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Evaluation and Selection of

ADHESIVE SYSTEMS FOR BONDING COMPONENT PARTS OF SPACECRAFT SOLAR BATTERIES

Report to

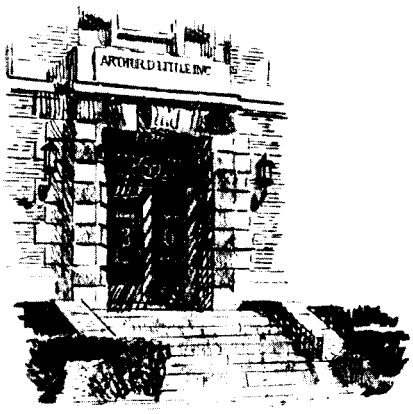
HOFFMAN ELECTRONICS CORPORATION

95006Y

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

March 1960

C-62487



Arthur D. Little, Inc.

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I. SUMMARY

A. PURPOSE AND SCOPE

The objective of this investigation was to evaluate and select adhesives suitable for use by Hoffman Electronics Corporation in bonding the components of spacecraft solar batteries. Such batteries at present are composed of shingle arrays of silicon photovoltaic cells, interconnected electrically, and mounted on aluminum honeycomb backings; the cells are individually surmounted with thin glass covers whose function is to increase transmission of light of desired wavelengths (0.43 - 1.1μ) and to minimize transmission of undesirable radiation, i.e., that of wavelengths $<0.43\mu$.

Hoffman Electronics Corporation has the assignment of fabricating a number of such solar batteries for the Jet Propulsion Laboratory of Pasadena. These batteries are expected to provide the power system for near-future interplanetary space probes.

Our prime function in this development has been to help select the proper adhesives to assure dependable bonding between the coated covers and the silicon cells, under the expected conditions of use. These conditions, which include the environmental factors of outer space, are still imperfectly understood and defined. In order that our adhesive selections might be made within a realistic frame of test reference Jet Propulsion Laboratories compiled a list of recommended conditioning tests. Although this list (Appendix) was conveyed to us after our investigation was rather well along, we tried to adhere to it throughout the latter part of our program.

We were expected to review and screen all available adhesives that we considered to be candidates for this use. Initially, we had been requested to include the investigation of adhesive systems suitable for bonding the silicon cells to the aluminum substrate, as well as the silicon cells to the glass covers. Later, we were requested to focus our main efforts on adhesive systems suitable for the latter application and, accordingly, have done so.

B. CONCLUSIONS

1. Our data show that unfilled epoxy adhesives can be used to attach optically coated glass covers (Optical Coating Laboratory, Inc.) to silicon photovoltaic cells without introducing more than a 5% reduction in the light transmitted by the covers alone.
2. On the basis of rather severe ultraviolet exposure testing, we found that the coated covers adequately protect the substrate epoxy adhesives from significant changes in light transmission properties.

3. The above findings mean that the choice for epoxy adhesive should be made on the basis of mechanical properties, since optical properties are satisfactory.

4. On the basis of our data, the best adhesive by a considerable margin for the projected use is Adhesive No. 7 in our list of final candidates. Designated by us EPON 828:EPON X-71(3:1)/HHPAA, it has regularly scored highest in bond strength tests conducted with optically coated glass and with glass-to-silicon test specimens. In general, it possesses a good balance of mechanical properties and handling convenience, along with outstanding high temperature characteristics and the requisite optical properties.

5. The above adhesive contains 0.5% of a (probably) noncombining catalyst, namely a tertiary amine--added to accelerate curing rate. We do not expect this additive to cause bubbling in adhesive films at high vacuum (2×10^{-7} mm Hg). Should bubbling occur, however, the present catalyst should be replaced by a less volatile one or else removed completely from the formulation. (In the event it is removed, the curing time should be increased from a 6-hour postcure at 250°F to 16 hours.)

6. The other adhesives which received final testing appear considerably less suited for the projected use. Bonding Agent R-314/A is a proprietary product which combines reasonably good mechanical properties with handling convenience and fairly good high temperature characteristics. Maraglas H655 and Bonding Agent 313/B, despite high test scores, cannot be recommended because they become subject to embrittlement with aging. EPOCAST adhesives showed mediocre mechanical properties, with 15-E looking somewhat superior to H-1321.

7. Of the conditioning tests proposed by JPL, the humidity and high temperature bond tests produced the most apparent bond strength reductions on candidate adhesives; the heat soak and UV-exposure tests actually improved the bond strength of several adhesives--evidently those in need of more cure time.

8. Presence of the optical coating reduced the bond strength of all of the epoxy adhesives tested. The extent of the reduction varied with the different adhesives. Whether this reduction in measurable strength will have a marked bearing on service life cannot be readily ascertained from our data.

9. Qualitative bond tests performed with several of the better adhesives showed strong bond between coated glass and silicon cells. Our evidence suggests that the shear strength of many epoxy adhesives exceeds the internal strength of silicon, at least for components in the dimensions of interest here.

C. RECOMMENDATIONS

1. We recommend that Adhesive No. 7 (EPON 828:EPON X-71(3:1)/HHPAA) be considered for the projected use; specifically, we think that its over-all properties qualify it for the further end use testing in progress now at Hoffman Electronics Corporation.

2. However, prior to further end use testing, cured films of Adhesive No. 7 should receive high vacuum exposure (2×10^{-7} mm Hg).

3. Our second and third choices for inclusion in the assembled solar battery testing program are Adhesives No. 2 and No. 5 (EPOCAST 15-E/9010 and BONDING AGENT R-314/A).

4. More generally, we recommend unfilled, semi-flexible, anhydride-cured epoxy resin adhesives as the most promising system we have found for meeting this materiel requirement.

5. Since the optical properties of epoxy resin candidates are satisfactory, we suggest that bond strength to the adherends of interest is the main criterion of selection.

II. INTRODUCTION

A. MEETINGS AND PROGRESS REPORTS

Our first report on this project was presented orally in San Francisco on November 17, 1959, to representatives of Hoffman Electronics Corporation and Jet Propulsion Laboratories.* The main purpose of this meeting, called at the request of Jet Propulsion Laboratories, was to assess ADL capabilities in the fields of adhesives and organic protective coatings to determine whether our help should be continued or terminated. Subjects discussed at this meeting included:

1. Candidate adhesives of interest at that time--e.g., Eastman 910, Epocast 15-E, Maraglas #655, and several ADL developmental epoxy systems.

2. Various space environmental factors likely to reduce adhesive life and cause power loss with service.

3. A test apparatus that might be assembled here to compare candidate adhesives quickly for glass-to-glass and glass-to-silicon bond.

4. Variations in the affinity of glass for adhesives as a function of surface--e.g., the effect of an ultraviolet reflectant coating or of a variable amount of adsorbed moisture on adhesive wetting characteristics.

A second report was made in Los Angeles on December 11, 1959, to the representatives of two operating divisions of Hoffman Electronics Corporation, Jet Propulsion Laboratories and Optical Coating Laboratory, Inc. (Santa Rosa, California). Subjects discussed at this meeting included:

1. Candidate adhesives of promise at that point. (It was agreed generally that the epoxy systems looked best.)

2. The need for adopting a bond strength test on which to obtain data for adhesive recommendation.

3. A group of environmental conditioning tests proposed by JPL for adoption in our investigation.

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* The three oral reports on this project were presented by Dr. T. F. Banigan, Jr. of our Western Division.

preparation in a "dry box". In view of the short duration of this investigation and the likelihood of finding candidate adhesives among the epoxy systems, however, we abandoned further development work with the urethanes.

4. Epoxy Resin Systems

While the exact structure of the epoxy resins is not known, nor are their reactions fully understood, structural knowledge is generally sufficient to describe and predict many of the products preparable from this important class of synthetic resins.

Epoxy resins may be prepared from a great variety of base materials. The most common epoxy resins are based on epichlorohydrin and a bivalent phenol, possessing molecular weights ranging from 175 to about 9000. The low-molecular-weight resins are liquid, whereas the higher-molecular-weight resins are fusible solids.

Commercial epoxy adhesives are supplied as resins, with or without fillers, flexibilizers, and other modifying ingredients. They react with hardening agents added at the time of bonding. Pot life and curing conditions vary widely depending on formulation and temperature. After addition of hardener, liquid adhesives have a pot life of about 30 minutes to 8 hours. They may gel and set to a moderately hard film in 15 hours at room temperature, but generally 4 to 6 days' curing time at room temperature is required for maximum strength and chemical resistance. Better cures are obtained by heating the joint at temperatures of 200°F or more, though color formation and reduction in ultimate mechanical properties can result from overcuring. Since the curing reaction is exothermic, curing conditions vary to some extent depending on the mass of the epoxy adhesive. The heat-hardening adhesives are considerably stronger at elevated temperatures than the room-temperature-setting types. Of particular importance is the fact that bond strength does not depend on the pressure applied during cure.*

Epoxy systems can be formulated to display a tough and durable bond with metallic and ceramic surfaces. Such systems can possess excellent optical, mechanical and electrical properties, qualifying them for exacting service condition. Accordingly, we placed epoxies in the forefront of this study.

C. PRELIMINARY SCREENING OF CANDIDATE ADHESIVES

The proprietary adhesives listed in the preceding section along with several experimental epoxy systems were qualitatively evaluated as follows. Glass-to-glass bonded samples were prepared by lap-jointing pre-washed 1 x 3 inch microscopic slides. The bond or glue lines were 1 - 2 mils thick. Relative comparisons of peel strength were made by razor blade splitting of these glass laminates both before and after humidity and thermal shock conditioning. Spectrophotometric measurements were made on similar sandwich samples before and after ultraviolet exposure. (See section III-C for description of apparatus.) Test results and recommendations were transmitted in earlier progress reports.

* H. A. Perry, "Adhesive Bonding of Reinforced Plastics," New York, McGraw-Hill Book Company, Inc., 1959, Chapter 4.

III. TEST METHODS

A. SIMULATED ENVIRONMENTAL TESTS

Shortly before our second progress report (December 11, 1959) we were presented with a list of simulated and accelerated environmental tests prepared by Jet Propulsion Laboratory for use by Hoffman Electronics Corporation and Arthur D. Little, Inc., in our studies of a solar cell cover glass adhesive. Many of the tests on this list are based on the JPL Vega Specification 30201. This recommended test program was received after the foregoing preliminary screening tests had been reported. However, we followed it for the latter portion of our investigation covering those adhesive systems described in section IV-A.

A list of the JPL recommended testing conditions for solar cell cover glass adhesives is given in the Appendix. Since this list is not a specification sheet but rather a testing program, we view it as a guide, presented to us so that our data may be collected under test conditions duplicatable in other laboratories and under environmental conditions approximating those of outer space that might affect the power output of solar batteries.

B. BOND STRENGTH APPARATUS

Early in this investigation we discussed adoption of a peel test for screening candidate adhesives. Such a test would have depended upon construction and successful operation of a "guillotine" device whereby a counterbalanced sharp wedge, such as a supported razor blade, could be driven, with measured stress, through the adhesive bond cementing two glass slides face-to-face. We felt, however, that without resorting to cumbersome test specimens it would be difficult to minimize glass breakage with adhesive systems as powerful as the epoxies. Accordingly, this apparatus was not built.

Another device was conceived and built; however, it had limited utility since it produced considerable glass failure with 1-inch x 3-inch glass slides. This device consists of a two-piece steel fixture. The main part holds T-shaped glass or glass-silicon samples in a horizontal slot, while the moving part, matched to slide in the main part, is recessed to hold the vertical portion of the glass sample. By proper application of measured stress, as with a laboratory hydraulic press, samples can be sheared at the glue line. This type of apparatus should be usable for weaker adhesives such as pressure-sensitive or thermoplastic types. In our work on epoxies we used it only for comparing samples after they had been subjected to various deteriorative influences.

1. Description of Final Apparatus

The apparatus finally adopted for general use also depended on test specimens prepared by adhesive bonding of 1-inch x 3-inch glass slides. In this instance, however, the slides were butt-joined along the main edges to form 2-inch x 3-inch flat test specimens. The slides thus joined were positioned and held between wax-coated wire separators in specially built wooden boxes during the oven curing operation. The specimens were then tested for bond strength in an apparatus where they were clamped horizontally between flat metal plates whose edges formed a line about 0.06-inch behind the glue line. A measured vertical stress was then applied along a line at the outer side of the cemented samples 0.30-inch from the glue line. Even distribution of applied stress was favored by clamping 3-inch sections of thin steel bar stock above and below the outer edge of the test specimens. Stress was applied manually through a spring-loaded tension gage calibrated in pounds with 1/4 pound sub-divisions. This gage, tested by direct measurement of applied known loads of 1, 2, 5 and 10 pounds, showed less than 1/2 pound variations from scale readings.

2. Stress Analysis

We have attempted to analyze stress characteristics of the bond strength test described in the foregoing section. While our treatment is certainly not rigorous it should provide a semi-quantitative basis for comparing bond strengths of candidate adhesives.

This test provides an indication of bond strength of adhesives in butt joint. Like other scarf joints, the butt joint enjoys the distinction of being relatively free of stress concentrations under tensile or compressive loads and is capable of developing the full compressive strength of the adherends under compressive loads. Under tension the adhesive in a butt joint tends to be drawn into the gap between the adherends. Under compression the adhesive tends to be extruded from the gap. The butt joint may be expected to be relatively free of stress concentrations if thin rigid films are used to join the adherends. Furthermore, the butt joint is among the easier types of joints to prepare. Accordingly, butt joints are used for the acquisition of test data on the mechanical behavior of adhesives and adherends.

In the present investigation, butt-jointed test samples were reduced to failure by application of stress in the direction of the glue line and perpendicular to the main plane of the sample surface. The equations for calculating the bending of a beam should apply, at least as a first approximation, for determining the strength of the candidate adhesive bonds under the conditions of this test. These equations are based on the use of Young's modulus.

The maximum bending moment M is given by $M = \frac{S_m I}{c}$

where S_m = maximum stress at upper and lower surfaces

I = moment of inertia of cross section

c = distance of extreme surface from neutral axis of beam.

The moment of inertia of cross section of a rectangular-sectioned beam about its neutral axis is $\frac{b\ d^3}{12}$ where b is the breadth and d the depth of the beam and is expressed in in^4.

The maximum bending moment of external forces acting on a beam is given by $M = W \cdot l$

where W = load

l = distance of load from support of the beam.

This formula, as written, applies to a beam supported at one end and loaded at the other and strictly speaking is valid only for a so-called "weightless" beam. In these experiements the weight of the glass can be neglected since the load is so great.

Combining the two equations, we can set up a formula for calculating the stress applied to the samples as follows:

$$W \cdot l = S_m\ I/c$$

$$S_m = \frac{W \cdot l \cdot c}{I}$$

But $c = d/2$ and $I = \frac{(b\ d^3)}{12}$

So $S_m = \frac{W \cdot l \cdot d \cdot 12}{2\ b\ d^3} = \frac{6\ Wl}{b\ d^2}$ psi

where W is in lb, and l, b, and d are in inches.

Substituting the appropriate constants applying to the present work, viz., 0.3, 3 and 0.04 for l, b, and d, one obtains the following approximate expression relating maximum stress in psi (S_m) to applied tension in pounds (W).

$$S_m = \frac{6 \cdot W \cdot 0.3}{3 \cdot 0.0016} = 3.75 \times 10^2 \times W \text{ psi}$$

This maximum stress is that to which the upper and lower surfaces of the beam would be subjected. We assume here that this stress is equal to the breaking point of the adhesive bond.

C. ULTRAVIOLET AND VISIBLE RADIATION EXPOSURE

The light source described below has been used in the preliminary and final screening phases of this work. In the preliminary phase radiation exposures were made with adhesives held between uncoated microscope slides (results reported in prior reports). In the final screening (data presented in section IV), exposures

were made with adhesives held between solar cell glass covers of the type selected by JPL for battery assembly. Final exposure test ensembles (measuring 1 cm. x 2 cm.) comprised a coated cover above the adhesive and an uncoated cover below. This was done both to conserve coated covers and to increase the sensitivity of subsequent transmissivity measurements through the test ensembles.

Exposure tests were conducted by placing samples on a white, matte surface placed 15.5 inches below the light source. Exposure time ranged from 24 hours up to 96 hours. The light source was a General Electric Co. UA-3 lamp connected to a George W. Gates & Co. ballast (serial no. 420-UI).

An attempt was made to measure the radiation intensity from the UA-3 photochemical lamp at a distance of 15.5 inches from the tube. A G.E. light meter with Germicidal attachment was used in conjunction with a Corning Filter #9863. This setup would normally provide a measure of the ultraviolet radiation between 2300 and 2900 A. The UA-3 is so intense, however, that the meter did not discriminate between the fluorescent light from the Germicidal attachment and the transmitted light from the lamp.

Although we are not presently equipped to determine the ultraviolet intensity of the UA-3 lamp, an approximation of the radiation energy can be made from data published in the G.E. bulletin "Engineering Publication LA-103" dated January 1952. The approximate average radiation intensities for UA-3 lamps are listed as follows:

Region	Watts Radiated
Far U.V. 2200 - 2800 A	14.8
Mid U.V. 2800 - 3200 A	13.3
Near U.V. 3200 - 3800 A	10.7
Visible 3800 - 7600 A	24.8

Treating the lamp as a point source, the illumination can be calculated from the following equation:

$E = F/A$ where F is the total light flux upon a surface area A.

For this lamp, the flux is the wattage of irradiated light, and the area, in^2, is that of the surface of a sphere whose radius is the distance between the point source and the object, i.e., 15.5 in. Then for each of the regions of the ultraviolet radiation, the energy is calculated, e.g.:

Far U.V. $E = \frac{4.9 \text{ milliwatts}}{in^2}$

Mid U.V. $E = \frac{4.4 \text{ milliwatts}}{in^2}$

Near U.V. $E = \frac{3.6 \text{ milliwatts}}{in^2}$

Of course these values are approximate since (1) the wattage irradiated is only approximate, (2) the lamp is not a point source, and (3) all samples are not exactly 15.5 inches from the lamp.

The energy expended per square inch of sample may be stated in terms of time as follows:

Exposure Time (Hours)	Far U.V.	Mid U.V. (Watt-Hours)	Near U.V.	Total U.V.
48	0.24	0.21	0.17	0.62
96	0.48	0.42	0.34	1.24

In the same manner the visible light energy can be calculated as follows:

$$\frac{24.8 \text{ watts}}{4 \cdot \pi \cdot (15.5\text{in.})^2} = \frac{8.3 \text{ milliwatts}}{\text{in}^2}$$

Then for one square inch of sample, the 48 hour exposure is equivalent to 0.40 watt-hours of visible light and the 96 hour period, 0.80 watt-hours.

D. PHYSICAL CONDITIONING PROCEDURES

In addition to ultraviolet and visible radiation exposure we employed various other physical conditioning procedures in line with the JPL Simulated Environmental Tests (Appendix). These included: (1) elevated temperature exposure, (2) low temperature exposure, (3) thermal shock, (4) moisture exposure, and (5) solvent exposure. As will be described later in section IV, bond strength data were obtained on samples subjected to various combinations of the conditioning procedures. These procedures are listed below in more detail.

1. Elevated Temperature Exposure

Test samples were heated to 250°F for 24 hours in a constant temperature, circulating air oven, set for minimum circulation.

2. Low Temperature Exposure

Samples sealed in polyethylene film envelopes were immersed for the designated numbers of times in a Dewar flask containing dry ice-diethyl ether mixtures. Temperatures of -100°F were recorded with these baths. Retention time was sufficient to assure thermal equilibrium.

3. Thermal Shock

The low temperature bath described above was used for the rapid (3 minute) temperature drop from +200°F to -100°F, before and after 250°F temperature soak.

4. Moisture Exposure

Test specimens were conditioned in a humidity cabinet maintained at 95% relative humidity and 130°F, with brief interval cooling to room temperature twice during the total period of 72 hours.

5. Solvent Exposure

The recommended adhesives (cured according to conditions defined in section IV-A)were examined for resistance to various commercial solvents.

IV. FINAL SCREENING OF CANDIDATE ADHESIVES

A group of eight epoxy resin systems was selected to receive the testing schedule recommended by Jet Propulsion Laboratories for solar cell glass slide adhesives. This group included five proprietary products favorably regarded by HLD and JPL, along with three ADL developmental formulations also considered promising by us at that time.

A. TECHNICAL DESCRIPTION OF ADHESIVES

The material presented in the following section has been extracted from both suppliers' technical bulletins and our own experimental observations. Attention is called to several instances of disagreement between the two informational sources.

1. Maraglas #655/H655

According to the Marblette Corporation of Long Island City, New York, MARAGLAS is described as a new, crystal clear, thermosetting epoxy casting resin. It has a 90% light transmission, and the resin has a 10-hour pot life. Being of low viscosity, MARAGLAS insures bubble-free castings. MARAGLAS is heat and weather resistant and has excellent adhesion to a variety of materials. When cured it becomes very hard, in fact, extremely hard when postcured. Among the properties listed in the Marblette data sheet are the following:

Viscosity, cps	500
Specific gravity	1.16
Rockwell Hardness	M95
Tensile strength, psi	8,900
Heat distortion point	190°F
Index of refraction N^{20}	1.55
Dielectric constant, 1000 cps	4.0
Dissipation factor, 1000 cps	0.02

Working instructions call for 2 parts, by weight, of Hardener #655H to 100 parts of the resin. For thin castings free from color a long, low-temperature cure is recommended; 155° - 160°F for 16 hours or more.

These published data suggested to us that MARAGLAS is probably based on a low molecular weight epoxy resin such as Shell's EPON 562, possibly thinned further with a reactive diluent, and cured by tertiary amine catalyzed self-polymerization. Such a system is capable of outstanding optical properties but rather mediocre mechanical properties, as evidenced by the low heat distortion point.

Our earlier interest in MARAGLAS for this application waned as we repeatedly experienced difficulty in finding the optimum cure conditions, the recommended time and temperature proving insufficient. Moreover, a number of our test specimens broke in a way that indicated embrittlement following post-curing. Only its excellent clarity and color stability kept it in the program until the end.

2. Epocast 15-E/9010

Supplied by Furane Plastics, Inc., of Los Angeles, EPOCAST 15-E is described as a clear epoxy resin system intended for use as a potting and impregnating resin for electrical and mechanical purposes where a tough, semi-rigid resin is required. Among the physical properties enumerated in the Furane Plastics data sheet are the following:

Viscosity (75°F), cps	4000
Hardness "D" (Inst./10 sec.)	46/24
Tensile strength, psi	1100
Vol. resis. (ohm-cm.) (66°F)	10^{15}
Dielectric Constant, 1000 cps	4.2

The supplier recommends that the resin be prepared for service by mixing 200 parts with 100 parts by weight of Hardener 9010. For harder castings the recommended proportions become 160 and 100, respectively. The pot life at room temperature is excellent, lasting a day or more. EPOCAST 15-E/9010 will gel at 200°F in about 3 to 4 hours. Curing requires about 8 to 10 hours at 200°F, followed by 2 hours at 250°F.

3. Epocast H-1321/9010

Furane Plastics, Inc. recommended that another of their adhesives, EPOCAST H-1321/9010, be included in our testing since it might have more flexibility than adhesives based on EPOCAST 15-E. No physical property data accompanied this sample. Recommended working instructions called for 100 parts by weight of H-1321 to 65 parts by weight of Hardener 9010. This system was stated to possess a three-day pot life and could be cured successfully in either 6 hours at 200°F or 3 hours at 250°F. We employed the former condition.

4. Bonding Agent R-313/Hardener B

Offered by the Carl H. Biggs Company of Santa Monica, California, BONDING AGENT R-313 is an epoxy resin system which will cure at room temperature to form transparent, nearly water white bonds. According to the supplier it is widely used for sealing glass to metal, as in the bonding and pressure sealing of windows in instrument cases. The technical data sheet offers the following pertinent information:

Viscosity, cps	3600
Specific gravity	1.2
Rockwell Hardness	B100
Tensile strength, psi	8500
Shear strength of bond, psi	3000
Heat resistance	-100°F to +350°F
Index of refraction	1.562
Dielectric constant, 1000 cps	5.0
Vol. resis. (ohm-cm.)	2.5×10^{13}

Operating instructions require addition of 6% by weight of Hardener B to yield a thermosetting compound which begins to gel within one hour at a room temperature of 70°F or higher. A pot life of several hours is claimed for mixtures maintained below 60°F. Hardener B seems quite reactive (probably diethylenetriamine), and accordingly, this formulation cures to its near ultimate shear strength (3200 psi) in 16 hours at 72°F. However, some 200°F oven curing or prolonged room temperature curing (>72 hours) are required to build up its heat and solvent resistance.

Our investigations with this adhesive have not revealed any inconsistencies with the supplier's claims.

5. Bonding Agent R-314/Hardener A

It is stated by the Carl H. Biggs Company that BONDING AGENT R-314 is similar in all respects to R-313, except for its curing cycle. The R-314 was developed due to demand for an adhesive with a longer pot life. Commercially, it has found utility in the applications cited for R-313. This yields a compound having an all-day pot life and a low-temperature oven cure (200°F for one hour). The mixture will also harden in 48 hours at room temperature but full cure takes about a week. Its reported physical properties differ only slightly from those of BONDING AGENT R-313:

Viscosity, cps	3600
Specific gravity	1.2
Rockwell Hardness	B100
Tensile strength, psi	7,300
Shear strength of bond, psi	2,500
Heat resistance	-100°F to +350°F
Index of refraction	1.562
Dielectric constant, 1000 cps	5.0
Volume resis. (ohm-cm.)	2.5×10^{13}

6. Epon X-18:Epon X-71(1:1)/HHPAA

This is an ADL experimental formulation based on two developmental resins from Shell Chemical Company and an anhydride hardener from Allied Chemical Company.

EPON X-18 was used on the basis that it offered improved color stability over the commercial EPON 828 which it resembles in other respects. (However, we detected no optical advantages for X-18 and therefore went back to EPON 828 for other experimental blends.)

Shell Chemical Company has developed EPON X-71 to provide products with greater postcure flexibility than conventional epoxy resins. Hitherto, product flexibility, a property needed to some degree in the solution of the present problem, has been obtained by the use of plasticizers or flexible curing agents in conjunction with conventional (inherently rather brittle) epoxy resins. Plasticizers are inclined to be fugitive additives; and, the flexible curing agents including THIOKOL (a linear, polysulfide polymer), VERSAMID (amino-amides) and DUOMEEN (long-chain, aliphatic diamines) are apt to introduce unstable color bodies and are certain to reduce mechanical properties including heat distortion point. However, according to Shell Chemical Company the EPON X-71 has considerable flexibility built into the resin itself, on the basis of physical property data disclosed for various blends of EPON X-71 and EPON 828 cured with several commercial hardeners. Wide variations in tensile elongation were shown for a series of blends varying only moderately in tensile strength, a desirable phenomenon rarely observed in epoxy systems.

Typical properties of EPON X-71 are summarized as follows:

Epoxy value, equivalent/100 gms.	0.250
Viscosity at 25°C, cps	500
Gardner color.	10-11
Density, 20°C.	0.987

Hexahydrophthalic anhydride (HHPAA) is one of the group of commercial acid anhydride curing agents. Products obtained through the use of anhydride curing agents are characterized by outstanding mechanical properties such as high strength at elevated temperatures. Such formulations have long pot life and require more oven curing than most other epoxy systems. Good clarity and color is favored by long low temperature precuring prior to applying the higher temperature postcuring needed for developing ultimate mechanical properties. HHPAA is a colorless solid which dissolves readily with minimum stirring in warmed liquid epoxy resins to produce low to medium viscosity curing systems.

This formulation was prepared from 50 parts by weight of EPON X-18, 50 parts of EPON X-71, 80 parts of HHPAA and 1 part of tris(n-octylamine) cured at 200°F for 16 hours and postcured at 250°F for 6 hours. (The tertiary amine functions as a catalyst to reduce the curing time.)

7. Epon 828:Epon X-71(3:1)/HHPAA

Also an experimental formulation, this may be described as an EPON X-71-flexibilized-EPON 828-anhydride cured system. Our objectives in developing such a system have been discussed in the preceding section. Here, we reduced the amount of flexibilizing resin to the minimum we thought necessary for bond protection in the face of the environmental thermal stresses likely to be encountered.

We also went over to Shell's general purpose epoxy resin EPON 828 for the reasons already given.

This formulation was prepared from 75 parts by weight of EPON 828, 25 parts of EPON X-71, 88 parts of HHPAA and 1 part of tris(n-octylamine). The system appeared to have a long pot life (eight hours or more) and required elevated temperature curing. Various curing conditions have been used here, possibly without discovering the optimum. However, the conditions used to prepare final screening samples were 16 hours at 200°F, followed by a 6-hour postcure at 250°F.

The freshly mixed adhesive had a viscosity of 450 cps at 77°F.

8. Epon 828:Epon X-71(3:1)/Menthane Diamine

This experimental adhesive is similar to the preceding one, differing only in choice of hardener. Here, menthane diamine was used in place of HHPAA. Menthane diamine, manufactured by the Rohm & Haas Company, has been found very effective as a curing agent for epoxy resins. Among the properties claimed are the following: (a) low viscosity, easily mixed fluid; (b) not a skin sensitizer, based on animal tests; (c) cured resin has high heat distortion temperature, very good electrical properties and mechanical properties; (d) gives lighter color prior to and after curing; and (e) mix has long pot life at room temperature.

This formulation was prepared from 75 parts by weight of EPON 828, 25 parts of EPON X-71, and 24 parts of menthane diamine. The system did appear to possess a long pot life (over six hours) and was cured by oven heating for 4 hours at 250°F.

Samples prepared from this adhesive and all others used in this investigation were aged at least 48 hours after curing prior to physical testing.

B. OUTLINE OF TESTING PROGRAM

Our approach to the laboratory testing of the eight remaining adhesives warranting final screening will be outlined briefly before presentation of the test data.

First, we prepared a sufficient number of test specimens (252 samples) to provide (a) bond strength data based on replicated measurements for each adhesive after physical conditioning according to JPL recommendation, and (b) light transmission data after appropriate conditioning. Tests under (a) (a) were performed in triplicate with uncoated glass-to-glass samples, prepared from one-inch x three-inch pre-cleaned microscope slides (BKH Cat. No. 48312), and used as described in section III-B-1. Tests under (b) were performed, mostly in duplicate, with the UV-exposure test ensembles described in section III-C.

To summarize, the eight candidate adhesives were rated on "total scores," compiled from the sum of averaged bond strength measurements (in pounds of force) of test samples conditioned by the following eight procedures:

1. No Treatment
2. Heat Soak (250°F for 24 hours)
3. Cold Soak, No Prior Treatment (-100°F)
4. Cold Soak, After Heat Soak (250°F for 24 hours followed by -100°F, one cycle)
5. Thermal Shock, No Prior Treatment (+200°F to -100°F in 3 minutes, two cycles)
6. Thermal Shock, After Heat Soak (250°F for 24 hours followed by -100°F to +200°F, two cycles in 3 minutes)
7. Ultraviolet and Visible Radiation (96 hour direct exposure to previously described lamp)
8. Moisture Effect (72 hour exposure to 95% relative humidity at 130°F, with brief interval cycling twice to room temperature).

On the basis of "total scores" (see Tables I through VIII) four adhesives were thus disqualified as a consequence of inferior mechanical properties. At this point, with the reduced number of candidates, we were in a position to utilize the one-inch x three-inch coated glass slides, specially prepared for this investigation.* These slides were covered with the same UV-reflectant coating as that used on the underside of the solar cell covers. These coated slides were of the proper size for use in our bond test. Test samples prepared from these covered slides were identical to those described in section III-B-1, except that these specimens comprised one coated slide cemented to one uncoated slide in the prescribed manner. Sample surface conditions were standardized as follows: all glass slides, coated and uncoated, were dipped first in benzene and then acetone, oven dried for one hour at 250°F, and stored in a capped bottle until used. To conserve coated slides and to accelerate the program, we reduced the number of conditioning procedures at this point to include only numbers 1, 2, 6, and 8. We introduced two other tests designated 9 and 10, however, which may be described as follows:

9. No Treatment, Bond Tested at 250°F
10. Solvent Effect (resistance to common solvents judged by soaking experiments at room temperature).

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* Optical Coating Laboratory, Inc., Santa Rosa, California; packing no. 11B24; November 24, 1959.

Using a Beckman Model DU spectrophotometer, transmission measurements were made for adhesive-bonded sandwich ensembles, comprising optically coated cell covers surmounting uncoated cell covers. These test specimens were measured for % transmission before and after exposure to ultraviolet light. The reference standard for 100% transmission was air without the sample holder in place.

C. TEST RESULTS

1. Bond Strength Data

Most of the data that we have developed on the eight candidate adhesives are presented in Tables I through VIII. It may be observed that bond strengths ranged from nil to over 4500 psi, depending on adhesive system and preconditioning. These data were obtained with the apparatus described in section IV-B-1. For convenience, adhesives are referred to below by the numbers used in part A of this section.

Solvent resistance tests have also been performed in addition to those referred to above. Solvents used included: acetone, 95% ethanol, and benzene. The four final group candidate adhesives (#1, 4, 5, and 7), (in the form of bond strength test samples) were immersed for measured periods of time in the above solvents at room temperature. Moderate finger pressure was applied to the various samples: (a) initially, (b) after one-half hour, and (c) after two hours. All samples using adhesive #4 broke in an initial pressure test and were excluded from the remainder of the test. On the basis of these qualitative data the candidate adhesives are resistant to the test solvents in the following order of decreasing strength: in acetone, #1, #5, #7; in ethanol, #1,#7, #5; in benzene, #1, #7, #5. (Only #1 remained unbroken after two hours immersion in all solvents.)

Silicon-to-glass adhesion was investigated for these same four adhesives (#1, 4, 5, and 7). It was judged good in each case, based on samples prepared from silicon solar cells* cemented to coated microscope slides. Attempts to break the bond invariably resulted in destruction of the silicon cells--a finding which indicates: (a) that the bond is basically good, and (b) that the shear strength of epoxies can sometimes exceed the internal strength of silicon, at least for components in the dimensions of interest here.

Impact tests were also made with various laminated glass and silicon-glass assemblies, using the four adhesives which qualified for final testing. No quantitative data were obtained. However, visual inspection of laminates deliberately smashed with various implements left no doubt of the superiority of adhesive #7 (EPON 828:EPON X-71(3:1)/HHPAA) in holding together the fragments, much in the manner of safety glass.

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* Supplied by Hoffman Laboratories, Inc., Los Angeles 7, California; D.M. No. 57514 and P.O. No. 60L-27124-470, December 3, 1959.

TABLE I

BOND STRENGTH DATA FOR EPOCAST H-1321/9010

Conditioning Test		Applied Tension (pounds)				Maximum Stress[a] (psi)
No.	Name	#1	#2	Average	1/Average[b]	
	UNCOATED GLASS					
1	No Treatment	1.5	3.5	2.5	0.40	950
2	Heat Soak	1.5	n.r.[c]	1.5	0.66	550
3	Cold Soak	3.0	3.0	3.0	0.33	1000
4	Cold Soak, after Heat Soak	1.0	n.r.	1.0	1.00	400
5	Thermal Shock	2.0	2.0	2.0	0.50	750
6	Thermal Shock, after Heat Soak	1.0	1.8	1.4	0.70	550
7	UV-Exposure	3.0	3.0	3.0	0.33	1000
8	Humidity	0.5	f.a.[d]	0.4	2.50	150
		Total Score =		14.8	6.42 (Sum of Reciprocals)	

[a] Calculated from the expression shown in section IV-B-2 and rounded off to the nearest 50 psi.

[b] The sum of the reciprocal averages gives a more sensitive indication of over-all suitability than does the "Total Score"; with reciprocals, low score is desirable.

[c] n.r. refers to samples not run through conditioning tests or the subsequent bond strength test because of failure to establish a bond on curing.

[d] f.a. means that the conditioned sample fell apart with a minimum application of stress in the bond strength test; for use in computing average tensions f.a. has been assigned an arbitrary value of 0.25 pound.

TABLE II

BOND STRENGTH DATA FOR EPOCAST 15-E/9010

Conditioning Test		Applied Tension (pounds)					Maximum Stress (psi)
No.	Name	#1	#2	#3	Average	1/Average	
	UNCOATED GLASS						
1	No Treatment	2.0	2.0	2.0	2.00	0.50	750
2	Heat Soak	0.8	1.8	1.8	1.45	0.69	550
3	Cold Soak	2.5	2.5	n.r.	2.50	0.40	950
4	Cold Soak, after Heat Soak	2.5	1.5	n.r.	2.00	0.50	750
5	Thermal Shock	2.0	3.0	n.r.	2.50	0.40	950
6	Thermal Shock, after Heat Soak	2.5	2.0	n.r.	2.25	0.44	850
7	UV-Exposure	2.5	2.0	3.0	2.50	0.40	950
8	Humidity	0.8	0.8	f.a.	0.80	1.25	300
				Total Score =	16.00	4.58 (Sum of Reciprocals)	

TABLE III

BOND STRENGTH DATA FOR MARAGLAS #655/H655

Conditioning Test		Applied Tension (pounds)					Maximum Stress (psi)
No.	Name	#1	#2	#3	Average	1/Average	
A. UNCOATED GLASS							
1	No Treatment	3.5	3.5	3.0	3.33	0.30	1250
2	Heat Soak (24 hr.)	10.3	9.5	6.5	9.10	0.11	3400
3	Cold Soak	4.0	n.r.	n.r.	4.00	0.25	1500
4	Cold Soak, after Heat Soak	10.0	9.5	n.r.	9.75	0.10	3650
5	Thermal Shock	1.0	1.5	n.r.	1.25	0.80	500
6	Thermal Shock, after Heat Soak	5.0	1.5	n.r.	3.25	0.31	1200
7	UV-Exposure	5.0	5.5	4.0	4.83	0.21	1800
8	Humidity	1.0	f.a.	n.r.	0.63	0.59	250
				Total Score =	36.14	2.67 (Sum of Reciprocals)	
B. COATED GLASS							
1	No Treatment	3.0	3.5		3.25	0.31	1200
2	Heat Soak (40 hr.)	6.5	7.0		6.75	0.15	2550
6	Thermal Shock, after Heat Soak	3.5	n.r.		3.50	0.29	1300
8	Humidity	3.5	f.a.		1.88	0.53	700
9	No Treatment, but Bond Tested at 250°F	(2 sec.)*(2 sec.)					
				Total Score =	15.38	1.28 (Sum of Reciprocals)	

* Time to failure for test specimen in a 250°F environment.

TABLE IV

BOND STRENGTH DATA FOR BONDING AGENT R-313/B

Conditioning Test		Applied Tension (pounds)					Maximum Stress (psi)
No.	Name	#1	#2	#3	Average	1/Average	
A. UNCOATED GLASS							
1	No Treatment	12.0	12.0	12.5	12.17	0.08	4550
2	Heat Soak (24 hr.)	10.0	10.5	n.r.	10.25	0.10	3850
3	Cold Soak	7.0	7.0	n.r.	7.00	0.14	2700
4	Cold Soak, after Heat Soak	10.0	10.0	n.r.	10.00	0.10	3750
5	Thermal Shock	7.0	6.0	n.r.	6.50	0.15	2450
6	Thermal Shock, after Heat Soak	5.0	n.r.	n.r.	5.00	0.20	1900
7	UV-Exposure	6.0	10.0	9.0	8.33	0.12	3100
8	Humidity	1.8	f.a.	f.a.	1.80	0.56	
9	No Treatment, but Bond Tested at 250°F	(5 sec.)					
				Total Score =	61.05	1.45 (Sum of Reciprocals)	
B. COATED GLASS							
1	No Treatment	3.0	2.0		2.50	0.40	950
2	Heat Soak (40 hr.)	3.0	2.0		2.50	0.40	950
6	Thermal Shock, after Heat Soak	1.5	1.5		1.50	0.66	550
8	Humidity	f.a.	f.a.		0.25	4.00	100
9	No Treatment, but Bond Tested at 250°F	(7 sec.)	(14 sec.)				
				Total Score =	6.75	5.46 (Sum of Reciprocals)	

TABLE V

BOND STRENGTH DATA FOR BONDING AGENT R-314/A

Conditioning Test		Applied Tension (pounds)					Maximum Stress (psi)
No.	Name	#1	#2	#3	Average	1/Average	
A. UNCOATED GLASS							
1	No Treatment	4.5	2.5	2.0	3.00	0.33	1000
2	Heat Soak (40 hr.)	7.0	6.5	5.0	6.17	0.16	2300
3	Cold Soak	3.0	3.0	n.r.	3.00	0.33	1000
4	Cold Soak, after Heat Soak	3.0	5.0	n.r.	4.00	0.25	1500
5	Thermal Shock	3.0	3.0	n.r.	3.00	0.33	1000
6	Thermal Shock, after Heat Soak	4.0	4.5	3.0	3.83	0.26	1450
7	UV-Exposure	4.0	2.0	6.0	4.00	0.25	1500
8	Humidity	1.8	2.8	f.a.	1.62	0.62	600
9	No Treatment, but Bond Tested at 250°F	(51 sec.)	(64 sec.)				
				Total Score =	28.62	2.53 (Sum of Reciprocals)	
B. COATED GLASS							
1	No Treatment	2.0	2.0		2.00	0.50	750
2	Heat Soak (40 hr.)	4.5	n.r.		4.50	0.22	1700
6	Thermal Shock, after Heat Soak	3.0	2.0		2.50	0.40	950
8	Humidity	0.5	f.a.		0.38	2.63	150
9	No Treatment, but Bond Tested at 250°F	(49 sec.)	n.r.				
				Total Score =	9.38	3.75 (Sum of Reciprocals)	

TABLE VI

BOND STRENGTH DATA FOR EPON X-18:EPON X-71(1:1)HHPAA

Conditioning Test		Applied Tension (pounds)				Maximum Stress (psi)
No.	Name	#1	#2	Average	1/Average	
	UNCOATED GLASS					
1	No Treatment	1.8	1.8	1.80	0.55	700
2	Heat Soak	0.8	3.0	1.90	0.53	700
3	Cold Soak	4.0	4.5	4.25	0.24	1600
4	Cold Soak, after Heat Soak	3.0	5.0	4.00	0.25	1500
5	Thermal Shock	1.0	2.0	1.50	0.66	550
6	Thermal Shock, after Heat Soak	2.5	n.r.	2.50	0.40	950
7	UV-Exposure	6.5	4.0	5.25	0.19	1950
8	Humidity	f.a.	f.a.	0.25	4.00	100
		Total Score =		21.45	6.82 (Sum of Reciprocals)	

TABLE VIII

BOND STRENGTH DATA FOR EPON 828:EPON X-71(3:1)/MENTHANE DIAMINE

Conditioning Test		Applied Tension (pounds)				Maximum Stress (psi)
No.	Name	#1	#2	Average	1/Average	
	UNCOATED GLASS					
1	No Treatment	2.0	3.0	2.50	0.40	950
2	Heat Soak	5.0	6.5	5.75	0.17	2150
3	Cold Soak	f.a.	2.5	1.38	0.72	500
4	Cold Soak, after Heat Soak	0.8	n.r.	0.80	1.25	300
5	Thermal Shock	f.a.	n.r.	0.25	4.00	(95)*
6	Thermal Shock, after Heat Soak	0.8	n.r.	0.80	1.25	300
7	UV-Exposure	2.0	2.0	2.00	0.50	750
8	Humidity	0.8	f.a.	0.80	1.25	300
		Total Score =		14.28	9.54 (Sum of Reciprocals)	

* Insufficient number of samples to have any quantitative significance.

2. Transmission Data

Measurements of % transmission of the eight adhesives of interest are presented in Tables IX through XII. Adhesive thickness of the sandwich samples ranged from 0.1 mil to 1.0 mils and averaged about 0.3 mil. The transmission values reported are mostly in the range of 50-60% rather than 90-100% simply because the test reference used was: air=100% without sample holder in place.

In general, the data revealed a high level of transmissivity over the regions of interest. There are no prominent absorption peaks shown for these epoxy resins; neither are there any clear indications of increasing opacity with continued exposure to ultraviolet radiation. Indeed, some of the spectrophotometric readings suggest that absorption peaks can shift and even decrease slightly under the continued influence of UV and visible radiation. The evidence is quite clear that all eight adhesives tested here contribute less than a 5% absorption to the incident integral light in the spectral region 0.43-1.1μ when used under a coated cover glass at thicknesses ranging up to about 1 mil.

TABLE IX

TRANSMISSION OF SOLAR CELL COVER GLASS

% Transmission (Air = 100%)

Wavelength (mμ)	Initial	48 hours UV	96 hours UV
UNCOATED GLASS			
400	52.0	55.8	52.8
450	51.8	55.2	54.0
500	54.0	55.8	54.8
550	53.6	56.3	55.0
600	54.3	56.6	55.3
650	49.8	49.8	51.3
700	48.8	48.8	48.0
750	49.4	50.5	50.2
800	49.8	49.0	50.2
850	49.2	49.5	47.2
900	49.8	50.2	50.0
950	49.5	50.0	50.0
1000	49.5	50.0	50.0
1050	50.8	50.2	51.0
1100	50.0	50.5	51.2
COATED GLASS			
400	0.2	0.0	0.2
450	30.0	26.5	21.0
500	61.5	61.0	56.2
550	59.0	62.8	62.2
600	63.0	64.3	63.3
650	57.7	56.3	58.2
700	55.0	56.0	53.3
750	55.3	56.8	56.0
800	54.5	55.2	55.0
850	54.0	55.8	50.7
900	54.7	56.8	53.0
950	54.0	56.8	55.5
1000	54.0	56.3	56.8
1050	57.8	54.0	56.0
1100	56.8	54.5	56.0

TABLE X

TRANSMISSIVITY DATA OF EPOCAST 15-E AND MARAGLAS 655

% Transmission (Air = 100%)

Wavelength (mμ)	Initial*	48 hours UV	96 hours UV
EPOCAST 15-E			
400	n.a.	0.5	0.2
450		15.8	15.0
500		58.5	59.2
550		66.6	67.0
600		67.4	67.4
650		62.0	64.5
700		62.3	63.0
750		63.5	64.2
800		63.7	64.3
850		63.7	64.2
900		63.8	64.3
950		63.8	64.2
1000		63.8	64.0
1050		63.8	64.3
1100		63.8	64.2
MARAGLAS 655			
400	1.0	1.0	n.r.**
450	49.0	48.0	
500	60.7	57.8	
550	64.8	64.2	
600	64.8		
650	58.8	60.8	
700	59.8		
750	60.2	62.0	
800	60.2		
850	60.0	60.2	
900	57.8		
950	60.0	61.5	
1000	60.0		
1050	60.0	62.3	
1100	60.8		

* n.a. - not available because initial readings were made on the basis of coated cover glass = 100% transmission; the test sandwiches exceeded 115% and could not be read; hence, the change of reference standard to air = 100%

** n.r. - not run

TABLE XI

TRANSMISSIVITY DATA OF

EPON X-18:EPON X-71/HHPAA AND EPON 828:EPON X-71/HHPAA

% Transmission (Air = 100%)

Wavelength (mμ)	Initial	48 hours UV	96 hours UV
EPON X-18:EPON X-71/HHPAA			
400	n.a.	0.8	0.5
450		45.8	42.3
500		62.5	62.5
550		63.0	63.3
600		62.8	64.0
650		57.7	59.7
700		57.4	56.8
750		59.0	58.2
800		57.2	57.3
850		58.0	58.0
900		57.2	57.2
950		56.2	58.0
1000		57.8	58.4
1050		57.7	59.0
1100		56.5	58.8
EPON 828:EPON X-71/HHPAA			
400	0.4	0.5	n.r.
450	9.3	9.2	
500	52.7	53.8	
550	55.0	56.8	
600	56.2		
650	48.7	49.0	
700	49.0		
750	50.3	50.0	
800	49.2		
850	49.6	50.0	
900	48.0		
950	48.5	50.2	
1000	49.8		
1050	50.0	51.0	
1100	50.7		

TABLE XII

TRANSMISSIVITY DATA OF

BONDING AGENTS R-313/B AND R-314/A

% Transmission (Air = 100%)

Wavelength (mμ)	Initial	48 hours UV
BONDING AGENT R-313/B		
400	1.0	1.0
450	46.0	50.0
500	60.0	61.0
550	59.8	60.7
600	62.0	
650	59.0	55.0
700	55.3	
750	55.8	56.0
800	55.3	
850	55.3	55.8
900	54.3	
950	55.0	55.0
1000	55.0	
1050	55.2	55.2
1100	55.7	
BONDING AGENT R-314/A		
400	0.4	0.6
450	9.2	12.2
500	56.3	56.0
550	64.3	65.0
600	65.2	
650	55.8	55.2
700	57.0	
750	58.0	57.3
800	57.3	
850	57.6	58.0
900	56.5	
950	57.2	58.2
1000	58.3	
1050	58.8	57.7
1100	59.0	

V. DISCUSSION OF RESULTS

A. BOND STRENGTH MEASUREMENTS

These data, at best, provide semi-quantitative bond strengths (reported in psi) and, at the least, offer a reproducible physical basis for separating promising adhesives from those obviously unsuited. However, we caution against relying solely on comparative total scores reported in the foregoing section. In general, low scores disqualify but high scores do not necessarily establish a winner. At present we do not know how to weight the parameters of interest to favor correlation of our bond test results with those that may be expected in service--for example, whether a low score here on temperature cycling is more serious than moisture sensitivity or low heat distortion point. Hence, our conclusions and materiels recommendations are based partly on various less-readily-measurable properties such as handling convenience, toxicity, and tendency toward property changes on aging.

Consideration solely of high score would establish BONDING AGENT R-313/B as superior to all others tested here, at least for uncoated glass. It cannot be recommended for this use, however, because: (a) the pot life is too short (1 hour) and (b) slightly overcured samples fail through embrittlement. We feel that BONDING AGENT R-314/A, being semi-flexible in the cured state, is a better prospect for long service life, despite its lower score.

Despite the high test scores for MARAGLAS it must be disqualified by virtue of its poor high-temperature properties.

The two EPOCAST adhesives gave only fair results by our test program. However, the 15-E at least should not be eliminated from further consideration as it possesses a modest balance of physical qualifications without any overpowering defects.

One of the ADL developmental adhesives, EPON 828:EPON X-71(3:1)/HHPAA, gave the highest comparative score on optically coated glass without displaying any disqualifying physical defects in marked degree. Of particular significance, we believe, is the excellent high temperature performance that this semi-flexible system has displayed in our studies. The other two ADL experimental epoxy systems were not outstanding.

B. LIGHT TRANSMISSION MEASUREMENTS

At the time of our second oral report in Los Angeles we were instructed by Jet Propulsion Laboratory to conduct future UV exposure tests and related transmission measurements only with samples incorporating coated glass cell covers of the type expected to be used on spacecraft solar batteries. This approach seemed to those present, including ourselves, to be both realistic and feasible for

acquiring optical data needed for adhesive selection in this projected use. We still agree that it appears to be a direct and ostensibly realistic approach, especially from a user's standpoint. From a data acquirer's standpoint, however, we now have certain reservations about (1) the technical feasibility and (2) the comparative significance of spectrophotometric measurements made with such samples when exercising the standard care and precautions for such work.

Using an aluminum sample holder specially constructed to hold four cell-cover sandwich samples at one time, we have obtained a considerable number of spectrophotometric measurements (most are reported here) on the final group of eight candidate adhesives. On inspection of the data, however, we found a remarkable agreement in transmission values among the various adhesives, UV-exposed and otherwise. We could only conclude that in such very thin films (0.3 mil) these adhesives are too transparent to permit detection of minor differences in transmission. Detection of such minor differences would require considerable refinement of technique and apparatus and would probably be academic in relation to the objectives of this investigation.

APPENDIX

TEST PROGRAM AS SUBMITTED TO

HOFFMAN ELECTRONICS CORPORATION AND ARTHUR D. LITTLE, INC.

BY JET PROPULSION LABORATORIES

Factor	Cognizance
1. TEMPERATURE	ADL and HLD
a. Maximum 250°F for 24 hours	
b. Minimum -130°F for 1 hour	
2. THERMAL SHOCK	ADL and HLD
a. +200°F to -100°F in 3 minutes	
b. Measured before and after maximum temperature soak	
3. MOISTURE AND SOLVENT RESISTANCE	ADL and HLD
a. Maximum 130°F, 95% relative humidity for 72 hours with interval cooling to room temperature twice.	
b. Must be resistant to commercial solvents	
4. ADHESIVE BOND STRENGTH	ADL
a. Measure at +250°F and at -130°F using the ADL recommended technique	
b. Surface condition must be defined	
c. The effect and degree of cleanliness of the glass must be defined	
d. The technique of cleaning glass and cells must be defined (i.e., alcohol, water, ultrasonics, degreaser, etc.)	

APPENDIX (Continued)

Factor	Cognizance
5. LIGHT TRANSMITTANCE	ADL
a. Original	
b. Loss from elevated temperature aging (250°F) measured with coated cover glass	
c. Loss due to exposure to visible and ultra-violet light with filter	
6. VIBRATION RESISTANT	HLD
(According to Vega TA Shake)	
7. MECHANICAL SHOCK	HLD
(50 g's, 1-millisec. raise time in 3 mutually perpendicular directions)	
8. HANDLING	ADL and HLD
a. Pot life characteristics must be defined	
b. Viscosity characteristics must be defined	
9. EFFECT OF ADHESIVE ON:	HLD
a. Solar cell junction. . .no degradation in observed output	
b. U.V. filter	
c. U.V. coating stability at 250°F for 24 hours and -130°F for 1 hour	
10. COVER GLASS	HLD
a. Characteristics of the filter	
b. Coefficient of thermal expansion	
c. Physical properties of glass	
11. APPLICATION PROCEDURES	ADL and HLD

APPENDIX (Continued)

Factor	Cognizance
12. VACUUM STABILITY	HLD
a. Final selected samples will be tested in a vacuum of 2×10^{-7} mm. of Hg for 7 continuous days.	
b. Upon completion of the vacuum test the thermal shock test will be administered again	
c. The extent of the degradation to output must be determined after vacuum stability test	
13. X-RAY BOMBARDMENT	