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SHUTTLE ORBITER TPS FLIGHT REPAIR KIT DEVELOPMENT
Final Report

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FOR
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ADMINISTRATION JOHNSON SPACE CENTER

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PREFACE

This report was prepared by the McDonnell Douglas Astronautics Company (MDAC) for the National Aeronautics and Space Administration Johnson Space Center (NASA-JSC) in accordance with Contract NAS9-15971. It documents the results of a 2-1/2-month program entitled Tile Protective System Flight Repair Kit Conceptual Design, which has as its major objective the conceptual development of a TPS Flight Repair Kit for use by the Shuttle crew for the on-orbit repair of any damage to the Orbiter TPS during launch.

The results of the 2-1/2-month program were generated from September 18 through December 17, 1979, including final report preparation. A midterm review was held at NASA-JSC on October 19, 1979, and the final briefing was held at NASA-JSC on November 30, 1979.

Overall project responsibility for the development of the TPS Flight Repair Kit was assigned to the MDAC Engineering Division, Research and Development directorate, responsible for all engineering studies and experimental activities. Supervisory authority for the project was given to Mr. A. P. Penton, Chief Technology Engineer, Materials and Processes, who reports to Mr. R. F. Zemer, Director, Structures and Materials, on all study related issues. Mr. H. K. Lauer was Program Manager. Mr. R. Gonzalez was Principal Investigator, responsible for coordinating all technical activities of the program. The J. L. Morse Company supported the contract by fabricating a functional mockup of the material dispenser.

The scope of this program was very broad and included many individuals who provided technical support. MDAC personnel who significantly contributed to this program include:

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CONTENTS

Section 1
INTRODUCTION

The probability of damage to the Shuttle Orbiter TPS during ascent has made it necessary to provide the Shuttle crew with a TPS flight repair kit. The repair kit is designed for on-orbit use by a crew member working in the manned maneuvering unit (MMU). The kit includes the necessary equipment and materials to accomplish the repair tasks which include the following:

- HRSI emittance coating repair
- Damaged tile repair
- Missing tile repair
- Multiple tile repair

Two types of repair materials are required to do the small area repair and the large area repair; a cure-in-place silicone base ablator for small damaged areas and precured ablator tile to repair larger damaged areas. The cure-in-place ablator is also used as an adhesive to bond the precured tiles in place. The cure-in-place ablator is dispensed through an applicator designed to contain a two-part silicone compound, mix the two components at the correct ratio, and dispense the materials at rates compatible with mission timelines established for the EVA. The dispenser and ablator materials are stored in a 0.34-m^3 (12 ft^3) module with an active heating system that maintains the materials between 278°K (40°F) and 325°K (125°F).

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Section 2
SUMMARY

This report documents the results of a 2-1/2-month development program funded to develop a TPS flight repair kit for on-orbit repair of the Shuttle Orbiter. The various tasks undertaken in this study are outlined in Figure 2-1. The Shuttle mission and systems requirements were defined under Task 1. Requirements for the repair kit were divided into the three distinct areas listed in Table 2-1 which include:

- Ablator materials
- Material applicator
- Flight kit module

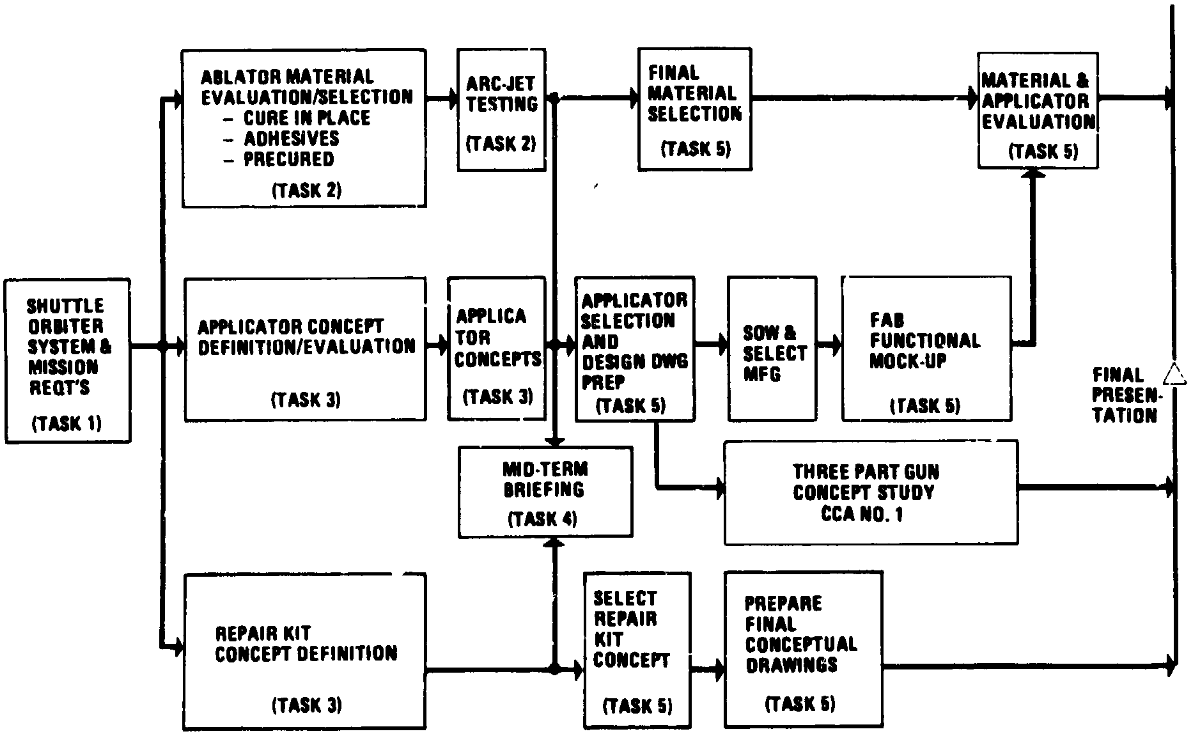

Figure 2-1. Program Plan

Table 2-1. Shuttle System and Mission Requirements

Materials	Applicator	Module
• Structure temperature <450°K (350°F) during reentry	• Reliable mixing and dispensing	• 0.34 m^3 (12 ft^3) volume maximum
• Tensile strength 276,000 N/m^2 (40 psi)	• One-hand operation	• 136 kg (300 lb) maximum
• Adhesion to substrates 276,000 N/m^2 (40 psi)	• Minimize crew fatigue	• Temperature control 278° - 325°K (40° - 125°F)
	• Easy to assemble (4 Operations maximum)	• Temperature monitoring
Cure-In-Place		
• Cure in vacuum 278°K - 325°K (40°F - 125°F) in 18 hours	• 0.01770 m^3 (1,080 in^3) minimum capacity	• Flight hardware design
• 1-hour work life	• Good visibility to repair area	
• Viscosity to remain in place after application	• Safe to handle	
• 6-month shelf life		

2.1 ABLATOR MATERIAL DEVELOPMENT

The ablator development effort was accomplished under Task 2. From numerous ablator materials evaluated one precured ablator, Purple Blend Mod 5, was tested and found to meet the requirements for precured ablator tiles listed in Table 2-2.

Of the seven cure-in-place ablators considered, RTV-560-55 and RTV-560-32 were developed and fully tested in this task. The requirements for cure-in-place ablators are listed in Table 2-3. Except for the char retention properties, these materials satisfy all of the requirements of Table 2-3. If char retention properties of these two materials need to be

Table 2-2. Precured Ablator Mission Requirements

Mission consideration	Mission requirement
Thermal performance	Maintain structure below 450°K (350°F) during reentry
Density	About 640 kg/m^3 (40 lb/ft^3)
Tensile strength	>276,000 N/m^2 (>40 psi)
Bond strength	>276,000 N/m^2 (>40 psi) when bonded to RTV-560
Flight status	Previous spacecraft use desirable
Dimensional stability	Minimal expansion during reentry
Property data base	Sufficient data for analysis
Availability	Material available
Durability	Ease of handling will not break up during crew handling

Table 2-3. Cure-in-Place Ablator/Adhesive Mission Requirements

Mission consideration	Mission requirement
Thermal performance	Maintain structure temperature below 450°K (350°F) during reentry
Cure properties	Cure in vacuum at 1.3×10^{-3} N/m^2 (10^{-5} Torr) and temperatures from 278°K to 325°K (40°F to 125°F)
Work life	1 hour after application at 278°K (40°F)
Cure time	Cure within 18 hours at 278°K (40°F)
Bond strength	Greater than 276,000 N/m^2 (40 psi) when bonded to RTV-560
Shelf life (unmixed)	Minimum of 6 months at 300°K (80°F)
Viscosity	Sufficient to remain in place after application
Low density	To minimize thermal stress on adjacent tiles and increase quantity of material for each mission

improved, refractory fibers can be added to the formulations. Fibers were not added initially due to concern that they would clog in the static mixing heads of the material applicator. Static mixing heads with larger orifices were later selected for use in the functional mockup producing high material delivery rates and good mixing. Optimization of the cure-in-place formulations by the addition of refractory fibers thus appears feasible.

2.2 MATERIAL APPLICATOR

Several applicator concepts were studied and evaluated to the requirements listed in Table 2-1. From this effort two concepts were selected.

- A self-contained applicator shown in Figure 2-2
- A three-part applicator design shown in Figures 2-3 and 2-4.

Both material applicators operate on the same concept, using gas pressure to expel the material and static mixing heads to mix the catalyst and resin. The basic difference between applicator concepts is in the containment of the material. The advantage of the three-part gun is the smaller applicator head. The self-contained gun does not have a hose, which makes it easier to handle and the amount of material remaining in the delivery system is less. Reliability of the self-contained gun is also better since a larger number of units (nine versus three for the three-part applicator) is required to meet mission requirements for cure-in-place material volume of 1,080 in^3. The loss of one self-contained gun would not be significant, while loss of one canister would reduce the available material by 33%.

The functional mockup shown in Figure 2-5 was constructed and used to verify the basic functions of the proposed gun concepts; i.e., static mixing, pressures required for material delivery and control of catalyst-to-resin ratio. The results of the test program conducted with the functional mockup verify that adequate mixing can be obtained with three Ross-type static mixing units and that a single gas cartridge of the size utilized in the functional mockup has the capacity to drive the piston to full extension and to obtain ample material delivery rates from the self-contained gun.

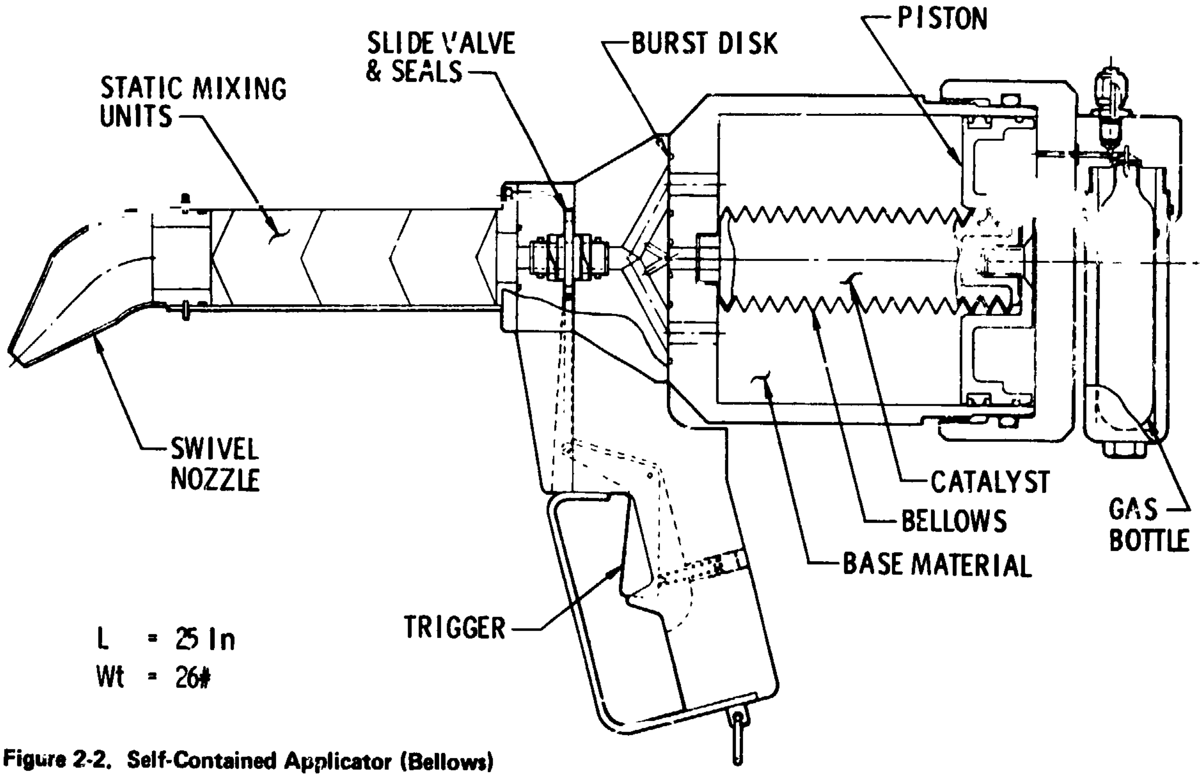

Figure 2-2. Self-Contained Applicator (Bellows)

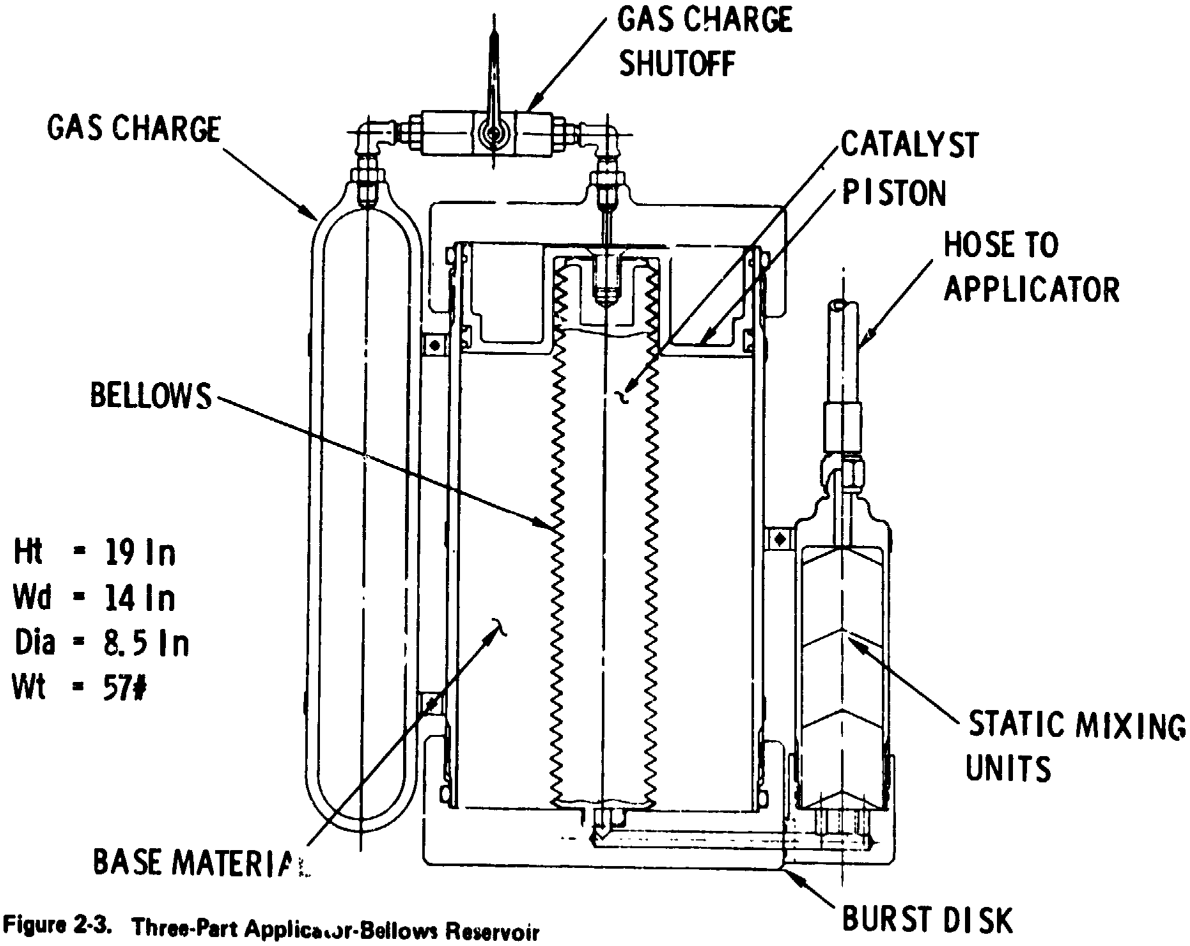

Figure 2-3. Three-Part Applicator-Bellows Reservoir

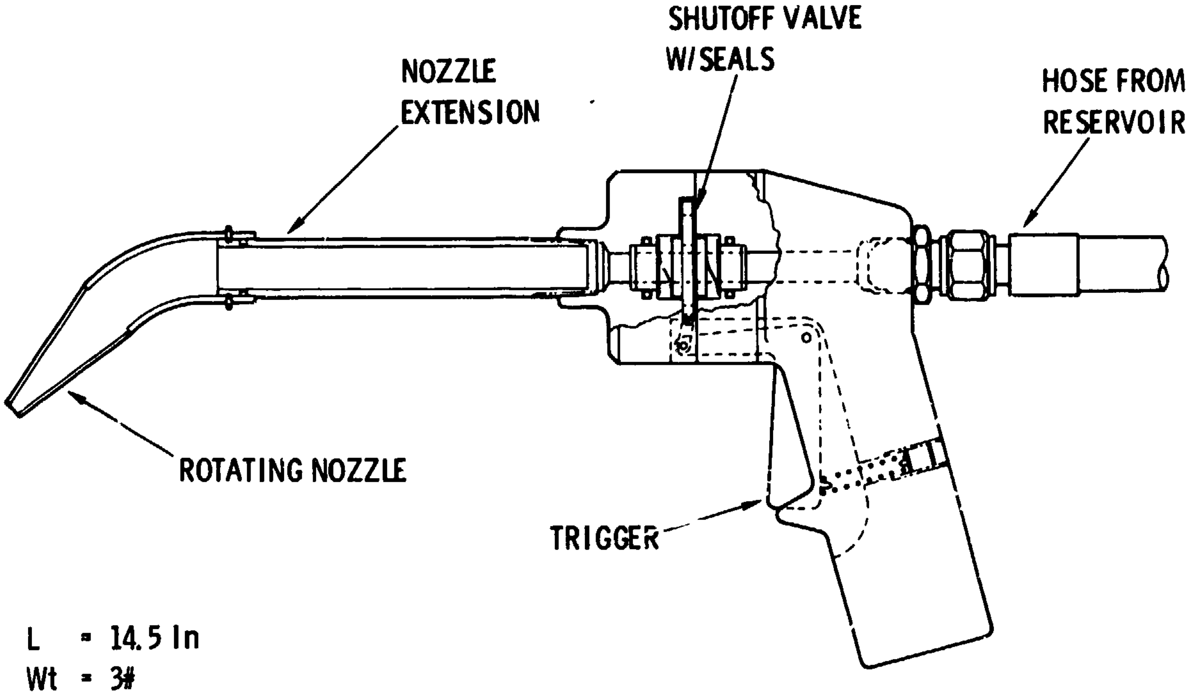

Figure 2-4. Three-Part Applicator

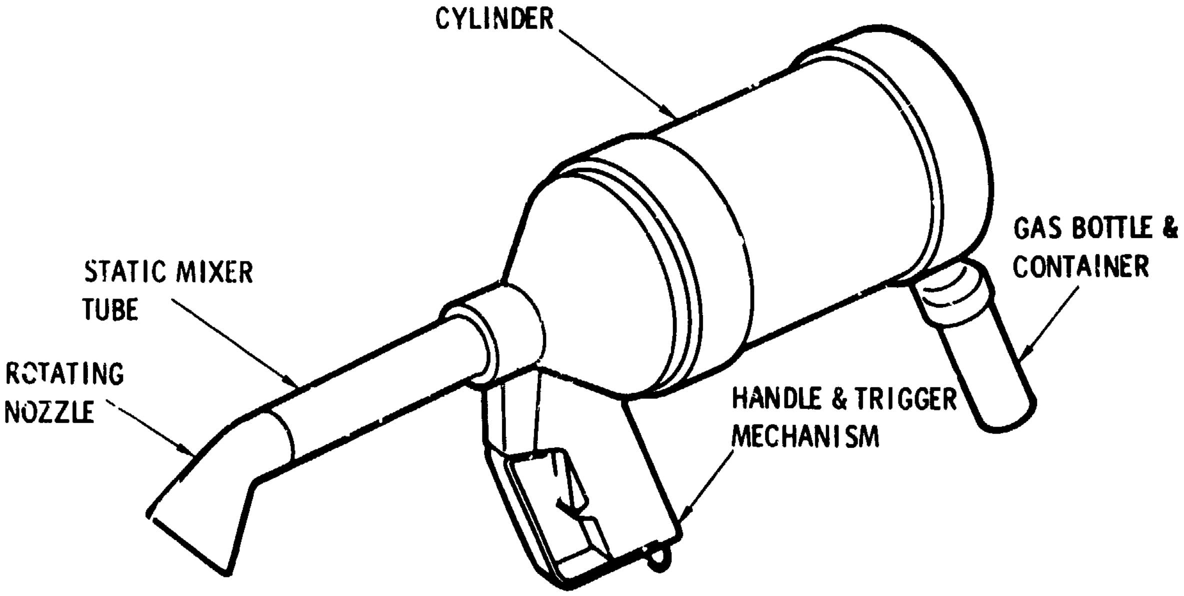

Figure 2-5. Functional Mockup

2.3 FLIGHT KIT MODULE

The requirements for the flight kit module are listed in Table 2-1. MDAC has studied the repair scenarios and requirements to develop our recommended kit which will sustain launch loads and provide a reliable TPS repair capability in orbit. It has evolved from a modular to a unit approach and back to a combination of the two which minimizes astronaut activity and permits specific selections for each repair mission based on just-completed inspection observations (see Figure 2-6). All items are readily accessible and easy to transfer to the work station; each applicable assembly as a complete unit and the rest of the materials and tools in their transfer modules. Unused materials, tools, and all waste packages also can be restowed quickly to complete the repair mission. No pre-EVA cabin preparation activities are contemplated. The unit has an overall volume of 0.34 m^3 (12 ft^3), is actively heated, is provided with a thermal insulation blanket to maintain the required temperature, and is designed for the Shuttle flight loads. Unit weight is a continuing problem and several means by which this problem can be approached are discussed in Sections 4 and 5 of this report.

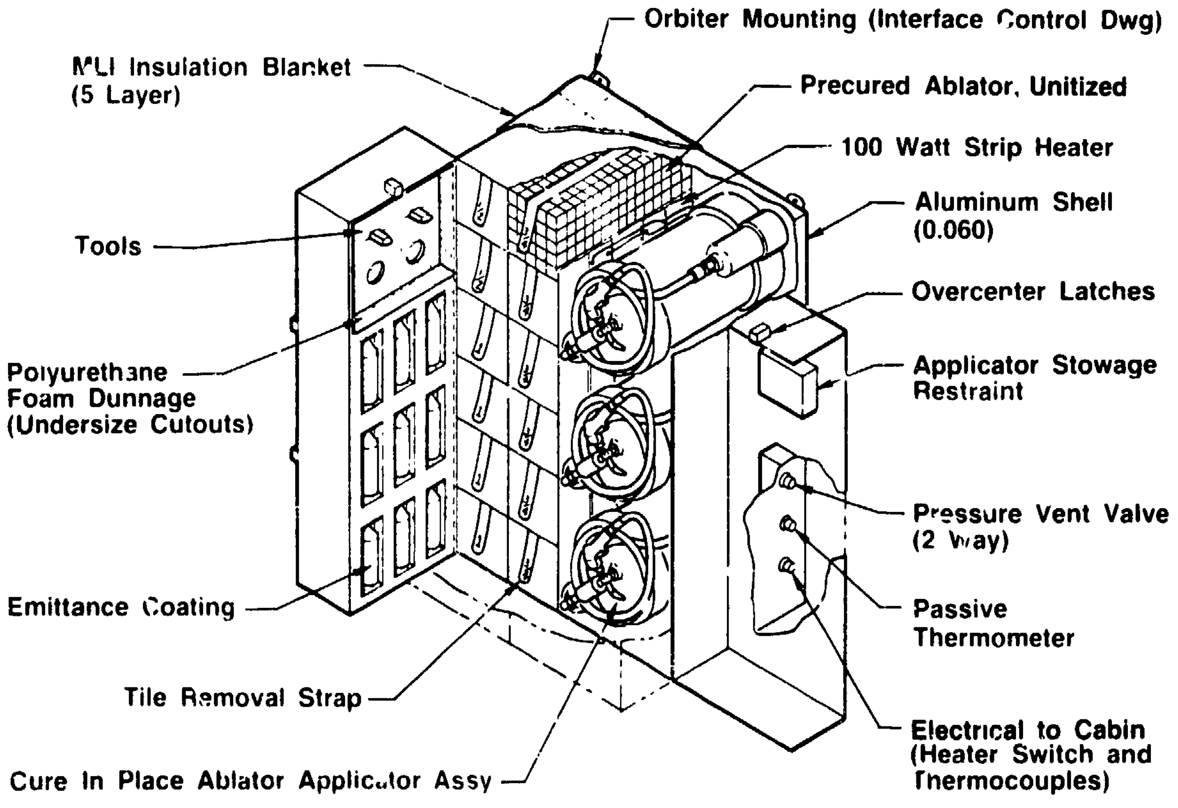

Figure 2-6. Complete Tile Repair Kit

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Section 3
ABLATOR MATERIALS

3.1 TECHNICAL APPROACH

The primary objective of this effort was to select or develop cure-in-place and precured ablators for use in repairing the Shuttle Orbiter TPS while in orbit. The initial task (2-1) was to define the requirements imposed on the repair materials. Once the requirements, listed in Tables 2-2 and 2-3, were established every effort was made to select materials for which a good data base for analysis was available. Unfortunately, to MDAC's knowledge, no previous experience in applying and curing ablator materials in space exists. Therefore, a material that could be applied and cured in the space environment and still perform its intended functions had to be developed. The precured ablator presented no major problem, since much development work had been done on ablators on numerous space and missile programs and as part of in-house IRAD studies. RTV-560 was chosen as the base elastomer for the cure-in-place ablative compound since it would be compatible with the existing Orbiter TPS and it possesses the best overall properties of the commercially available RTV silicones. This material is basically a sealant and the incorporation of additional fillers is required to provide improved ablative properties and to improve on-orbit processing characteristics, such as the ability to remain in-place in the repair area after application and prior to cure. The approach for improving the properties of RTV-560 to meet the requirements listed in Table 2-1 and reduce density are as follows:

A. Decrease ρ and k – Add microballoons, Eccospheres, or granular cork.

B. Increase char strength – Add refractory fibers

C. Decrease high temperature k – Add opaque powders

D. Increase oxidation resistance – Add silica

E. Increase char yield – Add phenolic microballoons or cork

F. Increase thixotropy – Add Cab-O-Sil

G. Reduce swell – Use honeycomb

3.2 CURE-IN-PLACE ABLATOR

The cure-in-place ablator consists of an uncured paste-like silicon elastomer that is applied as a paste and will cure to a solid rubber at ambient temperature.

3.2.1 Candidate Materials

Compounds selected for evaluation as cure-in-place ablators were restricted to formulations based on room temperature vulcanizing silicone rubber compounds. The RTV silicones have been successfully used in ablative applications and have excellent low, as well as high, temperature properties. The main factor limiting the candidate materials to the RTV silicones derives from the requirement to bond to an RTV-560 substrate, since it would be difficult to ensure adequate adhesion to this substrate with any cure-in-place ablator other than a silicone.

Formulation of the cure-in-place ablator from a silicone using an addition-type cure mechanism appears advantageous since these silicones do not require the presence of a volatile component for their cure and do not produce a volatile by-product in curing. In contrast, condensation-cure silicones require a trace of water to promote cure and they produce small quantities of a volatile, low molecular weight alcohol as a reaction product of the cure. However, the addition-cure silicone compounds are subject to cure inhibition in the presence of a variety of compounds including the metallic soap catalyst used to cure the RTV-560 substrate. Although the application of a primer to seal the RTV-560 substrate surface and prevent contact of ablator with the metal soap is conceptually feasible, in practice the difficulties of developing a primer/sealant which could be applied in vacuum, the added complexity of an additional component in the repair kit, and the difficulties inherent in verifying the absence of cure inhibition at the bond line all weigh heavily against the use of addition-cured silicones for the cure-in-place ablator. The presence of the volatile components in the condensation cure system may not be a serious limiting factor if it can be demonstrated that the materials can be cured in vacuum and dissolved and trapped gases are kept to a minimum. Candidate materials for the cure-in-place ablator were, therefore, selected from condensation cure-type RTV silicones as listed in Table 3-1.

Table 3-1. Candidates for Use as Cure-In-Place Ablation Adhesives

Material	Weight		Viscosity	Low temperature capability		Tensile strength		Comments
	kg/m^3	(lb/ft^3)	$N\ sec/m^2$	°K	(°F)	$10^6\ N/m^2$	(psi)	
RTV-560	1,420	(89)	40	58	(-175)	5.52	(800)	Same as substrate. Density and viscosity high.
RTV-566	1,420	(89)	40	58	(-175)	5.52	(800)	Low outgassing version of RTV-560. Very high cost, high weight.
RTV-577	1,350	(84)	600	58	(-175)	3.31	(480)	High viscosity and weight.
RTV-88	1,470	(92)	600	232	(-75)	5.17	(750)	Dimethyl polymer. High weight and viscosity.
PR-1977	1,350	(84)	600	232	(-75)	5.52	(800)	Dimethyl polymer. High weight and viscosity.

An obvious candidate to consider for the cure-in-place ablator is the material comprising the substrate to which the ablator is to be bonded, RTV-560. This material is a methyl-phenyl-type polymer which provides the best low-temperature flexibility at the lower temperature extremes and is formulated with an iron oxide filler to provide improved high-temperature stability. The density is high and the viscosity is low for the intended application. RTV-566 is a low offgassing version of RTV-560 available at a substantial cost premium. This compound probably represents RTV-560 which has been heated under vacuum to remove volatile components and low molecular weight polymer fractions. Since processing of the cure-in-place ablator is certain to include high vacuum conditioning, there is no substantial advantage to justify the premium required for this vacuum preconditioned material.

RTV-88, RTV-577, and PR-1977 represent typical paste-like products used for cast or trowel-in-place applications where high viscosities are required. Densities of these materials are high and viscosities are high in terms of mixer/applicator suitability. The PR-1977 is a commercially available ablative compound currently used by MDAC on the Delta launch vehicle.

Various low-density silicone ablators have been investigated and used for ablative applications. These materials typically are compounded using hollow microspheres to reduce density. A typical example is Purple Blend. In view of the extensive experience in the characterization and use of these low density ablators, in combination with the requirement for a condensation cure silicone compound, the use of a low-density ablator formulated with RTV-560 was selected as the best approach for the development of the TPS cure-in-place ablator material.

3.2.2 Low-Density RTV-560 Ablators

The formulation of the RTV-560 ablators was achieved primarily by the addition of hollow microspheres to the silicone compound. In view of the high iron oxide content, the use of additional opaque powder to reduce thermal conductivity was judged unnecessary. Although some refractory fiber may be required to obtain optimum performance, the use of a refractory fiber in the cure-in-place ablator was considered to be a potential source of problems with regard to clogging of the mixer/applicator. Refractory fibers were, therefore, not included in the candidate cure-in-place ablators formulated for this study. Subsequent studies with the applicator functional mockup suggest that acceptable material extrusion properties might be obtained with a cure-in-place formulation including refractory fibers.

Two approaches to the formulation of the cure-in-place ablator were investigated. In the first, hollow microspheres were added to the RTV-560 silicone until the viscosity was estimated to have reached a maximum consistent with the requirement to mix readily with the curing agent in the applicator gun. The compound thus formulated was designated RTV-560-55.

The second modified RTV-560 ablator compound was formulated by adding a substantially larger quantity of hollow microspheres. Incorporation of the microspheres into the RTV-560 and lowering of the viscosity to a workable level was accomplished by the addition of a low viscosity silicone fluid diluent. The formulation was designated RTV-560-32. Compositions of the two cure-in-place ablator compounds are given in Table 3-2.

Table 3-2. Composition of Cure-in-Place Ablators

Material	RTV-560-55	RTV-560-32
RTV-560	82.6 parts by weight	61.0 parts by weight
RTV-9811 Catalyst	4.6	3.4
RTV Catalyst F	4.6	3.4
Eccospheres Si	4.1	20.0
Microballoons, phenolic	4.1	--
Silicone fluid SF-99	--	12.2

3.2.3 Curing Agent

Two parameters related to the curing agent must be considered in order to provide a cure-in-place ablator with a specified work life, and cure properties suitable for use in a mixer/applicator gun for on-orbit repair. First, a means to adjust the curing speed of the ablator formulation should be available. Secondly, the volume and viscosity of the curing agent should be sufficiently large so that metering and mixing of the curing agent uniformly into the base compound are practical.

The curing agents for the condensation-cure silicone elastomers are normally metallic soaps. Dibutyl tin dilaurate is the more frequently used curing agent and provides a moderate cure rate (18 to 36 hours at 293°K). Stannous octoate provides a very rapid cure (4 to 12 hours at 293°K) and allows cure to be accomplished at lower temperatures. Both curing agents are available as concentrated liquids used in quantities of 1 to 5 parts per 1,000 parts of base compound. In this form, the curing agents are too concentrated to function well in an application requiring machine metering and mixing.

The metallic soaps are also available in the form of paste-type curing agents designed for use at concentrations of approximately 1 part by weight per 10 parts of the base compound. Curing agents RTV-9811 and catalyst F which are used in combination in the RTV-560-55 and RTV-560-32 formulations are paste-type curing agents. The RTV-9811 provides a moderate cure rate and the catalyst F, a paste version of stannous octoate, provides a fast cure. This combination of curing agents was initially selected to examine the feasibility of a paste curing agent with a cure rate which could be adjusted by varying the amounts of stannous octoate. An equivalent method also used in this study involved the use of RTV-9811 paste catalyst to which stannous octoate liquid was added to adjust the reactivity.

3.2.4 Specimen Preparation

In an initial evaluation of the mixing and curing behavior of the silicone ablators, the RTV-560 and the curing agents were each separately degassed under vacuum and were then mixed under vacuum conditions. This mixture did not cure because the condensation cure mechanism which requires the presence of trace amounts of water had been removed. In the specimens prepared, these trace amounts were provided by the use of curing agent which was not dried or degassed. Future studies to optimize these ablator materials should evaluate procedures in which both the silicone compound and curing agent are degassed and then the silicone compound is equilibrated under vacuum with a known partial pressure of water.

Specimens to evaluate the modified low-density RTV-560 compounds were fabricated as follows: the hollow microspheres (Eccospheres Si and phenolic microballoons) were dried 16 hours minimum in a vacuum over at 325°K (140°F). The RTV-560 was degassed under vacuum, the fillers were added, and the mixture was stirred under vacuum. Curing agent was then mixed into the RTV-560 compound while the material was exposed to atmospheric conditions.

3.2.5 Viscosity

Mixtures of the candidate materials without curing agents were prepared and viscosities were determined using a Model HB Brookfield viscosimeter. The viscosities are given in Table 3-3.

The tendency of the ablator compounds to flow out of the repair area prior to gelation of the silicone polymer was investigated using the RTV-560-32 formulation. No curing agent was added. Samples of this material were positioned in a cavity 0.013 m (0.5 in) deep with 0.0013 m (0.05 in) gaps shown in Figure 3-1. The RTV-560-32 material flowed a distance of approximately 0.0157 m (0.62 in) in 35 min. Increasing viscosity as a result of polymerization would be expected to retard viscous flow after this time. The viscosity of the RTV-560-32 is considered marginal with regard to its viscous flow properties. An increase of the filler content or the addition of a material to increase thixotropy is therefore recommended.

3.2.6 Cure Rate

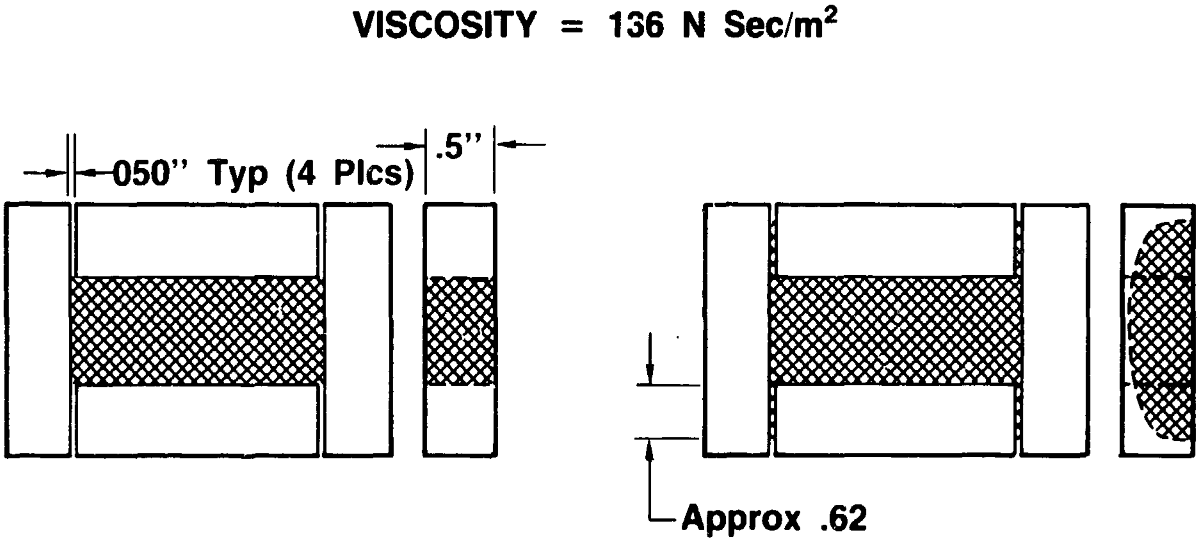
The cure rate of RTV-560-based ablator compound as a function of stannous octoate concentration and temperature was investigated. Approximate concentrations of curing agent were first established by adding varying quantities of stannous octoate diluted in dibutyl tin dilaurate. The cure rate of RTV-560-55 ablator compound was then investigated as a function of temperature at two selected concentrations of stannous octoate. The results are presented in Table 3-4 and Figure 3-2. It can be seen from these data that at the lower concentration of 1.25 parts by weight (pbw) of stannous octoate to 1,000 parts of RTV-560, cure at 278°K (40°F) is very close to meeting the mission requirements of 1-hour work life and fully cured within 18 hours. A slight reduction in stannous octoate could probably be tolerated to increase work life and still have an adequate cure after 18 hours. The 1.775 pbw

Table 3-3. Viscosities of Cure-In-Place Ablators

Material	Temperature °K (°F)	Spindle No.	Speed RPM	Viscosity N sec/m^2
RTV-560-55	278 (40)	7	20	344
	294 (70) Lot 1	7	20	275
				272
	294 (70) Lot 2	7	20	288
	Note 1			280
				272
				269
				277 Avg ±7
	325 (125)	7	20	108
RTV-560-32	294 (70)	6	20	128
				132
				140
				140
				140
				136 Avg ±5
	294 (70)	6	10	136
				144
				140
				140
				140 Avg ±2

concentration of curing agent provides a cure rate which satisfies mission requirements for cure within 18 hours even at 278°K (40°F). However, the work life at 125°F is too short.

A cure rate study of the type described above was not conducted with RTV-560-32. Small samples were mixed and monitored for 2 to 4 hours to determine the curing agent concentrations for specimen preparation. These



Initial Cavity One-Half Inch Deep Filled With Uncatalyzed RTV 560-32

After 35 Minutes RTV 560-32 Has Flowed Approx .62 Inch Thru .050 Gaps

Figure 3-1. Viscous Flow of RTV 560-32 (Uncatalyzed)

tests indicate that the cure of RTV-560-32 is slower and that a higher stannous octoate concentration may be required for this material.

It should be noted that these cure rate studies were run at atmospheric pressure and not under vacuum and that the effect of water concentration was not determined. These parameters should be examined in combination before the nominal curing agent concentration is established for the selected cure-in-place ablator compound. Reactivities for each individual production lot of the curing agent should be determined and cure rates adjusted by the addition of appropriate quantities of stannous octoate.

3.2.7 Tensile Strength

Tensile strength coupons were fabricated from sheets of cure-in-place ablator material cast in vacuum. The fillers were incorporated into the RTV-560 base compound under vacuum and the curing agent was then added and mixed at atmospheric pressure. The catalyzed mixture was loaded into a cylindrical tube (Semco cartridge) fitted with a piston at one end and a conical nozzle at the opposite end. The conical nozzle was inserted into a hole in the mold cavity and a vacuum was applied with air pressure forcing the material into the evacuated mold cavity.

Table 3-4. Cure Rate of RTV-560-55

Elapsed time minutes	Stannous octoate concentration, parts by weight (pbw) per 1,000 pbw RTV-560					
	1.25			1.775		
	278°K(40°F)	294°K(70°F)	325°K(125°F)	278°K(40°F)	294°K(70°F)	325°K(125°F)
0	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
3			Thick	Thick		Thick
10						10 Shore A
11			Very Thick		Thick	
12		Thick		Liquid		
16						30
18				Thick		
22					Very Thick	
24	Thick					
30						
31			5 Shore A			
40			18			40
49					10 Shore A	
50		Very Thick				50
51			25			
59					20	
68						52
70			35	Very Thick		
77					30	
82			40			
90	Very Thick					
91					35	
92		2 Shore A				
98			45	Very Thick		55
108		7			45	
135			52			60
138				9 Shore A		
145		25			45	
160						62
162				20		
170		25			52	
210						
212			62	40		
220		35			56	
258				46		62
266	Very Thick	45				
Approx 1310	52 Shore A	60		62	62	62

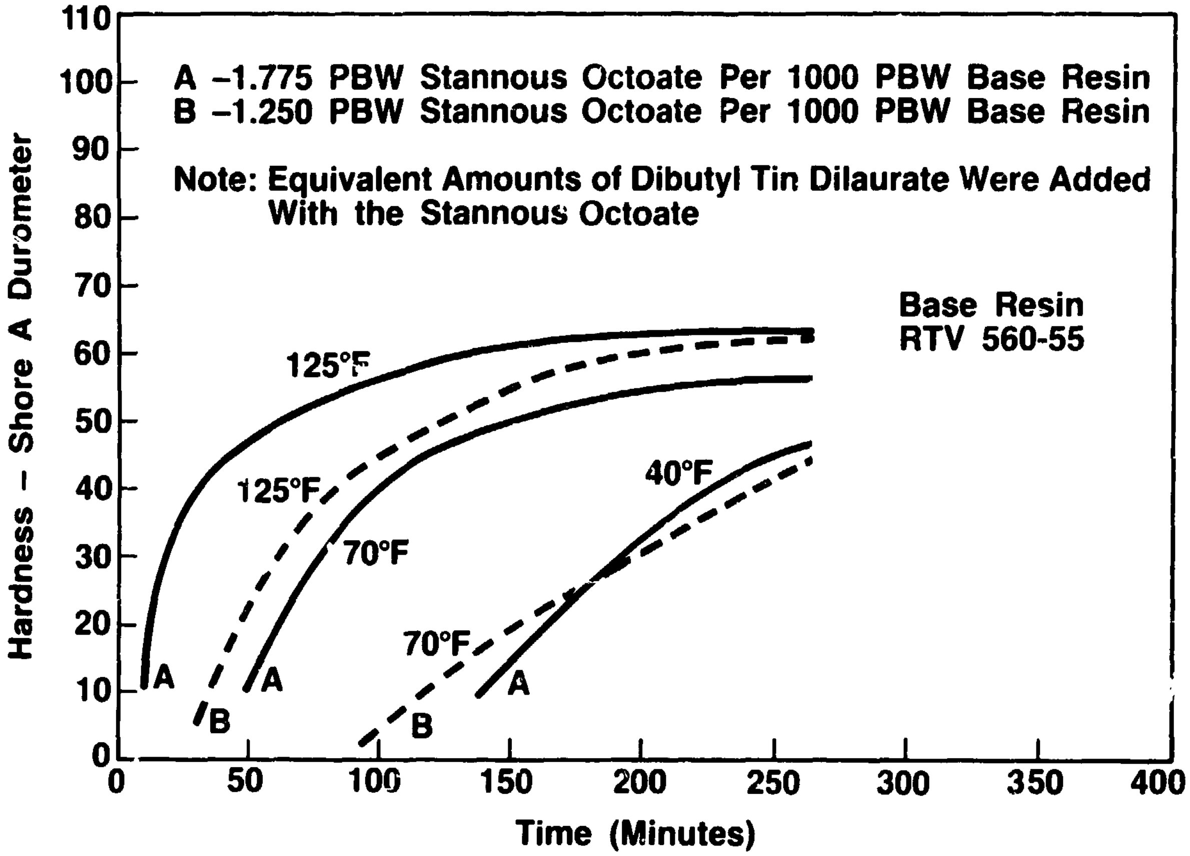


Figure 3-2 Cure Rates Versus Temperature

Tensile specimens were cut from the cured sheets using a die conforming to ASTM D412. Testing was accomplished at 0.00021 m/sec (0.5 in/min). Results are presented in Table 3-5. Tensile test results indicate that the modified RTV-560 formulations had sufficient strength to meet program requirements and additional strength tests were confined to tensile adhesion strength measurements.

Table 3-5. Tensile Strength of Cure-in-Place Ablators

Material	Cure	Tensile strength 10^6 N/m^2 (psi)
RTV-560-55	Room temp in vacuum	1.36, 1.04 (198, 151)
RTV-560-32	325°K (125°F) in vacuum	1.09, 0.903, 1.13 0.869, 1.20 (158, 131, 164, 126, 174) Avg = 1.04 (151)

3.2.8 Tensile Adhesion

Tensile adhesion tests were conducted using circular aluminum tensile blocks with a cross-sectional area of 0.000645 m^2 (2 in^2) conforming to ASTM D429. The aluminum blocks were prepared by abrading the surfaces with a nylon abrasive pad and wiping with clean methyl ethyl ketone solvent to remove any surface contamination. Dow Corning DC1200 silicone primer was applied to the clean bonding surfaces and allowed to air dry 30 minutes. A brush coat of catalyzed RTV-560 silicone rubber was applied and cured.

Mixtures of the cure-in-place ablator materials were prepared as previously described and applied to both surfaces of the RTV-560-coated tensile blocks. The blocks were assembled and positioned in the ASTM D429 cure fixture. The specimens cured at room temperature 294°K (70°F) and at 325°K (125°F) were placed in a vacuum chamber and vacuum was maintained continuously with a vacuum pump during cure. The cure fixture with specimens cured at 278°K (40°F) was placed in a vacuum desiccator preconditioned at 278°K. A vacuum was applied. the desiccator was sealed and placed in a refrigerator at 278°K for the cure.

The edges of the cured specimens were trimmed to the 0.041 m (1.6 in) diameter of the tensile blocks and tested in tension at a load rate 0.00021 m/sec (0.5 in/min).

Specimens to measure adhesion to the HRSI tile and to the ceramic tile with emittance coating were prepared using a different method. For these specimens, the cure-in-place ablator compound was applied to an RTV-560 coated tensile block and this block was then positioned on a rectangular sample of tile and cured in vacuum. A knife blade was run around the circumference of the tensile block to separate the flash from the ablator material bonding the tensile block to the tile.

Tensile adhesion samples to the ceramic tile failed by cohesive failure in the ceramic tile with the larger values yielding deep dished failure surfaces. The specimens in which the ablator compound was bonded to tile with emittance coating failed with fracture of the emittance coating in roughly spherical shape but with areas larger than the tensile block. Cohesive failure of the ceramic tile occurred so that the emittance coating pulled off the tile had a layer of adhering ceramic tile. One sample bonded with RTV-560-32 failed at a very high value. A circular area of emittance coating approximately 0.051 m ([illegible] in) in diameter failed on this specimen in a manner similar to the other specimens of this type. In addition a segment extending across the 0.076 m ([illegible]) width of the sample and passing through the edge of the bonded tensile block was broken out of the tile. This segment varied from 0.0127 m ([illegible] in) wide on one side to 0.028 m (1.12 in) wide on the opposite side of the specimen. The fracture surface in the ceramic tile on this segment was varied from just below the surface of the emittance coating at the narrow edge to 0.00021 m (0.5 in) deep into the tile at the wide edge.

Results of the tensile adhesion tests are listed in Tables 3-6 and 3-7 and indicate that both cure-in-place ablator formulations meet the tensile bond strength requirements for the on-orbit repair mission.

3.2.9 Densities

Densities of the ablative compounds were determined by measuring the dimensions of cured samples and weighing on an analytical balance. A sample of RTV-560-55 prepared to test the prototype applicator gun was found to have a substantially higher density than other measurements. The reasons for this anomalous mixture are unknown but may involve errors in the hollow microsphere content made in formulating the mixture or excessive breakage of the microspheres when stirring the mixture during vacuum degassing. It was determined that a reasonably close approximation of the cured density could be obtained by measuring the density of the uncatalyzed material using a weight per gallon cup or an equivalent method for fluid density, and this is recommended as an in-process quality control procedure during the formulation of production lots of the low-density ablator compounds.

Densities of the cure-in-place ablator compounds are as follows:

RTV-560-55	Cured in air	58.9 lb/ft^3
	Cured in vacuum	50.4 lb/ft^3
	Cured in air (anomalous value)	72.6 lb/ft^3
RTV-560-32	Cured in vacuum	32.8 lb/ft^3

Table 3-6. Adhesion of RTV-560-55 Cure-In-Place Ablator

Material	Substrate	Cure temperature °K (°F)*	Tensile bond strength 10^5 N/m^2 (psi)**	
RTV-560-55	RTV-560	278 (40)	3.70, 4.20, 3.30, 3.42 (53.7, 60.9, 48.0, 49.6	Avg = 3.65 Avg = 53.0)
RTV-560-55	RTV-560	Room temperature	4.20 4.92 3.95 (61.0, 71.3, 57.3, 43.9	Avg = 4.36 Avg = 58.4)
RTV-560-55	RTV-560	325 (125)	3.03*, 3.67, 4.03*, 4.3* (43.9*, 53.2, 58.4*, 63.0*	Avg = 3.77 Avg = 54.6)
RTV-560-55	Purple blend and RTV-560	Room temperature	5.91, 6.48, 6.48, 5.23 (85.7, 94.0, 94.0, 75.9	Avg = 6.03 Avg = 87.4)
RTV-560-55	HRSI Tile	Room temperature	1.08 2.28 (15.7 28.6	Avg = 1.18 Avg = 17.2)
RTV-560-55	Emittance coating on HRSI	Room temperature	2.42, 2.56 (35.1 37.2	Avg = 2.49 Avg = 36.2)

---

*All specimens cured under vacuum.
**All values identified thus * consist of adhesive failure between the RTV-560 substrate and the aluminum tensile block.

Table 3-7. Adhesion of RTV-560-32 Cure-in-Place Ablator

Material	Substrate	Cure temperature °K (°F)*	Tensile bond strength 10^5 N/m^2 (psi)**	
RTV-560-32	RTV-560	278 (40)	3.83, 4.91, 4.67, 4.81 (55.5, 71.3, 67.7, 69.7	Avg = 4.55 Avg = 66.0)
RTV-560-32	RTV-560	Room temperature	8.82* 4.52*, 5.16* (128*, 65.6* 74.9*	Avg = 6.17 Avg = 89.5)
RTV-560-32	RTV-560	325 (125)	5.56, 5.70, 6.52, 4.59 (80.6, 82.6, 94.5, 66.6	Avg = 5.59 Avg = 81.1)
RTV-560-32	HRSI Tile	Room temperature	0.731, 0.586 (10.6, 8.5	Avg = 0.659 Avg = 9.6)
RTV-560-32	Emittance Coating on HRSI***	Room temperature	8.20 2.56 (119, 37.2	5.38 Avg = 78)

---

*All specimens cured in vacuum

**All values identified thus * consist of adhesive failure between RTV-560 substrate and the aluminum tensile block

***Refer to text for discussion of anomalous high value

3.2.10 Thermal Expansion

The thermal expansion characteristics of the RTV-560-55 material were determined with a Perkin Elmer Thermal Mechanical Analyzer using a quartz expansion probe. The measurement was made on a cubic sample 0.0064 m (0.25 inch) on a side under argon. The measurement was conducted from ambient temperature to 473°K (200°C) at a heating rate of 5 degrees per minute.

3.2.11 Summary of Cure-In-Place Ablator Properties

The properties of the cure-in-place ablator materials are summarized in Table 3-8.

Table 3-8. Properties of RTV-560-55 and RTV-560-32 Cure-in-Place Ablators

Property	RTV-560-55	RTV-560-32
Density, lb/ft^3	50	32
Tensile Strength, psi	135	145
Hardness "A" Shore	70	66
Adhesion to RTV-560, psi	87	89.5
Viscosity, cps		
40°F	344,000	--
70°F	263,000	136,000
125°F	109,000	--
Thermal Conductivity, Btu/hr-ft-°F	0.031	0.025
Coefficient of Thermal Expansion, in/in/°F	1×10^{-5}	1×10^{-5}
Specific Heat, Btu/lb-°F	0.34	0.34
Thermal Diffusivity, ft^2/hr	0.00175	0.00230

3.3 PRECURED ABLATOR

Precured ablators are materials which have been casted and cured into useful shapes prior to installation.

3.3.1 Material Selection

MDAC has developed a number of proprietary low-density ablative compounds (S-3, S-6, S-10) for a variety of missile and space applications.

Test samples of one of these materials, S-10, were included in the initial arc jet screening tests conducted for this study described in Section 3.5 of this report. This S-10 material was incorporated into a honeycomb matrix. This approach was designed to minimize the effects of swell arising from thermal expansion of the ablator material.

A review of the material availability for the compounds used to formulate the proprietary MDAC ablative compounds indicated that a filler material used in the formulations was in short supply and continuing availability was uncertain. An alternate precured ablator material was therefore required which was formulated from readily available materials, had a density under 641 kg/m^3 (40 lb/ft) and was well characterized with a substantial property data base. Purple Blend Mod 5 was the material selected for evaluation. Composition of the Purple Blend Mod 5 material is as follows:

• Sylgard 184 silicone elastomer Dow Corning	60.0 parts by weight
• Sylgard 184 curing agent Dow Corning	6.0 parts by weight
• Eccospheres R Emerson and Cuming	10.0 parts by weight
• Phenolic Microballoons Shell Oil Company	16.0 parts by weight
• Quartz fibers 0.25 in, heat cleaned, J. P. Stevens	7.0 parts by weight
• Cab-o-Sil fumed silica, M57, Cabot Corp.	1.0 parts by weight

3.3.2 Properties

Samples of Purple Blend ablative compound were prepared and tested in the same manner as previously described for the cure-in-place materials except that all Purple Blend materials were mixed and cast under atmospheric pressure conditions. Properties measured in the Purple Blend Mod 5 material are listed in Table 3-9.

The purple blend meets the thermal performance (maintain structure below 450°K) and physical property requirements (density less than 641 kg/m^3,

Table 3-9. Properties of Precured Ablators Purple Blend Mod 5

Density, lb/ft^3	36
Tensile Strength, psi	133
Hardness, "A" Shore	67
Thermal Conductivity, Btu/hr-ft- F°	0.06
Coefficient of Thermal Expansion, in/in/°C	1.4×10^{-5}
Adhesion to RTV-560 (Adhesive - RTV-560-55), psi	87
Specific Heat, Btu/lb-°F	0.34
Thermal Diffusivity, ft^2/hr	0.00420

tensile strength and bond strength greater than 276,000 N/m^{2}0 for the on-orbit repair mission. The material can be prescored in a grid pattern and then can be readily broken during the on-orbit repair along selected score lines to yield optimum sized precured segments and yet retains sufficient durability so that crew handling should not prove difficult.

No effects resulting from excessive thermal expansion of the ablator materials were noted in the arc jet tests described in Section 3.5. However, these tests were not designed to examine all potential damage modes resulting from this property and it is not certain if an alternate approach such as a honeycomb matrix used for the S-10 arc jet specimens or an alternate precured or precast ablator with lower thermal expansion properties should not be considered. A preliminary analytical examination of this question is provided in Section 3.6.

3.4 THERMAL ANALYSIS

Thermal analyses were made to evaluate the performance of candidate thermal protection repair materials. The criteria were maximum aluminum skin temperatures of 450°K (350°F) for honeycomb structure areas and 478°K (400°F) for other locations. Body points 213 and 1702 (Figures 3-3 and 3-4) were selected to represent areas requiring thick and thin thermal protection material. The heating environments for these two body points were determined from the data furnished for the Design Trajectory (14414.1C). The candidate precured materials were the NASA Purple Blend and the MDAC

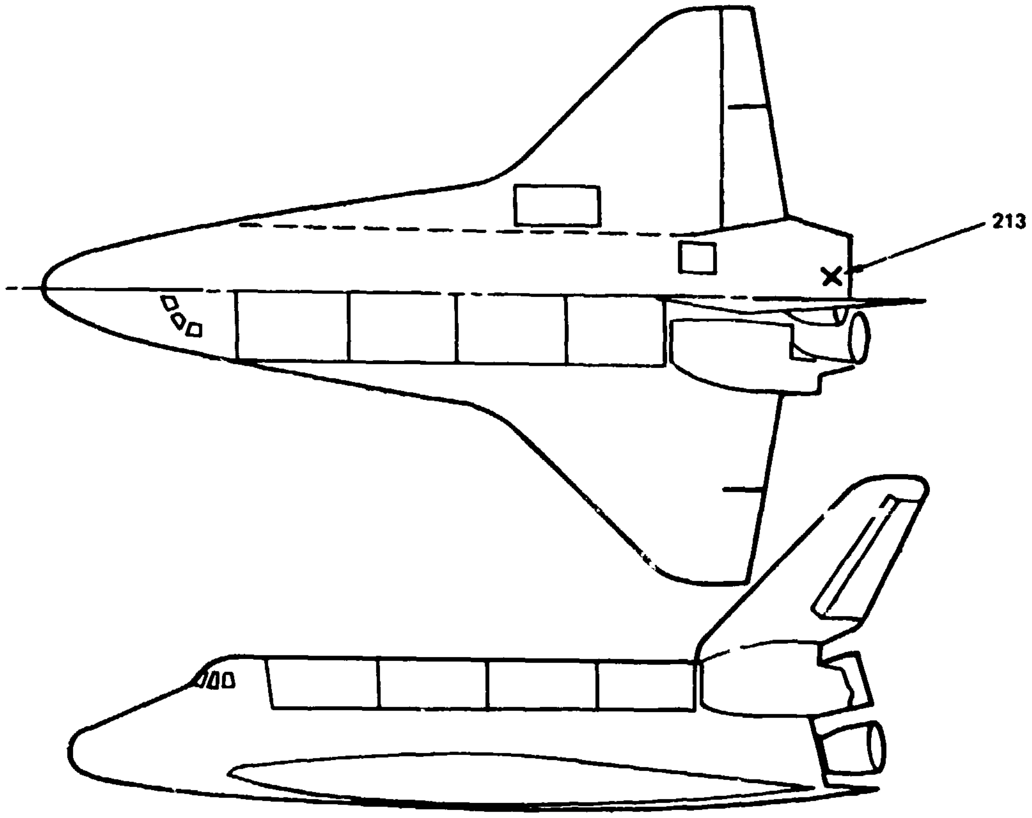


Figure 3-3. Body Point 213

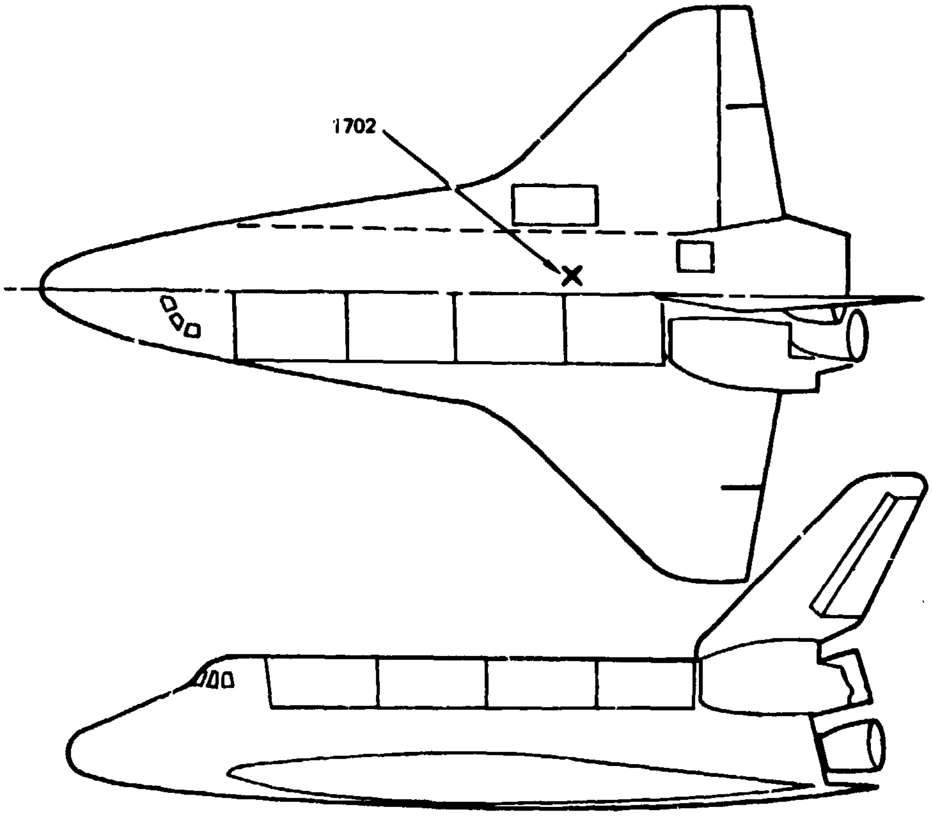


Figure 3-4. Body Point 1702

S-10 composites based upon the Dow-Corning Sylgard silicone resin. Cure-in-place materials were modified General Electric RTV-560 silicone designated by RTV-560-32 and RTV-560-55 for 513 and 881 kg/m^3 (32 and 55 lb/ft^3) densities, respectively. The available thermal properties data for these materials were sketchy during the early part of the program, necessitating the use of estimated values, generally.

3.4.1 Precured Materials

Precured material performance was evaluated at body point 213 (Figure 3-3). The design thermal protection is provided by 0.0930 m (3.66 in) of silica tile, 0.0041 m (0.16 in) of Nomex felt, and 3.81 x 10^{-4} m (0.015 in) of RTV-560 adhesive, for a total thickness of 0.0974 m (3.835 in) over the 3.40 x 10^{-3} m (0.134 in) aluminum structure. A minimum repair 6.35 x 10^{-3} m (0.25 in) less than the design thickness is made which consists of three 0.0254 m (1.0 in) thick precured tiles and 0.0148 m (0.585 in) of RTV-560 to provide significant thermal insulation as well as to serve as adhesive. This repair replaces the Nomex felt as well as the silica tile. Table 3-10 gives the analysis thermal property values. The MDAC charring ablator code CHAMP was used in the analysis. Two problems were

Table 3-10. Thermal Properties of Precured Ablator

Material	Purple blend		S-10		RTV-560*	
Density	670	(41.8)	497	(31.0)	1419	(88.6)
Specific Heat	1423	(0.34)	1423	(0.34)	1339	(0.32)
Conductivity						
Virgin:	1.30	(0.208)	1.30	(0.208)	3.11	(0.50)
Char: T = 222K (-60F)	1.00	(0.16)	1.00	(0.16)		
556K (540F)	1.25	(0.20)	1.25	(0.20)		
833K (1040F)	1.62	(0.26)	1.62	(0.26)		
1389K (2040F)	3.74	(0.60)	3.74	(0.60)		
2222K (3540F)	12.46	(2.00)	12.46	(2.00)		

Density: kg/m^3 (lb/ft^3); Specific Heat: J/kg·°K (Btu/lb·°F)
Conductivity: mW/cm·K (Btu/sec·ft·F x 10^4)
*Adhesive and partial tile thickness filler

encountered which prohibited complete results with this code. Convergence of test parameters during part of the flight was generally not obtainable without excessively long computer running time. Also, the available Arrhenius decomposition rate parameters indicated significant weight loss beginning at the 478°K (400°F) level rather than the 533°K (500°F) level expected for silicone-based materials. These data proved to be inapplicable to the environment, the CHAMP code model, or both. However, sufficient results were obtained to establish that the aluminum temperature rise is less than 0.56°K (1.0°F) at 1925.7 sec, the design trajectory end point.

This results from the heat pulse delay through nearly 0.10 m (4 in) of low diffusivity material, net cooling at the external surface after about 750 sec, and the substantial thermal capacity of 0.00340 m (0.134 in) of aluminum.

The Arrhenius rate equation used in the CHAMP code expresses the decomposition rate in terms of the change in uncharred weight fraction, W_V, of the decomposing constituent:

$$-\frac{dW_V}{dt} = K(W_V)^n$$

where

t = time
K = $A \exp(-\Delta E^*/RT)$
A = frequency factor
ΔE^* = activation energy
R = universal gas constant
T = temperature
n = reaction order

The rate parameters A and ΔE^* are determined from TGA measurements of W, the fraction of initial specimen weight, versus temperature at measured temperature-time heating rates, $r = dT/dt$. The final value of W, the residual char fraction, is designated as γ. Since $W_V(1 - \gamma) = W - \gamma$, the rate equation expressed in terms of TGA parameters becomes

$$\frac{-r}{1-\gamma} \frac{dW}{dt} = A\left(\frac{W-\gamma}{1-\gamma}\right)^n \exp(-\Delta E^*/RT)$$

The Arrhenius parameter values for Purple Blend Mod 5 used in the charring ablator code analysis were A = 520,000/sec, $\Delta E^*/R$ = 20,000° R, n = 1.0, and $\gamma = 0.287$. The weight fraction of decomposing constituents (silicone and phenolic) was 0.82. Background information was not available on the source and derivation of these properties as well as those given in Table 3-10.

3.4.2 Cure-In-Place Materials

Cure-in-place material performance was evaluated at body point 1702 (Figure 3-4). The design thermal protection is provided by 0.0206 m (0.81 in) of silica tile, 0.00406 m (0.16 in) of Nomex felt, and 0.0038 m (0.015 in) of RTV adhesive, for a total thickness of 0.0250 m (0.985 in) over the 0.00457 m (0.18 in) aluminum structure. Results were obtained for both the minimum repair thickness of 0.0187 m (0.735 in) and the design thermal protection thickness of 0.02502 m (0.985 in) with RTV-560-32 and RTV-560-55. The same problems encountered in the analysis of precured materials using the charring ablator code were encountered with the cure-in-place materials. Therefore, the analysis was continued with the MDAC aerodynamic heating code AERO HEAT. Because of the lack of ablation data, the heat transfer through the thermal protection material and structure was modeled as transient conduction using the properties listed in Table 3-11. The density-temperature dependency was based upon results from the charring ablator code analysis attempts. The use of this relationship accounts for loss of thermal capacity during heating and gives too great a thermal capacity during subsequent cooling. Consequently, more heat is conducted to the structure with conservative results. Further conservatism is incorporated in the analysis by not including the blocking effect of resin decomposition and transpiration processes.

A parallel analysis performed at JSC using a charring ablator model of RTV-560-32 indicated a significantly greater thickness requirement than obtained by this MDAC analysis. Reasonable increases in the estimated thermal conductivity values by solid conduction at low temperatures and radiation at high temperatures are not likely to be sufficient to account for the differences between JSC and MDAC results. For both MDAC codes, CHAMP and AERO HEAT, the heating environment was input as heat transfer coefficient, recovery enthalpy, and pressure histories derived from

Table 3-11. Thermal Properties of Cure-in-Place Materials

RTV-560-32				RTV-560-55			
Specific Heat: 1.423 J/g-°K (0.34-Btu/lb-°F)				Specific Heat: 1.423 J/g-°K (0.34 Btu/lb-°F)			
T, K(F)	Conductivity	T, °K(°F)	Density	T, °K(°F)	Conductivity	T, °K(°F)	Density
256 (0)	0.0399 (0.064)	256 (0)	513 (32.0)	256 (0)	0.0530 (0.085)	256 (0)	881 (55.0)
700 (800)	0.0685 (0.110)	533 (500)	513 (32.0)	644 (700)	0.0642 (0.103)	533 (500)	881 (55.0)
1000 (1340)	0.108 (0.174)	589 (600)	508 (31.7)	1000 (1340)	0.106 (0.170)	589 (600)	870 (54.3)
1200 (1700)	0.145 (0.233)	617 (650)	493 (30.8)	1200 (1700)	0.141 (0.227)	617 (650)	833 (52.0)
1400 (2060)	0.193 (0.310)	644 (700)	452 (28.2)	1400 (2060)	0.186 (0.299)	644 (700)	753 (47.0)
1600 (2420)	0.255 (0.409)	672 (750)	386 (24.1)	1600 (2420)	0.245 (0.393)	672 (750)	593 (37.0)
		700 (800)	296 (18.7)			700 (800)	416 (26.0)
		728 (850)	235 (14.7)			728 (850)	288 (18.0)
		756 (900)	202 (12.6)			756 (900)	256 (16.0)
		783 (950)	199 (12.4)			783 (950)	245 (15.3)

Conductivity: J/m sec °K (Btu/sec-ft-°F x 10^4);
Density: kg/m^3 (lb/ft^3)

design trajectory tables of radiation equilibrium heating rate (yielding wall temperature and enthalpy), convective heating rate, and pressure (taken as local). It seems unlikely that differences in heat transfer computation methods would account for the different JSC and MDAC results.

A detailed model was used to estimate the temperature-dependent values of thermal conductivity. The conductivity at a given temperature is expressed as follows:

$$k = a\, f_s k_s + f_v k_g + b f_v T^3$$

where a and b are weight factors, f_s and f_v are the solid and void fractions ($f_s + f_v = 1.0$), respectively, k_s is the solid conductivity (constant or temperature dependent), k_g is the temperature dependent gas (air) conductivity, and T is the absolute temperature. The values of a and b were derived from the conductivities of 352 kg/m^3 (22 lb/ft^3) HSRI (0.84 void fraction), 0.865 W/m°K (0.05 Btu/hr-ft-°F) at 294°K (70°F) and 2.942 W/m°K (0.17 Btu/hr-ft-°F) at 1,589°K (2,400°F), using a solid conductivity of 1.73 W/m°K (1.0 Btu/hr-ft-°F). The modified RTV-560 solid conductivity was taken as 3.115 W/m°K (0.18 Btu/hr-ft-°F). This infers the assumptions of equivalent pore radiation shielding characteristics of the HSRI and modified RTV-560 materials and the proportionality of the radiation contribution bf_vT^3 to the void fraction. The void fraction of RTV-560-32 ranges from 0.665 to 0.885 and of RTV-560-55, from 0.385 to 0.836.

The results for the cure-in-place analysis are shown in Figure 3-5. A linear relationship between the minimum thickness (0.00635 m recess) and full thickness results is assumed. Note that the aluminum temperature change is given. Consequently, for an initial temperature of 322°K (120°F), the maximum application temperature, the minimum thickness, 0.00867 m (0.735 in), is sufficient for RTV-560-55 to meet the 450°K (350°F) limit for the aluminum; whereas, 0.02261 m (0.89 in) of RTV-560-32 is needed to satisfy this requirement. In view of the generally small differences in thermal conductivity of the two materials, the thermal capacity (represented by the density since the same specific heat was used for the two materials) is shown to be a significant factor in determining the extent to which areas requiring replacement of thin silica tiles must be filled.

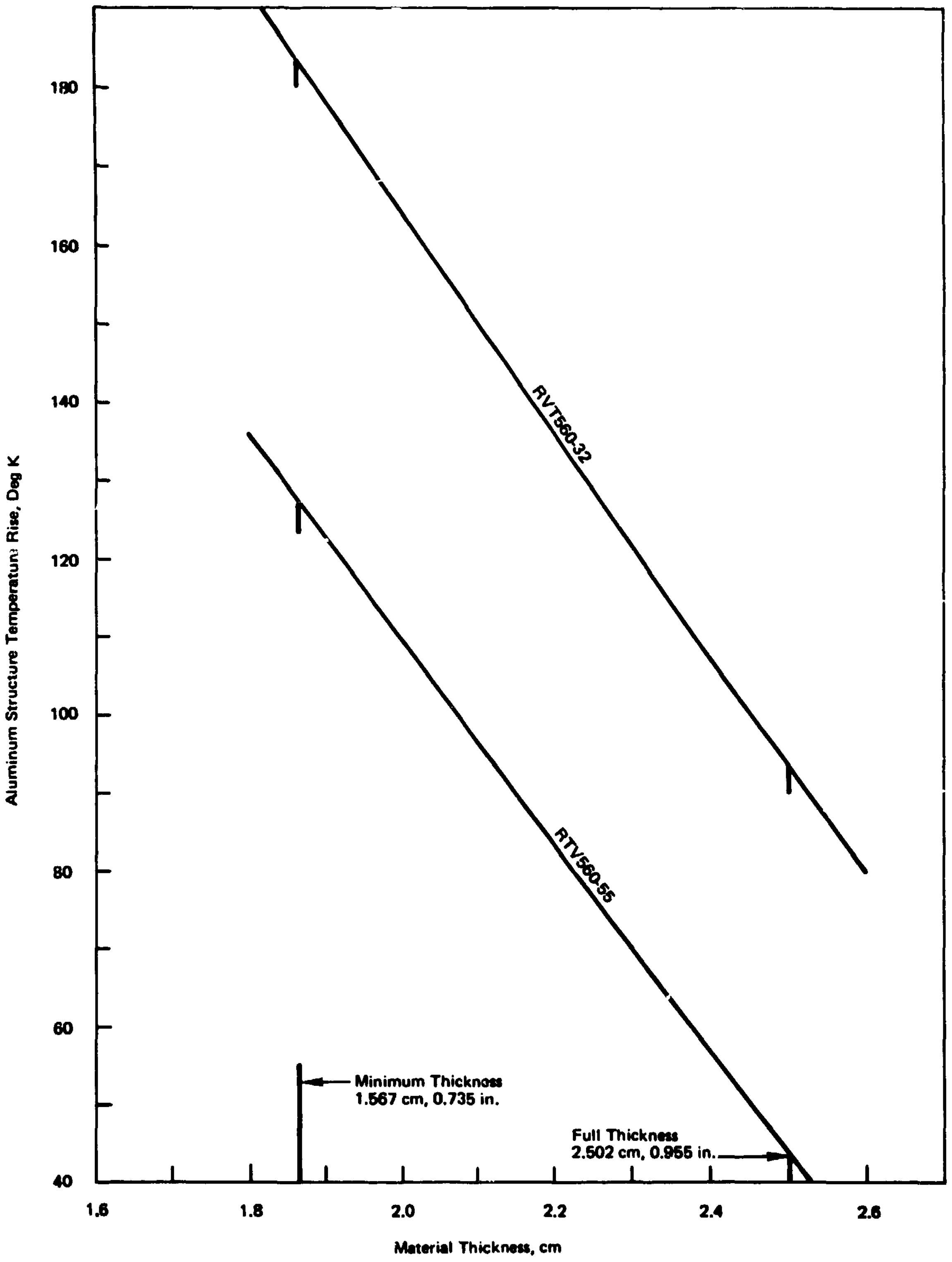


Figure 3-5. Body Point 1702 Cure-In-Place Repair

3.4.3 Arc Test Thermal Evaluation

Analytical simulations were attempted of the arc tests of Purple Blend, RTV-560-32, and RTV-560-55, using the properties given in Tables 3-10 and 3-11 and the AERO HEAT computer code. It is emphasized that the conductivities are estimates or values not traceable to laboratory measurements. Likewise, the single, constant value of specific heat is an estimate. Material density-temperature relations were obtained from CHAMP trials and increasing the temperature for a given density by 55.6°K (100°F) so that decomposition losses began at 533°K (500°F) rather than 478°K (400°F). The program schedule simply did not permit adequate characterization of these materials, especially the RTV-560 modifications. The arc test simulations were based on nominal conditions of 5×10^5 W/m^2 (44 Btu/sec-ft^2) cold wall heating, 1.512×10^7 J/kg (6500 Btu/lb) total enthalpy, and 1241 N/m^2 (0.18 psi) total pressure.

The arc test and simulation analysis results at 600 sec are given in Table 3-12. Pyrometer surface temperature measurements were increased by 4.15% corresponding to an emittance of 0.85. Thermocouples measured the temperatures at nominal depths of 0.00635, 0.0127, and 0.0254 m (0.25, 0.5, and 1.0 in).

The poor agreement between test and analysis temperatures at the 0.00635 and 0.0127 m nominal depths probably arises from inaccurate overall representation of blocking effects and thermal diffusivity changes over the decomposition temperature range by the analytical model. Comparisons for the 0.0254 m depth indicate that low temperature conductivities for Purple Blend are too high and for the RTV-560 modifications, at roughly one-half the Purple Blend value, they are too low. This, in turn, indicates that the solid conduction component was undervalued for the RTV-560 materials model.

3.4.4 Conclusions

For thick thermal protection sections the density, specific heat, and thermal conductivity of the repair material are of secondary importance to its ability to maintain structural integrity in the entry environment. For thinner sections the thermal diffusivity becomes increasingly important. Since the

Table 3-12. Arc Test Data and Simulation Analysis Temperature Rise at 600 sec

		Depth		Test		Analysis			Depth		Test		Analysis	
Material	Model	m($\times 10^{-2}$)	in.	K	F	K	F	Model	m($\times 10^{-2}$)	in.	K	F	K	F
Purple Blend	1A	0.00	0.00	1340	2410	1449	2608	1B	0.00	0.00	1389	2500	1449	2608
		0.74	0.29	1066	1919	1262	2271		0.61	0.24	1095	1971	1297	2335
		1.45	0.57	725	1305	1032	1858		1.40	0.55	822	1480	1046	1883
		2.67	1.05	68	123	366	658		2.59	1.02	90	162	414	746
MDAC S-10	2A	0.00	0.00	1311	2360			2B	0.00	0.00	1378	2480		
		0.71	0.28	1059	1906				0.74	0.29	1078	1940		
		1.22	0.48	891	1604				1.24	0.49	876	1578		
		2.59	1.02	101	182				2.62	1.03	101	181		
RTV-560-55	3A	0.00	0.00	1367	2460	1454	2617	3B	0.00	0.00	1450	2610	1454	2617
		0.69	0.27	951	1711	1150	2070		0.66	0.26	999	1798	1164	2095
		1.37	0.54	428	770	679	1222		1.35	0.53	477	858	696	1253
		2.67	1.05	60	108	6	11		2.62	1.03	74	132	7	13
RTV-560-32	4A	0.00	0.00	1355	2440	1456	2620	4B	0.00	0.00	1444	2600	1456	2620
		0.64	0.25	980	1765	1247	2245		0.65	0.26	944	1699	1241	2234
		1.32	0.52	617	1111	942	1696		1.50	0.59	453	815	842	1516
		2.54	1.00	142	255	124	224		2.74	1.08	94	170	61	109

specific heat values do not differ significantly between the materials under consideration, and their conductivities vary little over the range of densities, the density primarily determines the diffusivity. Thermal diffusivity is inversely proportional to the density since low values of diffusivity are desired, the higher density materials give better thermal protection, other factors being equal. The performance improvement afforded by ablation processes heat blocking was not determinable with currently available data.

Comparisons of arc test and simulation analysis results indicated that the RTV-560 material conductivity estimates were too low, as did analyses performed at JSC. The results also indicat hat a charring ablator characterization of the repair materials is required in order to have confidence in the analyses of their thermal suitability for critical repair locations.

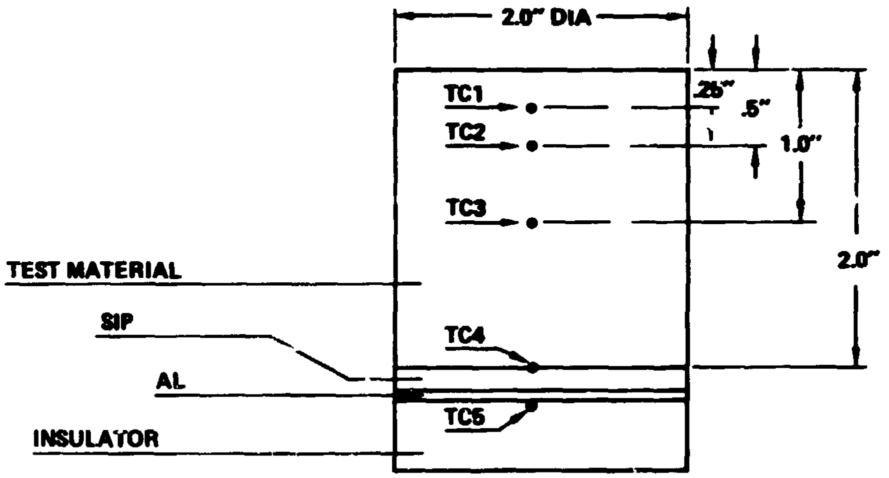
However, the class of silicone-based composites included in this study having a density of 513 kg/m^3 (32 lb/ft^3) or more appear satisfactory with respect to their thermal protection properties.

3.5 ARC JET TESTING

3.5.1 Samples

Three sets of specimens were fabricated and submitted for NASA-JSC arc jet testing. In the initial set of tests, the ablation characteristics of the candidate materials were evaluated to verify thermal performance of materials selected for continuing development and evaluation. Specimens consisted of 0.051 m (2 in) thick by 0.051 m (2 in) diameter samples of the ablative material contained in tubular holders of the HRSI tile and bonded to a substrate representative of an on-orbit repair substrate. Specimen configuration showing substrate materials and thermocouple location is illustrated in Figure 3-6 (the HRSI holder is not shown).

Five candidate materials were included in these tests. The precured ablator materials were S-10, an MDAC proprietary ablative compound which was cast into a phenolic/glass honeycomb matrix and Purple Blend Mod 5. The cure-in-place materials included RTV-560-55, RTV-560-32, and PR-1977.



MATERIAL	STRUCTURE TEMP RISE°F (TC 5)	CHAR DEPTH INCHES	CHAR CONDITIONS CHAR GAP INCHES	CHAR CONDITIONS CHAR SWELL INCHES	CHAR PROPERTIES
RTV 560-55	9	0.5	0.063	0.14	HARD CHAR
RTV 560-32	10	0.625	0.032	0.20	HARD CHAR
PR 1977	10	0.5	0.1	0.26	HARD CHAR
PURPLE BLEND	9	0.625	0.032	0.0	HARD CHAR
S-10	9	0.625	0.032	0.01	HARD CHAR

Figure 3-6. NASA-JSC Arc Jet Testing Was Used to Evaluate Ablation Characteristics of Selected Materials

With the exception of the S-10 material, the ablative materials in this initial set of specimens were cast into a cylindrical mold under atmospheric pressure. The cylindrical castings were allowed to cure, holes were located and drilled for the thermocouples, and the thermocouples were installed using fresh mixtures of the ablative materials as adhesives. The cast samples were then bonded into the HRSI holder using additional freshly mixed ablative material. The S-10 material was vacuum cast into a phenolic-glass honeycomb matrix. Discs were cut from the resulting sheet, thermocouples installed and the discs bonded into the HRSI holders using Sylgard silicone elastomer as an adhesive.

A second set of arc jet specimens was prepared using the RTV-560-55 and RTV-560-32 formulations. Procedures for sample preparation were identical to those described above except that the ablative materials were cast under vacuum. Specimen diameter was increased to 0.076 m (3 in).

A final set of arc jet specimens were prepared to evaluate char adherence. These specimens consisted of RTV-560-55 cast at atmospheric pressure into rectangular blocks 0.15 by 0.15 m by 0.051 m (6 by 2 in). In the initial arc jet tests, the loss of significant amounts of char as a result of low char strength or low char adherence was not observed. Post-test inspection of the specimens indicated, however, that a gap was formed between the char layer and the underlying virgin material. This raised concern that char separation might occur during exposure to reentry conditions on repair areas larger than those represented by the initial 0.051 m (2 in) diameter arc jet specimens. This is of particular concern with the cure-in-place formulations included in this study since refractory fibers were not included in the formulations to promote char strength and adherence. The rectangular arc jet specimens were, therefore, prepared to examine this question.

3.5.2 Results

All ablative materials included in the arc jet testing exhibited a thermal performance in the tests sufficient to meet the mission requirements to maintain the Shuttle structure temperature below 350°F during reentry conditions, assuming that initial structure temperatures are 325°K (125°F) or less.

Structure temperature increases of 5 to 5.5°K (9 to 10°F) were obtained with all of the materials. At an intermediate depth of 0.0254 m (1 in), temperature rise was primarily controlled by ablator density with the higher density materials providing the greater thermal protection.

Char separation occurred in the 0.15 by 0.15 by 0.05 m (6 by 6 by 2 in) RTV-560-55 samples. Modification of the modified RTV-560 formulations may, therefore, be required to maintain ablator integrity during reentry. This increase in char strength and adherence can probably best be achieved by the addition of refractory fibers to the material formulation.

The vacuum cast arc jet specimen performance was similar to the initial specimens cast at atmospheric pressure except that a gap was eroded in the former specimens between the ablative material and the HRSI holder on the side facing the impinging jet.

3.6 EFFECT OF THERMAL EXPANSION OF ABLATORS ON SHUTTLE TPS

Interactions between the (cure-in-place and precured) ablators and the Shuttle TPS will require careful analysis to establish the usable limits of the repaired area. A realistic aero/thermal profile imposed on a reasonable repair configuration (see Figure 3-7) will identify any limitations, should they exist. However, a simplistic analysis has provided some insight into what some of the failure modes might be. This analysis assumed:

A. Steady state temperature
B. HRSI rigid body
C. Constant thermal properties
D. Ablator/HRSI at equivalent temperature
E. $\alpha_{HRSI}/\alpha_{Ablator} << 1$
F. The repair fills the hole
G. HRSI tiles stand alone (gaps between HRSI tiles)

These assumptions lead to the conditions shown in Figure 3-8, where the loading on the HRSI tile would be a combination of shear stress (σ_s) and tension stress (σ_t). As the temperature of the ablators (and HRSI) rises the

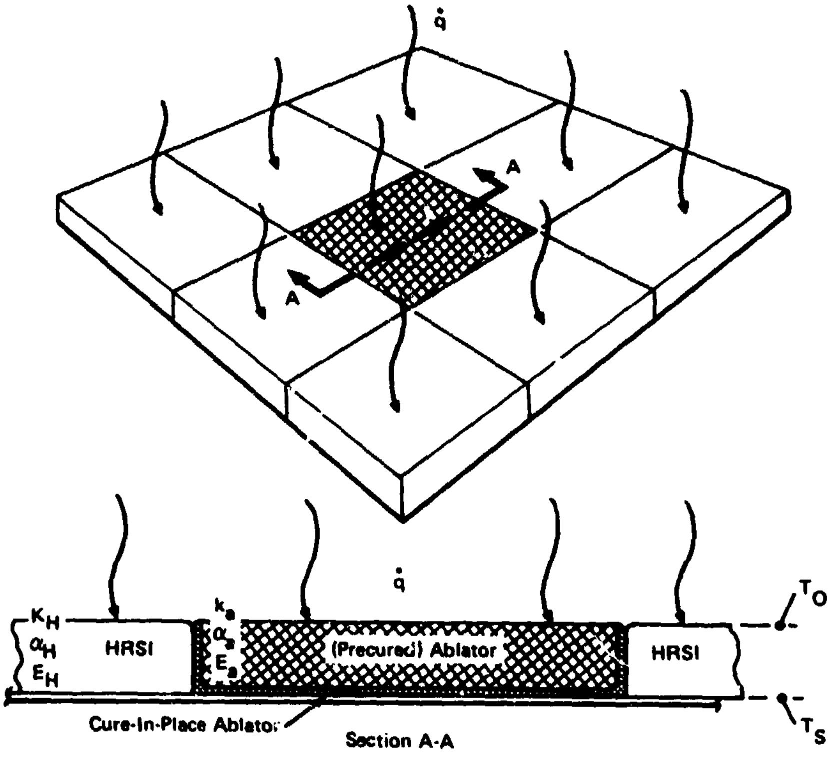


Figure 3-7. Assumed Repair Configuration

ablators expand, exerting a sideways force on the HRSI tile, tending to "shear" it off. It is reasonable to expect that the shearing force will dominate when the tiles are thin and the tension forces when they are thick. (This relationship becomes complicated when the char layer, thermal gradient and variable heating are taken into account.)

The conditions imposed on the HRSI tile shown in Figure 3-8 result in the following:

L = length of HRSI reacting expansion

α_A = ablator coefficient of thermal expansion

E_A = ablator modulus of elasticity

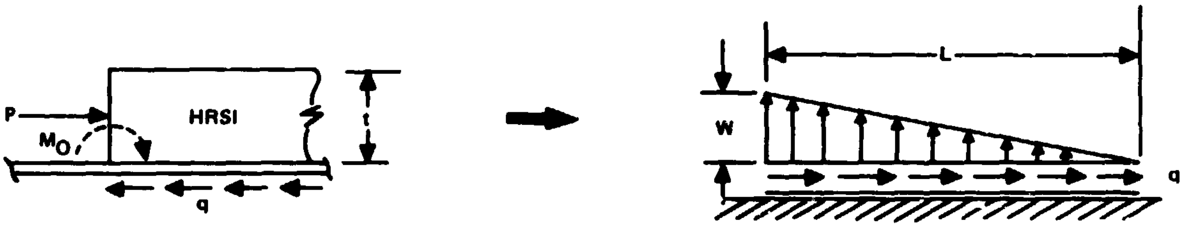
ΔT_A = ablator change in temperature = ΔT_{HRSI}

δ_A = thermal deformation of ablator

t_A = thickness of ablator = t_{HRSI}

W_A = 1 (unit width)

$$\delta_A = \frac{L}{2} \alpha_A \Delta T_A = \frac{P(L/2)}{A_A E_A} = \frac{P(L/2)}{t_A W_A E_A} = \frac{P(L/2)}{t_A E_A}$$



(a) (b)

Figure 3-8. Loading Condition on the HRSI

Simplify and solve for P

$$P = t_A E_A \alpha_A \Delta T_A \tag{1}$$

Solving for P in the tile/sep free body (Figure 3-8), substituting Equation (1) for P, then solving for q provides

$$P = qL, \quad q = \frac{t_A E_A \alpha_A \Delta T_A}{L} \doteq \sigma_s \tag{2}$$

Then combining cases 7 and 9 from Roark* Table III and solving for M_o,

$$M_o = \frac{11}{60} wL^2 \qquad (3)$$

Also from Figure 3-8,

$$M_o = P \frac{t_A}{2} \qquad (4)$$

Substituting Equation (1) into Equation (4) and equating to Equation (3) gives

$$\frac{11}{60} wL^2 = \frac{E_A t^2_A}{2} \alpha_A \Delta T_A$$

Therefore

$$w = \frac{30}{11} \left(\frac{t_A}{L}\right)^2 E_A \, \alpha_A \, \Delta T_A = \sigma_T \qquad (5)$$

The value for w is equivalent to the edge tension stresses (σ_T) and q is equivalent to shear stresses (σ_s) for the unit width considered. Relationships of Equations (2) and (5) are plotted and shown on Figure 3-9. Plotted in this manner it becomes evident that ablator thicknesses near one-third the HRSI tile length develop "shear" and "peeling" stresses of equivalent magnitude, and when $t_A/L \simeq 0.7$, the peeling stress is approximately double the shear stress.

Figure 3-9 indicates that areas where "thick" repairs are made will be subject to high shear and peel stresses and that some means should be taken to keep the repaired area as small as possible. It also indicates that for large

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*Raymond J. Roark, "Formulas for Stress and Strain," McGraw-Hill Book Company, 1965.

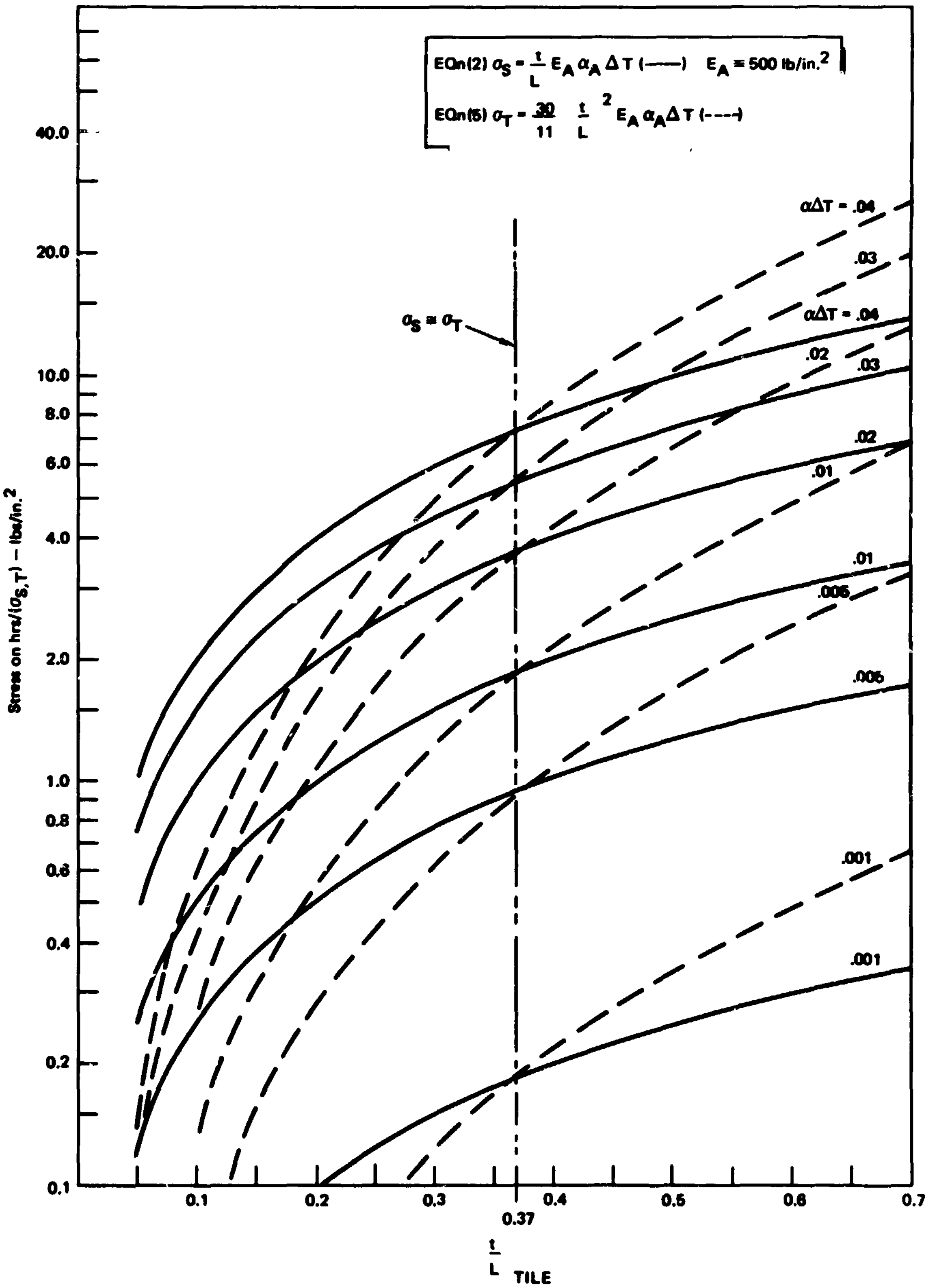

Figure 3-9. Stress vs Repair Thickness for Various Thermal Expansion Values

area repair it would not be desirable to "fill in" the gaps between the precured and HRSI with cure-in-place ablator. Leaving a gap will decouple the precured ablator from the HRSI and permit operation at greater ΔT's. (A gap of 0.040 in. will allow at least the surface of a full ablator tile to raise 120°F before contact is made with the HRSI for an $\alpha \simeq 11 \times 10^{-5}$ in/in/°F.)

This analysis is conservative because (1) total contact between repair and HRSI is assumed - which will not occur; (2) the temperature is constant throughout - which it will not be; and (3) the HRSI/sep is a rigid body - which in reality is somewhat flexible. An accurate picture of the repair area limitations can only be obtained through a three-dimensional/STS trajectory analysis where all these factors are taken into account.

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Section 4
MATERIAL APPLICATOR

This task was divided into three prime areas: a functional mockup, a self-contained applicator, and a three-part applicator as shown in Figure 4-1. The functional mockup schedule necessitated early design and fabrication phases in order to ensure completion of the mockup with time to perform tests prior to the delivery date. The self-contained and three-part design phases followed and drew upon the experience obtained during the mockup development period.

4.1 FUNCTIONAL MOCKUP

The design effort was concentrated toward the development of a simple working unit which would contain, mix, and deliver the resin in a reliable and efficient manner. No attempt to optimize weight or to expend effort in detailed mechanism design (such as trigger control of valving) which might have jeopardized our probability of meeting the schedule for delivery was made. The functional mockup is shown in Figures 4-2 and 4-3.

4.1.1 Design Approach

The three prime objectives of the functional mockup are to contain, mix, and apply the resin in a simple and reliable manner.

For containment, an aluminum body equipped with a self-contained gas pressure source as the basis for the design was selected. A primary concern was to prevent any contact between the resin base material and the catalyst prior to activation and subsequent mixing. The design used a thin aluminum burst disk to prevent contact of these materials. The disk was constructed of 2.0×10^{-5} m (0.0008 in) thick aluminum foil (Reynolds wrap) approximately 0.076 m (3.0 in) in diameter. This disk was found to rupture at approximately 1.65×10^5 N/m^2 (24.0 psig). The rupture caused a "petal" shaped residual which remained attached around the orifice without shedding into the delivered material.

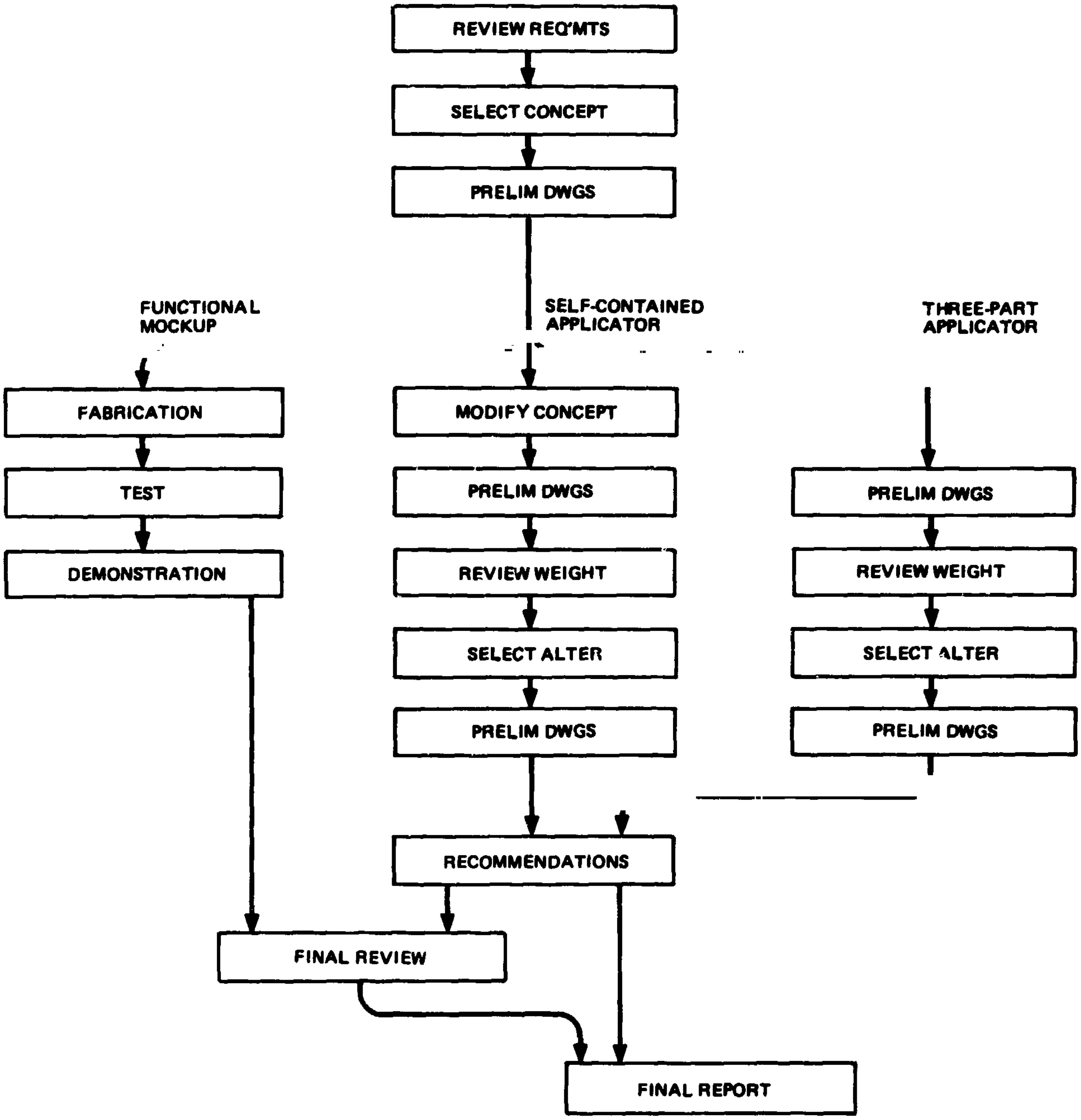

Figure 4-1. Applicator Design Sequence

The gas source selected was contained within a secondary handle at the back of the applicator. O-ring seals were provided to contain the gas charge when activated. A steel pin, centered in the body, pierces the gas bottle upon rotation of the handle to its seated position.

Figure 4-2. Functional Mockup

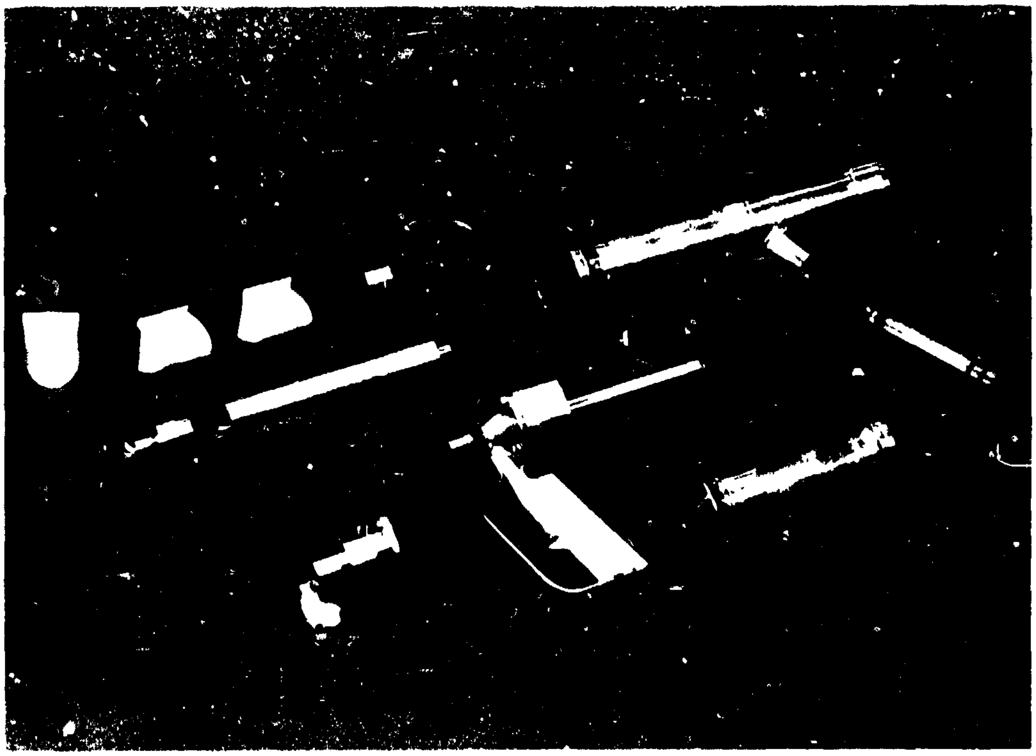

Figure 4-3. Functional Mockup Disassembled

Mixing of the two components is only as reliable as the metering mechanism and the static mixing units allow. The mix ratio selected (from the materials group) was 9.4 to 9.9:1. The ratio is critically controlled by the use of concentric pistons which are sized to an 9.59:1 area ratio. The two pistons are connected by a "bridge" which guarantees that the two pistons move synchronously, independent of the driving pressure or rate of expulsion.

Three mixing units (Charles Ross & Son Co.) are standard industrial elements. The three units are located in a nozzle extension tube (which also allows application into the bottom corner of a repair cavity under worst-case conditions). To reduce pressure differential across the elements to a minimum 2-in elements were selected. The three units proved to be more than adequate to mix the materials for curing.

4.1.1.1 Review Requirements

The functional mockup and the designs proposed for flight applications must meet the following requirements:

- Reliable mixing and dispensing
- One-hand operation (for application)
- Minimum operator fatigue
- Ease of assembly
- Good visibility of repair area
- Safe to handle

Reliable mixing and dispensing were discussed in Section 4.1.1.

One-hand operation for the functional mockup was overruled in favor of using a quarter-turn valve mounted in the nozzle base. The design complexity and cleaning difficulty precluded the use of a complicated valve system for this unit. The trigger-actuated, "shear-seal" valving is recommended for the follow-on design activity. Except for the valve action, application may be accomplished by one-hand operation.

Operator fatigue is minimum. Application of gas pressure is merely a matter of screwing in a knurled handle, while resin application is effected by use of the quarter-turn valve and pointing the applicator.

No assembly operations are required (other than application of gas pressure). Several other concepts were reviewed, including a hand-operated mixing vane and the use of a cartridge which must be loaded into the applicator gun. Each of these other concepts required excessive (in our opinion) crew member operations.

Although the functional mockup is longer than that proposed for flight use, adequate visibility is provided so that the crew member can see the repair area and adjacent tiles.

With the exception of charged gas cavities and the normal cautions attendant to use of charged systems, no special precautions need be exercised. The functional mockup was not machined with corner radius and fillets to prevent damage to crew member suits as would be accomplished on flight hardware.

4.1.1.2 Select Concepts

As mentioned in prior statements, the control of mixing ratios was felt to be of prime importance. The bridged, concentric pistons approach is simple and very reliable. The excellent success of the functional mockup at the Final Review (November 30, 1979) verifies that the containing, mixing, and application features are viable solutions. The weight and length are larger than for other concepts and therefore greatly influence the final decisions for flight units, since the weight of the applicator and of the total system becomes very important for the flight hardware.

Preliminary drawings were prepared and reviewed prior to release to a vendor for fabrication. Pressure drop, flow characteristics, case pressure profile, and strength were calculated to ensure that a realistic flow rate would be achieved. These parameters determined the gas bottle size.

Critical components (e.g., case wall, end caps, screw threads, etc.) were given a stress review to ensure that design ultimate to operating were at least 4:1. Minimum guaranteed values were used as follows:

	Yield Strength		Ultimate Strength		Shear Strength	
	N/m^2	psi	N/m^2	psi	N/m^2	psi
6061-T6-T651 Plate/Tube	2.41×10^8	35,000	2.90×10^8	42,000	1.86×10^8	27,000
6061-T6/T651 Extruded Bar	2.41×10^8	35,000	2.62×10^8	38,000	1.56×10^8	24,000

In addition, verification testing was accomplished to confirm the results from the analytical effort. The tests will be described in Section 4.1.2.2.

4.1.2 Hardware/Test

As the result of design and analytical effort, a model was "firmed up" and a vendor was selected to fabricate the functional model. Mr. Ron Collar from ROEAN Industries was contacted through their Marketing Agent, the S. L. Morse Company. We are pleased to find that they had years of experience in design and development of caulking and material dispensing systems. They were able to add expertise and many constructive changes to our preliminary design.

4.1.2.1 Fabrication

The functional mockup was fabricated in approximately 2 weeks and delivered to us for test. All active components are machined from 6061-T6/T651 aluminum.

4.1.2.2 Test

The operating case pressure was calculated from data given by the supplier of the gas bottles. A pneumatic proof test was conducted in a "bomb-shelter" with subsequent reduction in pressure for a leak test. The proof test was completed at 6.27×10^6 N/m^2 (910 psig) for 1 minute with nitrogen gas. The pressure was applied at the test port located on the back cap. The inner piston was fully forward with the quarter-turn valve closed. The leak test was accomplished in the same manner except 7.93×10^5 N/m^2 (115 psig) was applied while the unit was held under water. No leak bubbles were observed during 1 min.

After the unit was disassembled and dried, a test was performed to determine the pressure profile (i.e., operating pressure with the piston in each, the full and expended positions). The front end was fully filled with water and locked in that position by closure of the quarter-turn valve. A gage was added to the test port (minimum volume was added by use of very short connectors). A gas bottle was inserted and activated. The initial pressure was recorded at 4.17 x 10^6 N/m^2 (605 psig). The water was allowed to exit from the forward cavity to place the piston in the fully expended pisition. Pressure was first recorded at 1.24 x 10^6 N/m^2 (180 psig) with recovery to 1.41 x 10^6 N/m^2 (205 psig) after a few seconds.

Since the upper operating pressure of 4.17 x 10^6 N/m^2 (605 psig) was greater than the value calculated from vendor data, a new proof test 8.34 x 10^6 N/m^2 (1,210 psig) was conducted to fulfill the requirement of proof to two times the operating pressure (MDAC requirement). This proof test was done hydrostatically (because a leak test was not required to follow).

A burst disk was installed (with water against the inner surface) and nitrogen gas slowly applied to the aft cavity. The disk burst at 1.66 x 10^5 N/m^2 (24 psig).

After disassembly, the seals were lubricated (we used Molycoat silicon No. 55) and reassembled to a point where the resin could be added. See Appendixes A and B for assembly/disassembly and filling operations.

When assembly was completed, a nitrogen pressure source was attached to the test port and the unit pressurized to 1.38 x 10^6 N/m^2 (200 psig). A sample was expelled and timed. The pressure was increased to 2.76 x 10^6 N/m^2 (400 psig) and then 4.14 x 10^6 N/m^2 (600 psig) with time samples taken at each pressure. The samples were weighed and density calculated (the density of this sample was found to be very heavy - 72.518 lb/ft^3). The resulting flow rates are shown below in Figure 4-4.

4.1.2.3 Demonstration

The functional mockup was loaded at our facility and subsequently delivered to the NASA facility at Houston, Texas. On November 30, 1979, after a

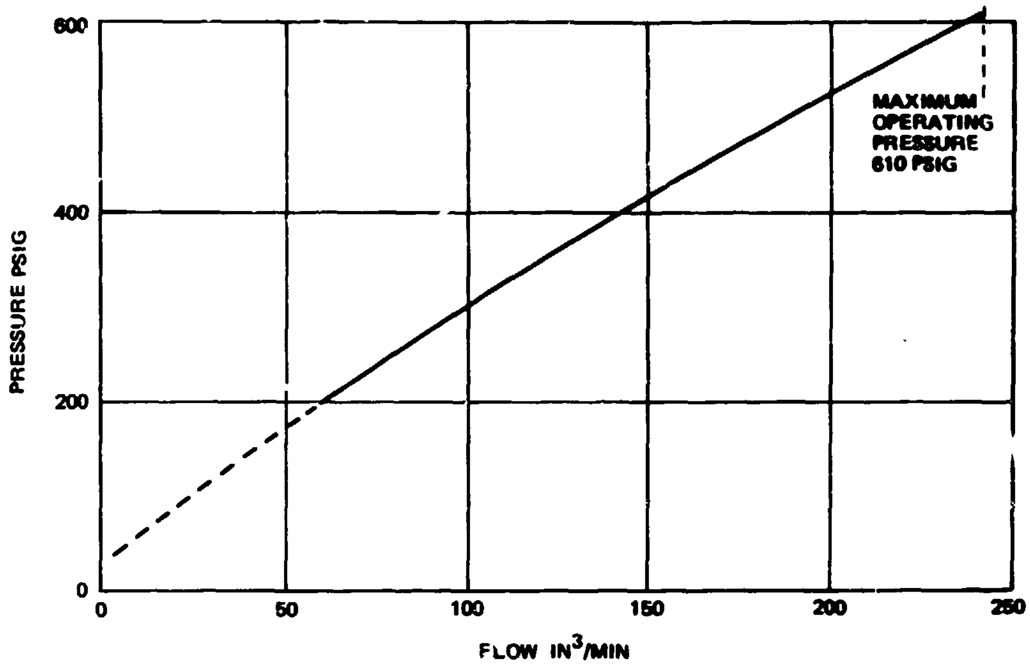

Figure 4-4. Test Flow Rates

portion of the final review, the mockup was presented for demonstration. Mr. E. S. Onizuka pressurized the unit and expelled three samples. He then filled a cavity of sample tile and placed an adhesive bed for a pre-cured tile.

The mockup was disassembled and cleaned, during which time the samples began to cure. Prior to the adjournment, the material had hardened to a satisfactory degree.

4.2 SELF-CONTAINED APPLICATOR

The second objective was to design, to a preliminary level, a system for delivery of the resin in a hand-held manner. We felt that the unit should be self-contained rather than relying upon an energy source in a separate unit.

4.2.1 Design Approach

The design effort was continued along the same lines as that of the mockup. The weaker attributes of the mockup were strengthened in this design. Weight and length were major areas for improvement.

4.2.1.1 Modify Concepts

Upon review of the total kit weight estimates, we shifted from our early concept of 1.18×10^{-3} to 1.31×10^{-3} m^3 (72 to 80 in^3) of deliverable resin toward 1.96×10^{-3} m^3 (120 in^3). This increase in volume/applicator ratio reduced the kit weight without adding excessive overall volume to the new unit. To reduce length, the diameter was increased, while maintaining the piston area ratio. A sketch of the design is in Figure 4-5.

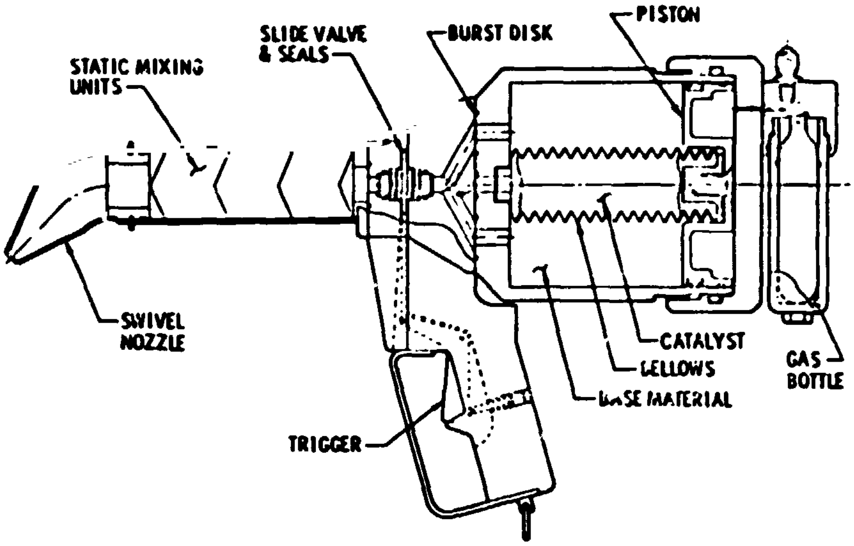

Figure 4-5. Self-Contained Applicator

In addition, the auxiliary handle was moved toward the rear to allow wrist access between the handles. This modification forced a cap and gas bottle redesign.

4.2.1.2 Preliminary Drawings

Two salient features of this design should be discussed. As the material is expelled, the viscosity, temperature and orifice sizing would normally be critical. To overcome these uncertainties, we chose to ensure a constant mixture ratio by use of the concentric piston pair connected by a bridge.

Figure 4-6 shows the two concentric pistons as they are bridged together in position within the applicator body and Figure 4-6 provides a more detailed view of the pistons and seals. (The sketch shows welded construction for simplicity - the center piston would, of necessity, be removable for cleaning and assembly of seals.)

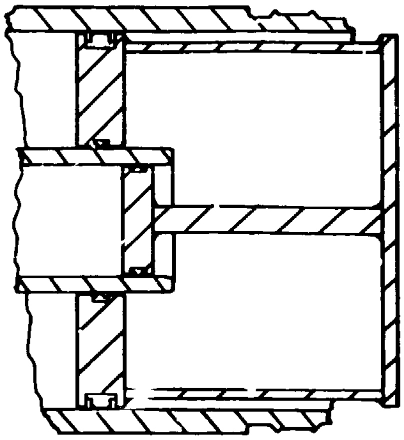

Figure 4-6. Applicator Body

During in-plant testing, the functional mockup used O-rings. In preparation for the demonstration, we were able to obtain T-seals (Green-Tweed part numbers 7338 MS-160-N, 7218 FS-160-N, and 7211 MR-160-N). These performed so well during the demonstration that we would recommend their use for future design efforts. The nylon wiper is used to gently scrap the cylinder surfaces to remove buildup of resin against the seal. (The formulation that uses eccospheres or microballoons as a component can score the aluminum walls when the material is packed between an O-ring and the sidewall.)

Figure 4-7 shows the valve assembly which is recommended. The mechanism is a simple gate valve with nylon seal elements against each surface. The gate is machined flat to $\sqrt{32}$ finish and fitted with a hole which can be moved to align with the body hole for full flow. (A modified contour may be used to allow a flow profile more suited to the mission requirements, i.e., a "tear drop" shape could allow very slow flow for application of thin adhesive layers.) The seal elements are held in contact with the "gate" by means of "wave" washers. An O-ring seals the body of each seal element. This seal concept has been very successful in valve applications (e.g., Barksdale Shear Seal valves).

4.2.1.3 Review Weight

When the design became firm and preliminary stress analysis had been completed, a weight estimate could be attempted. With the precured

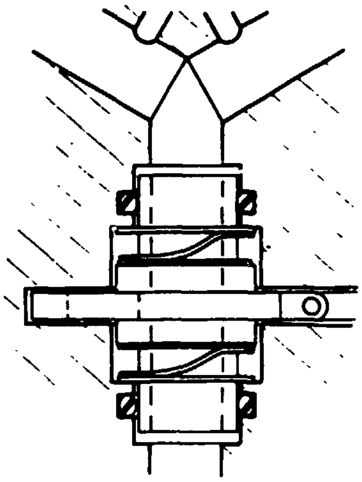

Figure 4-7. Recommended Seal Assembly

material proposed, the total kit weight would be well beyond the 136 kg (300 lb) limit. We believe that our selection of 1.97 x 10^{-3} m^3 (120 in^3) usable volume is the practical limit and, although some weight trimming could be accomplished by extra machining, the only weight saving option left open appeared to be to select an alternate design.

4.2.1.4 Select Alternate Design

Two other basic design concepts were explored. Both approaches would entail design and prototype effort beyond the schedule of this contract.

One concept uses an expanded bellows to contain one of the materials. As the piston advances, the bellows wall collapses so that, at the fully expended position, the folded bellows is contained within the piston recess. This detail may be seen in Figure 4-5. The column length of the bellows must be controlled to ensure that the bellows will collapse in an axial manner without "squirreling."

This control might be effected by changing the material/catalyst ratio (and therefore the respective areas). As the base diameter becomes larger with respect to the bellows length, the probability of uneven collapse is reduced.

A second concept which was investigated involved the use of coiled (stowed) tension/compression members tied to each piston. The application of a "stowed antenna" for this use was reviewed by Mr. Bruce Cambell from

Astro Research Corp. (6390 Cimby Lane, Carpenteria, CA, (805) 684-6641). His company designs and fabricates this type of antenna for various space applications. His cursory review indicated that the design had some merit. A sketch of this approach is shown in Figure 4-8. It will be noted that to ensure synchronization of the two pistons, and to prevent cocking of the outer piston, three of these units are coupled together with idlers.

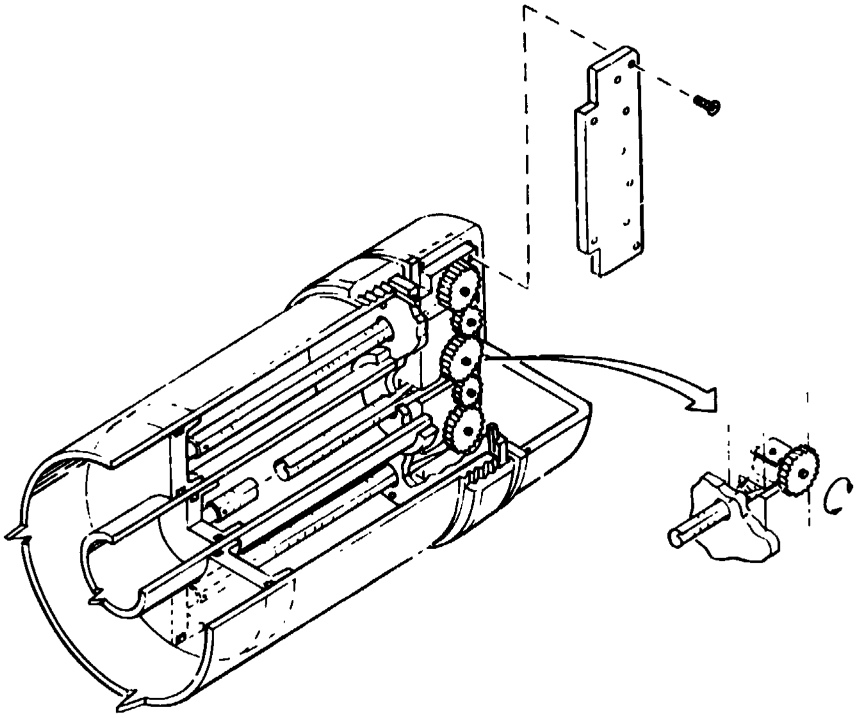

Figure 4-8. Alternate Tension/Compression Members

Both of the above concepts reduce overall weight by shortening the applicator and thereby reducing case weight.

4.2.1.5 Preliminary Drawings

These concepts were reviewed and the weight savings discussed. The weight advantage must be traded against the additional design and engineering time required.

4.3 THREE-PART APPLICATOR

The third objective was to design, to a preliminary level, a system for delivery of the resin from a canister which may be attached to the work station. The material would be expelled through a hose to a small hand-held applicator.

4.3.1 Design Approach

The design effort was continued along the same lines as that of the functional mockup and the original and modified concepts of the self-contained applicator. Weight is still a major design problem. Length is not a design constraint. It was reasoned that the approaches which were viable solutions to the self-contained applicator were workable also for the three-part canister. Also, the valving which appears to be well suited to the hand-held unit would work equally well for the gun portion of the three-part applicator.

4.3.1.1 Preliminary Drawings

Drawings were created for the assembly view of the three-part applicator in each of two basic design concepts. A bellows and a concentric piston approach were drawn to firm the design. Figure 4-9 shows these concepts.

4.3.1.2 Weight Review

After preliminary stress analysis, the wall thickness and end-cap thickness were firmed to a point where a good estimate of weight could be performed. An attempt to optimize the length versus diameter for a given column resulted in the graph in Figure 4-10.

From the curves shown in Figure 4-10, it is evident that the cylinder length increases to an unwieldly length as the diameter passes below about 7 in. The machining of long cylinders (especially thin wall) grows more difficult to a point where tapered walls will not seal against the piston.

4.3.1.3 Design Alternatives

As in the self-contained applicator, the alternate design which utilizes a bellows is to be considered. As with the smaller applicator, the length-to-diameter ratio of the bellows invites instability as the canister is lengthened.

4.3.1.4 Preliminary Drawings

The concentric-piston concept and the bellows concept were selected for further investigation. Drawings were prepared to allow component sizing with the associated stress analysis and weight estimation.

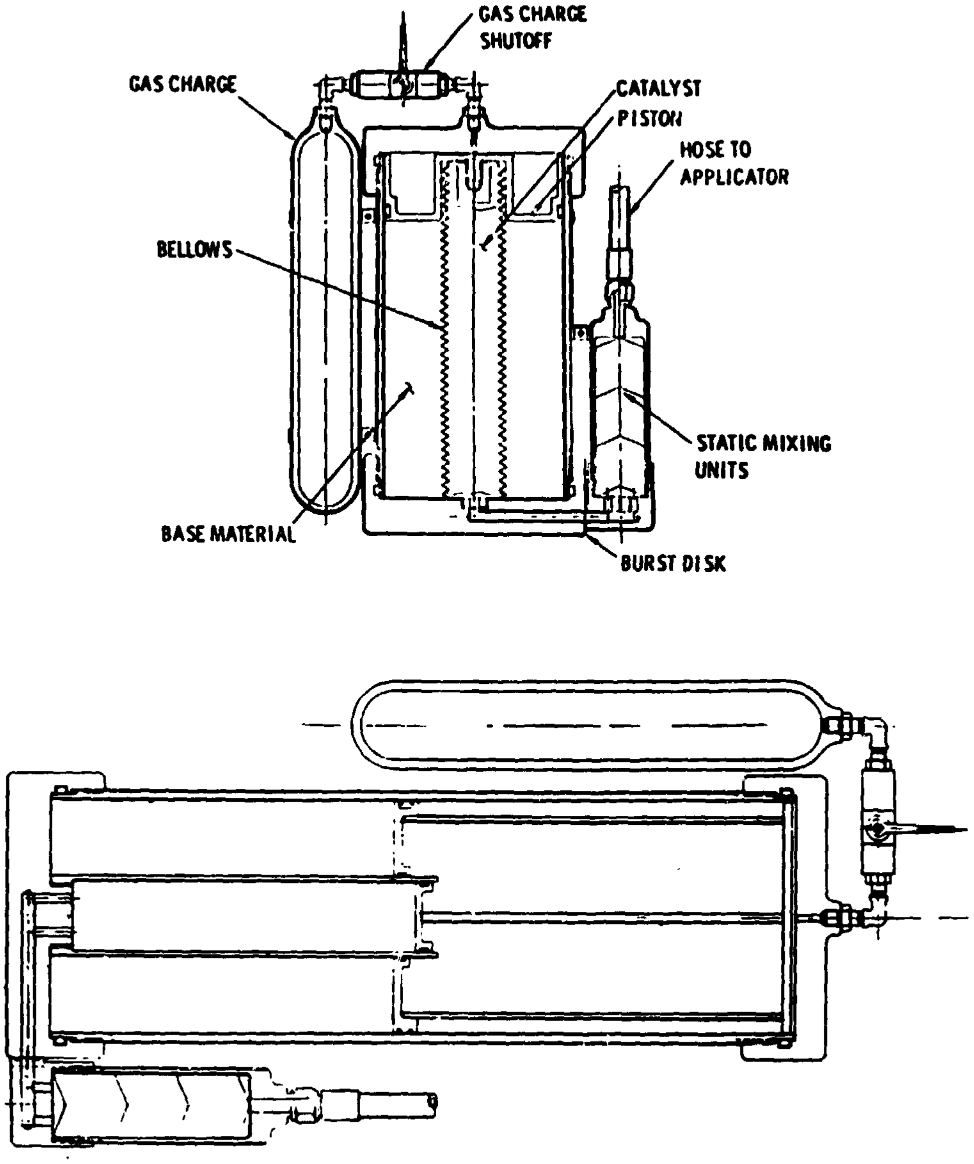

Figure 4-9. Preliminary Sketches of Concept

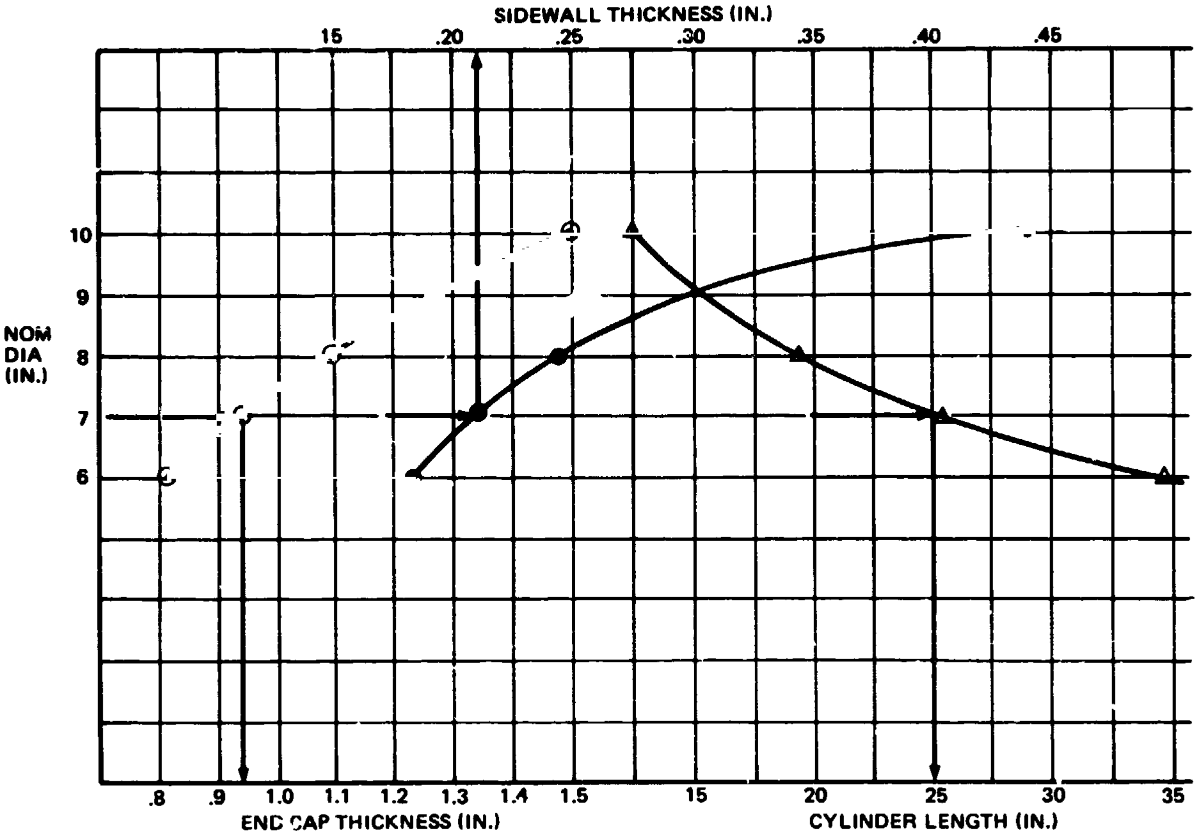

Figure 4-10. Optimization of Length Versus Diameter

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Section 5
REPAIR KIT

This section discusses repair kits concepts and repair mission activities.

5.1 KIT CONCEPTS

Cure-in-place and precured ablator materials, applicators, tools, storage container, and repair concepts have been developed by MDAC to provide efficient and effective TPS repair. Applicators and tools are tailored to material selections. The storage container holds the materials, applicators, and tools in a package which simplifies the repair mission. The following subsections discuss the container, its contents (e.g., applicators, materials, and tools), and how they are removed and used.

Two repair kit concepts that meet the requirements presented in Table 5-1 are shown in Figure 5-1. A combination of the two is actually recommended to minimize astronaut activities. General design details are further shown in Figure 5-2. Modules for tile and another for tools/emittance coating will eliminate the need to move individual blocks of tiles, tools and coating with attendant multiple tethering and handling steps. A module would be removed and transferred to the work station where it would be attached with simple overcenter latches. Applicators would be handled individually, not in a module, for work station attachment.

5.1.1 Container

An aluminum kit structure is planned for strength, ease of manufacturing, and heat conduction. Based on MDAC thermal analysis, a 100-W heating capacity will provide ample temperature control when used in conjunction with a five-layer multilayer insulation (MLI) blanket. Electrical connectors are provided for cabin heater activation and temperature monitoring before the repair mission EVA. Internal thermostatic high/low-temperature limit switches regulate heating after being turned on. Other features are a low

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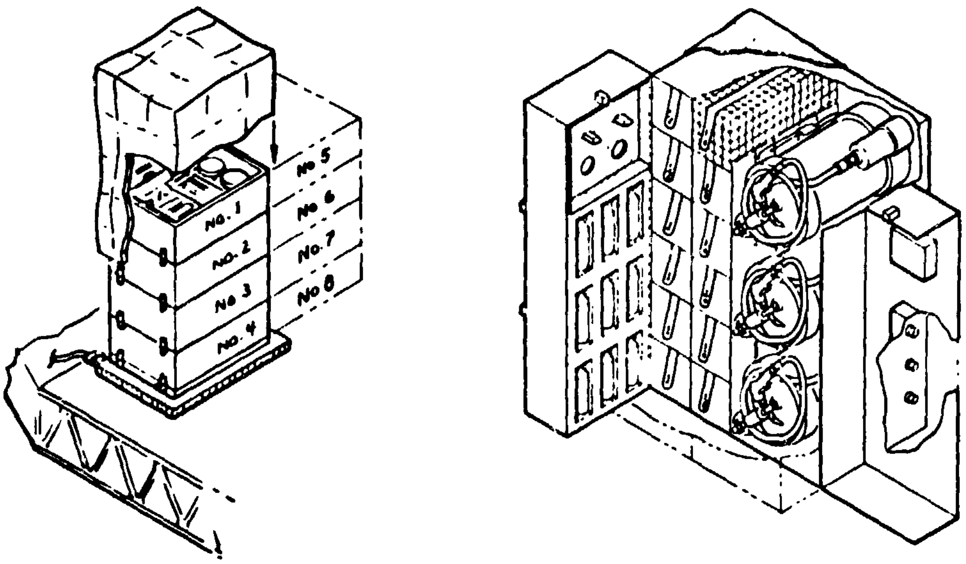


- Prepared Combination
- Ease of Handling
- Ready W/S Access

- Open Full Selection
- Minimum MMU Mission Weights
- Single Simple Design
- Manufacturing Advantage
- Minimum Bay Resupply Trips

Figure 5-1. Modules Vs Complete Kit

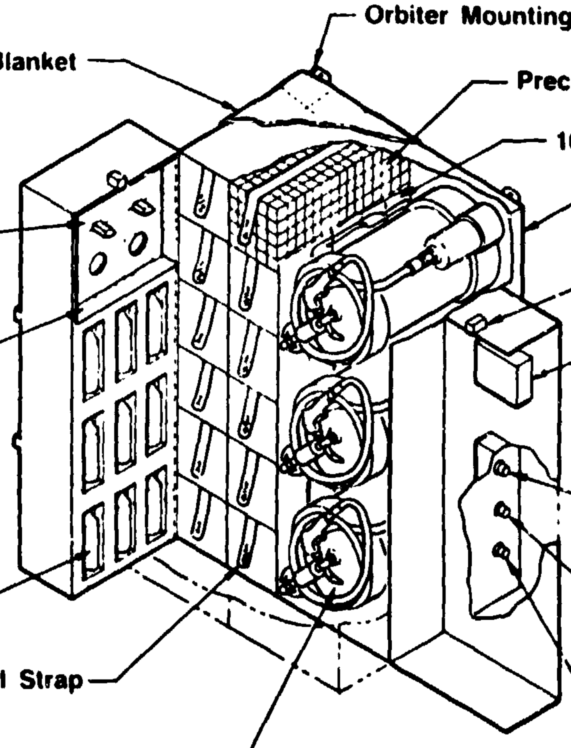


Figure 5-2. Complete Tile Repair Kit

Table 5-1. Repair Kit System/Mission Requirements

- 12 ft^3 volume
- 300-lb total kit weight
- 57-lb nominal MMU repair kit + 20-lb work station (90 + 60 Phase II RFP)
- Temperature control 40°F - 125°F and monitoring
- 6,480-in^3 precured, 1,080-in^3 cure-in-place, 25 ft^2 emittance coat
- Ease of material removal and return
- Flight hardware design
- Minimum cabin preparation, activation, monitoring
- Growth potential

differential pressure relief valve if the final design is sealed, passive thermometers for double-checking kit temperature directly before use, transfer modules for tile, emittence coating and tools, large tether rings and attachment clips, hand holds, Velcro tape fasteners and closures on the MLI, Velcro tethering attachments, and open-cell foam dunnage. Mounting brackets will be in accordance with NASA's Orbiter interface control drawing (ICD).

The space required to stow the precured ablator, cure-in-place ablator applicators, emittance coating, and all tools is approximately 0.34 m^3 (12 ft^3). Although MDAC has started with a 0.965 x 0.661 x 0.533m (38 in x 26 in x 21 in) size, exact dimensions of the final design should be developed starting with the transfer module and three-part applicator sizes to minimize both volume and weight. Repair kit weight is in excess of the 136 kg (300 lb) requirement at this stage of MDAC's development by 28 and 44% for the three-part system and the self-contained applicator designs. However, using lighter tiles such as HRSI dip coated with RTV-560-32 or precured material suggested by other study contractors and by also refining the applicator designs, the 136 kg (300 lb) goal is expected to be achievable. Our applicator weights are driven by the pressure safety requirements and 600 psi was felt necessary to achieve time line applicator dispensing rates for the high viscosity material. Pressure may be reduced based on continued testing of our functional mockup. Sizes and weights are summarized in Table 5-2.

Table 5-2. Kit Size and Weight Factors

	Unit Qty	Size (in.)	Unit Volume (ft^3)	Total Volume (ft^3)	Weight (lb)	Repair Kit Weight Self Cont (lb)	Repair Kit Weight Three Cont (lb)
Precured (32 lb)	240	3/4 x 6 x 6	0.0156	3.75	0.5	120	120
Three-part applicator	3	14 x 11 x 20	1.8	5.4	60	--	180
Self-contained applicator	10	21 x 10 x 6	0.73	(7.3)*	26	260	--
Emittance coat	9	3 x 3 x 8	0.04	0.36	2.5	22.5	22.5
Spatula	2	2 x 2 x 6	0.014	0.03	0.6	1.2	1.2
Nylon waste bag	4	0.004 x 12 x 18	0.03	0.12	0.2	0.8	0.8
Other tools	TBD	---	--	--	--	3.0	3.0
Container	1	26 x 38 x 21	(12)	(12)	50	50	50
Dunnage	1	---	--	2.00	4	4	4
MLI	1	26 x 38 x 21	0.34	0.34	3	3	3
Estimated totals				12.42		464.5	384.5
Designed goal				12.0		300	300

*Not nested, 5.4 nested

5.1.1.1 Structure

Conventional construction using aluminum sheet, angle, and expended mesh is recommended. Fiberglass was considered, but rejected because of the ease of manufacture using aluminum and the short time for design and fabrication. Fiberglass standoffs for mounting to the Orbiter structure will minimize heat transfer.

5.1.1.2 Heaters

Heating requirements were claculated for the MLI insulated container assuming an average external temperature of -250°F (240°R), internal temperature at heater activation of -40°F (420°R), and 80°F (540°R) as the desired temperature after 24-hr heating. This resulted in a 120°F temperature rise (ΔT). The heat transfer through 3.3 m^2 (32.4 ft^2) of MLI under these conditions is plotted in Figure 5-3. The average heat loss was 40.65 Btu/hr.

Heating energy required per hour is expressed by Equation (1) where m is the total mass, c is its heat capacity, ΔT is the heating temperature range, t is heating time in hours and K_{MLI} is the MLI heat transfer for the above stated conditions. Kit physical priorities are given in Table 5-3 for the worst-case weight condition summarized in Table 5-2.

Table 5-3. Kit Material Physical Properties

	m (lb)	C (Btu/lb-°F)	mc (Btu/°F)
ablator	140	0.3	42
other	325	0.2	65
	465		107

Using Equation (1), total heating requirements are calculated

$$Q_T = \frac{m\,c\,\Delta T}{t} + Q_{MLI} = \frac{107 \times 120}{24} + 40.65 \text{ Btu/hr} \qquad (1)$$

$$= 535 + 40.65$$

$$= 575.65 \text{ Btu/hr or } 169 \text{ watts}$$

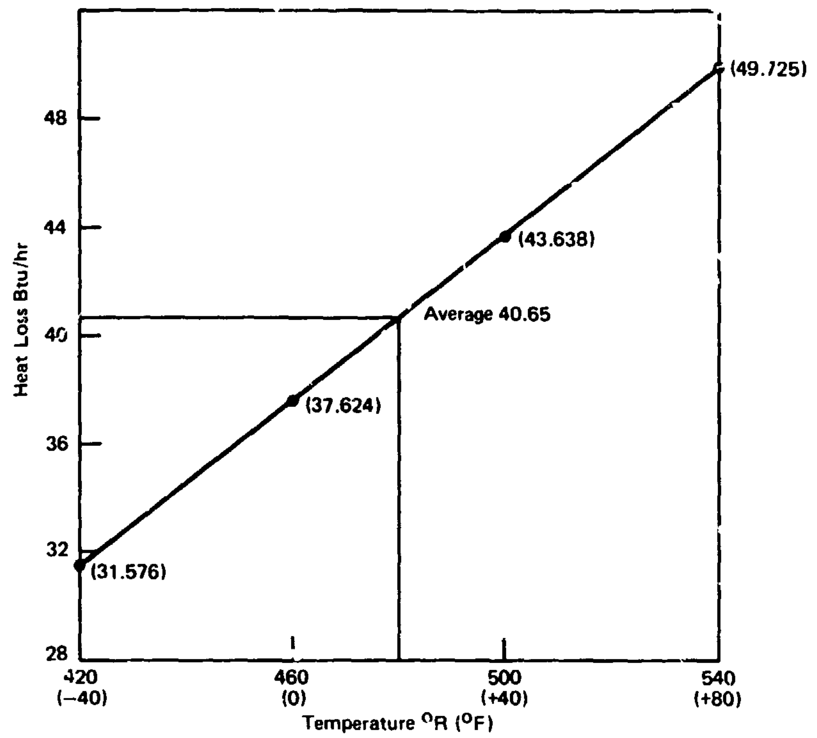


Figure 5-3. Kit MLI Steady State Heat Transfer

An additional 2W are lost for each support or restraint penetration of the MLI even with good thermal design. Worst-case condition would therefore require about 180 W. This can be reduced about 45% to near 100 W with lighter weight precured tile and redesign to reach the 300-lb design goal. Two types of 24 V heaters were investigated. Mobay Chemical Company has a metallized cloth that could be sewn into the MLI insulation blanket. Raychem Corporation has strip heaters which can be bonded onto the kit structure. Both have much design flexibility. Brochures for each are presented in Appendix C. The Raychem Cellotherm is recommended because of the short design and manufacturing time since it utilizes more conventional technology.

5.1.1.3 MLI Blankets

MDAC has designed and fabricated MLI for use on Delta launch vehicles, the Spacelab tunnel, and for other Orbiter equipment. Testing for these applications has verified the operating characteristics which were used in calculating the heating requirements (Section 5.1.1.2). MLI is fabricated using alternate layers of aluminized Mylar and separator mesh which are then faced with Beta cloth outside and Dacron inside. Normal attachment is with heat resistant Velcro fastener strips bonded to the structure on one side and sewn to the MLI on the other. Velcro side seams are also provided for easy opening of entry panels. Large tabs are provided for ready gripping with the spacesuit gloved hand.

5.1.1.4 Electrical

Electrical wiring will be provided for cabin heater activation and temperature monitoring. Internal thermostatic high/low-temperature limit switches would regulate heating after being turned on. They would be set to turn on below 60°F and turn off above 80°F to maintain an optimum working temperature. Higher temperatures should be avoided because of the resulting shorter working life of the RTV-560-32 cured-in-place material. As noted in Figure 3-5, the pot life is about 90 min at 70°F but shortens to about 30 min at 125 F. For a large area repair, the mission timeline analysis shows that this could be within the time period between uses so that applicator purging of mixed material would be needed to assure against it setting up and inactivating the applicator. Passive temperature monitoring would be included with thermometers mounted in the flight storage container and also on the mixing and applicator heads.

5.1 1.5 Pressure Relief Valve

Weight of the kit can be minimized using an open framework for the open mesh work station transfer modules. Should a sealed container be necessary for any reason, a two-way low differential pressure relief valve should be provided to assure pressure equalization during both launch and landing.

5.1.2 Kit Contents

Tile, emittance coating, and tools are stored in drawer-type modules to simplify handling. The applicators do not lend themselves to modular packaging and are therefore installed and removed individually for use.

5.1.2.1 Transfer Modules

Open-mesh aluminum modules are suggested for the precured ablator, tools, and emittance coating. One module 0.457 by 0.305 by 0.241m (18 by 12 by 8 in) would hold the tools and emittance coating (estimated at 9 to 12 pint aerosol cans, 7.7 cm (3 in.) diameter x 20.4 cm (8 in.) tall). Five modules 0.457 by 0.305 by 0.152m (18 by 12 by 6 in.) would hold the precured ablator, enough in each for one maximum repair 0.457 by 0.9[illegible] by 0.051m (18 by

36 by 2 in.). The module would be easily removed from the storage container, tethered for transfer and finally fastened to the work station with large, easy-to-operate overcenter latches. Horizontal orientation is shown in Figure 5-8 but having them at an angle could be easier to reach and use. If MMU operating weight limits are not exceeded, two modules of tile can be stacked to provide a two-location repair capability. Materials and tools would be attached inside with Velcro patches or tethered to assure positive control at all times with a minimum number of astronaut operations. A cloth cover permanently attached on one side and fastened on the other with Velcro should also be considered. Final design will evolve following tile size and thickness selection, aerosol versus dauber applied emittance coating and tool selection/design.

5.1.2.2 Precured Ablator

Precured ablator tiles would be individually molded and then cut-scored on one inch centers for breakaway shaping to better fit a repair area. Several tiles are then bonded on one edge to a thin backing sheet to form a larger block to aid in physical control. The backing sheet would have Velcro fastener strips applied which attach to a mating strip inside the module. See Figure 5-4. Backing sheet bonding would be light enough to permit easy tile removal by simply folding it over 90° using a tile handling and positioning tool and peeling one tile off as needed. RTV-560-32 and Purple Blend are moderately notch sensitive so by cutting 50% through, breaking to size at a cut is not a difficult action. The unused pieces can be stowed in a clean waste bag for future use. Tile initial length and width should be reviewed to be sure they are not so large as to make placement in a repair area difficult. Sizing 0.32 cm (0.12 in.) to 0.64 cm (0.25 in.) smaller than the typical original tile cavity would reduce the need to break a tile for installation - except for a partial tile repair.

Several thickness combination options which will provide complete layer building capability and meet the ±0.64 cm (±0.25 in.) finished surface step requirement are shown in Figure 5-5 along with original HRSI thicknesses. There should be no minus step below 2.54 cm (1.0 in.) thickness since thermal analysis shows the greatest reentry temperature rise behind the insulation in thin areas. Use of all 1.1 cm (0.44 in.) tile would simplify the kit and elim-

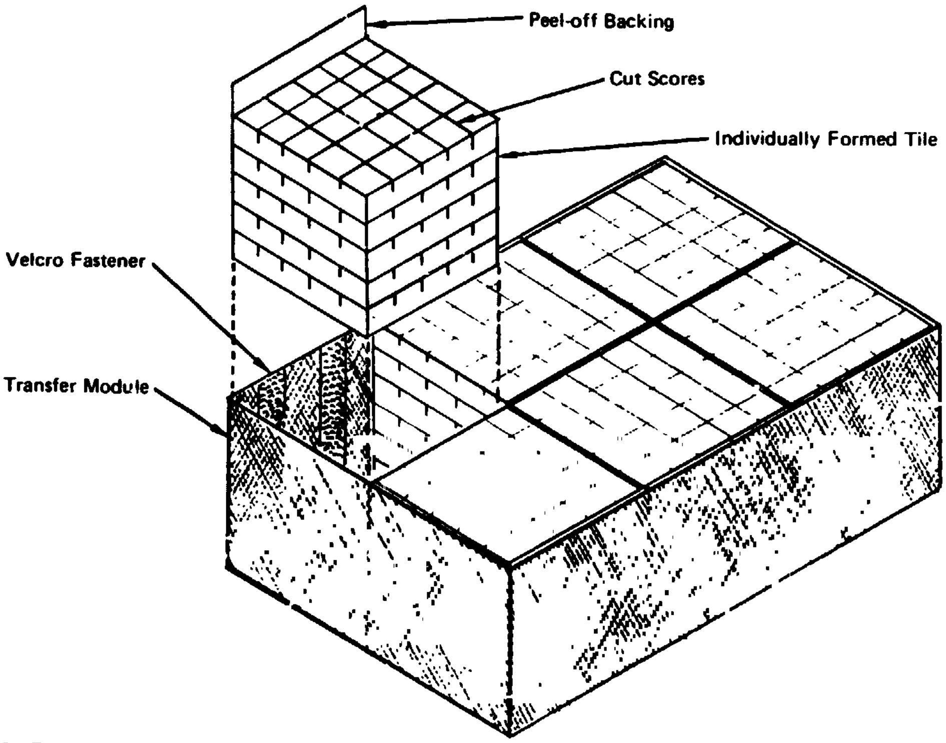
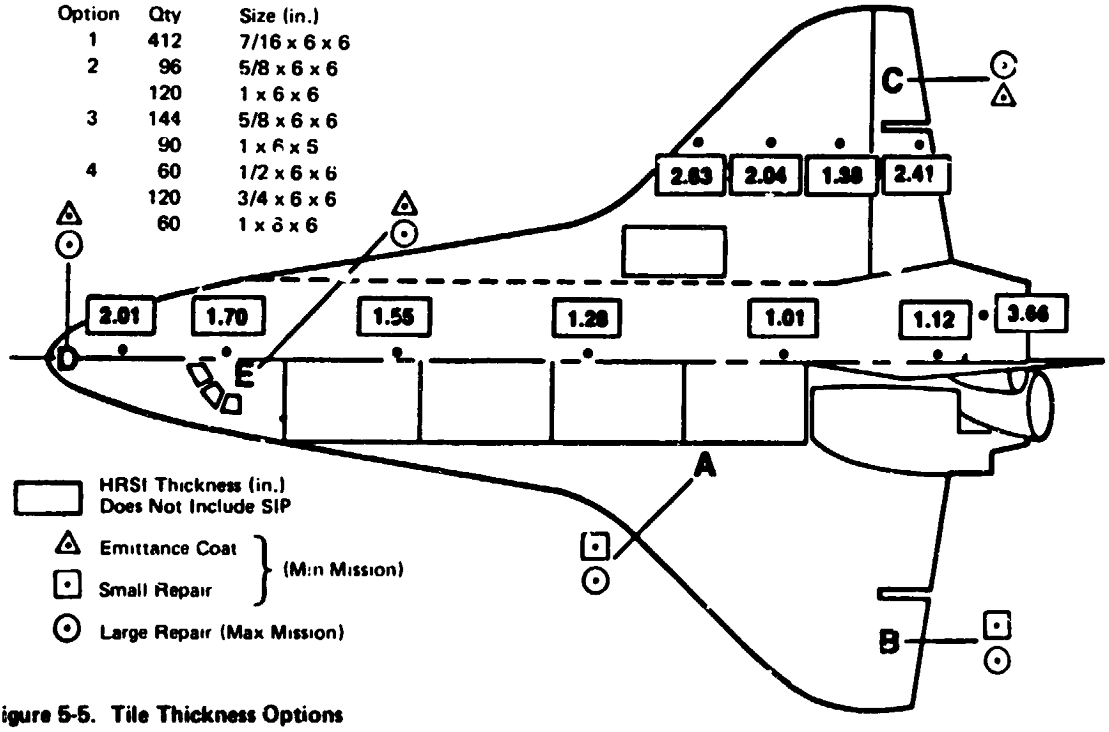


Figure 5-4. Precured Ablator Tile Module



Option	Qty	Size (in.)
1	412	7/16 x 6 x 6
2	96	5/8 x 6 x 6
	120	1 x 6 x 6
3	144	5/8 x 6 x 6
	90	1 x 6 x 5
4	60	1/2 x 6 x 6
	120	3/4 x 6 x 6
	60	1 x 6 x 6

Figure 5-5. Tile Thickness Options

inate the need to decide which thickness is necessary for the repair but it requires the careful control of applied amounts of cure-in-place material. Only 0.15 cm (0.06 in.) average thickness would be allowed per tile. This assumes a good feel by the astronaut of dispensed volume and an ability to smooth to a thin uniform layer. If practice does not support this premise, an additional quantity of cure-in-place material should be considered. It would also increase repair time. If more than one thickness is used, each tile would have its thickness stencilled on the upper side for ready identification and selection.

5.1.2.3 Cure-in-Place Applicators

The lighter weight of the three part applicator system, its minimal handling necessary for transfer to the work station and the compact dispensing unit are major factors leading to MDAC's preference for it over the self-contained units. However, the greater number of self-contained units needed results in somewhat increased reliability. Either can be fitted in the same space provided the self-contained units are nested. A clamp at the base would be used to secure either type applicator in the storage kit or on the work station. Added support for each applicator during launch and landing would be provided by self-centering locking devices built into the container door. The principal disadvantage of the three-part system is the possible loss of a substantial portion of the total material available should curing in the gun result in a premature freezeup. There are two ways to avoid this. The easiest is to purge the gun of all mixed material after a specified period of time following its last use until the unit is spent or the repairs are completed. The other is to have a spare mixer/hose/dispenser assembly. This would require a shutoff of both materials individually before any mixing and the addition of a spanner wrench type tool to make the change. Final selection also should consider the potential for design weight refinement and the comparable handling of the unincumbered self contained unit (except for a tether) versus the three-part system with the hose attached.

5.1.2.4 Emittance Coating

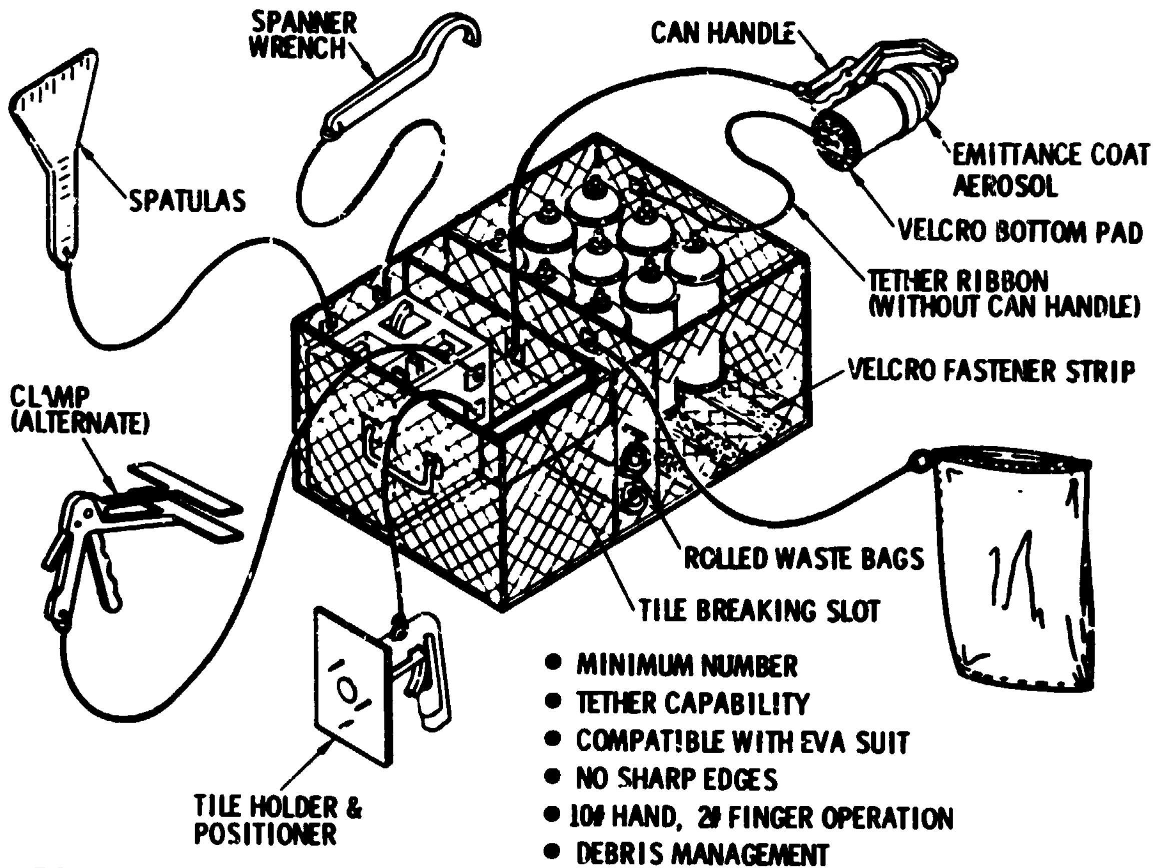
Nine to twelve standard pint aerosol cans meeting PPP-C-96, Type IX, have been assumed to provide the required amount of emittance coating. Covering only approximately 0.19 m^2 (2 ft^2) of area per can seems more than adequate considering household uses with spray paints and rubber cements. Application would be simplified using a pistol grip handle and actuator valve instead of relying on finger depression forces. The concave bottom of each can would have a Velcro patch bonded on for attachment to a mating strip in the bottom of the module. It would prevent floating away in zero g and also permit use of a simple ribbon tether with a Velcro attach area during coating application if the handle is not included in the kit. Expended cans are easily restowed in their original position eliminating the need to add them to the waste bag.

5.1.3 Tools

The number of tools has grown as details of the repair have evolved. MDAC now envisions one or two wide-blade plastic spatulas, several rolled nylon waste bags, a clamp or slot for breaking tile, a tile holder and positioning tools, an aerosol can handle with actuator valve, and possibly a spanner wrench. All would be stored and handled in a single storage/transfer module so no in-and-out transfer with associated piece-by-piece tethering would be needed. Each item would have a permanent tether to the module to minimize astronaut nuisance activities. Figure 5-6 illustrates tool requirements and MDAC's approach.

5.1.3.1 Spatulas

Cavity preparation will be accomplished with minimum effort using a blade to remove broken tile at the SIP. Trying to break out the HRSI in any other way would likely create a dust/sloughing contamination problem which would be difficult to contain or control. When a fracture occurs horizontally, it should be left if the remaining base portion is determined to be adequately bonded. A spatula will also be used to smooth each successive layer of cure-in-place adhesive before placing the tile in position and would finally be used for top surface finishing and step edge cleanup. It can be ruled in 0.64 cm (0.25 in.) graduations for determining repair depths and also can be used to verify the 0.64 cm (0.25 in.) finished surface step requirement. If cleaning the blade proves difficult and only a clean blade is effective for surface preparation, two will be needed. The one with cure-in-place material can be wiped of excess material on the metal reinforced edge of the waste bag or just cleaned as much as possible on the good Orbiter tile surface before stowing it in the transfer module.



- MINIMUM NUMBER
- TETHER CAPABILITY
- COMPATIBLE WITH EVA SUIT
- NO SHARP EDGES
- 10# HAND, 2# FINGER OPERATION
- DEBRIS MANAGEMENT

Figure 5-6. Tool and Emittance Coating Module

5.1.3.2 Waste Bags

Nylon tubing is our candidate for the waste bags because of its toughness and its wide working temperature range. A metal band heat sealed in the top edge provides necessary stiffness to control opening and closing. Velcro ribbon sewn along the top edge provides fastening capability outside the module during repairs. They would be rolled before use. After use they would be closed and left fastened to the outside of the transfer module for transition to the next work site or to the Orbiter bay. Each would be permanently stored after use in the kit container in one of the emptied precured tile modules.

5.1.3.3 Clamp

A clamp would be useful to aid breaking the precured tile along the desired cut line even though they are made to be easily broken. It would have parallel paddle blades as wide as the tile and a 7.7 cm (3 in.) open throat. It would open in parallel fashion to accept the maximum thickness tile when operated by the pistol grip handle. An over center clamp built into the tool cage would possibly be easier to use since it would be rigid. For complete simplicity, an open slot built into the tool module might be sufficient. The tile would be placed down the slot to the desired precut line and bent back to make the break. The remaining broken pieces in all cases would be stored in a waste bag for possible future use.

5.1.3.4 Tile Holder and Positioner

Placing a tile into the fresh cure-in-place coating in the repair cavity will require a great deal of dexterity to avoid spacesuit glove contamination. A holding tool would relocate the hand away from the cavity. It also permits the tile to be pushed down into the adhesive layer and firmly seated in position with a slight circular or lateral motion. Holding would rely on insertion of three pins into the tile through a surface plate by squeezing a pistol grip handle. Once the pins are extended into the tile, the grip could be locked by thumb or finger action to keep it fixed and permit total concentration on seating the tile into position. When the latch is released, the pins are safely retracted back through the surface plate by spring action leaving the tile in place and the tool ready for its next use or stowage in the module.

5.1.3.5 Aerosol Can Handle/Actuator

Small clip-on handles with a trigger mechanism are available. Their use would convert the spraying from a finger depression action to an easier to operate pistol grip. The handle would be tethered to the module so the cans would become automatically tethered when the handle is attached.

5.1.3.6 Spanner Wrench

One of the means to remove and replace the mixer/hose/applicator head on the three-part system would be to design it to uncouple with the aid of a spanner wrench. Other ways can be designed, i.e., an overcenter lock with self-sealing poppet valves. The emphasis here is to indicate that if a spare mixer/hose/applicator is included in the final design, some tool may be needed to make the change.

5.2 REPAIR MISSIONS

Repair requirements summarized in Table 5-4 have been considered during kit design and for making emittance coating repair, small area HRSI repair and large area HRSI repair as pictured in Figure 5-7. HRSI repair timelines are shown in Tables 5-5 and 5-6.

Table 5-4. Repair Mission Requirements

- Single crewman
- Tethering at all times
- Repair in light or darkness
- Debris control
- 5-10-lb hand, 2-10 finger forces
- 90-lb tools and materials
- 50-lb work station
- Positive repair assessment

PROBLEM	FIX	TIME, MIN
▪ COATING & MINOR HRSI LOSS	EMITTANCE COATING	2 – 3
▪ SMALL/SHALLOW AREA	CURE-IN-PLACE ABLATOR	20
▪ LARGE/DEEP AREA	PRECURED ABLATOR	46 – 60

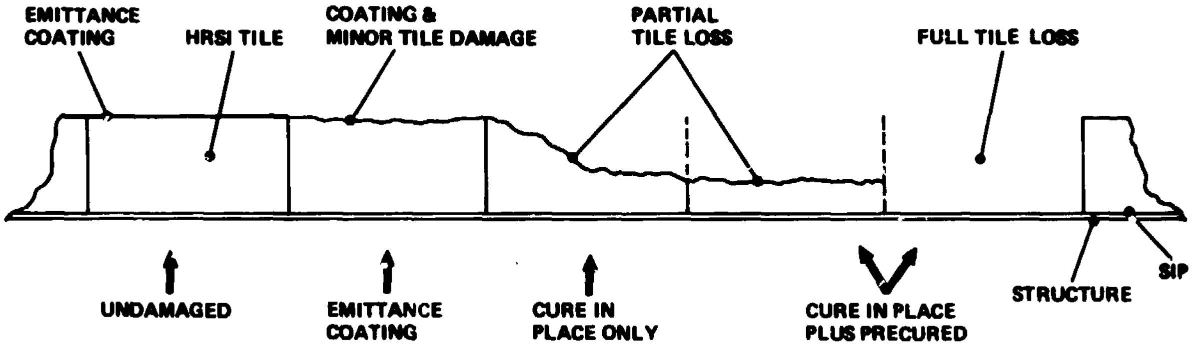


Figure 5-7. Repair Concepts

5.2.1 Emittance Coating Repair

Emittance coating damage can be repaired on an inspection mission using the MMU without the work station or in conjunction with other repairs. On an inspection mission, several aerosol cans of emittance coating would be removed from their storage module along with a handle/actuator assembly and a waste bag to use for carrying. The bag would be removed and tethered to the crewman in a readily accessible location. The cans would then be removed individually and tethered to the bag before being placed inside. The last one would have the handle/actuator attached.

No tools are expected to be needed to prepare the surface for emittance coating. Most loose HRSI material would have been blown away during launch. Any fines remaining would be entrapped in the coating and present no difficulty.

Table 5-5. Small Area Repair Timeline

Repair for repair	6.5	(4.0)	From design reference mission
Cavity preparation		1.5 min	
Stow waste		0.5	
Release applicator		0.5	
Apply cure-in-place test patch		1.0	1/8 x 4 x 4 to 1/4 x 6 x 6
Fill repair area*		3.0	72 in^3 (6 x 6 x 2)
Stow applicator		0.5	
Surface finishing	6.5	1.0	
Clean up and stow waste		1.5	
Positive repair assessment		1.0	
Stow kit and detach work station		(3.0)	From design reference mission
Total time		10.5 min	
Timeline goal		20.0	

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*Flow rate: 24 in^3/min for half-time operation

Table 5-6. Large Area Repair Timeline

Prepare for repair	11.5	(4.0)	From design reference mission
Cavity preparation		5.0 min	
Stow waste		2.0	
Release applicator		0.5	
Apply cure-in-place test patch		1.0	1/8 x 4 x 4 to 1/4 x 6 x 6
Apply base layer cure-in-place*		3.5	1/8 x 18 x 36 (81 in^3)
Stow applicator		0.5	
Surface smoothing		1.0	
Install tile at 0.5 min each		9.0	Bottom layer 18 pieces, 3/4 in.
Retrieve applicator		0.5	
Apply second layer cure-in-place*		3.5	1/8 x 18 x 36 (81 in^3)
Stow applicator		0.5	
Surface smoothing		1.0	
Install tile at 0.5 min each		9.0	Upper layer 18 pieces 3/4 in.
Retrieve applicator		0.5	
Apply cure-in-place to height*		7.0	1/4 x 18 x 36 (163 in^3)
Stow applicator	10.5	0.5	
Surface finishing		3.0	
Clean up and stow waste		2.0	
Positive repair assessment		2.0	
Stow kit and detach work station		(3.0)	From design reference mission
Total time		52.0 min	
Timeline goal		60.0	

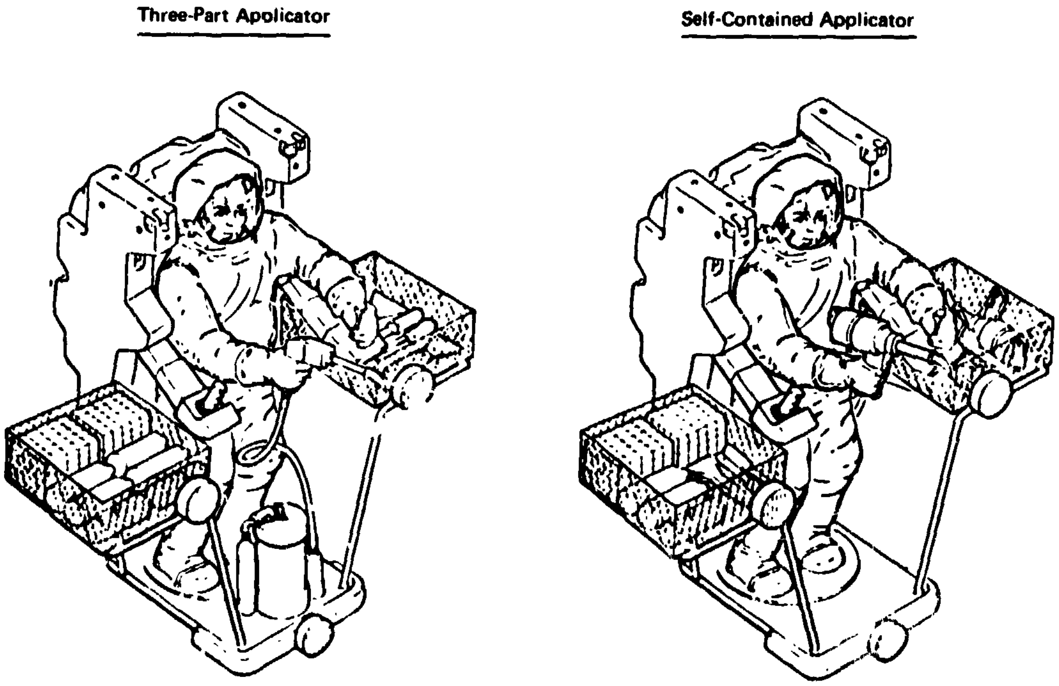
*Flow rate: 24 in^3/min for half-time operation

At the repair site, the unit with the handle would be removed and used until all material had been expelled. The handle would be detached, the spent can tethered and returned to the bag. A fresh container would be removed and the operation repeated. The handle would be removed only after a can has been emptied. Empty cans can be identified by observation of residual material on the nozzle or the nozzle might be removed and stowed in the waste bag to show the container was empty.

Operation from the work station would be the same but simplified to the extent that all items would be used directly from the transfer module. The individual tethering for positive handling control in and out of the bag and handling the bag itself would be eliminated. Empty cans would be returned directly to their original position in the module to accomplish waste management.

5.2.2 HRSI Repair

Work station configuration concepts are shown in Figure 5-8 for both the self-contained and three-part applicators with transfer modules containing all other necessary tools and materials. Storage container, applicators,


Three-Part Applicator

Self-Contained Applicator

Figure 5-8. Workstation Configurations

modules, tile and tool concepts are the basis for our repair timeline analysis. Allotted time for material transfer from the storage kit to the workstation and its return stowage after repair is minimized with module use and appears to be achievable within design reference mission guidelines.

No tools other than the spatula are anticipated for cavity preparation. If dust is present, it is expected to be readily absorbed into the substantially larger bulk of the cure-in-place material and not require removal before proceeding with the repair.

It is suggested that a small thin test sample of cure in place ablator be applied next to the actual repair area as the first repair operation to provide for positive repair assessment. By the end of the repair, the test patch would have had the longest time for curing so a preliminary evaluation of gelling and adhesion could be made. On a small area repair it would be only 7-10 minutes before being ready to move to the next repair site. For a large area, it takes about 45 minutes to complete the repair so curing of the test patch should be measurable. However, since the lower the temperature the slower the curing, a positive assessment may have to be deferred to a return trip after other repairs even for a large area if the application temperature was below 70°F.

Cure in place application is based on dispensing a minimum of 393 cm^3 24 in^3 of material per minute at low temperature (40°F) when operated at a 10 second on/off intermittant rate. Times when the applicators are inactive are shown with arrows in Tables 5-5 and 5-6. In addition to these times must be added the 2 minute translation times between repairs, or 16 minutes if a trip back to the bay is required, to have normally expected total times that curing is continuing in the applicator. This adds up to 38 minutes during a large area repair sequence and would mean possible trouble if the temperature approaches the 125°F maximum.

As discussed in Section 5.1.2.3, applicators may have to be purged periodically to prevent freeze up. A 1.83 m (6 ft) x 1.3 cm (0.5 in.) hose plus mixer and dispenser holds 328 cm^3 (20 in^3) of material which must be used at once or purged. This is enough for bonding 4-1/2 tiles using 0.32 cm (0.13 in.) thickness or 9 tile if 0.16 cm (0.06 in.) thickness as maintained.

Conserving cure in place material is essential to achieving maximum repair. An analysis of total repair volume after the inspection mission should be made and the complete repair mission planned. It is recommended that this be done by voice contact with the cabin crew who would map the repair areas and depths, calculate the total volume of materials needed and select the optimum combinations of cure in place and tile to be used. A shallow small area less than 0.95 cm (3/8 in.) deep would use only cure in place material. Deeper repair even if for a single tile area should always use both precured and cure-in-place if there is any question of running short of cure-in-place material. If multiple tile thicknesses are chosen, each repair should attempt to have the surface level with surrounding tile even though ±0.64 cm (0.25 in.) steps are permissible. Always end a repair with precured tile on top to simplify finishing. In that way, only the excess squeezed up around the edges requires clean up and blending to the adjacent tile. Avoid having a top coat of cure in place at any time except when making shallow repairs without precured tile.

Positive repair assessment before leaving a site seems unlikely more often than not. It is suggested that the first repair always be planned nearest the Orbiter bay egress/ingress point so that its test patch could be easily checked later upon return to the bay. An additional EVA inspection mission can then be considered if increased confidence is needed. Upon completion of repairs, and return to the bay, the modules and applicators would be removed from the workstation and stowed in the storage kit where they would be safely resecured to withstand reentry and landing loads.

Section 6
CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions reached from the results presented in the preceding sections and provides recommendations for subsequent program efforts.

6.1 CONCLUSIONS

The feasibility of repairing various kinds of damages that may occur to the Orbiter TPS during ascent has been demonstrated. Cure-in-place and precured ablators have been selected, tested and analyzed and found to possess the required thermal properties to maintain the Orbiter structure below 350°F during reentry. The cure-in-place ablators were formulated with a combination of curing agents to cure the RTV-560 resin in a vacuum at temperatures down to 40°F within 18 hours and have a useful work life, approximately one hour, at 125°F. The adhesion of the cure-in-place ablator to the precured tile (Purple Blend Mod. 5) and to the Orbiter TPS materials easily met the 40 psi requirement. The tensile strength of the lowest density ablator (RTV 560-32) is 145 psi, easily exceeding the 40 psi requirement, so the density of this ablator can be further reduced for weight savings and still meet the adhesion and strength requirements. The processing properties (viscosity and thixotropy) of the cure-in-place ablators were formulated for mixing and dispensing with the Ross static mixing heads as well as to have good thixotropic properties to remain in place after application. The cure-in-place ablators were evaluated in the functional mockup gun and were found to dispense at low pressure (< 200 psi) with efficient mixing of the catalyst and resin. Cure rates and properties of the cure-inplace ablators dispensed through the functional prototype gun correlated with earlier laboratory results where the catalyst and resins were mixed using conventional laboratory mixing equipment. The functional mockup was successfully tested in the laboratory and demonstrated during

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the final presentation at NASA-JSC. RTV-560-55 cure-in-place ablator mixed and dispensed through the gun cured to the required hardness within five hours. This test and demonstration verified the design concepts of our proposed self contained gun as well as the three part canister design. The design aspects of our proposed applicators which were verified with the functional mockup include the following.

- Isolated storage of resin and catalyst
- Gas pressures required to mix and dispense material
- Ratio control of resin to catalyst
- Metering and valving design
- Mixing efficiency of Ross type static mixers
- Dispensing rate

The repair kit module satisfies the system requirement imposed on the module. The overall weight of the repair kit module exceeds the 300 lb limit, but with design requirements of the material applicator and the selection of a light density ablators the 300 weight limit appears to be achievable.

Container contents are arranged so the crewman has easy access to all materials and equipment required to accomplish the repair task. The modules are easy to transfer and attach to the workstation. Their design and use all but eliminates repeated on/off tethering. Convenient tools are proposed to augment astronaut hand operations for simple measuring, cavity preparation, ablator application, tile sizing and positioning, surface finishing and waste management.

6.2 RECOMMENDATIONS

6.2.1 Ablator Materials

Based on results of the thermal analysis and arc jet tests, a modified version of RTV-560-32 will satisfy the requirements for a cure-in-place ablator as well as for the precured ablator. The modification would consist of adding refractory fibers and phenolic microballoons to achieve a density between 20-25 lb/ft^3. The fibers will improve the char retention properties and the microballoons will reduce the density and improve the char yield.

6.2.2 Material Applicator

Using weight, reliability and ease of use as the selection criteria, the three part gun with the canister is recommended. It is superior to the self-contained gun in weight and ease of use. The self-contained gun can be considered more reliable due to the larger number of units. The loss of one or two units would have a lesser impact on mission goals. Both systems have equal reliability with respect to containment, ratio control, mixing and metering.

The bellows approach is recommended over the piston design because of the lower weight and smaller unit size. The piston concept has an advantage in reliability. If the bellows approach is selected, a functional prototype should be fabricated and tested to verify performance.

6.2.3 Repair Kit Module

Kit/Mission related recommendations are: 1) use a single tile thickness, 2) include emittance coating repairs as part of the inspection mission, 3) map damaged areas and plan repairs with cabin crewman, 4) apply a test patch of cure in place ablator as the first step in each repair, 5) make first ablator repair nearest bay egress/ingress point for confident repair assessment 6) increase cure in place volume within size and weight constraints.

Using 1.1 cm (0.44 in.) thick tile will meet all finish step requirements and permits straightaway repair without planning to assure against running out of one size or another. It eliminates the hypothetical guesswork in making original thickness and quantity selections. Tools design is also simplified by not having to accommodate several thicknesses.

Emittance coating repair along with inspection will take little extra time and will result in a more thorough damage analysis. Several cans of emittance coating can be included with the camera and tether kit to avoid having to open the TPS kit container until ready for a general repair mission.

Mapping damage to plan repairs, applying the cure in place test patch and locating the first repair near the bay have been discussed in Section 5.

Increasing the cure-in-place volume within the three part applicator will permit larger variations in applied thicknesses and provide a greater backup supply in case inadvertent curing and setup should occur in one of the applicators.

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Appendix A
FUNCTIONAL MOCKUP ASSEMBLY AND FILLING

The following procedure should be followed for assembly and filling operations of the functional mockup. It is assumed that the applicator is completely disassembled and that the assembly prints are available.

1.0 Assemble nozzle subassembly

1.1 Insert three static mixing units into the nozzle barrel with the pointed end toward the nozzle tip. Be sure that each unit nests into the preceding unit.

1.2 Lubricate the O-ring and insert into nozzle groove. Slide nozzle into base ring and thread two setscrews into groove provided. Backoff setscrews to provide desired rotation of nozzle. Lubricate thread and screw base ring into nozzle barrel.

1.3 Wrap pipe thread of nozzle barrel with Teflon tape and thread into ball valve. (Ball valve handle will point forward when valve is open.)

1.4 Wrap Teflon tape around pipe threads of the handle assembly and thread into back of ball valve.

2.0 Assemble body subassembly

2.1 Lubricate the largest T-ring and insert into external groove of piston assembly. The backup rings have one radiused corner. Place one backup ring on each side of the T-ring. Be certain that the radius faces toward the radius of the T-ring in all cases.

Verify that the scarfed ends of the backup rings match. Lubricate the sealing surface.

2.2 Repeat the above sequence for the inner seal of the piston assembly.

2.3 Repeat again for the outer seal of the inner piston.

2.4 Lubricate two small 0-rings and position on each end of the piston stem. Add the Allen screw to secure the small piston to the stem and also the stem to the center of the piston assembly.

2.5 Verify that the case is free from dirt and grit. Insert the piston assembly into the case from the back end (port for second handle). Maintain a centered and "straight-in" position while inserting.

2.6 Slide the piston assembly to a position approximately 0.05 - 0.076 m (2 to 3 in) from the forward end. Position the unit on a work surface, horizontally.

2.7 Lubricate the large O-ring and insert into inside groove of forward cap. Lubricate inside and outside surfaces of central cylinder and thread onto forward cap.

2.8 While supporting the piston assembly with a hand inserted into the back of the case, insert the end of the central cylinder into the gap between the two concentric pistons (enter about 0.025 m (1 in)).

2.9 Lubricate a large O-ring and insert into inside groove of aft cap. Lubricate threads of cap. (Verify that O-ring is seated into groove - we stretched the O-ring slightly to ensure seating and prevent "pinching" upon assembly.)

2.10 Thread the aft cap onto the case. The engagement of O-ring will be felt. Continue to thread together until cap is "bottomed" (threads of case will not be exposed).

2.11 Lubricate small O-ring, tube fitting and cap. Assemble test port on cap.

2.12 Support the forward cap and rotate the assembly into a vertical position.

3.0 Hand filling operation

3.1 Use a spatula and place base material into the area between case and central cylinder. When filled flush with end of case, lower the piston assembly by pressing down on the forward cap. Repeat until gap between forward cap and upper end of case will not allow further filling.

3.2 Thoroughly clean the forward threads of the case, lubricate the threads and thread together as in 2.10 above.

3.3 The forward cap will now be upward. Apply tape over six screw holes and five material holes and O-rings. Freon or MEK may be required to ensure tape adhesion. Cut tape away from the four outer holes, but leave O-ring grooves covered.

3.4 Inject additional base material into one of the ports until it exists from the remaining three. Verify that air is not trapped inside case.

3.5 Scrape base material flush with surface and cover with another layer of tape.

3.6 Cut away tape from center hole - leaving O-ring covered.

3.7 Inject the catalyst material into the center hole. Verify that all air escapes as the central cylinder is filled.

3.8 Scrape catalyst flush with opening. Remove all tape carefully to prevent contamination of materials.

3.9 Verify that all five 0-ring grooves are clean. Lubricate 0-rings and insert into grooves.

3.10 Place an aluminum burst disk over the face of forward cap. (We used Reynolds wrap - 2.03×10^{-5} m (0.0008 in) thick foil.)

4.0 Final assembly

4.1 On the trigger assembly and forward cap, note the relationship between the screw pattern and the material ports. One position only will have two screw holes and three material ports in line. The forward end may be assembled in only two positions to allow material flow and only one correct position to also align the two handles.

4.2 Correctly position the forward assembly and bolt to the forward cap.

4.3 Lubricate the remaining O-rings and insert into the auxiliary handle.

4.4 It is recommended that an expended gas bottle be inserted into the handle (note that a spacer should be installed when using a 118-mm-long bottle - the handle will also accept a 138-mm bottle) when the applicator is not ready for immediate use.

4.5 For immediate use, insert a 38 gram, maximum, gas charge into the handle. CAUTION: Do not thread further than first resistance is felt, i.e., engagement of O-ring. (We used an XS-60-Cn3, 38 gm CO_2 cylinder supplied by Nippon Tancan Gas Co., LTD except that it was delivered in a 118 mm bottle.)

NOTE: An alternate method of filling may be preferred. An adapter cap has been provided for vacuum filling methods.

Appendix B

FUNCTIONAL MOCKUP DISASSEMBLY AND CLEANING

The following procedure should be followed for disassembly and cleaning operations of the functional mockup. It is assumed that the cleaning operation is performed immediately after expelling the material and before the material has hardened.

1.0 Disassemble nozzle subassembly.

CAUTION: Before any disassembly gently crack the cap on test port of rear cap. Do not remove cap until all pressure from case has been vented.

1.1 Remove six bolts that secure the handle and nozzle to the forward cap.

1.2 Immerse into a large container of MEK or other solvent.

1.3 Separate at both pipe threads. Remove Allen screws at nozzle tip, remove tip, base ring, and O-ring. Push the mixing units from nozzle barrel (use a dowel inserted into the back end).

1.4 Clean all holes, threads and valve with brush and solvent. Place into fresh solvent and totally clean O-rings, grooves, threads and all holes. Clean ball valve with ball in both open and closed positions. Dry all parts.

1.5 Verify that the case is fully vented before proceeding. Remove burst disk and discard. Remove handle with its gas bottle. Remove the forward and aft caps and immerse into solvent.

1.6 Remove O-ring from both caps. Remove the central cylinder. Clean all threads, holes, and grooves. Clean in fresh solvent and dry.

1.7 Remove piston assembly. Remove both cap screws which retain the center piston and stem. Remove three T-rings and their backup rings. Clean all grooves, holes, and threads. Clean in fresh solvent and dry.

1.8 Inspect all seals and replace if damage is found.

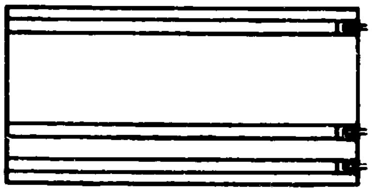
Appendix C
HEATING ELEMENTS

Custom engineered for your specific heating requirements

[illegible] th CelloTherm

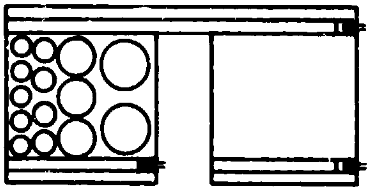
CelloTherm's versatility means ease of design for the user The customer provides the design parameters: size, voltage, wattage and maximum temperature Raychem manufactures CelloTherm to meet those specific requirements

If data on particular design parameters is not available, Raychem engineers can provide samples and are available to work with the customer to help define the requirements



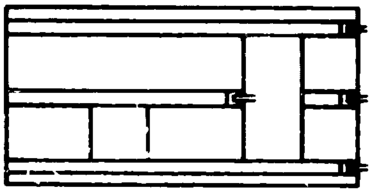
[illegible] voltage

CelloTherm can be manufactured with a third conductor Properly located this additional conductor will allow constant wattage at two different voltages, or multiple wattage zones at the same voltage



Selectively Heated Areas

Removing round sections of CelloTherm selectively eliminates wattage – a safe technique at densities of one watt per square inch or less



At higher densities complete-width rectangular sections may be cut out This provides the possibility of multiple heating zones

CelloTherm may be folded perpendicular to the busbars to produce selected areas of higher wattage output

Raychem Corporation is a world leader in radiation and additive chemistry, heat shrinkable plastics and metals, and conductive polymer technology Headquartered in Menlo Park, California, Raychem provides its customers with a full line of electrical interconnection products, heat shrinkable tubings, metals, and molded parts, high voltage terminations, corrosion prevention materials, and electrical heating systems

Raychem maintains worldwide field offices staffed by trained engineers to provide customers with prompt, effective solutions to their area heating problems.

For more information technical assistance for designing your CelloTherm, or ordering details, call or write

Raychem Corporation
300 Constitution Drive
Menlo Park, California 94025
415) 329 3273

Raychem

1. General Information

Woven fabrics and individual fibers with a thin uniform metal coating represent one of the most interesting recent developments in the textile field. The coating imparts many desirable characteristics of metals without impairing the inherent textile properties of the cloth or fiber.

Nickel, copper and gold are the metals used in coating fabrics such as cotton, wool, polyester, acrylic, polyolefin and polyamide.

The metal coating is applied to individual monofilaments in a uniformly thin continuous layer. Layer thicknesses range from about 0.05 to 1.0 micron in precisely controllable increments.

2. Properties

Textile Properties

The hand of the fabric is essentially unchanged and all normal qualities such as drape and appearance remain unaffected. Crimp, tenacity and elongation properties also remain unaffected by the metal coating.

Electrical Properties

Surface resistance for a 0.15-micron nickel coating is 10 ohms. The flow of electricity is uniform over the entire surface and the metallized fabric is permanently antistatic.

Shortwave radiation of the centimeter or decimeter range is effectively screened out by the metallized cloth. Absorption values of 30 db can effectively be reached to reflect more than 90% of ultra high frequency radiation.

Thermal Properties

When low voltages on the order of 10 to 40 volts are applied, metallized cloth can be maintained at constant temperatures. For example, a heating mantle for an orchid hydroculture was held at 28-29 C at 12 volts and 1.1 amps; temperatures did not vary from point-to-point on the cloth. Higher temperatures up to 180 C can be achieved depending on the textile fabric used.

3. Applications

The unique combination of properties of metallized cloth make this material suitable for a broad range of possible applications such as:

a. Antistatic garments for use in surgical operating rooms or explosion hazard areas. Antistatic carpet yarns

b. Protective garments for microwave screening

c. Radar reflections devices suitable for sea rescue operations

d. Heating mantles

e. Lightweight nickel elements for alkaline batteries

f. Antistatic fabric filters for industrial applications

g. Reinforcing fibers for conductive plastics

h. Conductive fabric sheathing for cables

i. Heated gloves and hose for hunting and other outdoor activities

Scanning electron microscope confirms textile characteristics

Scanning electron microscope at [illegible] magnification shows lack of bridging between metallized fibers

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