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AIRCRAFT BATTLE DAMAGE REPAIR OF TRANSPARENCIES

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Both induction heating and adhesive bonding techniques were used to perform rapid repairs on aircraft transparencies under "field" conditions. Patches were applied on various plastic laminated materials and were tested both for air leak rate and structural durability (cockpit air pressure representing ground-air-ground cycles).

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PREFACE

This report covers work performed during the period from October 1986 to December 1988 under Air Force Contract F33615-86-C-5031. The work was performed and evaluated by the University of Dayton Research Institute and administered under the direction of the Systems Support Division of the Wright Research and Development Center, Wright-Patterson Air Force Base, Ohio 45433-6533. Messrs. Robert Urzi, William Purcell, and Mark Forte were the Program Engineers. The Principal Investigators on this program were Ms. Susan S. Saliba and Mr. D. Robert Askins. The major portion of the laboratory work was conducted by Ms. Susan S. Saliba, Mr. Gary Andrews and Mr. L. Dee Pike. A significant portion of the adhesive bonding work was conducted on base by Sergeant Brian Cramer and is included in this report.

This report was submitted by the authors for publication May 1989.

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Section 1. Background and Introduction

Aircraft Battle Damage Repair (ABDR) is a growing area of concern in today's Air Force.[1] Repair methods are currently being developed to provide increased sortie generation rates in a wartime environment. Recently, several concepts which could provide ABDR capability for aircraft transparencies have become available. The objective of this project was to evaluate these concepts in the laboratory and to develop an approach for deployment to field units.

Prior to this program, there was little or no effort directed toward developing ABDR techniques for transparencies that would allow the transparency to be pressurized. Damaged transparencies were repaired by bolting a sheet of aluminum over the damaged area. This technique is sufficient to keep the windblast out of the cockpit, but would be less than optimum for an aircraft making a combat mission. The primary objective was to evaluate induction heating as a repair technique. Polycarbonate, cast and stretched acrylic transparencies of various classes and construction types were considered. The criteria for assessing the merit of a particular ABDR technique or of particular materials involved both structural as well as material and processes (M&P) considerations and are listed below.

Structural Criteria:

- Seal pressure leaks.
- Prevent excessive aerodynamic noise.

- Withstand 100 hours of simulated combat operations without flight restrictions.
- Damage not causing leaks or noise need not be repaired.

M&P Criteria:

- All materials and processes must be as simple to use as possible.
- Only those tools which are standard or multi-purpose, simple to operate, and which use readily available power should be required.
- The procedure and materials will require only simple instructions and little training and have wide process limits.
- Repairs must be capable of completion with less than 2 man-hours effort.

Section 2. Materials and Tasks

2.1 Materials and Equipment

The Inductron Corporation's TOROBONDER was used to fuse patches to polycarbonate, cast acrylic, and stretched acrylic canopies as well as to provide a heat source for structural bonding of patches to each type of transparency. Both polycarbonate and cast acrylic patches in thicknesses ranging from 1/16 inch to 3/8 inch were evaluated. Two patch sizes, large (4 in X 6 in) and small (3 in O.D.), were evaluated. These patch sizes are considered to be compatible with current ABDR practices. In addition, a heating blanket or hot-air gun was utilized to pre-form the patch prior to bonding.

2.1.1 The TOROBONDER

The TOROBONDER is based on a self-tuning, solid-state power oscillator feeding 30- to 80-kHz power to a ferrite toroid. The toroidal shape introduces a uniform, concentrated magnetic flux into the area to be heated. A susceptor is required to direct the heating energy in materials which are not paramagnetic. By positioning the susceptor directly in the bond line, concentrated local heating is possible. Two types of hand-held heating heads were employed for the fusion bonding or heat curing process.[2] Figures 1 and 2 illustrate the two types of heating heads.

2.1.2 Types of Adhesives

Adhesive bonding repair was carried out with ten different adhesives. These adhesives as well as their suppliers are listed in Table 1.

Table 1

ADHESIVES FOR ABDR APPLICATION

Adhesive	Type	Supplier
Epoxy 907	Epoxy	Miller-Stephenson
Plastic Steel Epoxy	Epoxy	Devcon
2-Ton Epoxy	Epoxy	Devcon
EC 3569	Epoxy	3M
PS-30 Acrylic	Acrylic	Caseway Industrial Products
Box Patch	Acrylic	Philadelphia Resins
Hot-Melt Adhesive 3779		3M
Zip Patch	Acrylic	Devcon
Loctite Depend	Acrylic	Loctite
Panel Patch	Acrylic	ITW
EA 9396	Epoxy	Hysol
Epon 828/ Curing Agent U	Epoxy	Shell

The TOROBONDER was used to accelerate the cure of these adhesives when bonding patches to various canopy materials.

2.2 Program Objectives

2.2.1 Fusion Bonding

The evaluation of the TOROBONDER for heat fusing of patches to damaged transparencies included program objectives listed in Table 1A:

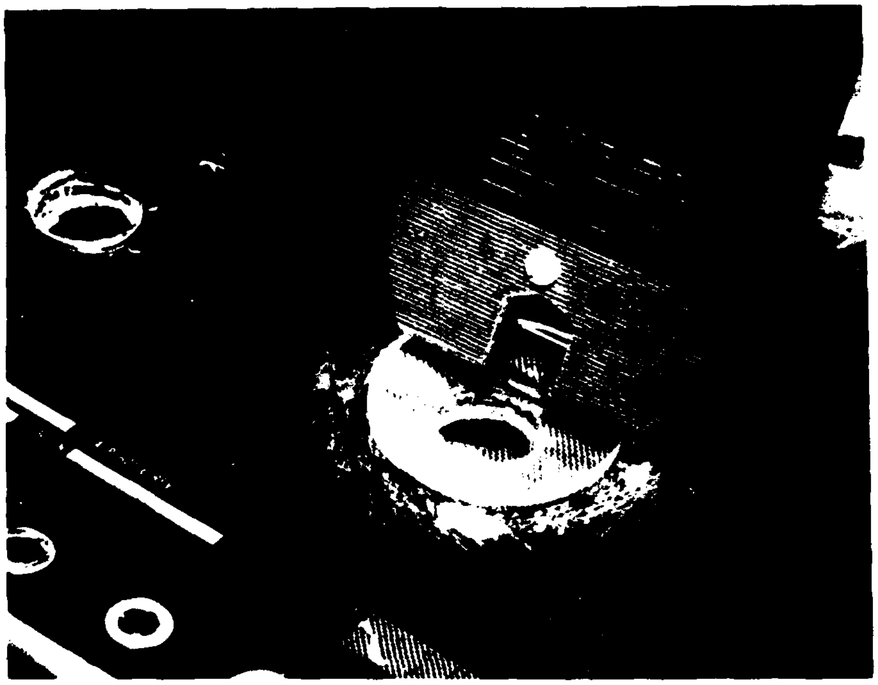

Figure 1. Vertical Heating Head.

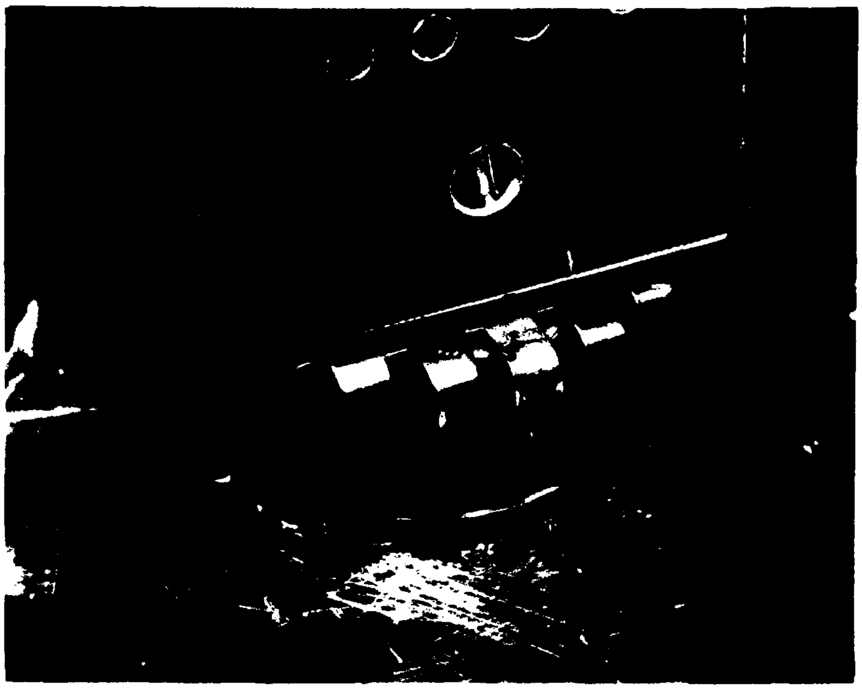

Figure 2. Pothead Heating Head.

TABLE 1A

TEST PROGRAM VARIABLES

Materials
1. Cast and stretched acrylic and polycarbonate.
2. Various constructions (different ply materials).
3. Applicability to various curvatures, transparency thicknesses, materials, construction types, and coatings.
Equipment Parameters
4. Various power settings.
5. Various susceptor types.
Technique Evaluation
6. Evaluate patches for visual appearance and leaks.
7. Demonstrate that each selected repair can withstand 10 pressure cycles.

2.2.2 Adhesive Bonding

The evaluation of the TOROBONDER for adhesive bonding of patches to damaged transparencies included program objectives listed in Table 1B:

TABLE 1B

TEST PROGRAM VARIABLES

Materials
1. Survey candidate adhesives compatible with various transparent materials, coatings, types, etc.
2. Evaluate promising candidates for repair processability. Important factors are process simplicity, shelf life, work life, minimum time to complete cure, surface preparation requirements, and equipment needed.
Technique Evaluation
3. Evaluate patch for visual appearance and leaks.
4. Demonstrate that each selected repair can withstand 10 pressure cycles.

Section 3. Experimental Procedure

3.1 Fusion Bonding

Initial experimentation included fusion bonding various cast acrylic patches to both thin (1/2 in) and thick (1 in), flat samples of polycarbonate, cast acrylic, and stretched acrylic. Once a technique for fusion bonding a patch to flat samples was developed, fusion bonding was used to patch canopy surfaces. The procedure employed to fuse patches to canopy surfaces utilizing the TOROBONDER is outlined in Appendix A.

Additional experiments were conducted to determine the ideal patch material, patch thickness, number of patches (single patch on one side of the canopy or a double patch with one patch on both sides of the canopy), as well as a method, if needed, for pre-forming the patch to the contour of the canopy surface. All of these parameters are enumerated in Table 2. In addition, an asterisk is included in Table 2 beside the parameter found to be best. Various repair techniques employed in this work are illustrated in Appendix D.

Once the fusion process was complete, the patch, canopy surface, and bond line were examined, noting the visual appearance. In addition, the bond integrity was subjected to a leak test criteria. A schematic of the leak test apparatus, as well as the leak test procedure are included in Appendix C.

3.2 Adhesive Bonding

The adhesives enumerated in Table 1 were utilized to patch both flat and curved canopy surfaces. Initial experimentation included adhesive bonding various patches to both thin (1/2 in) and thick (1

TABLE 2

PATCH PARAMETERS

Patch Parameter	Parameter Type	Recommended Material or Procedure
Material	Polycarbonate	
	Cast Acrylic	*
	Cellulose Acetate Butyrate	
Patch Thickness	3/8"	
	1/8"	*
	1/16"	
Number of Patches	Single	*
	Double	
Patch Preform Method	Heating Blanket	* (2)
	Hot Air Gun	* (2)
	Vacuum	* (2)
Patch Overlap (1)	1/2"	
	1"	
	2"	*

(1) Overlap implies the distance which the patch extends beyond the damaged area of the canopy.

(2) Availability dictates the use of any of these successful preform methods.

(3) Asterisk indicates recommended parameter.

in), flat samples of polycarbonate, cast acrylic, and stretched acrylic. The TOROBONDER was used to accelerate the cure of these adhesives. Once a technique for adhesive bonding a patch to flat samples was developed, adhesive bonding was used to patch canopy surfaces. The procedure employed to adhesively bond patches to canopy surfaces utilizing the TOROBONDER is outlined in Appendix A.

As an alternative, a heating blanket was utilized when adhesive bonding a large patch to a canopy surface to accelerate the cure of the selected adhesive. A heating blanket was selected because it could uniformly heat the entire bond line in a relatively short period of time. The procedure employed to adhesively bond large patches to canopy surfaces utilizing a heating blanket is outlined in Appendix B.

As with the fusion bonding technique, the patch, canopy surface, and bond line were examined once the patch had been secured, noting the visual appearance. In addition, the bond integrity was subjected to the leak test criteria.

Section 4. Results

This section summarizes the results of each independent program objective outlined in Section 2 for both fusion bonding and adhesive bonding repair.

4.1 Fusion Bonding

4.1.1 Materials

Initial experimentation included fusion bonding of various patches to both thin and thick, flat samples of polycarbonate, cast acrylic, and stretched acrylic. This experimentation indicated that fusion bonding could be used successfully to apply a patch to both polycarbonate and cast acrylic samples. In addition, it was determined that the TOROBONDER could not be used to apply a patch to any type of stretched acrylic material because the temperatures necessary to effect melting of the stretched acrylic surface caused significant shrinkage and cavitation of the stretched acrylic substrate. Based on these results, actual canopy surfaces were then utilized as substrates for additional bonding studies. As in the case of the flat samples, we determined that the TOROBONDER alone could not be used to apply a patch to any type of stretched acrylic canopy surface. Figure 3 illustrates a typical cavitated stretched acrylic surface. The cavitated areas in the bond line between the patch and the stretched acrylic canopy leaked, although the patch adhered to the canopy at certain points in the bond line. The application of an RTV sealant to the cavitated areas of the patch resulted in a leak-proof patch.

4.1.1.1 Canopy Curvatures

In general, the TOROBONDER (induction heating) could be successfully used to patch any part of a polycarbonate and/or cast acrylic transparency, regardless of the curvature. Note that a pre-formed patch which conforms to the contour of the transparency is required to achieve a successful bond.

4.1.1.2 Transparency Thicknesses

Both monolithic and laminated canopy surfaces of various thicknesses were employed as substrates for this work. No apparent effect of the substrate thickness was observed during the fusion

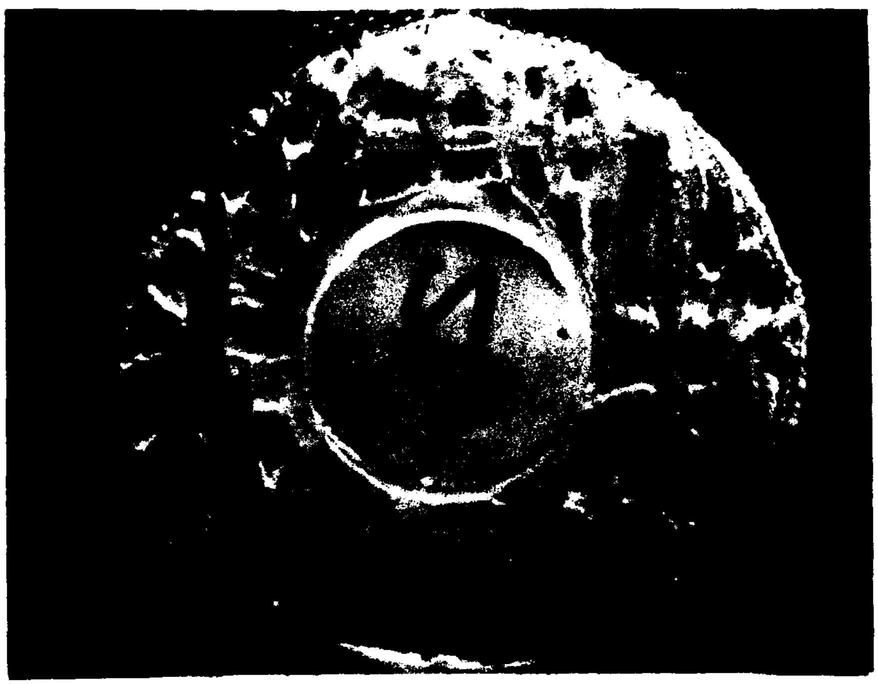

Figure 3. Stretched Acrylic Surface Showing Cavitation Which Occurs as a Result of Induction Heating the Surface to its Melting Temperature.

bonding process since successful patches could be achieved on all thicknesses tested, ranging from 1/2 inch to 1 inch.

4.1.1.3 Construction Types

The construction of the transparency (laminated vs. monolithic) had no apparent effect on the fusion bonding unless the lamina that the patch was being fused to was stretched acrylic. As we stated previously, fusion bonding to stretched acrylic results in shrinkage and cavitation of the canopy material.

4.1.1.4 Coatings

While the majority of the transparencies utilized as substrates for this program had no type of coating on either the inner or the outer surface, one canopy with a gold film laminated onto the interior surface of the canopy was employed to determine its effect on the fusion bonding process. The presence of the gold film was determined not to affect the fusion bonding process. In contrast, a polymer film laminated on the interior surface of one canopy did require removal prior to fusion bonding because the polymer film burned during the fusion bonding process.

4.1.2 Equipment Parameters

The TOROBONDER was set at various power settings prior to the use of induction heating to fuse a patch to a canopy surface. Power settings of less than 100 percent proved to be ineffective for fusion bonding because they did not provide a satisfactory bond between the patch and either a flat or a curved surface.

In fusion bonding, a uniform concentrated magnetic flux is introduced into the area to be bonded, causing eddy currents to flow in a ferromagnetic or a paramagnetic susceptor placed in the magnetic field. With the susceptor properly sized and positioned, these currents heat only the susceptor placed at the bond line. The ability to successfully fuse the substrate to the patch depends not only on the power setting, but in the choice of the susceptor material. The susceptor material recommended by the manufacturer of the TOROBONDER was a nickel coated, steel screen, and was thus utilized for the majority of the experiments. Additional susceptors, such as a paramagnetic steel screen and graphite cloth, were used with little or no success.

4.1.3 Technique Evaluation

Once the fusion process was complete, the patch, canopy surface, and bond line were examined, noting the visual appearance. In addition, the bond integrity was subjected to a leak test criteria.

Prior to fusion bonding, both the patch and the canopy are clear. After fusion bonding, the entire bond line becomes opaque. Bubbles are also evident in the bond line, due to the localized melting of both the patch and the canopy materials. Figure 4 illustrates the appearance of a fusion bonded cast acrylic patch to a cast acrylic canopy surface.

Each fused patch was subjected to the leak test criteria. In summary, for a fused patch to pass the leak test criteria, it had to hold an initial static vacuum of approximately 29.0 inHg for at least 15 min with less than a 1.5 inHg loss of vacuum. If the vacuum loss exceeded 1.5 inHg in 15 min or less the patch failed the leak test. Appendix C outlines the detailed vacuum leak test

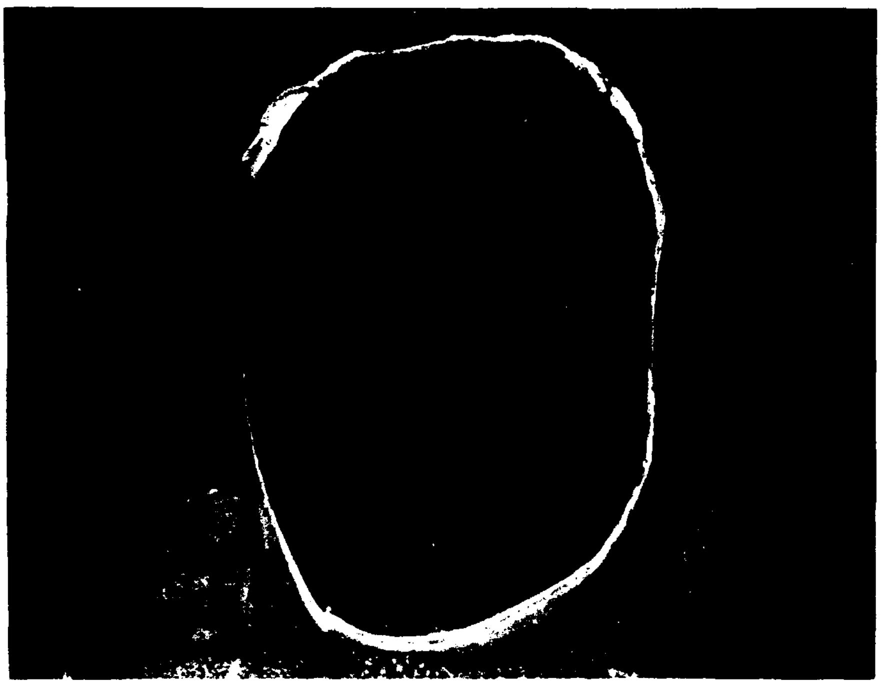

Figure 4. Fusion Bonded Cast Acrylic Patch Over a 4 in x 6 in Hole on a Cast Acrylic Canopy Surface.

procedure used. In most cases, failure to pass the leak test occurred very quickly if it occurred at all, indicating a severe leak in the patch bond line.

Selected repairs which successfully passed the leak test criteria were subjected to pressure cycling. The pressure cycling was conducted at room temperature on both large, single and double patched canopies. For the pressure cycling, a wooden box large enough to fit around the perimeter of the patch was placed over the patch. Holes were drilled in the box to allow a vacuum to be drawn over the patch. A vacuum bag was placed over the box and a partial vacuum (14 inHg) was applied. Since atmospheric pressure was present on the opposite side of the patch, this 14 inHg pressure differential placed the patch bond line under a stress acting to pop the patch off the canopy. This is illustrated in Appendix E. Once the system equilibrated, the vacuum was released. This sequence was repeated 10 times. Selection of this pressure cycle was based on current test flight pressure cycles. In general, the bond integrity of those patches subjected to this procedure was so that neither the substrate canopy or the fusion bond were affected by the pressure cycling. Once the pressure cycling was completed the patch was subjected to the vacuum leak test criteria to determine if the bond line had been damaged.

4.2 Adhesive Bonding

4.2.1 Materials

Candidate adhesives compatible with the transparency materials were selected for this project. These adhesives have been listed previously in Table 1. Compatibility was based on whether or not application of the adhesive resulted in stress crazing of the transparency surface.

Initial candidate adhesives were evaluated for repair simplicity, shelf life, work life, surface preparation requirements, and equipment needed.

4.2.1.1 Repair Simplicity

Each of the candidate adhesives was evaluated for repair process simplicity on actual transparencies considering size, shape, material, construction, and coating. Results indicated that the workability of the adhesive system dictated the ease of adhesive application to both the canopy surface as well as the patch. In general, the majority of the candidate adhesives were workable. Exceptions were Caseway Industrial Products' PS-30 acrylic adhesive and 3M's hot-melt adhesive 3779. These adhesives have a very low viscosity and were difficult to work with.

4.2.1.2 Shelf Life

The shelf life of each candidate adhesive was a consideration during the selection of the final adhesives chosen for ABDR. A required shelf life of at least 1 year was specified for all adhesives. Since the majority of the candidate adhesives have a manufacturer specified shelf life of approximately 1 year, none were eliminated due to insufficient shelf life. We should mention that an adhesive with unlimited or at least a 10 year shelf life would be desirable for ABDR applications.

4.2.1.3 Work Life

The work life of each candidate adhesive was an important consideration during the selection of the final adhesives recommended for ABDR. A required work life of at least 15 min was specified for all adhesives. The majority of the adhesives have a work life of more than the specified time, with two exceptions: Devcon's 2-Ton Epoxy and 3M's hot-melt adhesive 3779. These adhesive systems were consequently eliminated from the list of final adhesives appropriate for ABDR applications.

4.2.1.4 Surface Preparation Requirements

Surface preparation requirements were evaluated to determine if a method for surface preparation at all was needed, and if so, what type. Studies indicated that both the patch as well as the canopy should be sanded prior to adhesive bonding. Sanding the surfaces not only enhances the bond integrity, but also increases the peel strength of the bond.

4.2.1.5 Equipment Needed

Several types of heating equipment for accelerating the cure of the various adhesives were evaluated. For some of the adhesives, no heat was required for the adhesive to cure in a reasonable amount of time (< 1 hour). These included the Box Patch, Zip Patch, and Panel Patch. For the other candidate adhesives which do require the application of heat to cure in a reasonable amount of time, two heating techniques were evaluated. These include the TOROBONDER and a heating blanket. Although evaluation of the TOROBONDER was the primary objective of this work, the results of the heating blanket as an alternate heat source are included.

4.2.1.5.1 TOROBONDER

The amount of heat, as well as the maximum temperature that the TOROBONDER attains, can be controlled either manually or by setting the controller on the power supply. Based on our studies, manual control (holding the heating head in contact with the patch for a specific amount of time, while the unit is on 100 percent power) is recommended to cure the adhesive, because no additional equipment is required. The pre-set control method requires the use of a thermocouple in the bond line.

4.2.1.5.2 Heating Blanket

The heating blanket was utilized to pre-form the patch prior to bonding, and as a heat source for adhesive bonding large patches to canopy surfaces. Use of the heating blanket resulted in sufficient bonding more expeditiously than the use of induction heating as a heat source. This is due to the fact that the heating blanket is large enough to cover the entire bonding area at one time, whereas the induction heating bonding guns are capable of heating a circular area with a maximum of 2 inch diameter.

4.2.2 Technique Evaluation

As with induction heating, selected repairs which successfully passed the leak test criteria were subjected to pressure cycling. The pressure cycling was conducted at room temperature on both large, single and double patched canopies. For the pressure cycling, a wooden box large enough to fit around the perimeter of the patch was placed over the patch. Holes were drilled in the box to allow a vacuum to be drawn over the patch. A vacuum bag was placed over the box and a partial vacuum (14 inHg) was applied. Since atmospheric pressure was present on the opposite side of the patch, this 14 inHg pressure differential placed the patch bond line under a stress acting to pop the patch off the canopy. This is illustrated in Appendix E.

Once the system equilibrated, the vacuum was released. This sequence was repeated 10 times. Note that selection of this pressure cycle was based on current test flight pressure cycles. In general, the bond integrity of those patches subjected to this procedure, was so that the adhesive bond was not affected by the pressure cycling. In some cases, pressure cycling resulted in a fractured canopy, while the adhesive bond remained intact. Once the pressure cycling was completed the patch was subjected to the vacuum leak test criteria to determine if the bond line had been damaged.

4.3 Summary of Results

Summaries of experimental results obtained for each type of transparency and both types of induction heating methods are listed in Tables 3, 4, and 5. A summary of the results obtained using the heating blanket as a heat source in adhesive bonding repair is included in Appendix B. Recommendations reflect evaluation of all structural criteria as well as material and process considerations. Since fusion bonding resulted in cavitation of the stretched acrylic canopy, this technique was not recommended since it failed to pass the leak check criteria. Recognizing that this criteria may be more stringent than the actual cabin pressurization test, supplementary experiments were conducted to determine additional steps in the fusion bonding procedure which would result in a leak-proof patch. The supplementary experiments included the application of various RTV sealants to the cavitated areas of the stretched acrylic canopy.

Section 5. Conclusions and Recommendations

Both induction heating and adhesive bonding can be used successfully

TABLE 3

POLYCARBONATE CANOPY

		FUSION BONDING		ADHESIVE BONDING	
PATCH	PRE-FORM	LARGE PATCH	SMALL PATCH	LARGE PATCH	SMALL PATCH
CA (3/8")	HEAT	###	###	###	###
	VACUUM	▒▒▒	▒▒▒	▒▒▒	
	NONE	▒▒▒	▒▒▒	▒▒▒	###
CA (1/8")	HEAT	///	///	///	///
	VACUUM	///	///	///	///
	NONE	▒▒▒	▒▒▒	▒▒▒	▒▒▒
CAB (1/16")	HEAT			▒▒▒	▒▒▒
	VACUUM				
	NONE				

/// = PASSED TEST
= PASSED TEST BUT NOT RECOMMENDED
▒▒▒ = FAILED TEST

TABLE 4

CAST ACRYLIC CANOPY

		FUSION BONDING		ADHESIVE BONDING	
PATCH	PRE-FORM	LARGE PATCH	SMALL PATCH	LARGE PATCH	SMALL PATCH
CA (3/8")	HEAT	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED
	VACUUM	FAILED TEST		FAILED TEST	FAILED TEST
	NONE	FAILED TEST	PASSED TEST BUT NOT RECOMMENDED	FAILED TEST	FAILED TEST
CA (1/8")	HEAT	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST
	VACUUM	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST
	NONE	FAILED TEST	FAILED TEST	FAILED TEST	FAILED TEST
CAB (1/16")	HEAT	FAILED TEST	FAILED TEST		
	VACUUM				
	NONE				

= PASSED TEST
= PASSED TEST BUT NOT RECOMMENDED
= FAILED TEST

TABLE 5

STRETCHED ACRYLIC CANOPY

		FUSION BONDING		ADHESIVE BONDING	
PATCH	PRE-FORM	LARGE PATCH	SMALL PATCH	LARGE PATCH	SMALL PATCH
CA (3/8")	HEAT				
	VACUUM				
	NONE				
CA (1/8")	HEAT				
	VACUUM				
	NONE				

= PASSED TEST
= PASSED TEST BUT NOT RECOMMENDED
= FAILED TEST
= IMPLIES FAILED LEAK TEST, BUT WITH ADDITIONAL SEALANT APPLIED, THIS TECHNIQUE IS RECOMMENDED

to accomplish ABDR. As discussed previously, many structural criteria as well as material and process considerations were evaluated in this work.

Induction heating was utilized to accomplish both fusion bonding as well as adhesive bonding. Conclusions on these methods are included below.

The following conclusions concerning fusion bonding are based on experimental results. This technique is better suited for smaller damage, but can successfully patch larger damaged areas with only a slight amount of difficulty. Although the difficulty increases slightly when fusing a large patch to a canopy substrate, less time is required to fuse a large patch than to adhesively bond a large patch using induction heating. In addition, induction heating results in the cavitation of stretched acrylic material but successfully fuses patches to all other canopy materials.

The following conclusions concerning the use of induction heating to adhesively bond canopies are based on experimental results. This technique is very good for small patches, but requires more time than fusion bonding when curing the adhesive for a large patch. The use of a heating blanket to cure the adhesive on a large patch required less time than induction heating. In addition, the use of induction heating to adhesively bond canopies requires the use of more equipment than fusion bonding. Adhesive bonding using the induction heater is viable on all canopy materials.

The use of the T-1000 TOROBONDER is not recommended for aircraft battle damage repair of canopies. Putting the unit in the ABDR kits for repair of canopies, and training the personnel to operate the equipment does not provide an advantage over the existing T O repairs which are primarily bolt-on patches. The current T-1000 induction heating equipment does not have the temperature control that is desired. However, the use of induction heating will be re-evaluated after additional work on structures and hydraulic tubing (under separate efforts) is completed since these efforts involve modifying the equipment to make it more field usable and controllable.

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1. T O 1-1H-39, Technical Manual General - Aircraft Battle Damage Repair, USAF, March 1980.

2. Fox, R.L. and James R. Tyeryar, " Field Repair of Thermoplastic Windows and Composites," Langley Research Center, NASA Tech Briefs, January 1988, p. 94.

Appendix A

Recommended Procedures for ABDR

The recommended procedures utilized in the ABDR studies included the following: Fusion Bonding Procedure and Adhesive Bonding Procedure.

A.1 Fusion Bonding Procedure

1. Remove the damage area (Use a drill for a small hole (< 2 in O.D.) and a saw for a larger damage area (> 2 in O.D.), making sure to remove all cracks from around the potential bonding area.
2. Remove any surface film on the patch side of the canopy using either sand paper or a sanding drill.
3. Soften the patch for approximately 15 minutes at 200°F so that it will conform easily to the canopy surface using a heating blanket, hot air gun, or some alternative heat source.
4. While the patch is being softened, place a ferromagnetic wire screen, the diameter of the patch, over the damage area. Screens for large patches, should have a hole the size of the damage area removed from the center of the screen.
5. Place the patch on the canopy surface.
6. Place a vacuum bag over the patch and secure.
7. Set the TOROBONDER power level to 100 percent.

8a. For a small patch, place the Pot-Head heating head in contact with the patch for approximately 45 s.

8b. For large patches, place the Flat-Head heating head in contact with the patch at one position for approx. 45 s. Move the head around the entire circumference of the patch to complete the fusion process.

9. Subject the patch to the cabin pressurization leakage test.

Note that if visual observation indicates areas of insufficient bonding, step 8a or 8b of the above procedure can be repeated for that specific area.

Many of these steps for both the large and the small patch are illustrated in Figures A.1 - A.8.

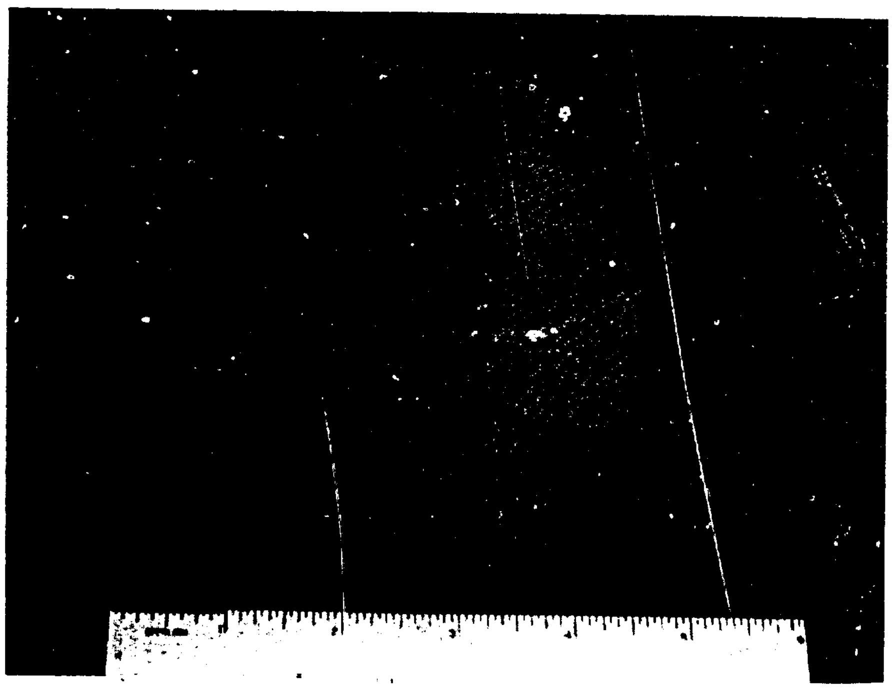

Figure A.1. Large Hole in Cast Acrylic Canopy Prior to the Patching Procedure.

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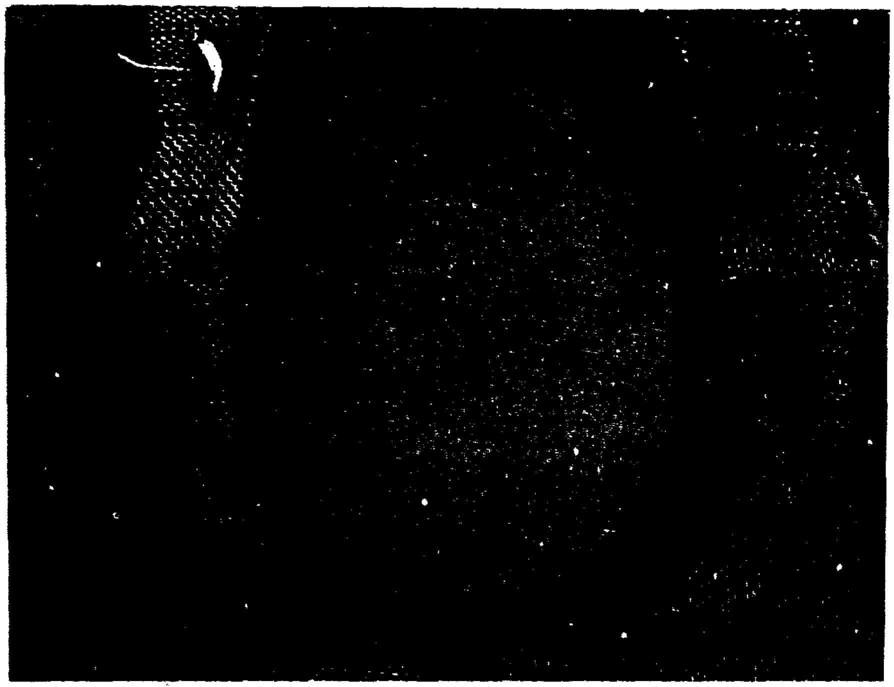

Figure A.2. The Paramagnetic Screen Placed Around the Hole Prior to Fusion Bonding.

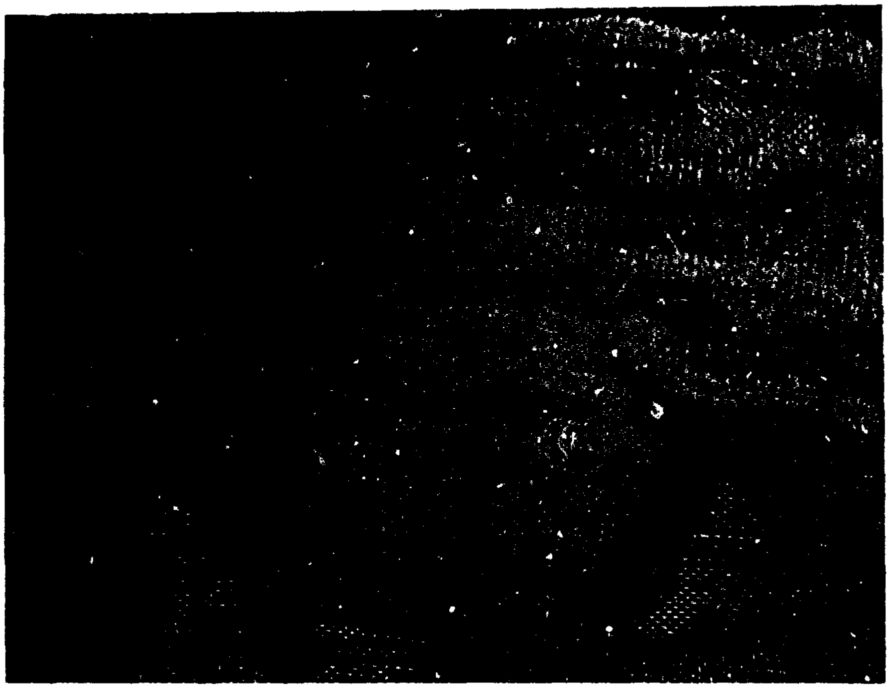

Figure A.3. A Cast Acrylic Patch is Placed Over the Screen.

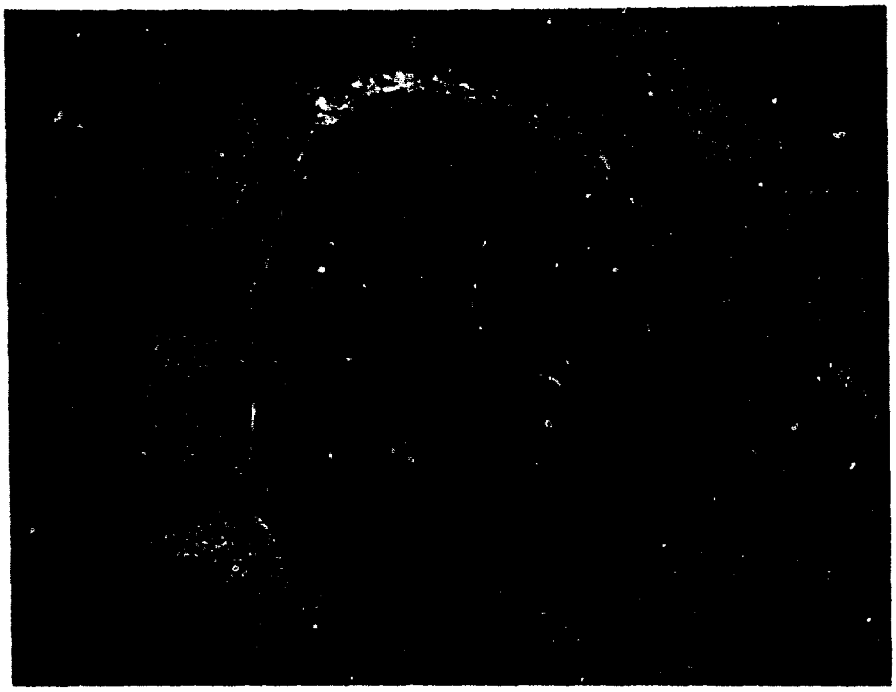

Figure A.4. A Large Fusion Bonded Patch.

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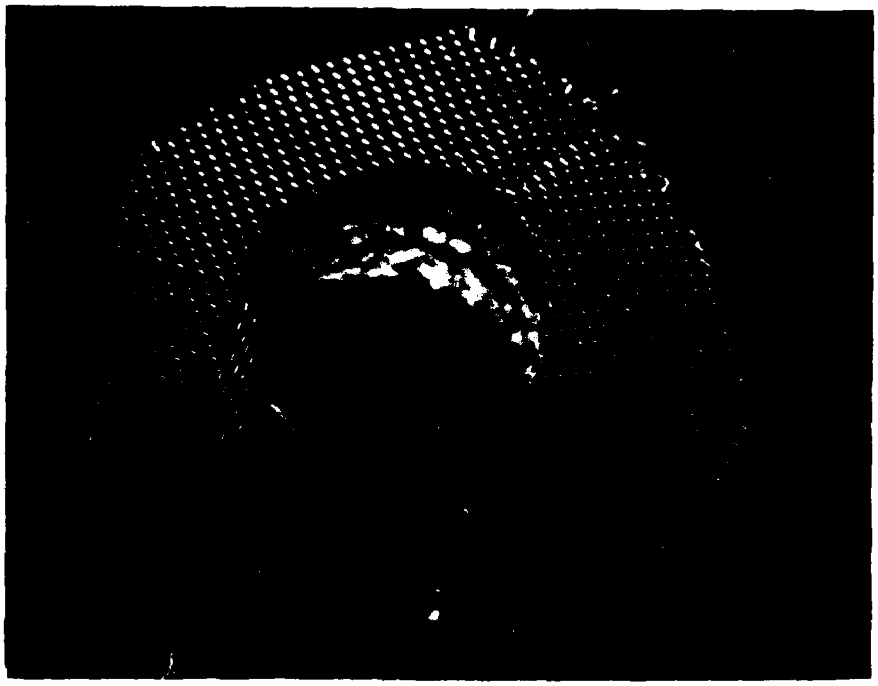

Figure A.5. A Small Hole With Paramagnetic Screen Around it.

Figure A.6. A Small Patch is Placed over the Hole and Secured.

Figure A.7. The Front Side of a Fusion Bonded Cast Acrylic Patch to a Cast Acrylic Canopy.

Figure A.8. The Back Side of a Fusion Bonded Cast Acrylic Patch to a Cast Acrylic Canopy.

A.2 Adhesive Bonding Procedures

A.2.1 Procedure for Adhesive Bonding a Small Patch Using the TOROBONDER

1. Remove the damage area using a drill. Make sure to remove all cracks in the potential bonding area.
2. Remove any surface film on the patch side of the canopy using either sand paper or a sanding drill.
3. Sand both the canopy and patch (1/8 in) using the same equipment used in step 2.
4. Soften the patch for approximately 15 minutes at 200°F so that it will conform easily to the canopy surface using a heating blanket, hot-air gun, or some alternative heat source.
5. While the patch is being softened, place a ferromagnetic wire screen, the diameter of the patch, over the damage area.
6. Apply the selected adhesive to both the patch and the canopy and place the patch on the canopy surface.
7. Set the TOROBONDER power level to 100 percent.
8. Place the Pot-Head heating head in contact with the patch for approximately 10 min to cure the adhesive.(1) This can be accomplished by depressing the button on the heating head for the duration of the curing time.
9. Subject the patch to the cabin pressurization leakage test.

Many of these steps are illustrated in Figures A.9 - A.12.

(1) For stretched acrylic canopies, a thermocouple should be placed in the bond line and the TOROBONDER temperature controller set at 160°F. The thermocouple bead will be permanently bonded into the bond line when the repair is completed so the wire will have to be snipped off and a new bead prepared for subsequent use.

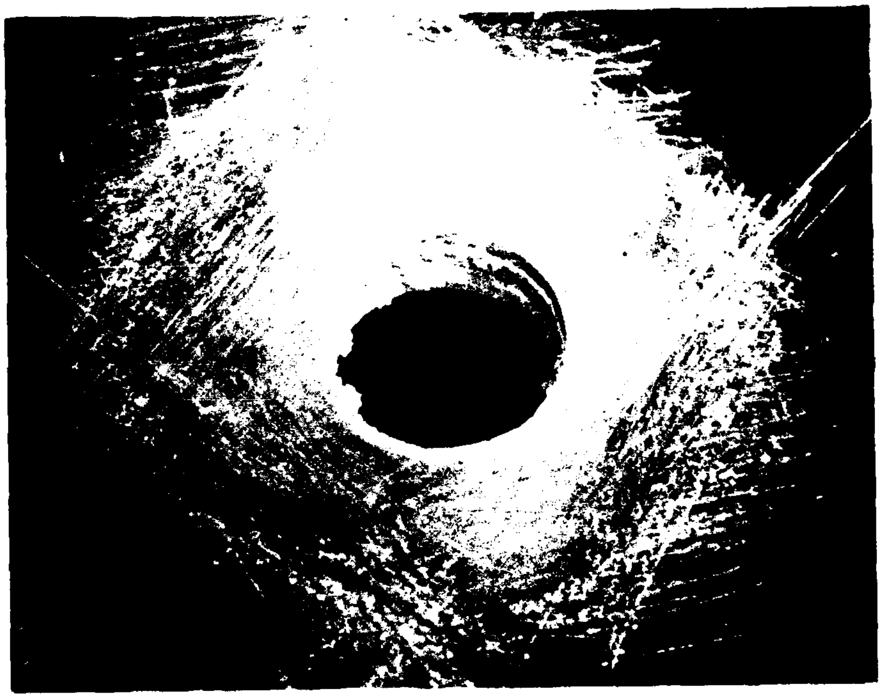

Figure A.9. The Bonding Area Around the Hole is Sanded Prior to the Application of Adhesive.

Figure A.10. Adhesive is Applied and a Thermocouple Placed in the Bond Line.

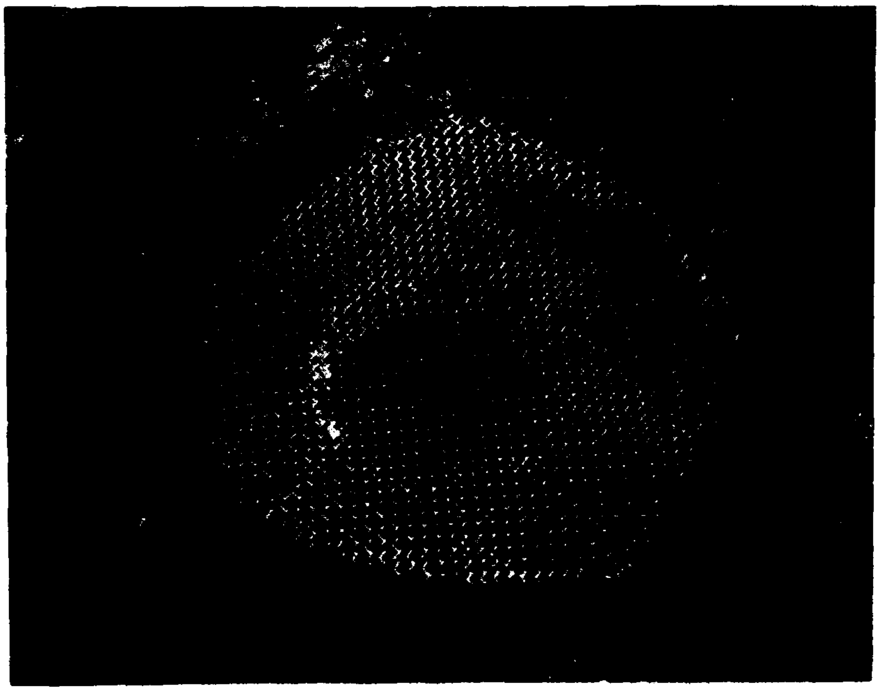

Figure A.11. A Paramagnetic Screen is Placed Over the Adhesive.

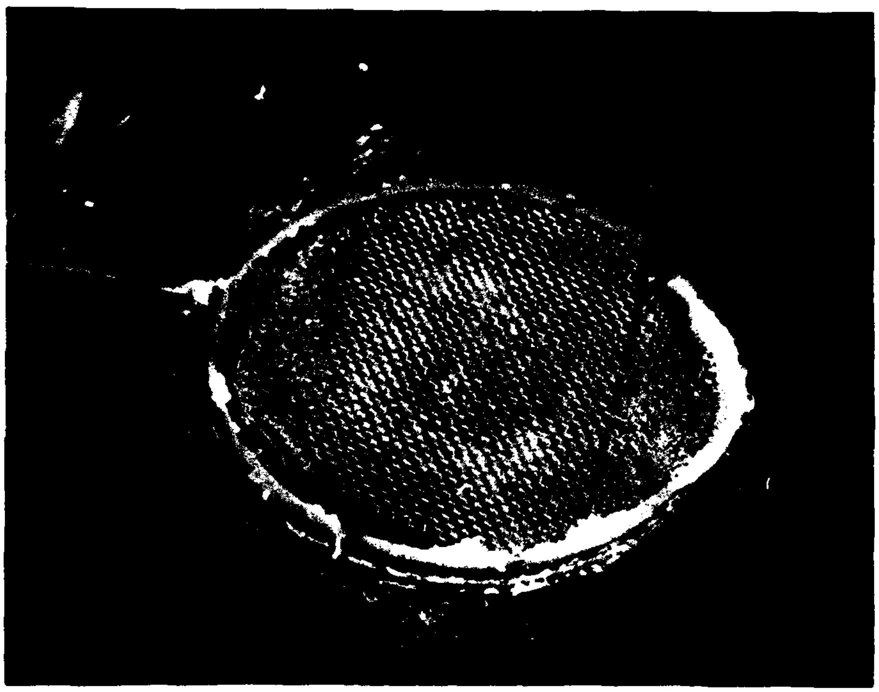

Figure A.12. The Cast Acrylic Patch is Placed over the Screen and the TOROBONDER is used to Cure the Adhesive.

A.2.2 Procedure for Adhesive Bonding Using the Acrylic Adhesives

1. Remove the damage area using a drill. Make sure to remove all cracks in the potential bonding area.
2. Remove any surface film on the patch side of the canopy using either sand paper or a sanding drill.
3. Sand both the canopy and patch (1/8 in) using the same equipment used in step 2.
4. Soften the patch for approximately 15 minutes at 200°F so that it will conform easily to the canopy surface using a heating blanket, hot-air gun, or some alternative heat source.
5. Apply the acrylic adhesive to the canopy.
6. Apply the hardener to the patch surface to be bonded.
7. Place the patch on the canopy and secure with tape.
8. Seal the backside of the canopy by placing any RTV sealant in the damage area.
9. Vacuum bag the entire assembly and allow to cure for 45 min.
10. Once curing is complete, subject the patch to the leak test criteria. (3)

(3) No heat is required for curing these adhesive systems.

Appendix B

Procedure for Adhesive Bonding a Large Patch

1. Remove the damage area using a drill. Make sure to remove all cracks in the potential bonding area.
2. Remove any surface film on the patch side of the canopy using either sand paper or a sanding drill.
3. Sand both the canopy and patch (1/8 in) using the same equipment used in step 2.
4. Soften the patch for approximately 15 minutes at 200°F using a heating blanket so that it will conform easily to the canopy surface.
5. Apply the selected adhesive to both the patch and the canopy and place the patch on the canopy surface.
6. Place a heating blanket over the patch with its controller set at 200°F.
7. Vacuum bag the entire assembly and cure for 20 min. (2)
8. Once curing is complete, remove the heating blanket and and vacuum bag assembly.
9. Subject the patch to the cabin pressurization leakage test.

(2) Use of the TOROBONDER as a heat source would require a much longer time because the bonding gun is capable of heating only a 2 inch diameter area.

Table B.1 summarizes the results of using the heating blanket as a heat source for adhesive bonding both a small and large patch.

TABLE B1

ADHESIVE BONDING USING A HEATING BLANKET AS THE HEAT SOURCE

		POLYCARBONATE		CAST ACRYLIC		STRETCHED ACRYLIC	
PATCH	PRE-FORM	LARGE PATCH	SMALL PATCH	LARGE PATCH	SMALL PATCH	LARGE PATCH	SMALL PATCH
CA (3/8")	HEAT	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED
	VACUUM	FAILED TEST	PASSED TEST BUT NOT RECOMMENDED	FAILED TEST	PASSED TEST BUT NOT RECOMMENDED		
	NONE	FAILED TEST	FAILED TEST	FAILED TEST	FAILED TEST	FAILED TEST	FAILED TEST
CA (1/8")	HEAT	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST
	VACUUM	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST	PASSED TEST
	NONE		PASSED TEST BUT NOT RECOMMENDED		PASSED TEST BUT NOT RECOMMENDED		
CAB (1/16")	HEAT	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED		
	VACUUM	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED		
	NONE	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED	PASSED TEST BUT NOT RECOMMENDED		

= PASSED TEST
= PASSED TEST BUT NOT RECOMMENDED
= FAILED TEST

Appendix C

Vacuum Leak Test Procedure

The vacuum leak test procedure was adopted as a means for determining the integrity of the bond between the patch and the canopy surface. A schematic of the vacuum leak test system is illustrated in Figure C.1. The leak test procedure requires that the patched canopy be vacuum bagged. In summary, for a fused patch to pass the leak test criteria, it had to hold an initial static vacuum of approximately 29.0 inHg for at least 15 min with less than a 1.5 inHg loss of vacuum. If the vacuum loss exceeded 1.5 inHg in 15 min or less the patch failed the leak test. Measuring the vacuum loss was accomplished by valving off the vacuum pump (Shut valve 2 noted in schematic) therefore isolating the patched system, and noting the movement of the mercury level in the manometer. In most cases, failure to pass the leak test occurred very quickly if it occurred at all, indicating a severe leak in the patch bond line. In many cases, the air leakage rate which resulted in failure to pass the leak test criteria, might be minimal with respect to the specified maximum allowable air leakage rate.

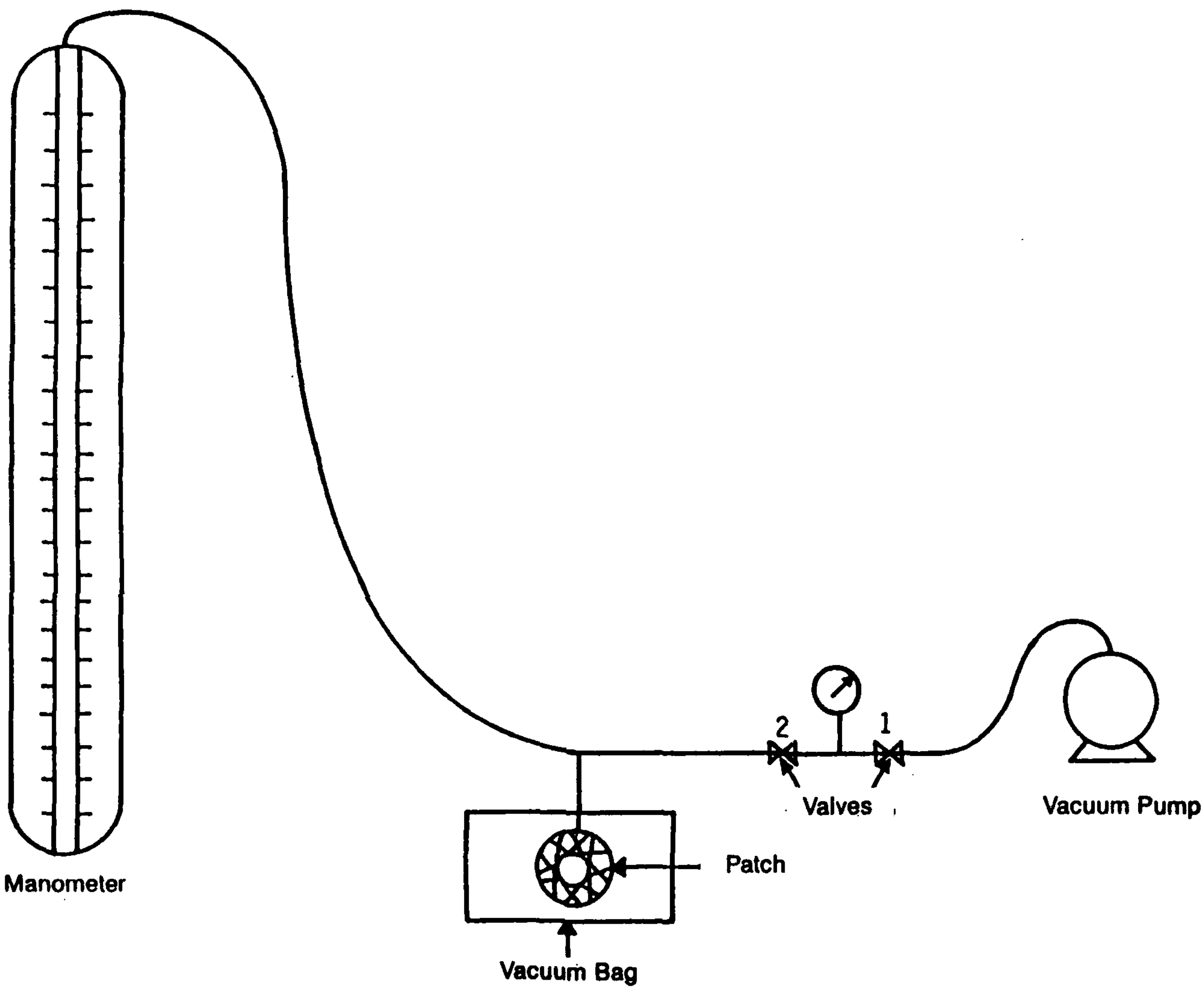

Figure C.1. Schematic of Vacuum Leak Test System.

Appendix D

Repair Techniques

The following types of repair techniques were employed during this work:

1. Single patch over damage area.
2. Double patch over damage area.
3. Double patch with rohacell foam inside damage area.
4. Countersunk patch inside damage area.

Each of these repair techniques are illustrated in Figures D.1 - D.4.

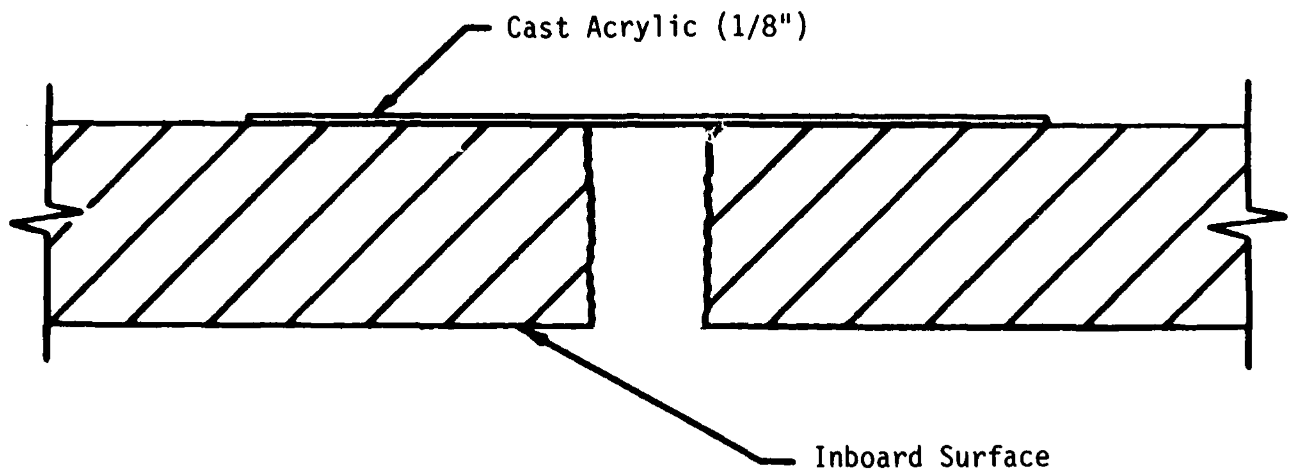

Figure D.1. Single Patch.

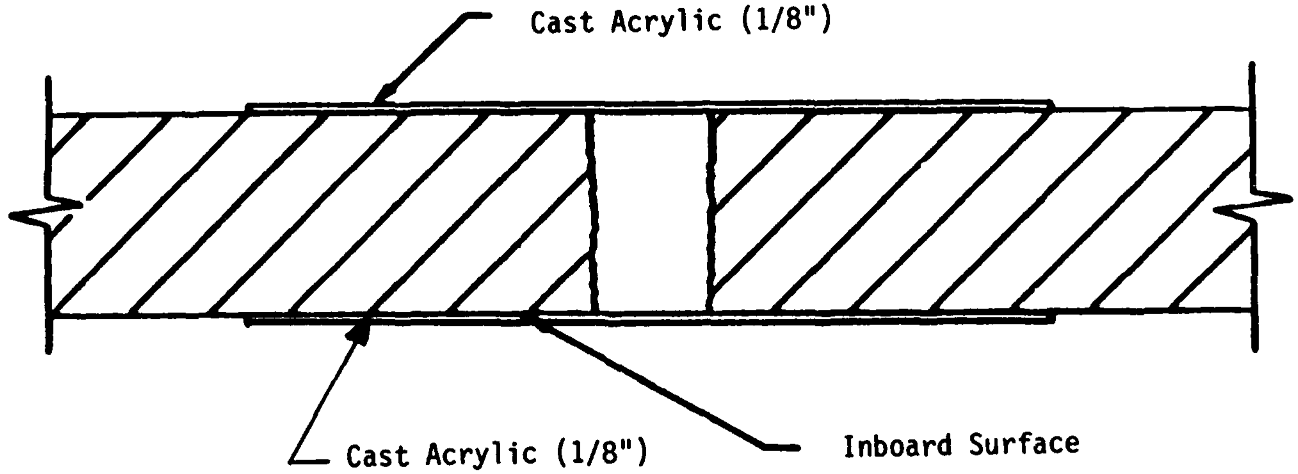

Figure D.2. Double Patch.

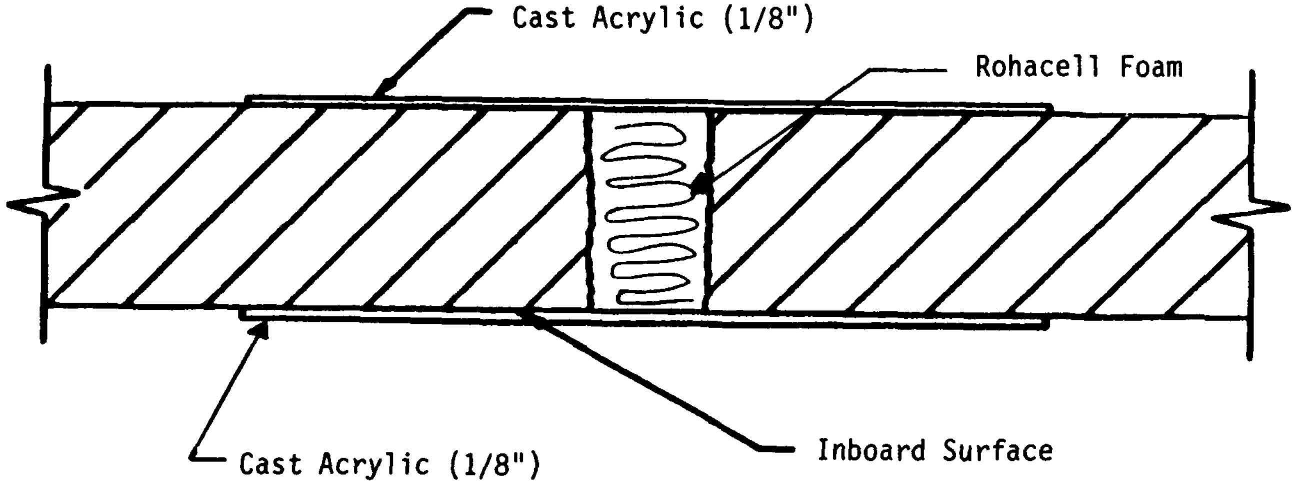

Figure D.3. Double Patch with Rohacell Foam.

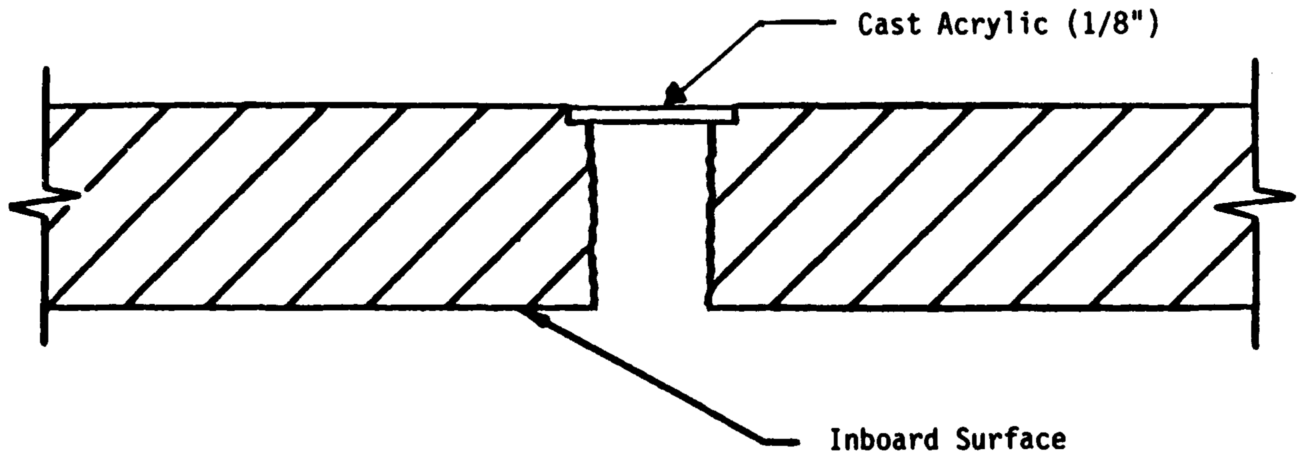

Figure D.4. Countersunk Patch.

Appendix E

Pressure Cycling Procedure

Selected repairs which successfully passed the leak test criteria were subjected to pressure cycling. The pressure cycling was conducted at room temperature on both large, single and double patched canopies. For the pressure cycling, a wooden box large enough to fit around the perimeter of the patch was placed over the patch. Holes were drilled in the box to allow a vacuum to be drawn over the patch. A vacuum bag was placed over the box and a partial vacuum (14 inHg) was applied. Since atmospheric pressure was present on the opposite side of the patch, this 14 inHg pressure differential placed the patch bond line under a stress acting to pop the patch off the canopy. This is illustrated in Figure E.1. Once the system equilibrated, the vacuum was released. This sequence was repeated 10 times.

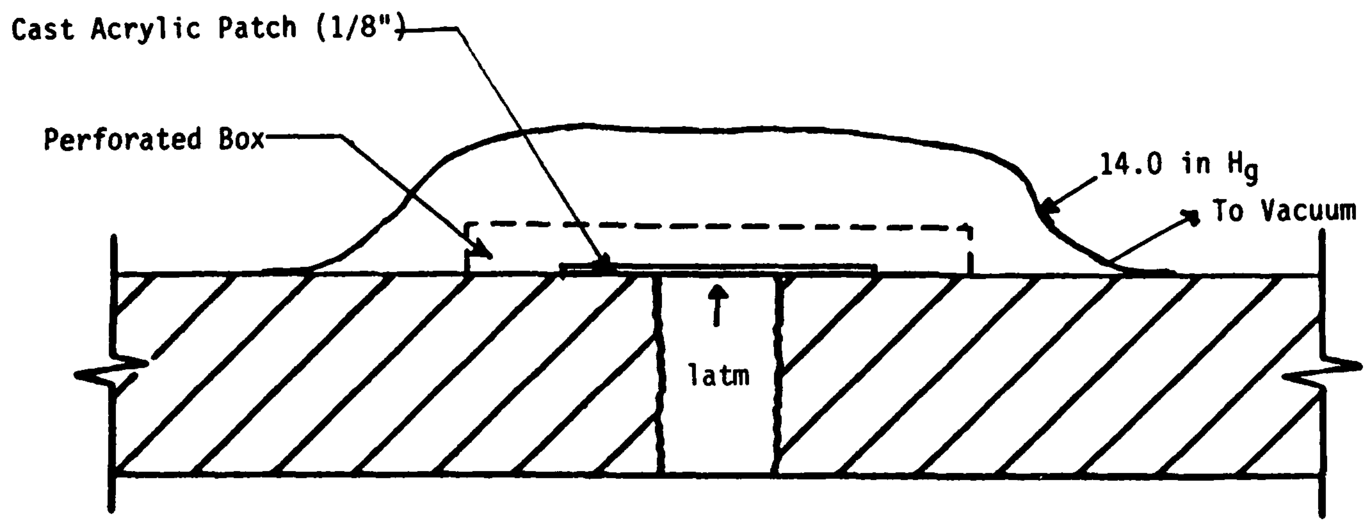

Figure E.1. Pressure Cycling Approach.

*U.S.Government Printing Office: 1990—748-056/24383