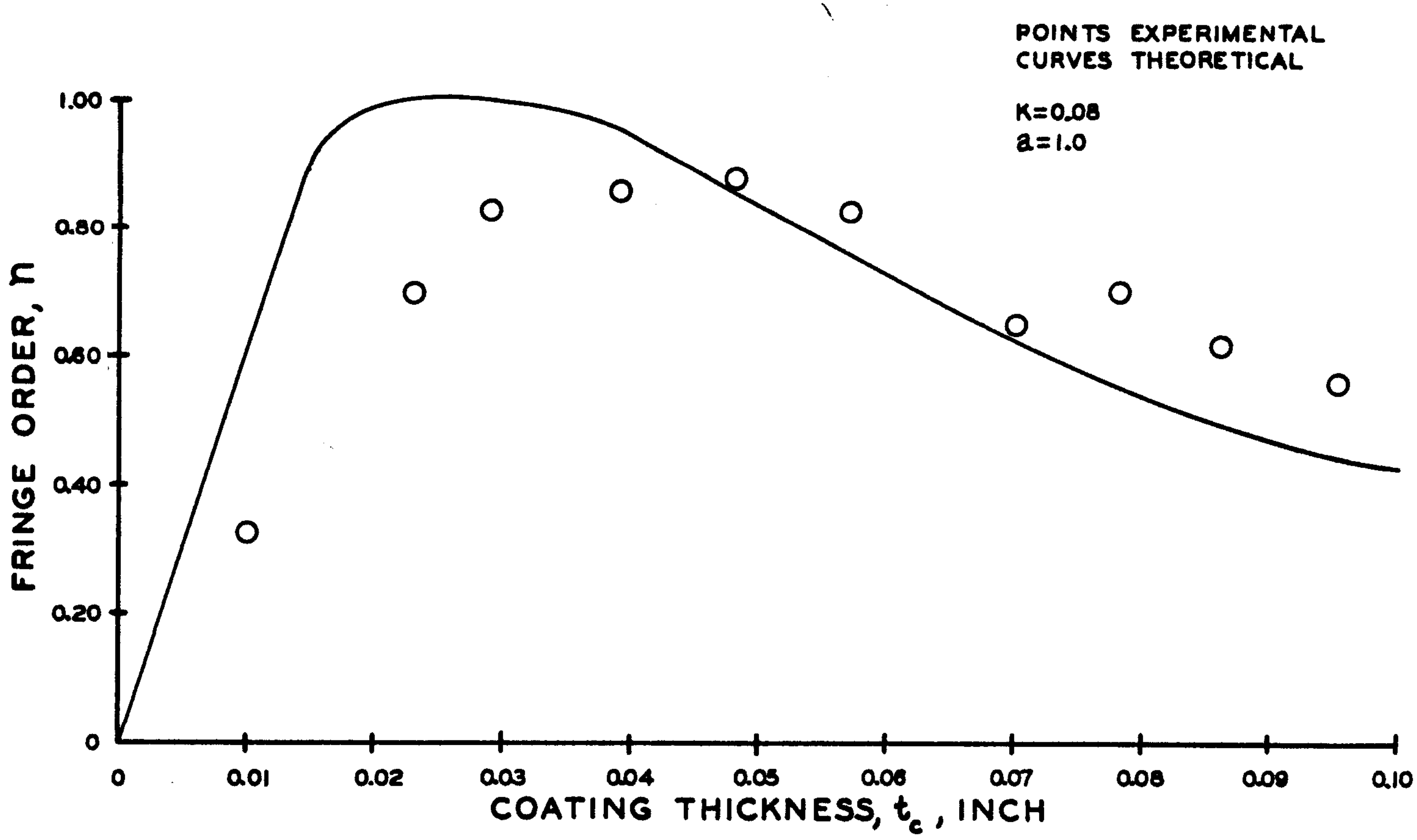


FIGURE 14: CORRELATION OF EXPERIMENTAL AND THEORETICAL FRINGE ORDER FOR BIREFRINGENT COATINGS ON 0.014 INCH THICK ALUMINUM ALLOY SHEET AT A PRESSURE OF 20 PSIG

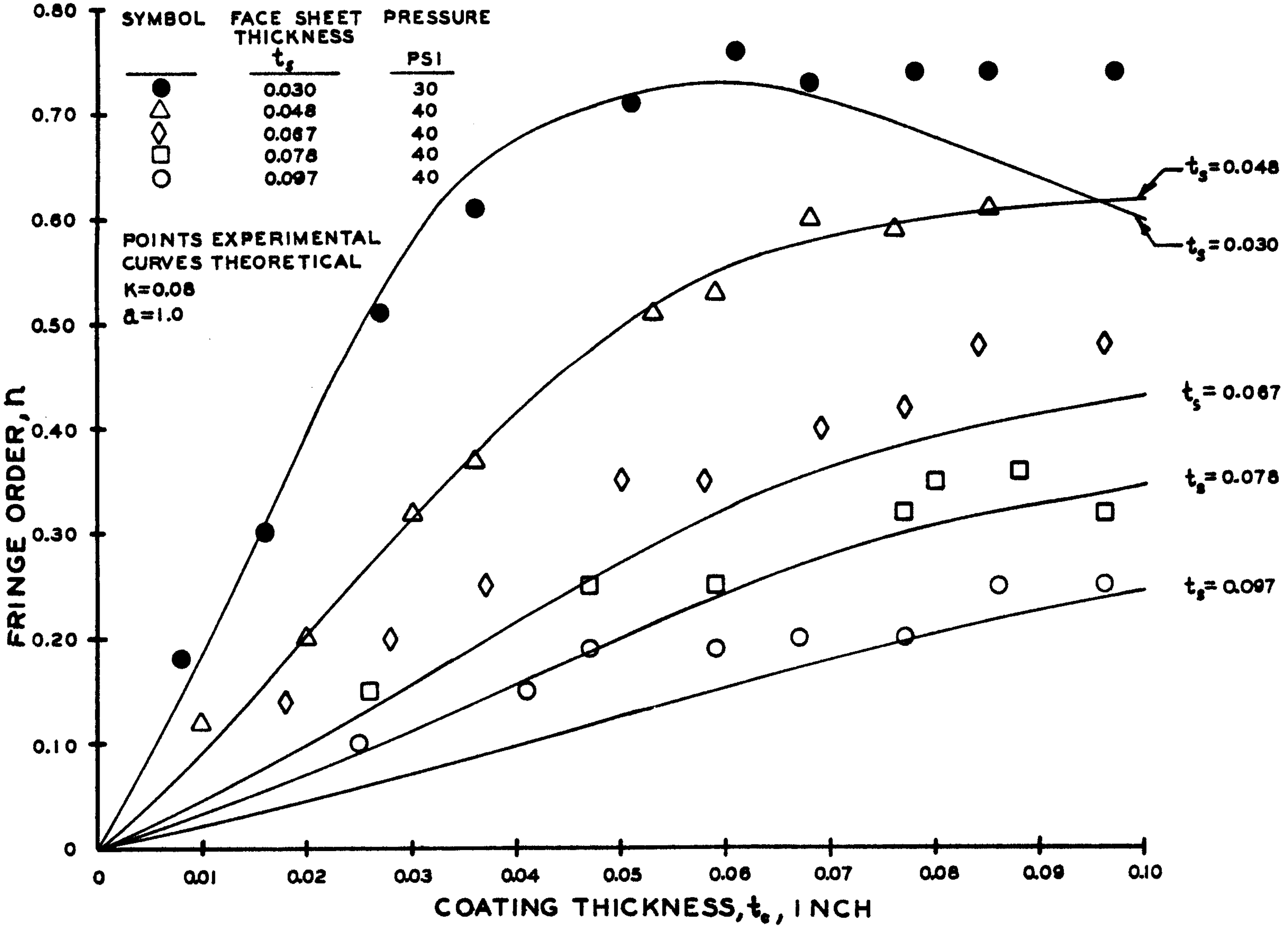


FIGURE 15: CORRELATION OF EXPERIMENTAL AND THEORETICAL FRINGE ORDER FOR BIREFRINGENT COATINGS ON FIVE DIFFERENT THICKNESSES OF ALUMINUM ALLOY SHEET

Low temperature thermal shock was found to be effective in cracking the coating and destroying the bond. The coating was initially cracked by continuously applying liquid carbon dioxide to a local area for approximately one minute. Once the coating ruptured in this local area, the cracks were propagated by applying the cold fluid to the surrounding area until the entire coated area was crazed or cracked in a mosaic pattern as shown in Figure 16. The bond was completely destroyed for many of the pieces while a prying action by a thin spatula was required for others. Response of the thick coatings to thermal shock was better than for thin ones.

Aluminized Mylar film having pressure sensitive adhesive on the aluminized side was evaluated on a small aluminum alloy sheet panel. The film was applied to provide a peelable interface, and after application was sprayed with epoxy. Although a peelable interface was provided, the epoxy Mylar bond was insufficient to provide adequate strain transfer from the aluminum to epoxy.

A commercial stripper, 1717 AMX manufactured by B and B Chemical Company, was applied to the center of a panel having a 0.100 inch thick coating. After approximately one hour, the coating had been softened and partially dissolved. The panel was then cleaned and another stripper coat applied. Three such applications were required before the epoxy was removed from the aluminum; however, only one stripper application was required for thin coats. Although removal was accomplished, a thorough cleaning was required to remove all residue from the panels. The aggressiveness of this acid type stripper could adversely affect bonded joints, consequently, entrapment of the stripper in joints should be avoided.

Another commercial stripper, Sprazee, was evaluated and found to produce more desirable results. A generous coat of Sprazee was found to swell the coating and destroy the bond after approximately 24 hours. Associated with the swelling, was increased toughness which allowed the coating to

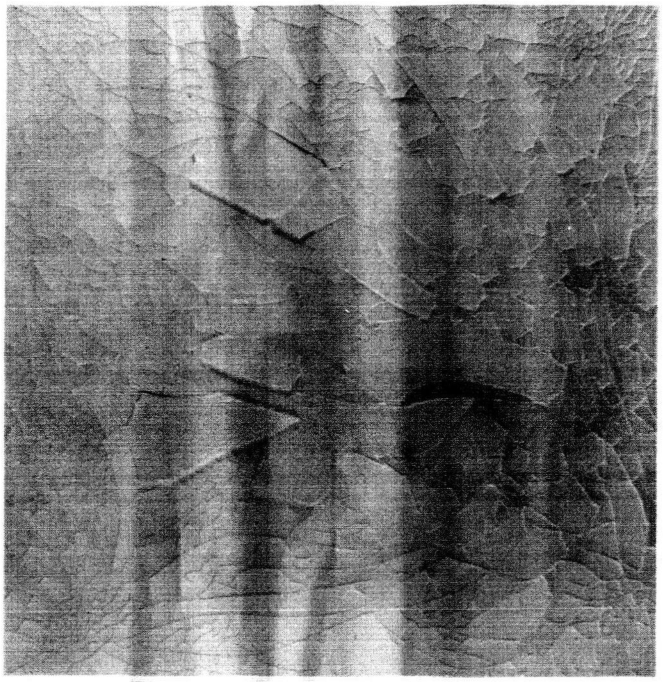


FIGURE 16: CRACKS IN EPOXY COATING AFTER LOW TEMPERATURE THERMAL SHOCK

be peeled away in large pieces. The aluminum panel was relatively free of residue and required only a solvent clean. Heavy coats of the stripper were required since light coats dried and became ineffective prior to swelling the epoxy. Sprazee is a produce of Wyandotte Chemical Corporation.

Heating the coating was also found to impart toughness and allow peeling. Temperatures in the 160°F to 180°F range were required and were applied by a heat gun while the bondline was pryed with a spatula.

Of the removal methods evaluated, a combination of Sprazee and heat is recommended. Apply generous coat of Sprazee to the epoxy, and leave an uncoated strip approximately four inches wide along bonded joints. Keep the coated area moist with stripper until the epoxy swells, blisters and finally ruptures in areas. Remove the affected epoxy and solvent clean the substrate. During removal, leave some unbonded epoxy coating along edges of the four inch wide strips covering bonded joints. Then remove the remaining strips by applying a peeling or prying force to their edges while applying heat with a heat gun. The temperature required for such a short time is not considered to adversely affect the aluminum alloys and conventional adhesives. In the event other type face sheets and special adhesives are employed, the temperature effect should be considered.

V - POLYURETHANE COATING EVALUATION

A preliminary evaluation of polyurethanes was performed to determine their suitability as birefringent coatings for possible use on honeycomb having non-metallic face sheets. Polyurethanes have a relatively low modulus of elasticity, which is required to minimize reinforcement of low modulus face sheet materials. Also, polyurethanes generally are not good adhesives which is a favorable property for easy removal.

The materials evaluated were single component moisture curing polyurethanes manufactured by Spencer Kellogg. Three different materials were evaluated and were designated by the manufacturer as 1491, M80-50CX and M86-50CX. Spray evaluations were initially performed using the materials as supplied which were approximately 50 percent solids. Even in thin coats, objectionable bubbles formed during curing, and curing was very slow for the 1491 and M80-50CX. The cured films were quite tough and were easily peeled from the aluminum surface. Further spray evaluations revealed that an addition of 20 percent by weight xylene allowed wet coats approximately 0.006 inch thick to be applied and cured without formation of objectionable bubbles. However, this film thickness was not applicable to a vertical surface, and a shrinkage of approximately 50 percent occurred during cure.

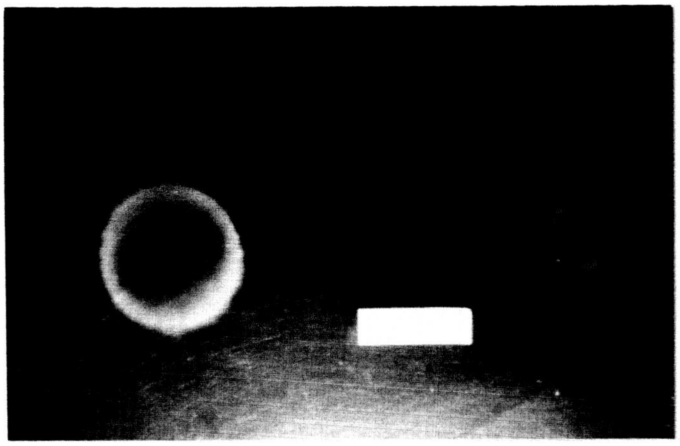
Calibration beams were sprayed with the three polyurethanes containing xylene. Several hours were required for the 1491 and M80-50CX to cure to a tack-free condition and support an additional spray coat. The M86-50CX, however, cured to a tack-free condition in approximately one hour. This short cure time allowed a reasonable film thickness of M86 to be accumulated in a relatively short time. After a dry film thickness of approximately 0.030 inch had been applied, the beams were loaded in the same manner as previously described for calibrations of the epoxy coating. No measurable birefringence was immediately observed for the 1491 and M80; however, birefringence was observed for the M86. Calibration checks were made periodically for several days.

Little change was observed in the M86 after the last coat cured approximately 24 hours, and the manufacturer's literature shows the coating to fully cure in 24 hours as determined by hardness. Strain-optic coefficient was estimated to be approximately 0.04, however, an accurate value could not be computed since Poisson's ratio and modulus of elasticity were not measured or reported by the manufacturer. Approximately seven days were required for the M80 and 1491 to exhibit birefringence approaching that of the M86.

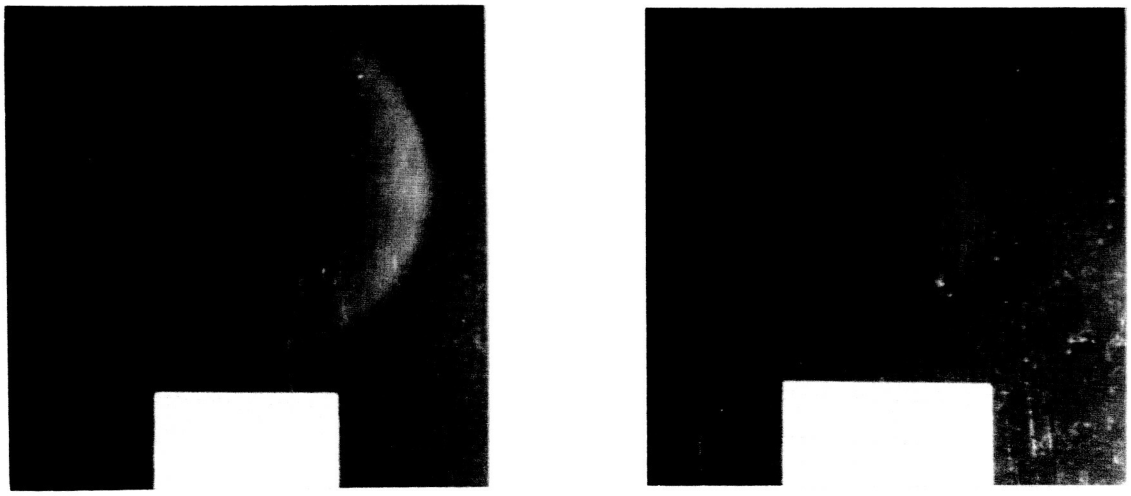
The coatings were easily stripped in one piece from the calibration beams, however, their bond to the aluminum surface remained intact during the calibration loadings. The ease of coating removal indicated low peel and shear strength, but little shear strength was required to transfer strain because of the low modulus.

After these evaluations, the epoxy coatings were stripped from one-half of each of three honeycomb panels having 0.016 inch thick face sheets. The areas stripped each contained a row of 0.5, 1.0 and 2.0 inch diameter voids produced by cutting holes in the HT-424 adhesive. The face sheets were solvent cleaned, and each panel was spray coated with a different polyurethane. Wet film thicknesses of approximately 0.006 inch were applied and allowed to cure at 70°F and 30 percent relative humidity. Spray procedures and equipment utilized were practically the same utilized for the epoxy system. Void detection evaluations were then performed on these panels in the same manner as previously described for the epoxy coating.

Results of these evaluations are contained in Table XV, and photographs of the birefringence observed for the M86-50CX are shown in Figure 17. These photographs are comparable to those shown in Figure 8 for the epoxy coating.



(a) 1.0 and 2.0 Inch Diameter Voids, Pressure = 12 psig.



(b) 2.0 Inch Diameter Void,
Pressure = 2 psig.

(c) 1.0 Inch Diameter Void,
Pressure = 4 psig.

FIGURE 17: BIREFRINGENCE OBTAINED FOR HONEYCOMB PANEL HAVING 0.014 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEET COATED WITH 0.031 INCH THICK M86-50CX POLYURETHANE.

VI - CONCLUSIONS AND RECOMMENDATIONS

Results obtained for the epoxy spray system generally satisfied the somewhat idealized requirements specified in Section III. Some compromises were made in that solvent additions were necessary, and the desired ease of removal was not achieved. Even with solvent additions, the system has approximately 70 percent solid content, and the cured coating can be removed by combining chemical strippers and thermal exposure. The coating modulus and required removal method somewhat limit the epoxy system to structures having metallic face sheets.

As to void detection, excellent results were obtained in that 0.5 inch diameter voids were detectable at pressures not exceeding seven psig for face sheet thicknesses up to 0.050 inch. This also was the maximum pressure required to detect 1.0 inch diameter voids for face sheet thicknesses in the 0.050 to 0.100 inch range. Of course much lower pressures were required to detect voids of larger diameters. Little difference in detectability was observed between face sheet bond voids and core bond voids.

The pot life and cure time achieved were well suited for large area coverage; however, further modifications could possibly decrease the cure time and allow more rapid coating of small structures. The coating system also offers much promise as a method of determining general stress distributions on structures having simulated service loads applied.

Results of the preliminary evaluation on M86-50CX polyurethane were very encouraging. The fast cure time and ease of removal are very attractive properties, and sensitivity to void detection was good as shown by comparing results in Tables V and XV and the photographs in Figures 8 and 17. The only undesirable property was the low solid content which resulted in high shrinkage during cure. The polyurethane offers promise of being a universal material usable on both metallic and non-metallic face sheets. Even though the strain-optic coefficient is low, this does not directly reflect the loss in sensitivity to void detection where the pressure loading produces a bending condition. By analyzing equation (3), it is shown that sensitivity is also a function of modulus of elasticity, consequently, the low strain-optic coefficient is greatly compensated by a low modulus of elasticity.

This preliminary program shows that additional evaluations of the polyurethanes are warranted. Specifically, these evaluations should be directed toward increasing solid content for spraying, evaluating thixotroping agents to increase film thickness sprayable on a vertical surface, and measurement of cured film properties. Also, pigmenting the polyurethane with a reflective material should be evaluated to allow evaluations to be made on face sheets having non-reflective surfaces. The pigmented material would be used as a reflective prime coat. Evaluations to relate coating thickness to face sheet thickness and modulus of elasticity would also be desirable.

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TABLE I

SCREENING PROGRAM FORMULATIONS AND RESULTS

COATING SYSTEM NUMBER / COATING (5) SYSTEM COMPONENTS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	17	17	17	18	18	19	20	21	22	23	24	24	25	25	26	27	28	29	30	31	31
RESINS																																						
EPON 828	100	100	100	100	100	100	100	100	100	100	100	100	90	90	93	100	100	100	100	100			100	100		100		100	100	100	100	100	100	100	100	100	100	100
EPON 812													10																									
CARDOLITE NC-513														10																								
BUTYL GLYCIDYL ETHER															7																							
CIBA 6020																					100	100			100		100											
ACCELERATORS																																						
TRI CRESYL PHOSPHATE				15	25			15															15												10	10	5	5
PHENOL						5	10		5															5														
SUB-TOTAL (1) TOTAL PARTS RESIN AND ACCELERATOR	100	100	100	115	125	105	110	115	105	100	100	100	100	100	100	100	100	100	100	100	100	100	115	105	100	100	100	100	100	100	100	100	100	100	110	110	105	105
CURING AGENTS																																						
EPON H-1	28	20	36	28	20.5	28	28	20.5	20.5	24	20.5	20.5	28	28	28	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	28	28	20.5	54	54	61	61	40	40	40	54	40	48	48
EPON H-3																																						
DIETHYLENE TRIAMINE								3	3		3	6																										
TRI-DIMETHYL AMINO METHYL PHENOL																3	6	6	6	6	6	6	3	3		3	9					6	3	9		3	3	3
SUB-TOTAL (2) - PARTS CURING AGENT TO SUB-TOTAL (1)	28	20	36	28	20.5	28	28	23.5	23.5	24	23.5	26.5	28	28	28	23.5	26.5	26.5	26.5	26.5	26.5	26.5	23.5	23.5	28	31	29.5	54	54	61	61	46	43	49	54	43	51	51
STRAIN OPTIC COEFFICIENT, K																																						
(a) CURED 24 HRS. AT 70°F AFTER FINAL COAT	.062	(2) .040	(2) .040	.050	(2) .040	.067	.068	.051	.060	(2) .040	(2) .040	.050	(2) .040	(2) .040	(2) .040	.058	.070	.067	.084	.086	.075	.080	(2) .040	.048	.056	.075	.082	.070	.054	.080	.067	.083	.078	.084	.038	.060	.080	.070
(b) - (a) PLUS 24 HOUR CURE AT 120°F	(1) .076					(1) .068	(1) .070		(1) .082							.081	(4) .086	(4) .090	(4) .094	(4) .093	(4) .099	.097				(1) .080	(4) .082	(1) .065	(1) .069		(4) .074	.087	.090	.083	(1) .056	(4) .083		(4) .075
(C) - (a) PLUS 20 DAYS AT 70°F																						(3) .097				.080						(3) .087	(3) .090	(4) .083	.056			

NOTES

(1) BLUSHED OR CRAZED

(2) LESS THAN .040

(3) VERY GOOD OPTICAL COATING

(4) GOOD OPTICAL COATING

(5) SYSTEM COMPONENTS COMBINED IN PARTS BY WEIGHT

TABLE II

HONEYCOMB SANDWICH PANEL SERIALIZATION AND MEASURED FACE SHEET THICKNESSES

PANEL SERIAL NUMBER	NOMINAL FACE SHEET THICKNESS, INCH	MEASURED FACE SHEET THICKNESS, INCH				AVERAGE THICKNESS, INCH	TYPE VOID IMPLANTS
		A	B	C	D		
16-1	0.016	0.0140	0.0139	0.0139	0.0140	0.0140	0.5, 1.0 and 2.0 inch diameter voids produced by adhesive cuts
16-2		0.0139	0.0141	0.0141	0.0140	0.0140	
16-3		0.0142	0.0142	0.0143	0.0144	0.0143	
16-4		0.0141	0.0140	0.0139	0.0138	0.0140	
16-5		0.0139	0.0139	0.0140	0.0142	0.0140	
32-1	0.032	0.0300	0.0303	0.0302	0.0298	0.0301	
32-2		0.0298	0.0299	0.0301	0.0300	0.0300	
32-3		0.0296	0.0300	0.0301	0.0297	0.0298	
32-4		0.0301	0.0299	0.0299	0.0301	0.0300	
32-5		0.0303	0.0302	0.0303	0.0305	0.0303	
50-1	0.050	0.0476	0.0474	0.0475	0.0469	0.0474	
50-2		0.0476	0.0476	0.0481	0.0482	0.0479	
50-3		0.0469	0.0473	0.0479	0.0473	0.0474	
50-4		0.0482	0.0484	0.0479	0.0482	0.0482	
50-5		0.0477	0.0482	0.0476	0.0478	0.0478	
63-1	0.063	0.0610	0.0618	0.0612	0.0605	0.0611	1.0, 2.0 and 3.0 inch diameter voids produced by adhesive cuts
63-2		0.0615	0.0612	0.0604	0.0605	0.0609	
63-3		0.0610	0.0608	0.0614	0.0616	0.0612	
63-4		0.0599	0.0601	0.0609	0.0598	0.0602	
63-5		0.0600	0.0611	0.0615	0.0611	0.0609	
80-1	0.080	0.0711	0.0773	0.0787	0.0786	0.0779	
80-2		0.0772	0.0786	0.0776	0.0777	0.0778	
80-3		0.0777	0.0772	0.0779	0.0779	0.0777	
80-4		0.0767	0.0780	0.0779	0.0768	0.0774	
80-5		0.0781	0.0778	0.0769	0.0768	0.0774	
100-1	0.100	0.0967	0.0976	0.0977	0.0972	0.0973	
100-2		0.0964	0.0965	0.0972	0.0969	0.0968	
100-3		0.0971	0.0975	0.0977	0.0974	0.0974	
100-4		0.0970	0.0965	0.0974	0.0976	0.0971	
100-5		0.0977	0.0969	0.0969	0.0972	0.0972	

TABLE II (Continued)

HONEYCOMB SANDWICH PANEL SERIALIZATION AND MEASURED FACE SHEET THICKNESSES

PANEL SERIAL NUMBER	NOMINAL FACE SHEET THICKNESS, INCH	MEASURED FACE SHEET THICKNESS, INCH				AVERAGE THICKNESS, INCH	TYPE VOID IMPLANTS	
		A	B	C	D			
32-T1	0.032	0.0297	0.0295	0.0295	0.0295	0.0296	0.50 and 1.0 Dia. voids	Voids produced by adhesive cuts and Teflon
32-T2		0.0301	0.0299	0.0303	0.0306	0.0302	1.0 and 2.0 Dia. voids	
32-T3		0.0300	0.0303	0.0303	0.0300	0.0302	Rectangular voids	
63-T1	0.063	0.0584	0.0586	0.0590	0.0590	0.0588	0.50 and 1.0 Dia. voids	
63-T2		0.0584	0.0587	0.0590	0.0586	0.0587	1.0 and 2.0 Dia. voids	
63-T3		0.0603	0.0603	0.0603	0.0607	0.0604	Rectangular voids	
32-M1	0.032	0.0302	0.0305	0.0307	0.0300	0.0304	1.0 and 2.0 Dia. marginal bond voids	
32-M2		0.0302	0.0300	0.0302	0.0303	0.0302		
32-M3		0.0301	0.0301	0.0302	0.0303	0.0302		
63-M1	0.063	0.0610	0.0616	0.0615	0.0605	0.0612	2.0 and 3.0 Dia. marginal bond voids	
63-M2		0.0606	0.0615	0.0617	0.0605	0.0611		
63-M3		0.0585	0.0587	0.0589	0.0584	0.0586		
32-D1	0.032	0.0305	0.0305	0.0302	0.0308	0.0305	Face sheet splice with external doubler - 2.0 Dia. Teflon voids	
		0.0305	0.0308			0.0306		
32-C1	0.032	0.0303	0.0303	0.0306	0.0307	0.0305	Good core splice	
32-C2		0.0310	0.0310	0.0308	0.0305	0.0308	Good and bad core splice	
63-C1	0.063	0.0600	0.0598	0.0599	0.0600	0.0599	Good core splice	
63-C2		0.0584	0.0581	0.0587	0.0599	0.0588	Good and bad core splice	
32-S1	0.032	0.0307	0.0295	0.0296	0.0300	0.0300	Poor bonding practice	
32-S2		0.0303	0.0304	0.0304	0.0302	0.0303		
32-S3		0.0302	0.0297	0.0308	0.0300	0.0302		

TABLE III

BIREFRINGENT COATING THICKNESS MEASUREMENTS FOR 30 HONEYCOMB SANDWICH PANELS UTILIZED FOR FACE SHEET THICKNESS vs COATING THICKNESS EVALUATIONS

Panel Number And Area (1) / Measurement Location (2)	1	2	3	4	5	Average Thickness, Inch
16-1A	0.0118	0.0101	0.0097	0.0109	0.0101	0.0105
16-1B	0.0244	0.0235	0.0227	0.0217	0.0209	0.0226
16-2A	0.0272	0.0284	0.0294	0.0306	0.0299	0.0291
16-2B	0.0376	0.0381	0.0397	0.0400	0.0389	0.0389
16-3A	0.0501	0.0497	0.0490	0.0484	0.0459	0.0486
16-3B	0.0568	0.0558	0.0573	0.0585	0.0564	0.0570
16-4A	0.0704	0.0723	0.0701	0.0705	0.0689	0.0705
16-4B	0.0771	0.0766	0.0747	0.0772	0.0787	0.0770
16-5A	0.0884	0.0868	0.0859	0.0880	0.0828	0.0864
16-5B	0.0877	0.1000	0.0990	0.1002	0.0947	0.0964
32-1A	0.0087	0.0088	0.0083	0.0075	0.0078	0.0082
32-1B	0.0177	0.0173	0.0165	0.0161	0.0164	0.0168
32-2A	0.0272	0.0274	0.0268	0.0264	0.0267	0.0269
32-2B	0.0369	0.0382	0.0358	0.0370	0.0359	0.0367
32-3A	0.0518	0.0512	0.0527	0.0530	0.0495	0.0516
32-3B	0.0606	0.0613	0.0643	0.0650	0.0597	0.0623
32-4A	0.0688	0.0684	0.0676	0.0683	0.0655	0.0678
32-4B	0.0773	0.0772	0.0780	0.0787	0.0784	0.0780
32-5A	0.0855	0.0851	0.0853	0.0880	0.0851	0.0850
32-5B	0.0954	0.0966	0.0970	0.1006	0.0985	0.0963
50-1A	0.0107	0.0107	0.0099	0.0095	0.0088	0.0099
50-1B	0.0193	0.0204	0.0200	0.0200	0.0195	0.0198
50-2A	0.0301	0.0308	0.0339	0.0320	0.0286	0.0311
50-2B	0.0363	0.0386	0.0381	0.0376	0.0356	0.0373
50-3A	0.0519	0.0517	0.0541	0.0550	0.0532	0.0531
50-3B	0.0601	0.0583	0.0566	0.0619	0.0593	0.0594
50-4A	0.0698	0.0696	0.0680	0.0698	0.0681	0.0690
50-4B	0.0781	0.0779	0.0748	0.0768	0.0752	0.0766
50-5A	0.0858	0.0877	0.0864	0.0868	0.0829	0.0858
50-5B	0.0997	0.1028	0.1038	0.1025	0.0981	0.1013
63-1A	0.0090	0.0092	0.0085	0.0089	0.0084	0.0088
63-1B	0.0195	0.0183	0.0173	0.0157	0.0172	0.0176
63-2A	0.0274	0.0291	0.0283	0.0290	0.0285	0.0285
63-2B	0.0359	0.0360	0.0404	0.0393	0.0356	0.0375
63-3A	0.0519	0.0517	0.0541	0.0550	0.0532	0.0531
63-3B	0.0601	0.0583	0.0566	0.0619	0.0593	0.0594
63-4A	0.0691	0.0705	0.0689	0.0696	0.0686	0.0694
63-4B	0.0769	0.0783	0.0766	0.0798	0.0767	0.0778
63-5A	0.0865	0.0882	0.0843	0.0857	0.0821	0.0854
63-5B	0.0965	0.0995	0.0981	0.0974	0.0946	0.0974

TABLE III (CONTINUED)

Panel Number And Area (1) / Measurement Location (2)	1	2	3	4	5	Average Thickness, Inch
80-1A	0.0087	0.0082	0.0078	0.0072	0.0076	0.0079
80-1B	0.0172	0.0173	0.0164	0.0154	0.0154	0.0161
80-2A	0.0273	0.0281	0.0254	0.0269	0.0255	0.0267
80-2B	0.0409	0.0420	0.0425	0.0431	0.0405	0.0417
80-3A	0.0466	0.0478	0.0465	0.0487	0.0468	0.0473
80-3B	0.0579	0.0612	0.0600	0.0614	0.0586	0.0590
80-4A	0.0712	0.0713	0.0725	0.0735	0.0717	0.0722
80-4B	0.0775	0.0813	0.0823	0.0813	0.0799	0.0804
80-5A	0.0884	0.0897	0.0894	0.0890	0.0861	0.0884
80-5B	0.0979	0.1000	0.1008	0.1019	0.0980	0.1000
100-1A	0.0085	0.0082	0.0073	0.0082	0.0079	0.0082
100-1B	0.0163	0.0167	0.0167	0.0164	0.0165	0.0165
100-2A	0.0248	0.0269	0.0244	0.0247	0.0254	0.0253
100-2B	0.0416	0.0423	0.0422	0.0419	0.0401	0.0417
100-3A	0.0470	0.0474	0.0472	0.0478	0.0471	0.0474
100-3B	0.0606	0.0555	0.0575	0.0589	0.0574	0.0580
100-4A	0.0673	0.0690	0.0654	0.0693	0.0686	0.0680
100-4B	0.0743	0.0763	0.0775	0.0810	0.0785	0.0775
100-5A	0.0844	0.0861	0.0866	0.0910	0.0977	0.0872
100-5B	0.0926	0.0963	0.0988	0.1032	0.0882	0.0976

(1) Panels identified by number in Table II.

(2) Measurement locations shown in Figure 5.

TABLE IV

BIREFRINGENT COATING THICKNESS MEASUREMENTS FOR 20 HONEYCOMB SANDWICH PANELS HAVING NEAR OPTIMAL COATING THICKNESS

Panel Number (1) / Measurement Location (2)	1A	2A	3A	4A	5A	1B	2B	3B	4B	5B	Average Thickness, Inch
32-T1	0.0330	0.0319	0.0315	0.0310	0.0310	0.0337	0.0358	0.0362	0.0358	0.0343	0.0334
32-T2	0.0345	0.0349	0.0330	0.0321	0.0295	0.0373	0.0380	0.0378	0.0360	0.0354	0.0348
32-T3	0.0375	0.0397	0.0393	0.0392	0.0383	0.0349	0.0338	0.0332	0.0320	0.0307	0.0359
63-T1	0.0658	0.0653	0.0620	0.0616	0.0606	0.0715	0.0678	0.0672	0.0657	0.0649	0.0652
63-T2	0.0628	0.0625	0.0613	0.0606	0.0602	0.0642	0.0633	0.0640	0.0663	0.0647	0.0630
63-T3	0.0592	0.0612	0.0609	0.0630	0.0636	0.0587	0.0590	0.0584	0.0558	0.0558	0.0596
32-M1	0.0304	0.0261	0.0315	0.0306	0.0299	0.0281	0.0287	0.0290	0.0277	0.0263	0.0288
32-M2	Panel Was Not Coated										
32-M3	0.0331	0.0340	0.0356	0.0345	0.0339	0.0316	0.0313	0.0315	0.0308	0.0282	0.0324
63-M1	Panel Was Not Coated										
63-M2	0.0653	0.0628	0.0617	0.0627	0.0718	0.0603	0.0607	0.0598	0.0594	0.0572	0.0622
63-M3	0.0630	0.0624	0.0610	0.0624	0.0613	0.0629	0.0601	0.0588	0.0575	0.0560	0.0605
32-D1	0.0311	0.0332	0.0365	0.0318	0.0328	0.0304	0.0319	0.0325	0.0309	0.0305	0.0322
32-C1	0.0422	0.0417	0.0414	0.0391	0.0388	0.0395	0.0385	0.0370	0.0365	0.0344	0.0389
32-C2	0.0480	0.0459	0.0444	0.0418	0.0391	0.0419	0.0403	0.0369	0.0343	0.0321	0.0405
63-C1	0.0700	0.0654	0.0665	0.0673	0.0683	0.0655	0.0653	0.0637	0.0628	0.0628	0.0658
63-C2	0.0683	0.0683	0.0682	0.0696	0.0710	0.0700	0.0684	0.0657	0.0630	0.0638	0.0676
32-S1	0.0323	0.0338	0.0297	0.0358	0.0353	0.0300	0.0300	0.0308	0.0302	0.0288	0.0317
32-S2	0.0301	0.0313	0.0336	0.0332	0.0332	0.0356	0.0350	0.0346	0.0346	0.0349	0.0336
32-S3	0.0315	0.0315	0.0325	0.0329	0.0345	0.0352	0.0354	0.0362	0.0362	0.0369	0.0343

(1) Panels Identified by Number in Table II

(2) Measurement Locations Shown in Figure 5

TABLE V

RESULTS OF BIREFRINGENT COATING THICKNESS EVALUATION ON HONEYCOMB PANELS HAVING 0.014 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS

PANEL NUMBER	COATING THICKNESS, INCH	DETECTION PRESSURE, PSIG, FOR 0.5 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 1.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 2.0 INCH DIA. VOID(1)			FRINGE ORDER, n, FOR PRESSURE OF 20 PSIG		
		A	B	C	A	B	C	A	B	C	0.5 IN. DIA. VOID	1.0 IN. DIA. VOID	2.0 IN. DIA. VOID
16-1A	0.010	12.0	(2)	(2)	0.5	1.5	2.5	0.1	0.5	0.5	(4)	0.24	0.33
16-1B	0.023	2.5	8.0	12.0	0.5	1.5	2.0	0.1	0.5	0.5	0.12	0.27	0.70
16-2A	0.029	2.0	9.0	12.0	0.1	1.0	2.0	0.1	0.1	0.5	0.10	0.28	0.83
16-2B	0.039	2.0	9.0	12.0	0.1	1.0	2.0	0.1	0.1	0.5	0.10	0.30	0.86
16-3A	0.049	2.0	12.0	15.0	0.1	1.5	2.0	0.1	0.1	0.5	0.10	0.28	0.88
16-3B	0.057	2.0	12.0	15.0	0.1	1.5	2.0	0.1	0.1	0.5	0.10	0.25	0.83
16-4A	0.070	2.0	13.0	20.0	0.1	2.0	3.0	0.1	0.1	0.5	(4)	0.21	0.65
16-4B	0.077	3.0	13.0	20.0	(3)	(3)	(3)	0.1	0.1	0.5	(4)	(3)	0.70
16-5A	0.086	5.0	20.0	(2)	0.5	4.0	7.0	0.1	0.5	1.0	(4)	0.12	0.62
16-5B	0.096	9.0	(2)	(2)	0.5	4.0	7.0	0.1	0.5	1.0	(4)	0.20	0.56

(1) A-DETECTION PRESSURE WHEN USING PLANE POLARISCOPE AND ROTATING ANALYZER
B-DETECTION PRESSURE WHEN USING CIRCULAR POLARISCOPE
C-PRESSURE REQUIRED TO CLEARLY SHOW VOID SHAPE WHEN USING CIRCULAR POLARISCOPE

(2) NOT DETECTABLE FOR PRESSURE UP TO 20 PSIG

(3) NOT MEASURED

(4) LESS THAN 0.10 FRINGE

TABLE VI

RESULTS OF BIREFRINGENT COATING THICKNESS EVALUATION ON HONEYCOMB PANELS HAVING 0.030 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS

PANEL NUMBER	COATING THICKNESS, INCH	DETECTION PRESSURE, PSIG, FOR 0.5 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 1.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 2.0 INCH DIA. VOID(1)			FRINGE ORDER, n, FOR PRESSURE OF 30 PSIG		
		A	B	C	A	B	C	A	B	C	0.5 IN. DIA. VOID	1.0 IN. DIA. VOID	2.0 IN. DIA. VOID
32-1A	0.008	16.0	(2)	(2)	3.5	12.0	15.0	2.0	4.0	6.0	(3)	(3)	0.18
32-1B	0.017	6.5	30.0	40.0	2.0	6.0	9.0	0.2	0.5	1.5	(3)	0.12	0.30
32-2A	0.027	5.0	20.0	22.0	1.2	3.5	5.0	0.1	0.5	1.0	(3)	0.17	0.51
32-2B	0.037	4.0	18.0	20.0	1.0	3.0	3.5	0.1	0.2	0.5	(3)	0.22	0.61
32-3A	0.052	4.0	18.0	22.0	0.5	2.0	3.5	0.1	0.1	0.5	(3)	0.22	0.71
32-3B	0.062	3.5	18.0	22.0	0.1	1.0	3.0	0.1	0.1	0.5	(3)	0.24	0.76
32-4A	0.068	4.0	19.0	24.0	0.5	3.0	5.0	0.1	0.5	1.0	(3)	0.22	0.73
32-4B	0.078	4.0	19.0	24.0	0.5	3.5	5.0	0.1	0.5	1.0	(3)	0.22	0.74
32-5A	0.085	4.0	22.0	30.0	0.5	4.0	6.0	0.1	1.0	2.0	(3)	0.20	0.74
32-5B	0.096	4.0	22.0	30.0	0.5	4.5	6.0	0.1	1.0	2.0	(3)	0.20	0.74

(1) A- DETECTION PRESSURE WHEN USING PLANE POLARISCOPE AND ROTATING ANALYZER
B- DETECTION PRESSURE WHEN USING CIRCULAR POLARISCOPE
C- PRESSURE REQUIRED TO CLEARLY SHOW VOID SHAPE WHEN USING CIRCULAR POLARISCOPE

(2) NOT DETECTABLE FOR PRESSURE UP TO 30 PSIG

(3) LESS THAN 0.10 FRINGE

TABLE VII

RESULTS OF BIREFRINGENT COATING THICKNESS EVALUATION OF HONEYCOMB PANELS HAVING 0.048 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS

PANEL NUMBER	COATING THICKNESS, INCH	DETECTION PRESSURE, PSIG, FOR 0.5 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 1.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 2.0 INCH DIA. VOID(1)			FRINGE ORDER, n, FOR PRESSURE OF 40 PSIG		
		A	B	C	A	B	C	A	B	C	0.5 IN. DIA. VOID	1.0 IN. DIA. VOID	2.0 IN. DIA. VOID
50-1A	0.010	(2)	(2)	(2)	14.0	(2)	(2)	3.5	11.0	16.5	(3)	(3)	0.12
50-1B	0.020	23.0	(2)	(2)	6.5	17.0	22.0	1.0	3.0	5.5	(3)	(3)	0.20
50-2A	0.031	18.0	(2)	(2)	2.0	14.5	16.0	0.5	3.0	5.0	(3)	0.10	0.32
50-2B	0.037	14.5	(2)	(2)	1.5	9.0	11.0	0.2	2.0	3.0	(3)	0.12	0.37
50-3A	0.053	10.0	(2)	(2)	1.0	6.0	9.0	0.1	1.5	2.0	(3)	0.15	0.51
50-3B	0.059	7.0	35.0	(2)	1.0	6.0	9.0	0.1	1.0	1.5	(3)	0.17	0.53
50-4A	0.069	7.0	30.0	(2)	1.0	5.0	9.0	0.1	1.0	2.0	(3)	0.16	0.60
50-4B	0.077	7.0	30.0	(2)	1.0	5.0	8.0	0.1	1.0	2.0	(3)	0.16	0.59
50-5A	0.086	9.0	40.0	(2)	1.0	5.0	10.0	0.1	1.5	2.0	(3)	0.16	0.61
50-5B	0.101	11.0	40.0	(2)	1.5	8.0	11.0	0.2	2.0	2.5	(3)	0.16	0.60

(1) A- DETECTION PRESSURE WHEN USING PLANE POLARISCOPE AND ROTATING ANALYZER
B- DETECTION PRESSURE WHEN USING CIRCULAR POLARISCOPE
C- PRESSURE REQUIRED TO CLEARLY SHOW VOID SHAPE WHEN USING CIRCULAR POLARISCOPE

(2) NOT DETECTABLE FOR PRESSURE UP TO 40 PSIG

(3) LESS THAN 0.10 FRINGE

TABLE VIII

RESULTS OF BIREFRINGENT COATING THICKNESS EVALUATION ON HONEYCOMB PANELS HAVING 0.061 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS

PANEL NUMBER	COATING THICKNESS, INCH	DETECTION PRESSURE, PSIG, FOR 1.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 2.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 3.0 INCH DIA. VOID(1)			FRINGE ORDER, n, FOR PRESSURE OF 40 PSIG		
		A	B	C	A	B	C	A	B	C	1.0 IN. DIA. VOID	2.0 IN. DIA. VOID	3.0 IN. DIA VOID
63-1A	0.008	18.0	(2)	(2)	4.0	18.5	22.0	1.5	8.5	11.0	(3)	(3)	0.12
63-1B	0.018	10.0	20.0	35.0	1.5	3.5	8.0	0.5	2.0	3.0	(3)	0.14	0.25
63-2A	0.028	6.0	19.0	28.0	2.0	3.5	7.5	0.5	2.0	3.0	(3)	0.20	0.36
63-2B	0.037	5.0	15.0	22.0	1.5	3.0	5.0	0.5	1.5	3.0	(3)	0.25	0.50
63-3A	0.053	3.0	10.0	17.0	0.5	2.0	3.0	0.1	1.0	1.5	(3)	0.35	0.78
63-3B	0.059	2.0	9.0	14.0	0.3	1.5	2.0	0.1	0.5	1.0	(3)	0.35	0.79
63-4A	0.069	2.0	8.0	12.0	0.2	1.0	2.0	0.1	0.5	1.0	0.10	0.40	0.91
63-4B	0.078	2.0	8.0	12.0	0.2	1.0	2.0	0.1	0.5	1.0	0.10	0.42	0.92
63-5A	0.085	2.0	9.0	14.0	0.1	1.0	2.5	0.1	0.3	1.0	0.10	0.48	1.05
63-5B	0.097	2.0	8.0	14.0	0.1	1.0	2.5	0.1	0.3	1.0	0.10	0.48	1.05

(1) A- DETECTION PRESSURE WHEN USING PLANE POLARISCOPE AND ROTATING ANALYZER
B- DETECTION PRESSURE WHEN USING CIRCULAR POLARISCOPE
C- PRESSURE REQUIRED TO CLEARLY SHOW VOID SHAPE WHEN USING CIRCULAR POLARISCOPE

(2) NOT DETECTABLE FOR PRESSURE UP TO 40 PSIG

(3) LESS THAN 0.10 FRINGE

TABLE IX

RESULTS OF BIREFRINGENT COATING THICKNESS EVALUATION ON HONEYCOMB PANELS HAVING 0.078 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS

PANEL NUMBER	COATING THICKNESS, INCH	DETECTION PRESSURE, PSIG, FOR 1.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 2.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 3.0 INCH DIA. VOID(1)			FRINGE ORDER, n, FOR PRESSURE OF 40 PSIG		
		A	B	C	A	B	C	A	B	C	1.0 IN. DIA. VOID	2.0 IN. DIA. VOID	3.0 IN. DIA. VOID
80-1A	0.008	30.0	(3)	(3)	7.5	28.0	40.0	3.0	13.0	19.0	(4)	(4)	(4)
80-1B	0.016	15.0	(3)	(3)	3.5	11.0	15.0	1.5	6.0	9.0	(4)	(4)	(4)
80-2A	0.027	4.0	26.0	35.0	2.0	5.0	8.0	1.0	2.5	3.0	(4)	0.10	0.20
80-2B	0.042	4.0	15.0	23.0	(3)	(3)	(3)	0.5	1.5	2.5	(4)	0.15	0.24
80-3A	0.047	4.0	16.0	24.0	0.7	3.5	4.5	0.1	1.0	2.5	(4)	0.19	0.35
80-3B	0.059	4.0	13.0	20.0	0.5	3.0	4.0	0.1	1.0	2.0	(4)	0.19	0.32
80-4A	0.072	3.0	12.0	18.0	0.1	3.0	3.5	0.1	1.0	2.0	(4)	0.20	0.45
80-4B	0.080	3.0	12.0	18.0	0.1	3.0	3.5	0.1	1.0	2.0	(4)	0.20	0.44
80-5A	0.088	2.5	12.0	16.0	0.1	3.0	3.5	0.1	1.0	2.0	(4)	0.25	0.49
80-5B	0.100	2.5	12.0	16.0	0.1	3.0	3.5	0.1	1.0	2.0	(4)	0.25	0.48

(1) A- DETECTION PRESSURE WHEN USING PLANE POLARISCOPE AND ROTATING ANALYZER
B- DETECTION PRESSURE WHEN USING CIRCULAR POLARISCOPE
C- PRESSURE REQUIRED TO CLEARLY SHOW VOID SHAPE WHEN USING CIRCULAR POLARISCOPE

(2) NOT DETECTABLE FOR PRESSURE UP TO 40 PSIG

(3) NOT MEASURED

(4) LESS THAN 0.10 FRINGE

TABLE X

RESULTS OF BIREFRINGENT COATING THICKNESS EVALUATION ON HONEYCOMB PANELS HAVING 0.097 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS

PANEL NUMBER	COATING THICKNESS, INCH	DETECTION PRESSURE, PSIG, FOR 1.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 2.0 INCH DIA. VOID(1)			DETECTION PRESSURE, PSIG, FOR 3.0 INCH DIA. VOID(1)			FRINGE ORDER, n, FOR PRESSURE OF 40 PSIG		
		A	B	C	A	B	C	A	B	C	1.0 IN. DIA. VOID	2.0 IN. DIA. VOID	3.0 IN. DIA. VOID
100-1A	0.008	40.0	(2)	(2)	17.0	40.0	(2)	9.0	23.0	31.0	(3)	(3)	(3)
100-1B	0.016	28.0	(2)	(2)	8.0	19.0	30.0	6.0	10.0	17.0	(3)	(3)	(3)
100-2A	0.025	10.0	30.0	(2)	2.5	10.0	13.0	1.0	5.0	7.0	(3)	0.10	0.20
100-2B	0.042	6.0	28.0	40.0	2.0	7.0	9.0	0.5	2.5	5.0	(3)	0.15	0.24
100-3A	0.047	6.0	28.0	40.0	1.5	6.0	8.0	0.5	2.5	4.0	(3)	0.19	0.35
100-3B	0.058	6.0	27.0	35.0	1.5	6.0	8.0	0.5	2.5	4.0	(3)	0.19	0.32
100-4A	0.068	6.0	22.0	32.0	1.5	5.0	8.0	0.5	2.5	3.0	(3)	0.20	0.45
100-4B	0.077	6.0	22.0	32.0	1.5	5.0	8.0	0.5	2.5	3.0	(3)	0.20	0.44
100-5A	0.087	6.5	24.0	35.0	1.5	5.0	7.0	0.5	2.5	3.0	(3)	0.25	0.49
100-5B	0.098	6.5	24.0	35.0	1.5	5.0	7.0	0.5	2.5	3.0	(3)	0.25	0.48

(1) A- DETECTION PRESSURE WHEN USING PLANE POLARISCOPE AND ROTATING ANALYZER
B- DETECTION PRESSURE WHEN USING CIRCULAR POLARISCOPE
C- PRESSURE REQUIRED TO CLEARLY SHOW VOID SHAPE WHEN USING CIRCULAR POLARISCOPE

(2) NOT DETECTABLE FOR PRESSURE UP TO 40 PSIG

(3) LESS THAN 0.10 FRINGE

TABLE XI

RESULTS OF BONDLINE VOID LOCATION EVALUATIONS ON HONEYCOMB PANELS HAVING 0.030 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS WITH OPTIMUM BIREFRINGENT COATING THICKNESS

Type Void	Void Size, Inch (1)	Coating Thickness, Inch	DETECTION PRESSURE, PSIG(2)			Fringe Order, n, For Pressure of 30 PSIG
			A	B	C	
Teflon on Face Sheet	0.50 Dia.	0.033	5.0	18.0	27.0	(3)
Teflon on Core	0.50 Dia.	0.031	5.0	18.0	27.0	(3)
Adhesive Cut	0.50 Dia.	0.032	5.0	18.0	27.0	(3)
Teflon on Face Sheet	1.0 Dia.	0.034	1.5	3.5	4.5	0.17
Teflon on Core	1.0 Dia.	0.034	2.0	6.0	7.0	0.13
Adhesive Cut	1.0 Dia.	0.036	1.5	3.5	4.5	0.17
Teflon on Face Sheet	2.0 Dia.	0.034	0.5	1.5	2.0	0.64
Teflon on Core	2.0 Dia.	0.030	0.5	2.5	3.5	0.50
Adhesive Cut	2.0 Dia.	0.033	0.1	0.5	2.0	0.62
Teflon on Face Sheet	3.0 Dia.	0.037	0.1	0.1	0.5	1.05
Teflon on Core	3.0 Dia.	0.035	0.5	1.5	2.0	1.00
Adhesive Cut	3.0 Dia.	0.038	0.1	0.1	0.5	1.08
Teflon on Face Sheet	1.25 x 0.63	0.038	3.0	8.0	13.0	0.10
Teflon on Core	1.25 x 0.63	0.038	3.0	8.0	13.0	0.10
Adhesive Cut	1.25 x 0.63	0.039	2.0	8.0	13.0	0.10
Teflon on Face Sheet	2.50 x 1.26	0.035	2.0	2.0	4.0	0.46
Teflon on Core	2.50 x 1.26	0.031	1.5	2.0	6.0	0.35
Adhesive Cut	2.50 x 1.26	0.033	0.5	1.5	3.0	0.50

(1) 0.50 Dia. and 1.0 Dia. Voids in Panel No. 32-T1
2.0 Dia. and 3.0 Dia. Voids in Panel No. 32-T2
Rectangular Voids in Panel No. 32-T3

(2) A - Detection Pressure When using Plane Polariscope and Rotating Analyzer
B - Detection Pressure When Using Circular Polariscope
C - Pressure Required to Clearly Show Void Shape When Using Circular Polariscope

(3) Less than 0.10 Fringe

TABLE XII

RESULTS OF BONDLINE VOID LOCATION EVALUATIONS ON HONEYCOMB PANELS HAVING 0.060 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS WITH OPTIMUM BIREFRINGENT COATING THICKNESS

Type Void	Void Size, Inch (1)	Coating Thickness, Inch	DETECTION PRESSURE, PSIG(2)			Fringe Order, n, For Pressure of 40 PSIG
			A	B	C	
Teflon on Face Sheet	0.50 Dia.	0.066	18.0	(3)	(3)	(4)
Teflon on Core	0.50 Dia.	0.061	18.0	(3)	(3)	(4)
Adhesive Cut	0.50 Dia.	0.062	18.0	(3)	(3)	(4)
Teflon on Face Sheet	1.0 Dia.	0.072	7.5	10.0	15.0	0.10
Teflon on Core	1.0 Dia.	0.065	3.5	10.0	15.0	0.10
Adhesive Cut	1.0 Dia.	0.067	3.5	10.0	15.0	0.10
Teflon on Face Sheet	2.0 Dia.	0.063	3.0	5.0	6.0	0.43
Teflon on Core	2.0 Dia.	0.060	1.5	5.0	6.0	0.36
Adhesive Cut	2.0 Dia.	0.061	1.0	3.0	4.0	0.44
Teflon on Face Sheet	3.0 Dia.	0.064	0.5	1.0	2.0	0.96
Teflon on Core	3.0 Dia.	0.065	1.0	2.5	4.0	0.91
Adhesive Cut	3.0 Dia.	0.064	0.5	1.0	2.0	0.98
Teflon on Face Sheet	1.26 x 0.63	0.059	6.0	13.0	20.0	0.15
Teflon on Core	1.26 x 0.63	0.064	6.0	13.0	20.0	0.15
Adhesive Cut	1.26 x 0.63	0.061	6.0	13.0	20.0	0.15
Teflon on Face Sheet	2.50 x 1.26	0.059	3.0	5.0	6.0	0.35
Teflon on Core	2.50 x 1.26	0.056	2.0	5.0	6.0	0.35
Adhesive Cut	2.50 x 1.26	0.058	2.0	5.0	6.0	0.35

(1) 0.50 Dia. and 1.0 Dia. Voids in Panel No. 63-T1
1.0 Dia. and 3.0 Dia. Voids in Panel No. 63-T2
Rectangular Voids in Panel No. 63-T3

(2) A - Detection Pressure When Using Plane Polariscope and Rotating Analyzer
B - Detection Pressure When Using Circular Polariscope
C - Pressure Required to Clearly Show Void Shape When Using Circular Polariscope

(3) Not Detectable For Pressure Up To 40 PSIG

(4) Less Than 0.10 Fringe

TABLE XIII

RESULTS OF BONDLINE VOID DETECTION EVALUATIONS FOR PANEL 32-D1 HAVING 0.030 INCH THICK FACE SHEET AND FACE SHEET SPLICE, 0.032 INCH THICK COATING AND 2.0 INCH DIAMETER VOIDS

Void Number (1)	Void Type and Location	Detection Pressure, PSIG (2)		
		A	B	C
1TF	Teflon on face sheet. Void under face sheet and doubler.	9.0	31.0	40.0
1TC	Teflon on core. Void under face sheet and doubler.	12.0	31.0	40.0
2TF	Teflon on face sheet. Portion of void under face sheet.	6.0	14.0	18.0
	Teflon on face sheet. Portion of void under face sheet and doubler.	6.0	28.0	34.0
2TC	Teflon on core. Portion of void under face sheet	6.0	14.0	18.0
	Teflon on core. Portion of void under face sheet and doubler.	6.0	28.0	34.0

(1) Void locations shown in Figure 4

(2) A - Detection pressure when using plane polariscope and rotating analyzer

B - Detection pressure when using circular polariscope

C - Pressure required to clearly show void shape when using circular polariscope

TABLE XIV

STRAIN-OPTIC COEFFICIENTS DETERMINED FROM CALIBRATION BEAMS WHICH WERE SPRAYED ALONG WITH THE HONEYCOMB PANELS

Calibration Beam Number	Coating Thickness, Inch	Strain-Optic Coefficient, K, at Various Days After Last Spray Coat										
		1	2	3	4	5	6	7	8	10	11	(1)
1	0.014	0.079	0.081	---	---	---	0.086	---	---	---	---	0.099
2	0.040	---	---	0.080	---	---	---	---	---	0.086	---	---
3	0.044	0.063	---	---	---	0.077	---	0.081	---	---	---	0.081
4	0.044	---	---	0.080	---	---	---	---	---	0.084	---	---
5	0.046	---	---	0.082	---	0.083	---	---	---	---	0.086	0.086
6	0.052	---	---	0.075	---	---	---	---	---	0.078	---	---
7	0.066	---	0.076	---	0.080	---	---	---	---	0.082	---	0.082
8	0.066	---	0.083	---	---	---	---	---	0.083	---	---	0.085
9	0.072	---	0.084	---	---	---	---	---	0.089	---	---	0.090
10	0.073	---	---	---	---	---	---	0.078	---	---	0.079	---
11	0.073	---	---	---	---	---	---	0.079	---	---	0.080	---
12	0.077	---	0.081	---	---	---	---	---	0.083	---	---	0.088
13	0.077	---	0.082	---	---	---	---	---	0.084	---	---	0.087

(1) Last number of days shown plus 24 hours at 120°F.

TABLE XV

VOID DETECTION EVALUATIONS FOR POLYURETHANE TYPE COATINGS ON HONEYCOMB SANDWICH PANELS HAVING 0.014 INCH THICK CLAD 7075-T6 ALUMINUM ALLOY FACE SHEETS

COATING	THICKNESS, INCH	CURE TIME (1)	DETECTION PRESSURE, PSIG, FOR 0.5 INCH DIA. VOID(2)			DETECTION PRESSURE, PSIG, FOR 1.0 INCH DIA. VOID(2)			DETECTION PRESSURE, PSIG, FOR 2.0 INCH DIA. VOID(2)		
			A	B	C	A	B	C	A	B	C
1491	0.018	7 Days	9.0	(3)	(3)	2.0	4.0	6.5	0.5	1.0	2.0
1491	0.018	15 Days	9.0	(3)	(3)	1.5	3.5	6.0	0.3	1.0	2.0
M80-50CX	0.018	12 Hours	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)
M80-50CX	0.018	15 Days	7.0	(3)	(3)	1.0	4.0	5.0	0.1	0.5	1.0
M86-50CX	0.018	12 Hours	6.0	20.0	(3)	1.0	3.0	5.0	0.2	0.5	1.0
M86-50CX	0.031	24 Hours	3.0	15.0	20.0	0.2	1.0	2.0	0.1	0.1	0.1

(1) Cure time after last coat.

(2) A - Detection pressure when using plane polariscope and rotating analyzer.
B - Detection pressure when using circular polariscope.
C - Pressure required to clearly show void shape when using circular polariscope.

(3) Not detectable for pressure up to 20 psig.