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DESIGN, DEVELOPMENT, AND FABRICATION OF A FUNCTIONAL ADHESIVE BONDING REPAIR EXPERIMENT TO BE PERFORMED DURING SPACE FLIGHT

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ABSTRACT

Three specially formulated adhesive systems were developed for application in the space adhesive bonding repair experiment. The three adhesive systems are suitable for application in the zero-g, hard vacuum space environment over a temperature range from 30°F to 130°F, yielding tensile shear strengths in excess of 1000 psi.

A suitable adhesive package, dispenser, and vacuum glove box were developed to carry out the adhesive bonding repair experiment in the SIV-B Work Shop.

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INTRODUCTION

Adhesive bonding has found wide acceptance in the aerospace industry as an efficient method for joining various components ranging from primary structural members to decorative wall panels. Adhesive bonding offers unique potential for application in actual in flight repair of damaged space vehicles. With the utilization of suitable adhesives, very compact and weight-efficient repair kits could be developed for patching up micormeteoride impact craters in the skin of a space vehicle, for example. Bonded joints could also be utilized for in-space assembly of large structures requiring minimum tooling. Adhesive-bonded clips or brackets on the external surface of the vehicle could greatly improve the mobility and security of an astronaut during extravehicular activity.

All these potential applications depend on the successful demonstration that specially formulated adhesives are suitable for bonding in an actual space environment at zero-g and hard vacuum, over a wide range of temperatures. It was the purpose of this program to develop adhesive systems that could be utilized under these conditions and would yield useful mechanical properties.

The demonstration of the feasibility of adhesive bonding under actual space environmental conditions is planned as one of the experiments in the Saturn IV-B Work Shop program.

This experiment will involve mixing of the two-part adhesive by the astronaut and using it to bond tensile lap shear specimens. The specimens will later be tested by the astronaut, who will use a small hand-operated tensile test apparatus. The interior of the work shop is planned to be pressurized to 5 psia. Thus, in order to conduct the bonding experiment under actual space environmental conditions, a specially designed vacuum chamber will be utilized. This chamber will be vented to the exterior of the vehicle. The astronaut will work in this chamber by means of flexible arm inserts and gloves, as in a conventional laboratory glove box.

TECHNICAL DISCUSSION

The work under this program was divided into two major areas. The objective of the first part of the program was the development of adhesive systems suitable for bonding repair applications in space. This work was performed by the Polymer Chemistry Department of Narmco R&D. The second part consisted of the design, fabrication, and testing of a vacuum chamber (glove box) and adhesive dispenser, which were the responsibility of the Engineering Department.

ADHESIVE DEVELOPMENT

The goal of the adhesive development effort was to formulate an adhesive system with a working temperature range from 30°F to 130°F in hard vacuum. Short curing characteristics were also considered desirable for facilitating quick repair operation resulting in bond shear strengths of at least a 1000 psi within a few hours after application.

ADHESIVE FORMULATIONS

Attempts to satisfy the requirements of a single space adhesive system capable of being used between 30°F and 130°F led to the conclusion that such a system is not presently available. Those systems which worked well at 130°F were solid at 30°F or had inherent low-temperature cure times whose duration was prohibitive. Conversely, those systems which were usable at 30°F degassed badly at 130°F or set up so fast that they could not be applied.

With these problems in mind, three matched adhesive systems were formulated. Each system acts in essentially the same manner as the others in its own temperature range. Mixing and application must be completed within 7 minutes, and contact pressure must be applied rapidly and held 30 minutes from mix initiation. The 1000-psi tensile shear strength limit is reached in all cases within 90 minutes from mix initiation. There is a 5°F overlap in the usable temperature ranges of these systems.

System A will be used between 30°F and 77°F. According to the literature, this system will also work at 15°F, but requires a 3-day cure to reach a strength level of 1000 psi. System B will be used between 72°F and 107°F. System C will be used between 102°F and 130°F. This latter system still has a usable pot lift and vapor pressure at 150°F.

The formulation chosen for adhesive System A is:

1.00-g Epirez 5109 resin
1.00-g Epicure 861 curing agent
1.00-g MD 105 aluminum filler

The formulation chosen for adhesive System B is:

1.000-g Epon 828V resin
0.353-g Genamid 2000 fatty amidoamine curing agent
0.758-g Epicure 861 polymercaptan curing agent
0.03-g Bisphenol A cure catalyst
1.07-g MD 105 aluminum filler

The formulation chosen for adhesive System C is:

1.000-g Epon 828V resin
0.158-g Genamid 2000 fatty amidoamine curing agent
0.237-g Shell U polyamine curing agent
0.027-g Bisphenol A cure catalyst
0.711-g MD 105 aluminum filler

The formulations of the adhesive systems were varied to permit proper pot lives and high tensile shear strength after aging.

Adhesive System A is basically a 50/50 mixture of Epirez 5109 and Epicure 861. A-1100 pretreatment of the bonds did not increase the tensile shear strengths appreciably upon aging.

Adhesive System B presented a problem in that the increase of Epicure 861 led to weak bonds upon aging. The increase of Genamid 2000 increased the aged tensile shear strength but slowed the reaction time. This was compensated for by adding a catalytic amount of Bisphenol A as an accelerator.

Adhesive System C also required Bisphenol A due to the addition of Genamid 2000.

The variations in the pot lives and the reaction times of these adhesive systems with differing concentrations of reactants can be found in Table 1.

In no case was an attempt made to find a cure cycle which would increase the tensile shear strength. It was felt that this would be inappropriate for space bonding due to its added complications.

EXPERIMENTAL EVALUATION

All bonds made were on silicon carbide abraded aluminum in an attempt to duplicate actual space bonding techniques. Eight bonds were made at one time and the testing of these bonds was in duplicate for each elapsed time investigated.

TABLE 1

ADHESIVE FORMULATIONS AND RESULTING POT LIVES AND TENSILE SHEAR STRENGTHS

Trial No.	Formulation Attempts for Adhesive System	Pot Life @ Temp	Tensile Shear Strength	Remarks
System A 30°F to 77°F				
1	Epirez 5109 1.0 g Epicure 861 1.0 g MD 105 2.0 g	20 min @ 30°F	317 psi in 35 min, 796 psi in 75 min, 1320 psi in 4 days all @ 30°F aging, 1080 psi after additional 9 days @ 75°F	
2	Same as above except MD 105 1.0 g	22 min @ 30°F	67 psi in 30 min, 809 psi in 75 min, 1600 psi in 4 days all @ 30°F aging, 1180 psi after additional 9 days @ 75°F	Reduced MD 105 facilitated handling and gave higher tensile shear strength. This is adhesive System A in its final form.
3	Same as above	8 min @ 75°F	1230 psi in 30 min, 1025 psi in 3 days	
4	Same as above except applied to A-1100 treated bonds	7 min @ 75°F	1300 psi in 30 min, 1170 psi in 3 days	Very slight increase in tensile shear due to addition of A-1100. This may have easily been due to the length of time #3 bonds were exposed to atmosphere before resin application since #2 bonds were stronger than either #3 or #4.
System B 72°F to 107°F				
5	Epon 828V 1.90 g Genamid 2000 0.30 g Epicure 861 1.54 g	22 min @ 70°F	446 psi in 30 min, 900 psi in 75 min, 460 psi in 4 days	
6	Same as above except additional 3.74 g of MD 105	~ 8 min @ 100°F	1016 psi in 30 min, 975 psi in 75 min, 990 psi in 4 days & 735 psi in 22 days	Aluminum filled bonds were only slightly better than unfilled.

TABLE 1 (Continued)

Trial No.	Formulation Attempts for Adhesive System	Pot Life @ Temp	Tensile Shear Strength	Remarks
7	Same as (5) except addition of 0.06 g of Bisphenol A	18 min @ 70°F	128 psi in 30 min, 1370 psi in 75 min, 593 psi in 7 days	Bisphenol A reduced the pot life but did little for increased tensile shear strength.
8	Same as above except addition of 1.5 g of MD 105	18 min @ 70°F	297 psi in 30 min, 1595 psi in 90 min, 1160 psi in 7 days & 1500 psi in 14 days	The addition of MD 105 gave an increase in the tensile shear strength upon aging.
9	Same as above except 2 g of MD 105	7 min @ 100°F	1715 psi in 30 min, 1030 psi in 90 min, 995 psi in 7 days & 1220 in 14 days	The pot life was too short at 100°F.
10	Epon 828V 1.90 g Genamid 2000 0.50 g Epicure 861 1.49 g Bisphenol A 0.06 g MD 105 2.0 g	20 min @ 74°F	299 psi in 30 min, 1720 psi in 105 min, 790 psi in 6 days, 724 psi in 20 days	
11	Epon 828V 1.90 g Genamid 2000 0.67 g Epicure 861 1.44 g Bisphenol A 0.06 g MD 105 2.0 g	26 min @ 70°F	31 psi in 34 min, 990 psi in 90 min	This is adhesive System B in its final form.
12	Same as above	~ 10 min @ 100°F	1290 psi in 30 min, 2120 psi in 90 min, 1375 psi in 1 day, 1570 psi in 4 days	Bonds were allowed to set over 1 hour after sanding before adhesive application.
13	Same as above on A-1100 treated bonds	~ 10 min @ 100°F	910 psi in 30 min, 1490 psi in 90 min, 2510 psi in 1 day	

TABLE 1 (Continued)

Trial No.	Formulation Attempts for Adhesive System	Pot Life @ Temp	Tensile Shear Strength	Remarks
System C 102°F to 130°F				
14	Epon 828V 1.90 g Shell U 0.47 g MD 105 2.37 g	~ 25 min @ 100°F	2 psi in 30 min, 850 psi in 75 min, 1020 psi in 4 days, 1045 psi in 22 days	
15	Epon 828V 1.90 g Genamid 2000 0.30 g Shell U 0.45 g	~ 25 min @ 100°F	16 psi in 30 min, 1090 psi in 75 min, 1100 psi in 4 days, 1150 psi in 16 days	
16	Epon 828V 1.90 g Genamid 2000 0.60 g Shell U 0.43 g Bisphenol A 0.05 g	~ 27 min @ 100°F	1 psi in 30 min, 1020 psi in 75 min, 900 psi in 4 days, 1100 psi in 16 days	Too long a pot life, overall weakness may have been due to motion during specimen cutting after 29 minutes contact pressure.
17	Epon 828V 1.90 g Genamid 2000 0.30 g Shell U 0.45 g Bisphenol A 0.05 g MD 105 2.7 g	~ 25 min @ 100°F	4 psi in 30 min, 1100 psi in 2 hours, 1100 psi in 4 days, 1000 psi in 14 days	Good pot life but too low tensile shear upon aging.
18	Same as above except MD 105 1.4 g	~ 26 min @ 100°F	77 psi in 34 min, 1180 psi in 75 min, 1980 psi in 1 day, 1760 psi in 17 days	The reduction of MD 105 to a lower level gave adequate results. This is adhesive System C in its final form.
19	Same as above	> 10 min @ 150°F	1082 psi in 1 hr, 1260 in 2 days, 1220 psi in 4 days	Bonds allowed to stand over 1 hour after sanding before adhesive was applied.
20	Same as above except A-1100 treated bonds	~ 10 min @ 150°F	1290 psi in 1 hr, 1880 in 2 days, 1961 in 4 days	

A summary of the results of the experimental evaluation of the various adhesive formulations is presented in Table 1. The results of aging studies on the three selected systems are given in Figures 1 through 3. After aging for 13 days, 4 days at 30°F and 9 days at 75°F, System A had an average tensile shear strength of 1180 psi which did not show a decline from a rerun aged 3 days giving 1025 psi in tensile shear.

After 1-day aging at 100°F, System B gave a 1370-psi tensile shear strength value; after 4 days, this value increased to 1570 psi. There was no sign of decline in the bond strength.

The shear strength for System C after 1-day aging at 150°F was 1260 psi, after 4 days was 1220 psi.

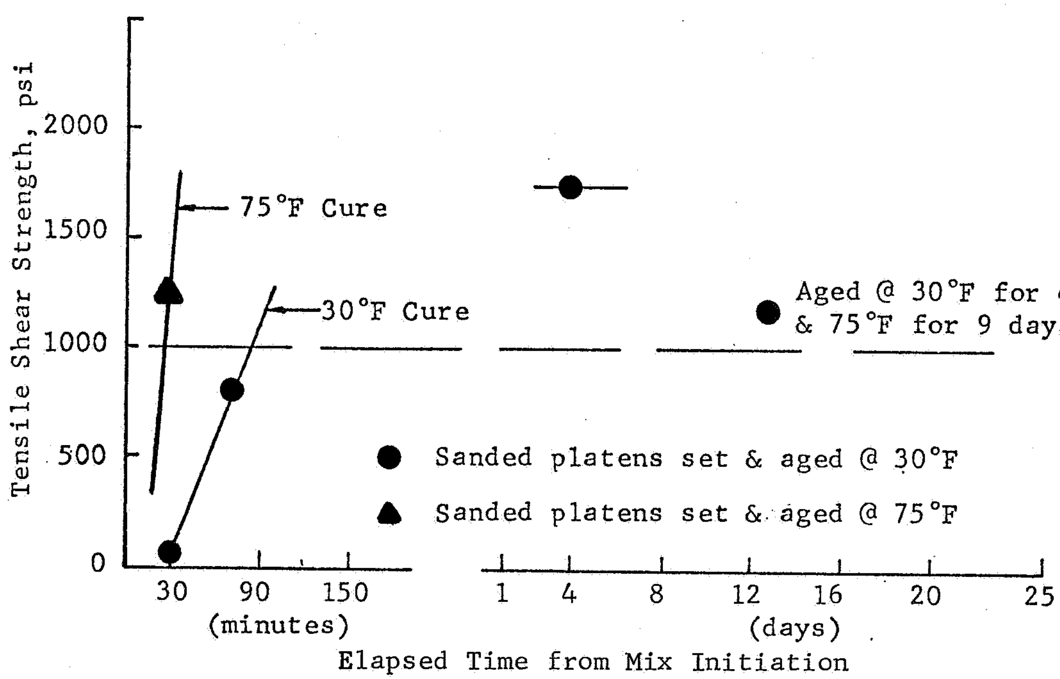

Figure 1. Tensile Shear Strength versus Aging Time for Adhesive System A. (Each data point represents an average of two values)

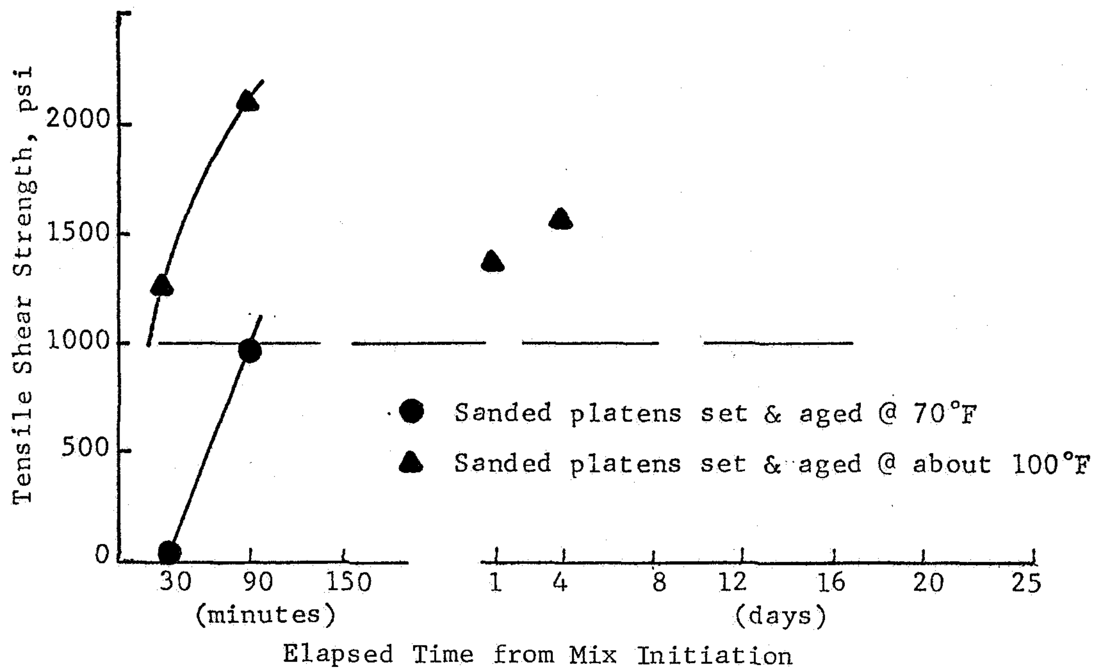

Figure 2. Tensile Shear Strength versus Aging Time for Adhesive System B

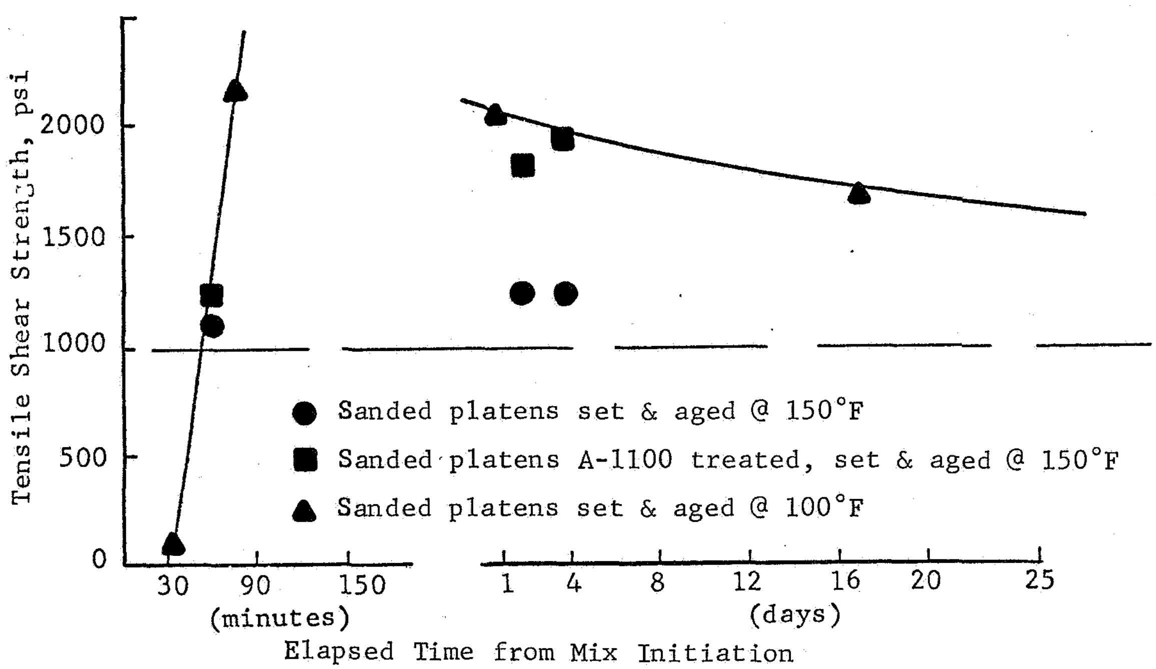

Figure 3. Tensile Shear Strength versus Aging Time (100°F to 150°F) for Adhesive System C

A surface active agent was employed in an attempt to increase the tensile shear strength of aged bonds. The results are given in Table 1 and Figures 3, 4, and 5. From Figures 3 and 5, one would surmise that A-1100 definitely improved aged tensile shear strengths but from Figure 4 this would not seem to be the case. The difference is that the untreated bonds (Figures 3 and 5) were exposed to the atmosphere for over 1 hour before adhesive application, whereas the untreated bonds (Figure 4) were exposed to the atmosphere for less than 10 minutes. A look at the literature reveals that air at 50% relative humidity will severely deteriorate the surface of silicon carbide abraded aluminum (see Figure 6). In the case of the long-term exposure (Figures 3 and 5), the A-1100 protected the aluminum. In the case of Figure 4, however, the aluminum was coated with adhesive before severe exposure deterioration could occur. It can be surmised that the bonds formed in space will be stronger than those formed on earth due to a lack of oxygen and humidity; therefore, a primer is not recommended.

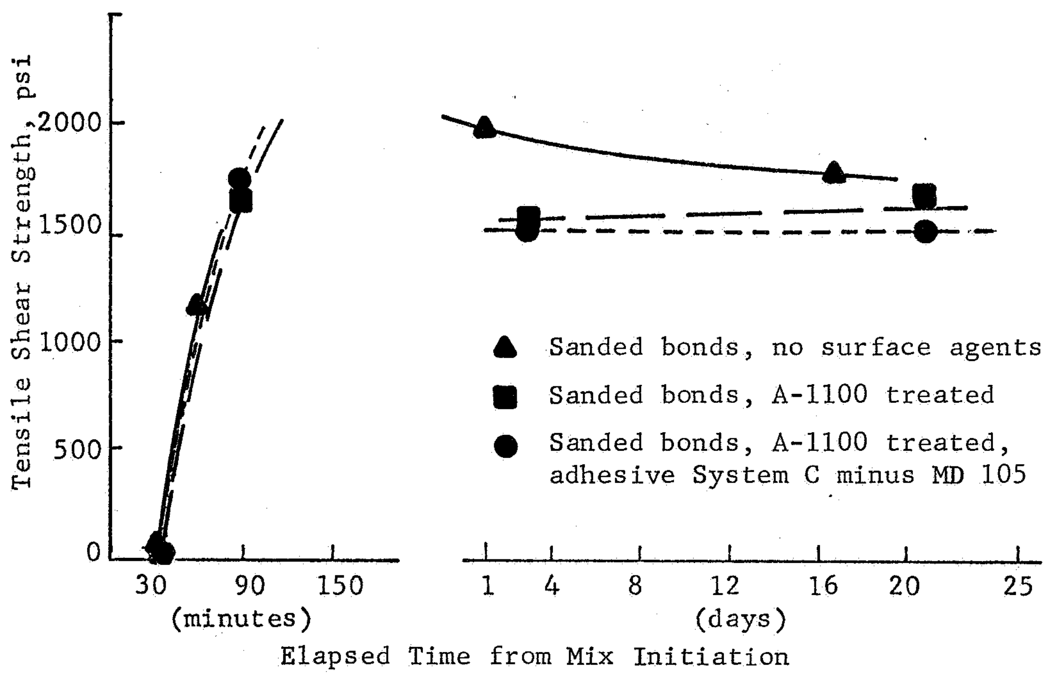

Figure 4. Tensile Shear Strength versus Aging Time for Adhesive System C

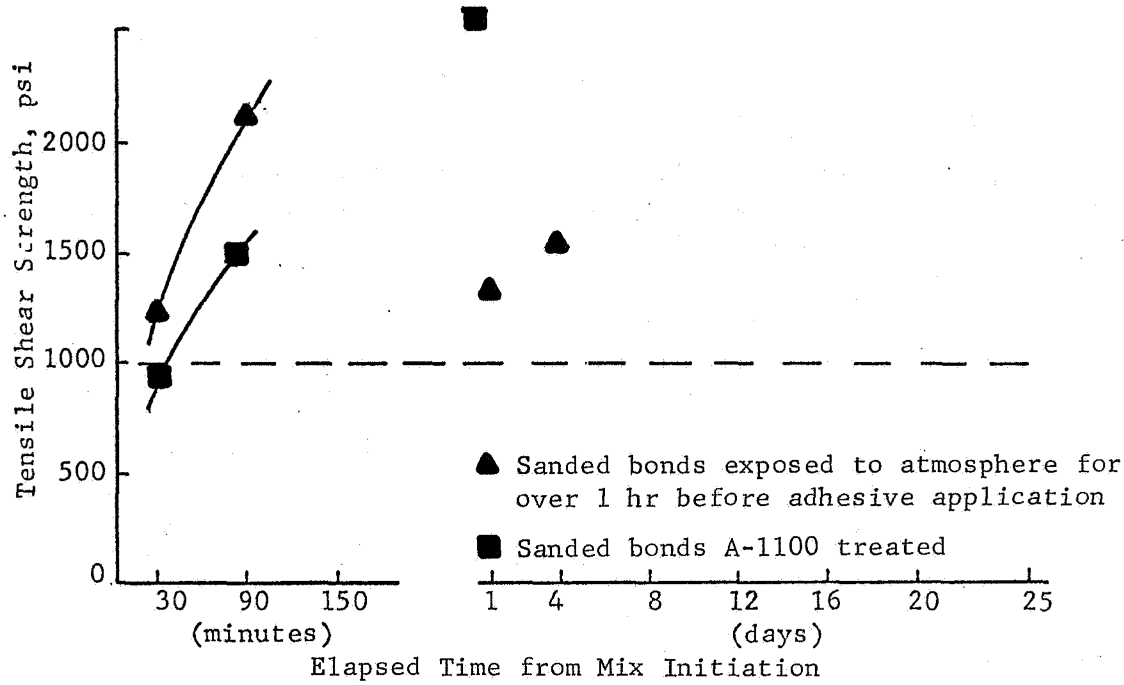

Figure 5. Tensile Shear Strength versus Aging Time for Adhesive System B Set and Aged at 100°F

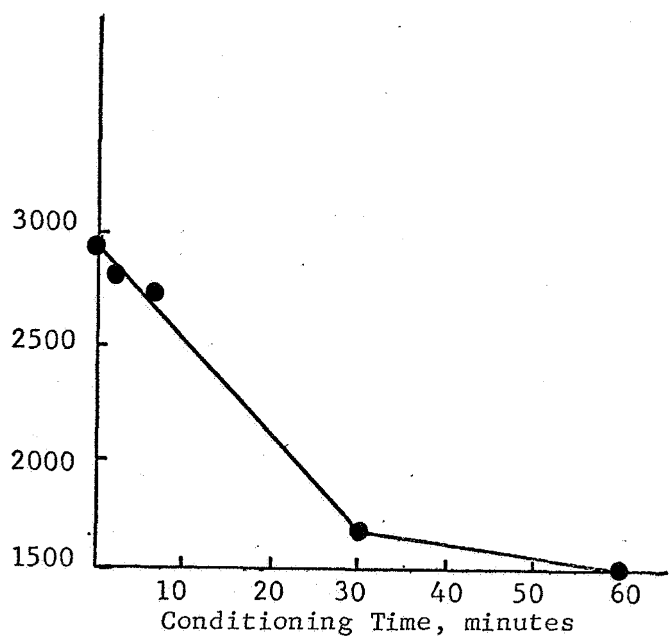

Figure 6. Epoxy Aluminum Tensile Shear Strength versus Exposure Time of Silicon Carbide Abraded Aluminum Exposed to Air at 20% Oxygen and 50% Relative Humidity. Source: Adhesives Age, 21 (1967)

ADHESIVE PACKAGE

A Tedlar* film package and mixing chamber has been designed and satisfactorily tested at 30°F, 75°F, and 100°F. The package is divided into two compartments, the resin in one section and the curing agent in another. The outer portion of the package is made of 2-mil Tedlar and the divider is made of 0.5-mil Tedlar. All portions are heat sealed. Mixing is accomplished by bursting the 0.5-mil divider and kneading the package. This has been accomplished successfully while wearing heavy asbestos gloves, however, not without some difficulties. While this adhesive packaging and mixing system is considered workable by an astronaut wearing a space suit and gloves, further optimization of this concept is recommended. A mechanical clip type separator for example would facilitate easier mixing of the two part adhesives.

ADHESIVE DISPENSER AND GLOVE BOX DEVELOPMENT

Upon the successful completion of the adhesive development effort, the design and fabrication of a suitable adhesive dispenser and vacuum chamber was undertaken.

Adhesive Dispenser

The primary criteria governing the design of the adhesive dispenser unit was to make the application of the adhesive as easy as possible for the astronaut.

The gun like unit shown in an exploded view in Figure 7, is simple to operate and requires a minimum effort on the part of the astronaut to carry out the adhesive bonding operation.

Figure 7. Exploded View of Adhesive Dispenser

* Product of DuPont.

The mixed adhesive still contained in the Tedlar package is folded in half and placed inside the plastic cylinder of the dispenser. This plastic cylinder and nozzle slides inside the retainer and threads onto the grip part of the gun. When the trigger is squeezed the piston advances in the cylinder pushing the adhesive package against the sharp edges of the nozzle which protrude into the cylinder. The Tedlar package is punctured and the adhesive is skeeted through the nozzle.

The plastic cylinder and piston cap are the only parts directly in contact with the adhesive, and can be disposed and replaced after each application, making the dispenser reuseable, requiring no solvant cleaning.

Glove Box

Due to the requirement for conducting the adhesive bonding repair experiment inside the Work Shop, a suitable chamber has to be provided to conduct the experiment in vacuum.

A glove box was designed which is capable to withstand an external pressure of 5 psi, representative of the presently planned 5 psia oxygen atmosphere for the Work Shop. The design could be easily upgraded to carry a 15 psi external pressure load in case a two gas one atmosphere system is adopted for the Work Shop program. The current glove box design has a proof pressure rating of 10 psi and an ultimate load of 15 psi differential pressure.

The glove box (Narmco Drawing No. NR 370) has a welded sheet metal frame with two major bonded stiffening channels which carry the loads along the window cutout. All side panels are aluminum honeycomb construction to minimize weight. Figure 8 shows the welded sheet metal frame and the partially assembled glove box illustrating the typical honeycomb wall panels. The completed glove box is shown in Figure 9, including the hand operated tensile test unit installed on the back wall of the chamber. Two modified Apollo hard suit arms will adopt directly to the port holes in the front of the box. The large hold in the bottom, covered with a fine mesh screen is the opening of the vent tube which will be connected to other hardware in the Work Shop vented directly to the exterior of the vehicle.

The complete experimental system for the adhesive bonding repair experiment (except gloves) is shown in Figure 10 with two typical adhesive packages, the dispenser unit and blank tensile shear test specimen blanks in front of the glove box.

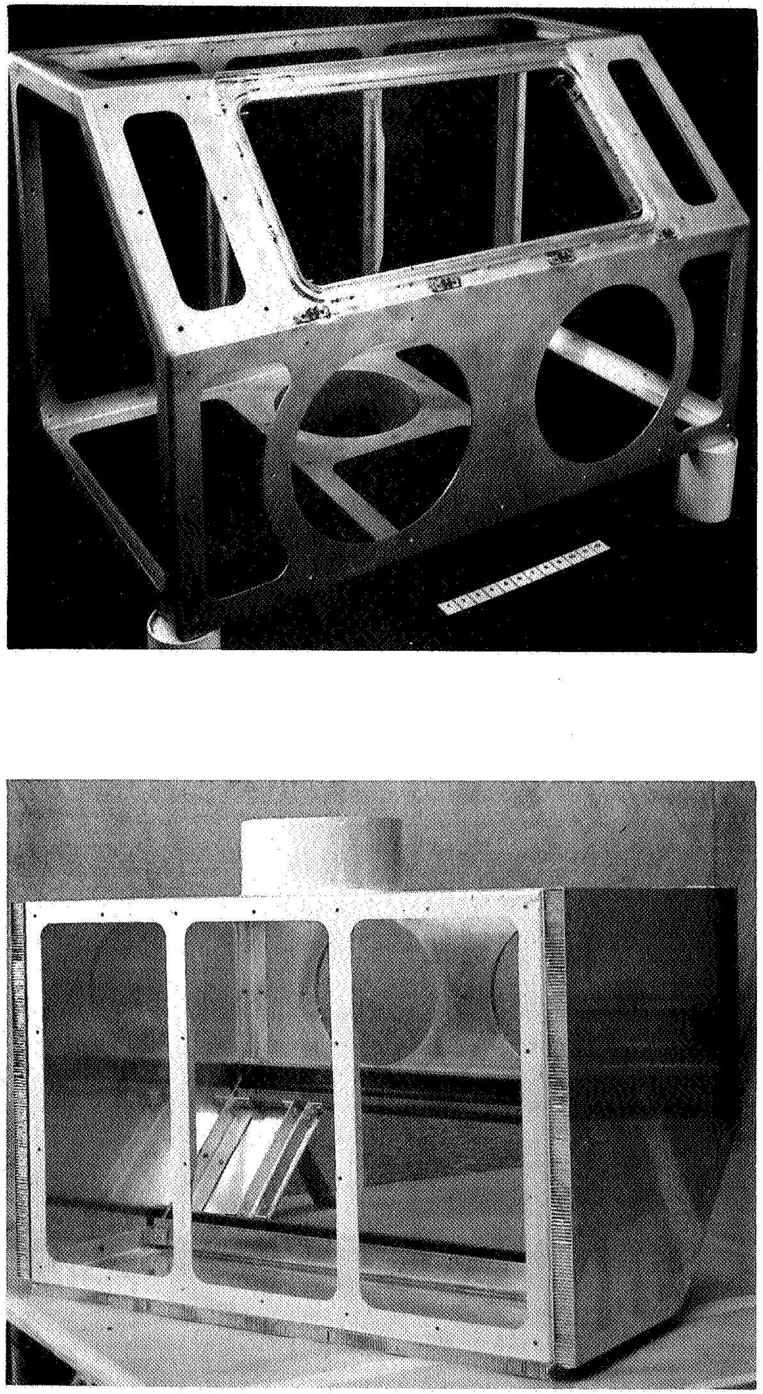

Figure 8. Welded Sheet Metal Frame and Partially Assembled Glove Box

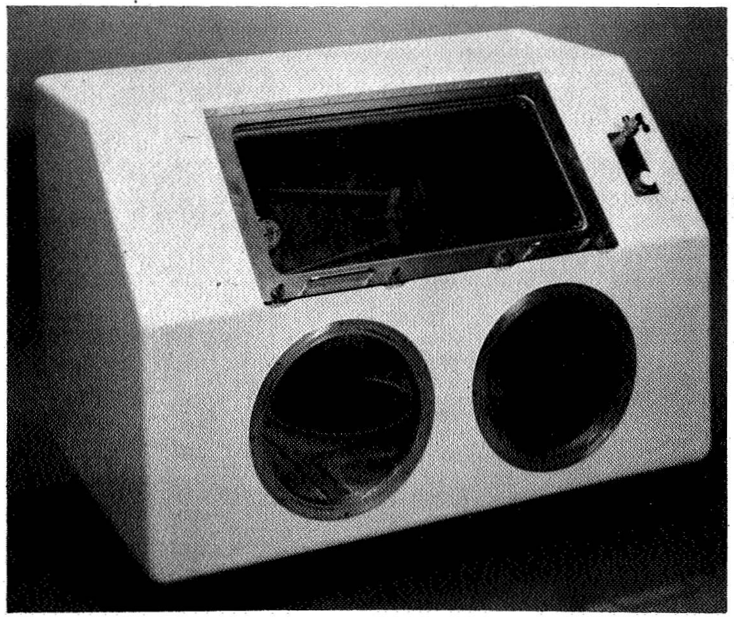

Figure 9. Glove Box with Tensile Test Unit

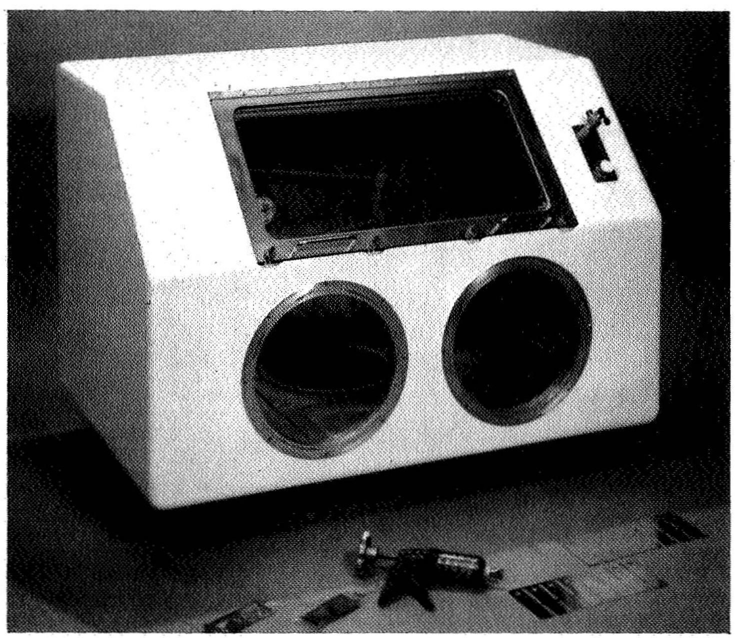

Figure 10. Complete Experiment System
(Except gloves)

PROOF PRESSURE AND LEAKAGE TEST

The glove box was submitted to a 1 minute duration, 10 psi differential proof pressure load by pulling approximately 20 inches of mercury vacuum inside the chamber. Visual inspection of the structure showed no sign of damage of permanent deformation of any component.

Following the proof pressure test, the glove box was leak-tested at 5 psi differential pressure. During the 24 hour test, a change in vacuum pressure was less than 1 inch of mercury inside the chamber. This leakage rate is well within the allowable value of 5 cc/minute.

CONCLUSIONS AND RECOMMENDATIONS

The three adhesive systems developed under this program provide a wide temperature range from 30°F to 130°F in which actual in space adhesive bonding operation could be performed.

The glove box and adhesive dispenser are believed to be suitable to carry out a realistic adhesive bonding repair experiment on board the SIV-B Work Shop.

The following additional work is recommended to improve the usefullness and inhance the success of the experiment:

1. The working temperature of the adhesive systems should be increased in both directions. A temperature range of 0°F to 160°F appears feasible with modification of the adhesive systems developed under this program.
2. The adhesive package design should be improved to facilitate easier and faster mixing.
3. Accessory fixtures and devices should be developed to provide aid in performing the experiment inside the glove box under zero-g conditions.