

## Vacuum/Zero Net-Gravity Application for On-Orbit TPS Tile Repair

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### ABSTRACT

The Orbiter Columbia catastrophically failed during reentry February 1, 2003. All Space Shuttle flights were suspended, including logistics support for the International Space Station. NASA Langley Research Center's (LaRC) Structures and Materials Competency is performing characterizations of candidate materials for on-orbit repair of orbiter Thermal Protection System (TPS) tiles to support Return-to-Flight activities led by Johnson Space Center (JSC). At least ten materials properties or attributes (adhesion to damage site, thermal protection, char/ash strength, thermal expansion, blistering, flaming, mixing ease, application in vacuum and zero gravity, cure time, shelf or storage life, and short-term outgassing and foaming) of candidate materials are of interest for on-orbit repair. This paper reports application in vacuum and zero net-gravity (for viscous flow repair materials). A description of the test apparatus and preliminary results of several candidate materials are presented. The filling of damage cavities is different for some candidate repair materials in combined vacuum and zero net-gravity than in either vacuum or zero net-gravity alone.

### INTRODUCTION

The Space Transportation System (STS) Orbiter Columbia catastrophically failed during reentry February 1, 2003. The Columbia Accident Investigation Board determined that the direct cause of failure was a breach in the Orbiter's left wing Thermal Protection System (TPS) (ref. 1). The TPS (figure 1) consists of three main types of materials to protect the orbiters from reentry heating (ref. 2). Reinforced carbon-carbon (RCC) composite is used on the highest heating areas of the nose and wing leading edges. High temperature reusable surface insulation (HRSI, TPS tile) is used for the moderate heating areas of most of the underside of the Orbiters. The Orbiters reenter at very high angles of attack (~40 degrees), so most of the impending air (and hence heat) is directed onto the bottom of the Orbiters during the thirty minutes of peak reentry heating.

NASA LaRC's Structure and Materials Competency is performing characterizations of candidate materials for on-orbit repair of Orbiter TPS tile (HRSI) to support Return-to-Flight activities led by JSC. The numbers of HRSI damage sites greater than one inch in diameter after each mission are shown in figure 2 (ref.1). More detailed descriptions of HRSI damage after missions are in Thermal Protection System Post-Flight Assessment reports<sup>1</sup>. Damage sites of the order of centimeters diameter are known to not be mission critical. Impact damage on HRSI of several centimeters dimensions are shown in figure 3. The on-orbit TPS tile repair damage this report addresses is tens of centimeters diameter and larger.

At least ten properties or characteristics (adhesion to damage site, thermal protection, char/ash strength, thermal expansion, blistering, flaming, mixing ease, application in vacuum and zero gravity, cure time, shelf or storage life, and short-term outgassing and foaming) of candidate materials are of interest for on-orbit repair of HRSI. Two material properties that are primary requirements for HRSI, but not for HRSI on-orbit repair are: low weight (because of the small area of a square meter or less to be repaired) and reusable (must survive more than one reentry). That is, an ablative material can be used for the on-orbit HRSI repair.

1: Rockwell Aerospace Space Systems Division, Florida Operations Thermal Protection system Post-Flight Reports

Some Room Temperature Vulcanizing silicones (RTVs) have several redeemable characteristics which make them amenable for HRSI application. They have relatively high resistance to heat (low thermal degradation), low thermal conductivity, elasticity, and are non-toxic. For these reasons they are used as the adhesive for HRSI and for external seals on the Orbiters. In addition, these RTVs have long shelf life as a viscous liquid, but have convenient cure times of several hours at standard temperature and pressure (STP) when mixed with the appropriate catalyst.

Early in the characterization of RTV materials it was learned that some RTVs would bubble and foam when curing in a vacuum, and hence leave voids in the cured material. The bubbling and foaming were due to short-term outgassing, particularly of ethanol and entrained air. Ethanol was present in the resin of some RTVs, and was also a by-product of some cure chemistries. Small volumes of air entrained during mixing in air would expand under vacuum to form bubbles and foam. These bubbles would tend to rise to the surface and burst under the influence of gravity. A facility was needed in order to evaluate the effects of short-term outgassing on damage site repairs in vacuum and zero net-gravity (for viscous flow). This paper describes such a facility, and the application of several candidate RTV repair materials under the environmental conditions of vacuum and zero net-gravity (for viscous flow).

## **FACILITY DESCRIPTION**

A vertical turn-table was used to provide zero net-gravity for viscous flow over the cure time of the test RTVs. That is, the integrated vector sum of the gravitational force on the repair material with respect to all points on the rotating cavity/cup is zero over one complete revolution (or many complete revolutions). If the viscosity of material in the cup is high enough that the material flows only small distances with respect to the cup dimensions during one half rotation, then the effect of gravity on the flow of this viscous material is nearly zero over one or more complete revolutions. Bubbles have buoyancy in the opposite direction of gravity. Hence bubbles will tend to move in small circles in the material. There is a small centrifugal force at the edge of the cavity/cup. For the 6 rpm turntable and a one-inch cavity the centrifugal force is approximately  $5 \times 10^{-4}$  g at the edge of the cavity.

A one meter by one meter top-loading chamber was available and amenable to modification for vacuum and zero-net gravity testing (figure 4). A one meter by one meter mockup chamber was fabricated in order to size and fit-check the apparatus to be placed in the chamber. The vacuum chamber was refitted with a new Pirani gauge and a new cold cathode gauge, and tests were run to establish the chamber's vacuum integrity and pumping characteristics. Two manual feed-through manipulators were installed on the chamber, one to provide ratcheted dispensing of test RTV repair material, and one to move the target (cavity-cup) to and from the dispenser nozzle. A photograph of these feed-through manipulators, mixing-dispenser gun, and a HRSI core (sintered micron size amorphous silica fibers) cavity-cup is shown in figure 5.

## **CANDIDATE HRSI REPAIR MATERIALS**

The silicone materials currently used in the TPS and other space applications provide a starting point for TPS HRSI on-orbit repair materials characterization. The wide use of dibutyl tin dilaurate cured phenyl methyl silicone on all STS missions evidence a general compatibility of these materials with the STS and STS operations. There have been isolated cases of materials incompatibility with TPS silicones (ref. 2). The approach for on-orbit HRSI repair has been to start with a silicone polymer material and mix (fill) in additives to enhance performance characteristics. Thus, a TPS silicone polymer, and a filled silicone polymer have been chosen as the baseline materials to compare other candidate repair materials to. Small samples are tested, and then the relevant behavior is scaled up.

Many samples of these baseline materials have been prepared and or cured under standard temperature and pressure (STP), vacuum, and zero net-gravity. These samples were used for many of

the materials characterizations listed in the introduction. Observations of the samples during preparation and curing revealed that little was understood about the short-term outgassing of these materials in vacuum. The TPS silicones are generally mixed and cured at STP, and little outgassing of ethanol or entrained air occurs at STP. However, ethanol is dissolved in the phenyl methyl silicone resin, and if the pressure around the resin drops below the vapor pressure of ethanol (40 Torr at room temperature), the ethanol comes out of solution forming bubbles. The bubbles rise under the influence of gravity and burst at the surface of the liquid resin. The outgassing of dissolved ethanol in silicone resin several centimeters deep can result in violent boiling of the resin under rapid decrease of pressure from atmosphere to a few Torr. The outgassing of ethanol can push the curing repair material out of a cavity or damage site, and can result in bubbles (voids) in the cured repair material in vacuum and zero gravity. Therefore, an understanding and characterization of the candidate repair materials in vacuum and zero gravity is essential.

The ethanol and entrained air bubbles will rise to the top of low and medium viscosity silicones and burst, leaving nearly void-free material to cure (over cure times of several hours at STP). Zero net-gravity tests at STP of medium viscosity silicones (100 to 1000 Poise) injected into a one-inch diameter cavity in HRSI core showed that the silicones cured to be void-free and with a smooth meniscus surface. That is, the surface tension of the medium viscosity silicones caused the material to be self-smoothing under zero net-gravity. A photograph of the white, medium viscosity silicone in HRSI core cured under zero net-gravity at STP is shown in figure 6. A few small bubbles are at the surface of the cured silicone. No material dripped out of the cavity during the application and curing of the silicone.

## **INITIAL VACUUM/ZERO NET-GRAVITY RESULTS**

The first vacuum/zero net-gravity test was performed September 14, 2004. The first four tests are listed in Table 1. The first test demonstrated the operability of the facility. The phenyl-methyl silicone based repair material was premixed and placed in the cartridge of a small caulking gun-like dispenser. The tin catalyst-cure liquid resin had been previously vacuum degassed, but was not degassed again after the catalyst had been mixed in. Large bubbles (air and ethanol) were observed forming and bursting in the silicone injected into the HRSI core cavity-cup. A photograph of the cured silicone in the HRSI core cavity-cup is shown in figure 7.

The second vacuum/zero net-gravity test was performed September 28, 2004. The clear, vinyl silicone based repair material was not degassed, was premixed, and hence had many small air bubbles entrained in the material. The tip of the nozzle of the dispensing gun was positioned ¼-inch into the plastic cavity-cup. The vinyl based silicone started foaming during the chamber pump-down below 100 Torr. The froth formed a cover over the top of the cavity-cup, preventing the silicone from wicking into the bottom of the rotating cup. Most of the silicone dripped out of the cup (Table 2). A photograph of the cured silicone in the cup is shown in figure 8.

The third vacuum/zero-net gravity test was performed September 29, 2004. The phenyl methyl silicone based repair material was premixed and vacuum degassed after mixing in the catalyst. Again the tip of the dispensing nozzle was inserted about ¼-inch into the cavity-cup. A few bubbles formed and burst during dispensing of the silicone into the cup. The silicone wicked into the cup, covering the floor of the cup. About half of the silicone remained in the cup and about half dripped onto the floor (and was collected in an aluminum foil pan). A photograph of the cured silicone in the cup is shown in figure 9.

The fourth vacuum/zero-net gravity test was performed October 6, 2004. The vinyl silicone based repair material was not degassed and was not premixed. That is the resin and catalyst were mixed in the mixing nozzle during the dispensing of the material into the cavity cup. The tip of the nozzle was inserted about ¾-inch into the cavity-cup. A very few bubbles formed at the tip of the nozzle at the beginning of the dispensing of the silicone, and then no bubbles were observed for the remainder of the dispensing. 3.8 gm of silicone wicked into the bottom of the cup, and formed a deep meniscus within the cup. About 6.3 gm of the silicone dripped out of the cup. The vinyl silicone is a low viscosity

material immediately after mixing. A photograph of the cured silicone in the cup is shown in figure 10.

Table 1 – Vacuum/zero-net Gravity Tests

	Date	Material	Resin degassed	Pre-mixed	Post-mixed degassed	Bubbles
1.	9-14-04	phenyl methyl Si	Y	Y	N	Y
2.	9-28-04	vinyl Si	N	Y	N	Y
3.	9-29-04	phenyl methyl Si	Y	Y	Y	Y
4.	10-6-04	vinyl Si	N	N	N	N

Table 2 – Percent of material retained in Cup

	Date	Vacuum	Mass in cup, gm	Dripped mass, gm	Percent retained in cup
1.	7-19-04	N			100
2.	9-28-04	Y	1.4	5.4	20
3.	9-29-04	Y	9.0	11.4	43
4.	10-6-04	Y	4.1	6.3	35

## CONCLUSIONS

The Vacuum/zero-net gravity facility for evaluating viscous flow candidate TPS tile repair material has been demonstrated to be operational. The facility can be operated on a daily basis. About two hours are required to install and position the sample cup and mixer/dispenser, pumpdown the chamber, and dispense viscous repair material into a sample cup.

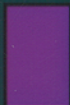


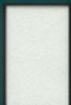

Initial test results show that short-term outgassing, either from dissolved ethanol, or from entrained air bubbles can be detrimental to application of medium viscosity TPS tile repair material in vacuum and zero gravity. There is at least one silicone chemistry that does not produce short term outgassing, and can be mixed without entraining air.

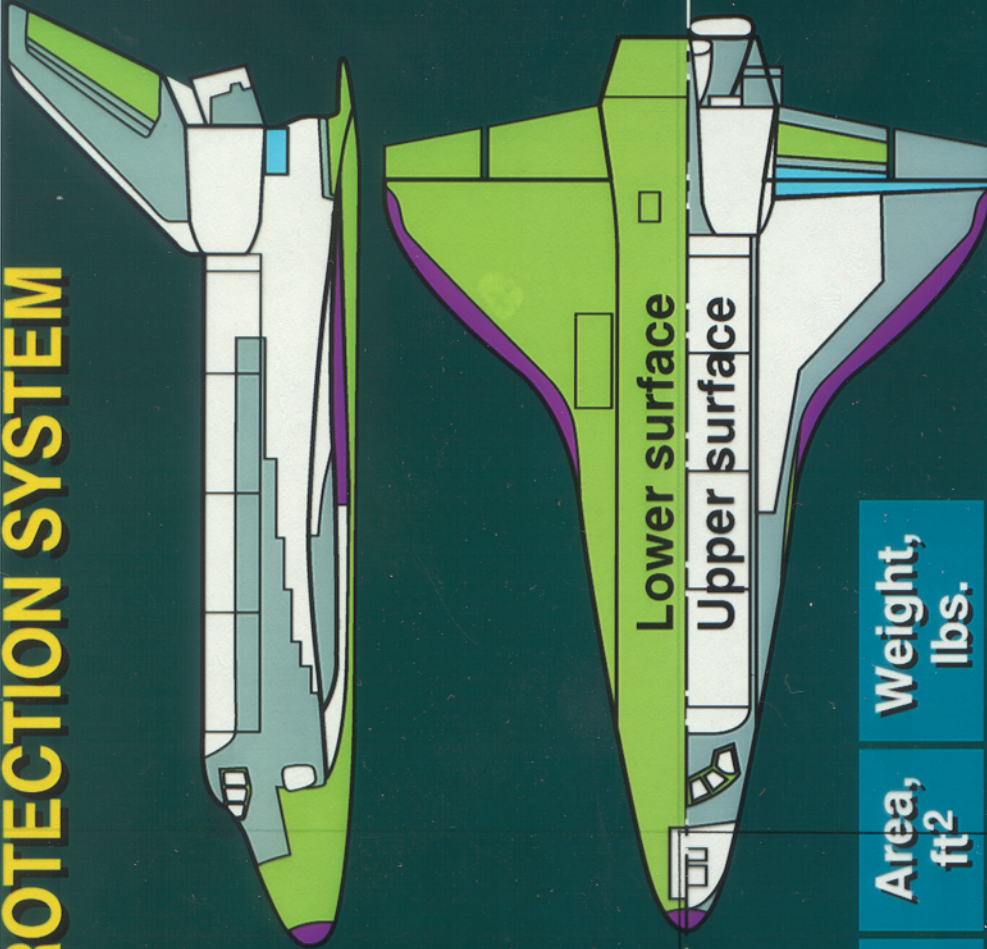
Additional work should be done to better evaluate and understand the effects of short-term outgassing and viscosity on application of TPS repair materials in vacuum and zero net gravity.

## REFERENCES

1. *Columbia Accident Investigation Board, Report Volume 1*, US Government Printing Office, August 2003.
2. Leiser, D. B., "Space Shuttle Thermal Protection System," *American Ceramic Society Bulletin*, Vol. 83, No. 8, p44, 2004.
3. Harvey, G. A., "Silizane to Silica," NASA CP 3194, pp797-810, 1993.

# THERMAL PROTECTION SYSTEM

-  Reinforced carbon carbon (RCC)
-  High temperature, reusable surface insulation (HRSI)
-  Low-temperature, reusable surface insulation (LRSI)
-  Coated Nomex felt reusable surface insulation (FRSI)
-  Metal or glass

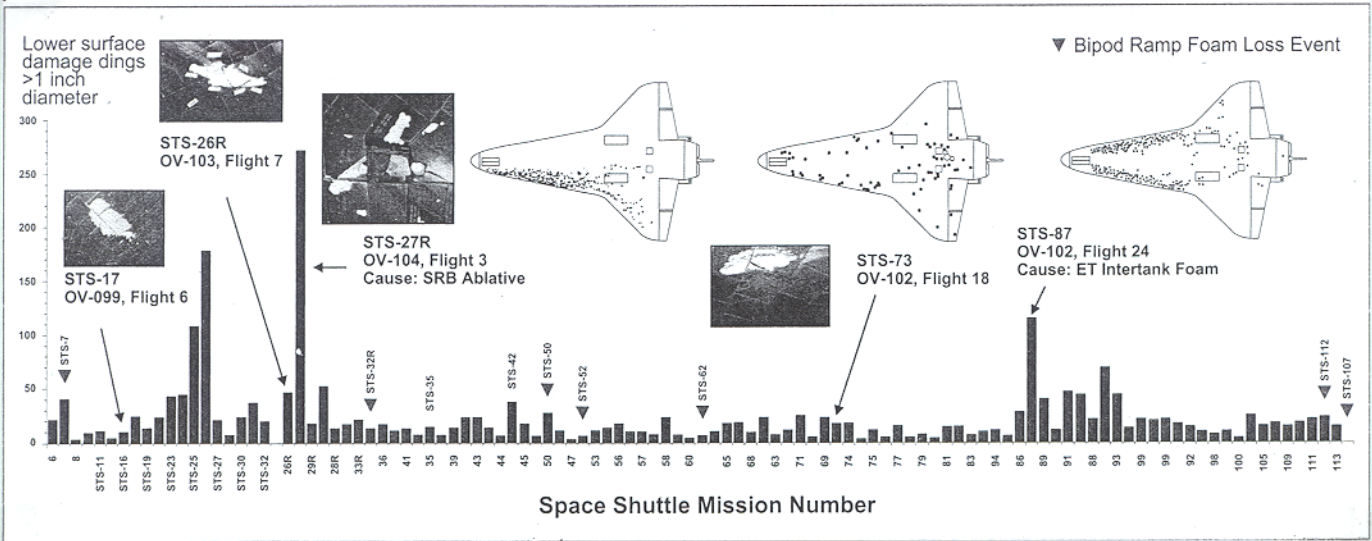


TPS (Thermal Protection System)*	Area, ft <sup>2</sup>	Weight, lbs.
FRSI	3,581	1,173
LRSI	2,741	2,236
HRSI	5,164	9,728
RCC	409	3,742
Miscellaneous	—	2,025
<b>Total</b>	<b>11,895</b>	<b>18,904</b>

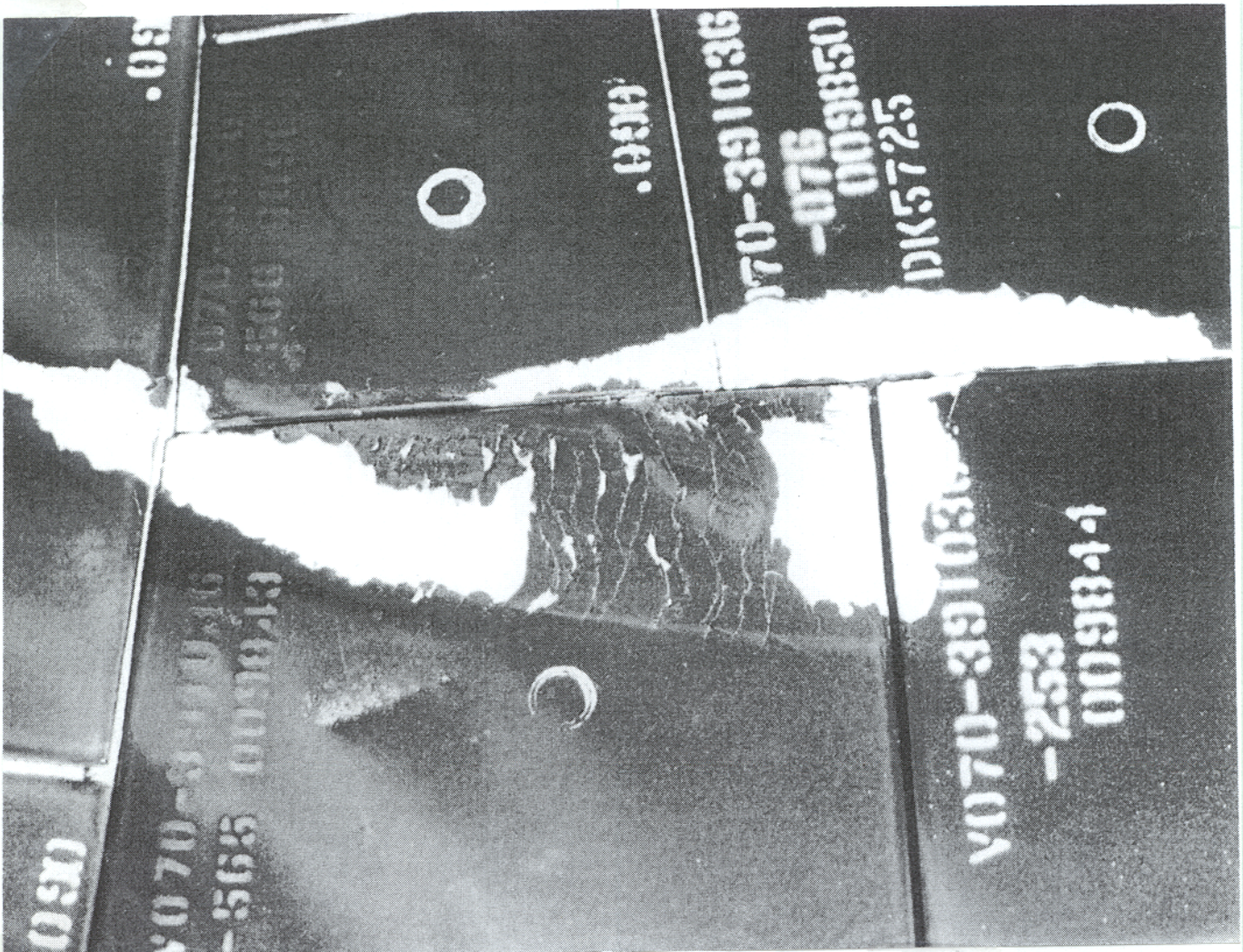
\* Includes:  
Bulk insulation,  
thermal barriers,  
and closeouts

1. Space Shuttle Orbiter Thermal Protection System.

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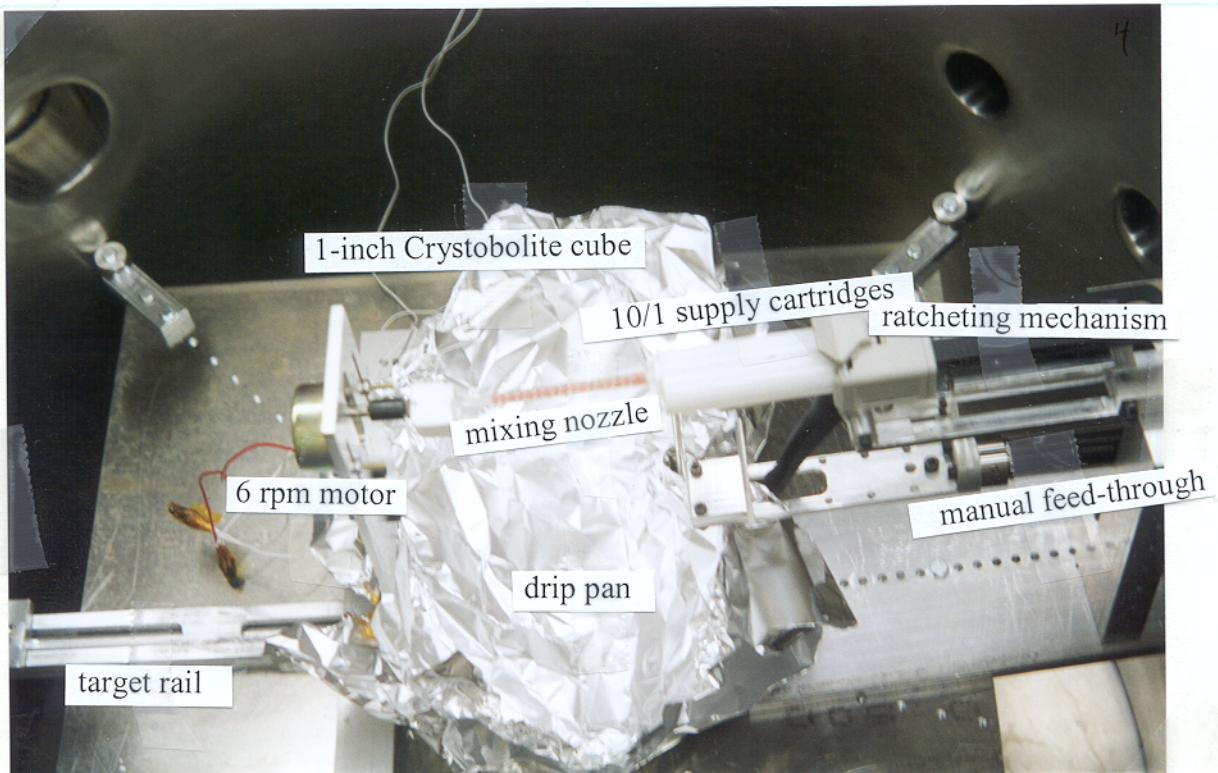
2. This chart shows the number of dings greater than one inch in diameter on the lower surface of the Orbiter after each mission from STS-6 through STS-113.



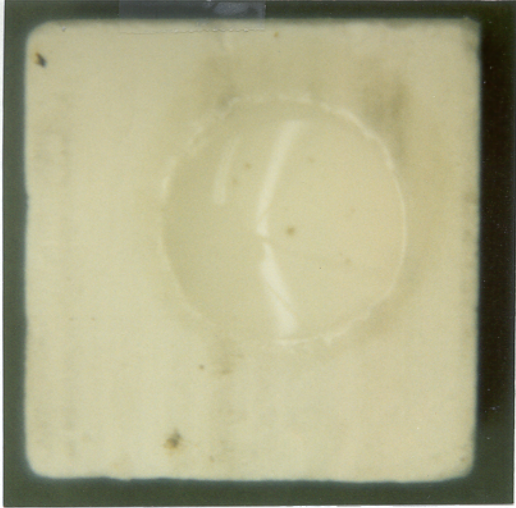
3. Impact damage in HRSI (TPS tile), right hand forward chine, STS 49.



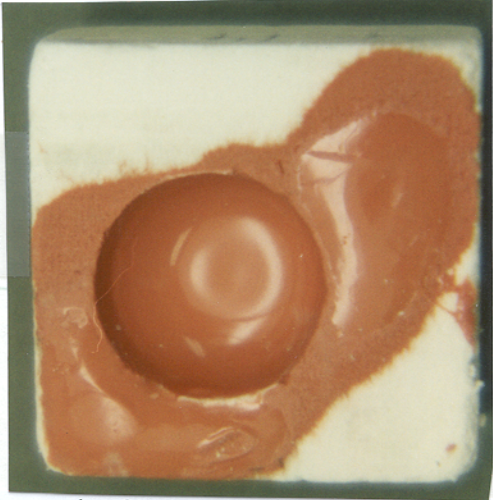
4. 1 m x 1m top loading vacuum chamber (top off).



5. Interior of 1 m x 1 m chamber with vertical turntable, manual feed-through for positioning the target, and manual feed-through for positioning the mixing-dispenser.



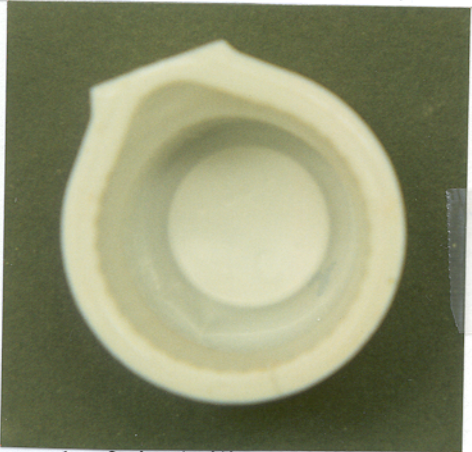
6. Photograph of phenyl methyl silicone mixed in air and dispensed in air into 1-inch pit in tile core on zero net-gravity turntable.



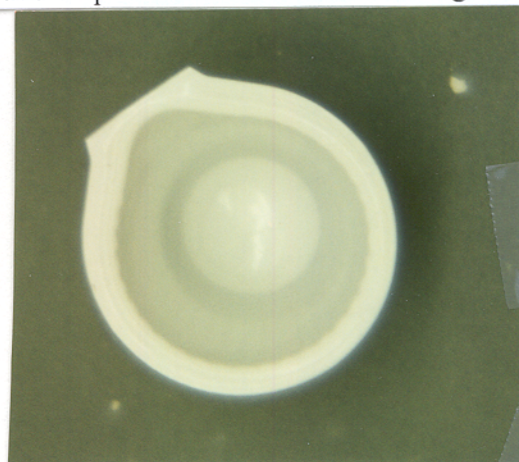
7. Photograph of color-enhanced phenyl methyl silicone mixed in air and dispensed into 1-inch pit in tile core in vacuum zero net gravity facility.



9. Photograph of color enhanced phenyl methyl silicone vacuum degassed after mixing in air and dispensed in vacuum/zero-net gravity facility.



8. Photograph of vinyl silicone mixed in air and dispensed in 1-inch cup in vacuum/zero net-gravity facility.



10. Photograph of vinyl silicone mixed and dispensed into 1-inch cup in vacuum/zero net gravity facility.

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# Vacuum/Zero Net-Gravity Application for On-Orbit TPS Tile Repair

Gale A. Harvey

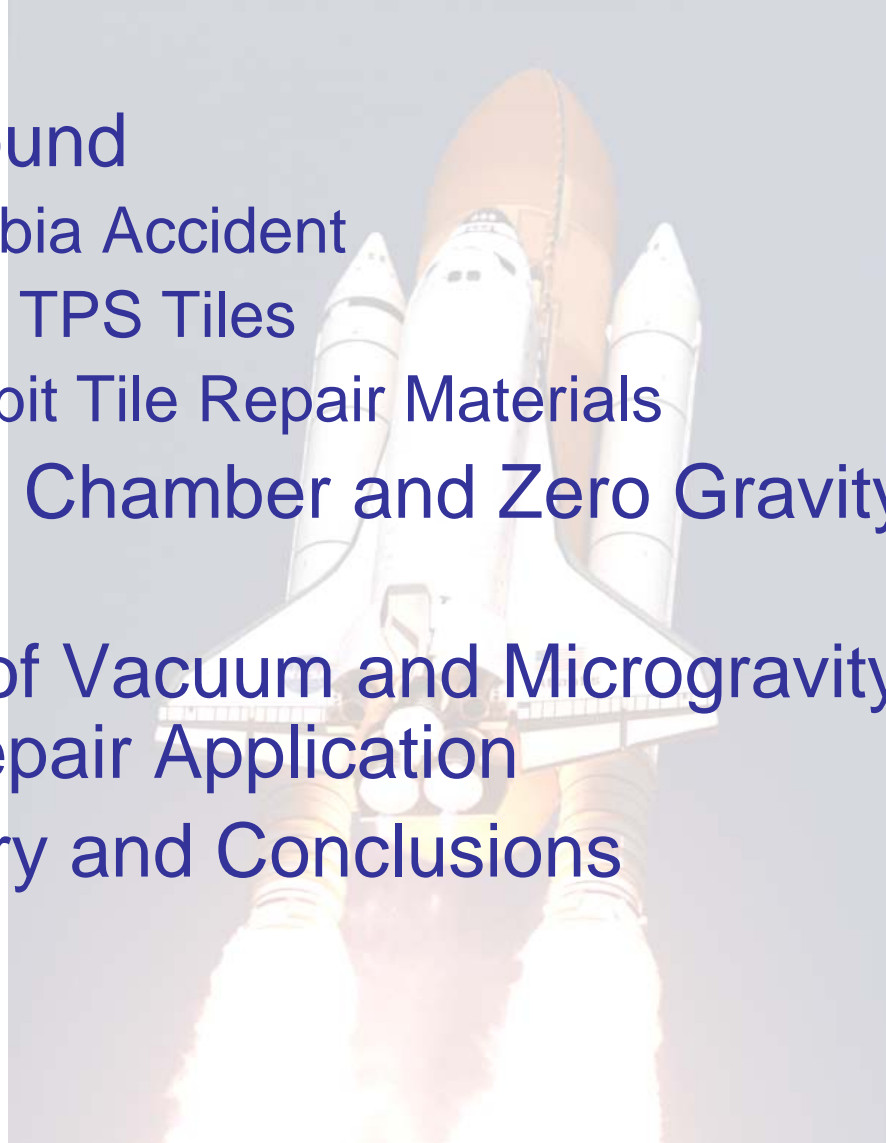
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Twenty-Third IEST-NASA/AST/AIAA/CSA  
Space Simulation Conference  
Annapolis, MD  
November 11, 2004



# Presentation Outline

- Background
  - Columbia Accident
  - Orbital TPS Tiles
  - On-Orbit Tile Repair Materials
- Vacuum Chamber and Zero Gravity Test Facility
- Effects of Vacuum and Microgravity on On-Orbit Repair Application
- Summary and Conclusions










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TIFF (LZW) decompressor  
are needed to see this picture.

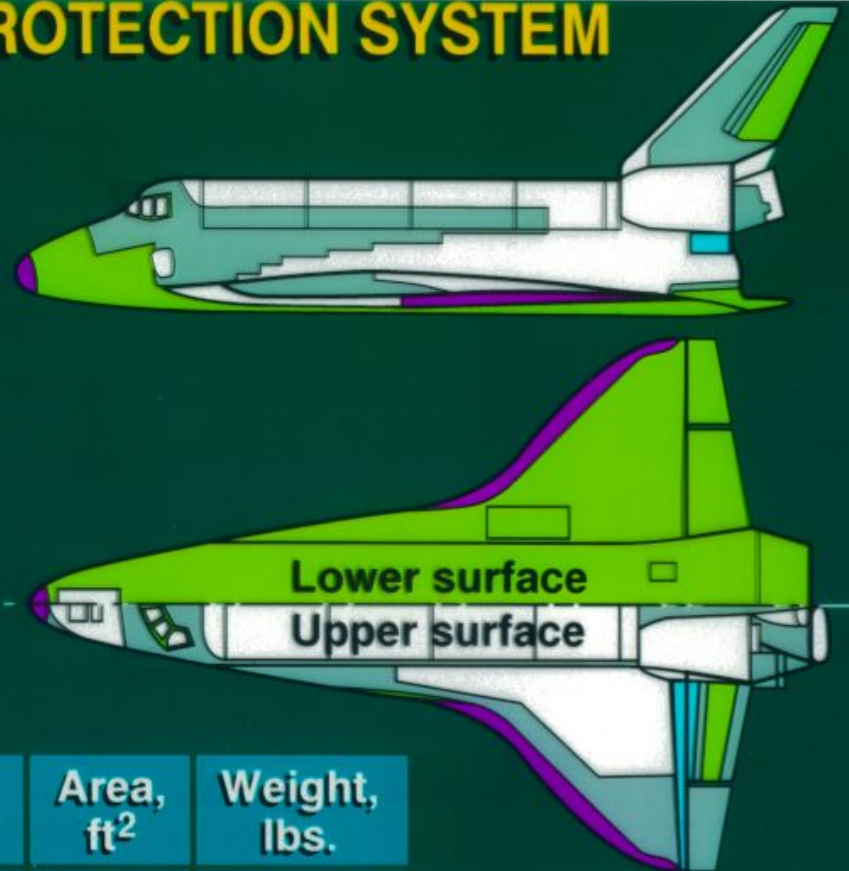
- R5.4-1 For missions to the International Space Station, develop a practicable capability to inspect and effect emergency repairs to the widest possible range of damage to the Thermal Protection System including both tile and Reinforced Carbon-Carbon, taking advantage of the additional capabilities available when near to or docked at the International Space Station.



# Orbiter TPS Tiles

## THERMAL PROTECTION SYSTEM

-  Reinforced carbon carbon (RCC)
-  High temperature, reusable surface insulation (HRSI)
-  Low-temperature, reusable surface insulation (LRSI)
-  Coated Nomex felt reusable surface insulation (FRSI)
-  Metal or glass



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<b>Total</b>	<b>11,895</b>	<b>18,904</b>

\* Includes:  
Bulk insulation,  
thermal barriers,  
and closeouts



# History of TPS Tile Damage

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TIFF (LZW) decompressor  
are needed to see this picture.

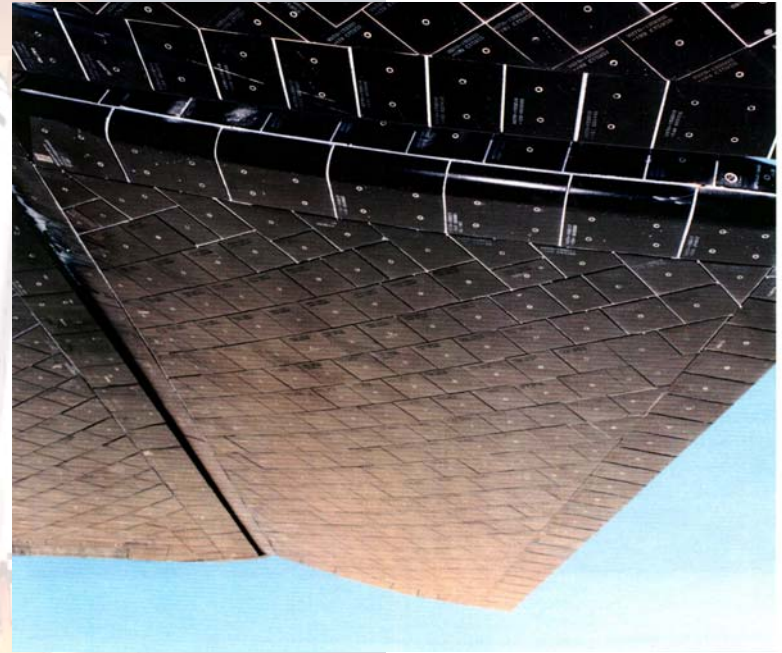




# TPS Tile Areas



Lower Surface of  
Orbiter



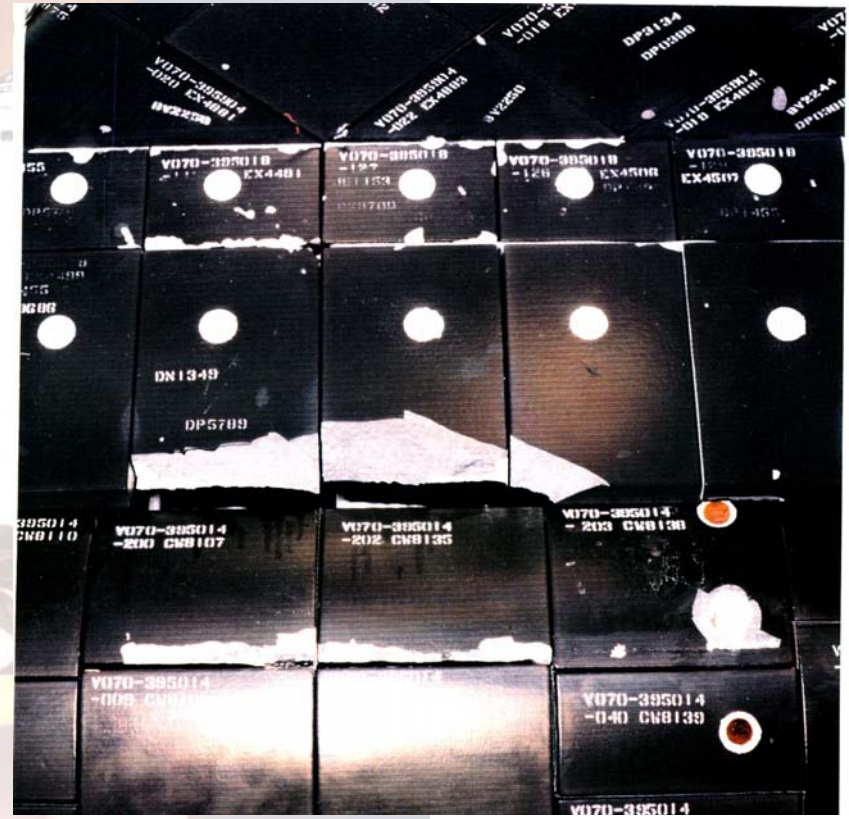
Lower Surface of  
Orbiter Wing



# TPS Tile Damage



Impact Damage



Chatter Damage



# On-Orbit Repair Application



Prior to Application  
of Reduced  
Pressure

A Few Seconds After  
Application of Reduced  
Pressure

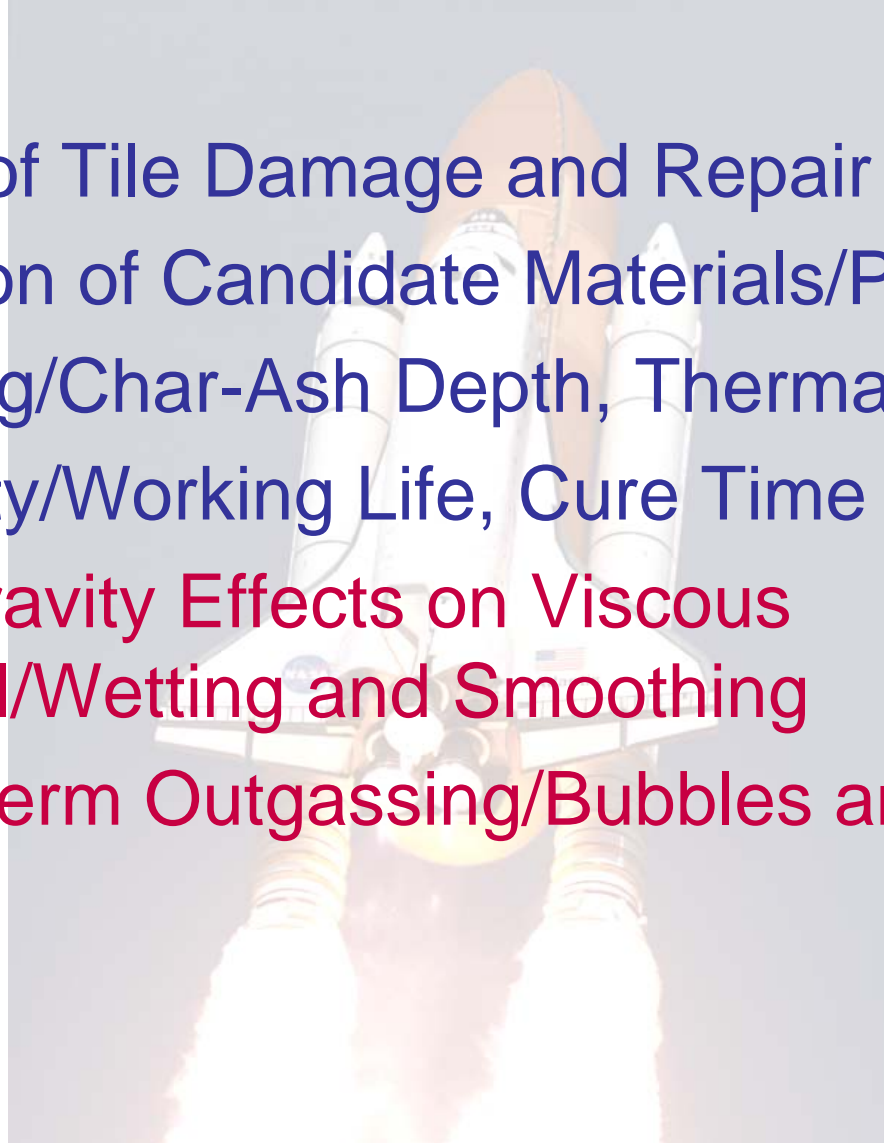






# Principal Study Areas

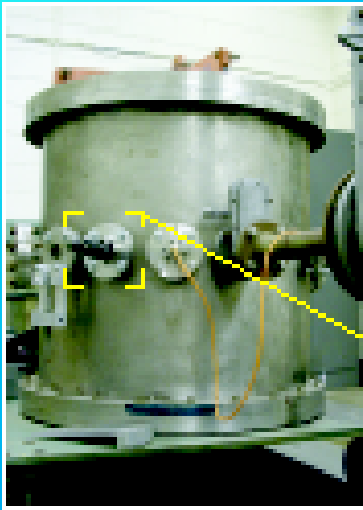
- Scope of Tile Damage and Repair
- Adhesion of Candidate Materials/Pull Tests
- Torching/Char-Ash Depth, Thermal Profiles
- Viscosity/Working Life, Cure Time
- Zero Gravity Effects on Viscous Material/Wetting and Smoothing
- Short-Term Outgassing/Bubbles and Voids





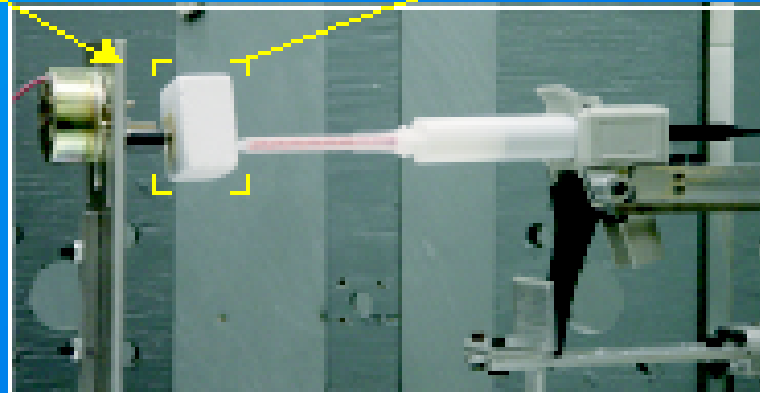
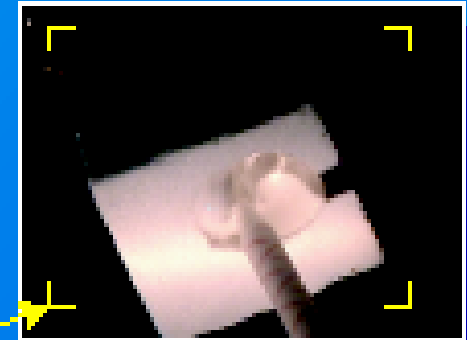


# Combined Test Facility



**Vacuum Chamber**

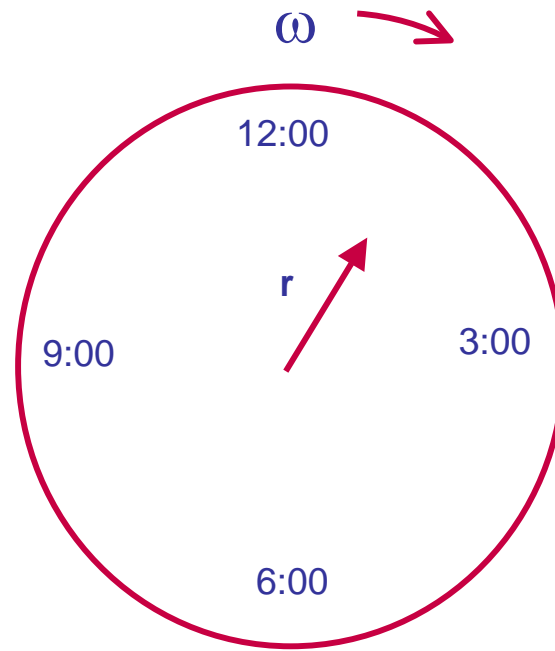
**Application of Tile  
Repair Material**



**Microgravity Jig Inside Vacuum Chamber**



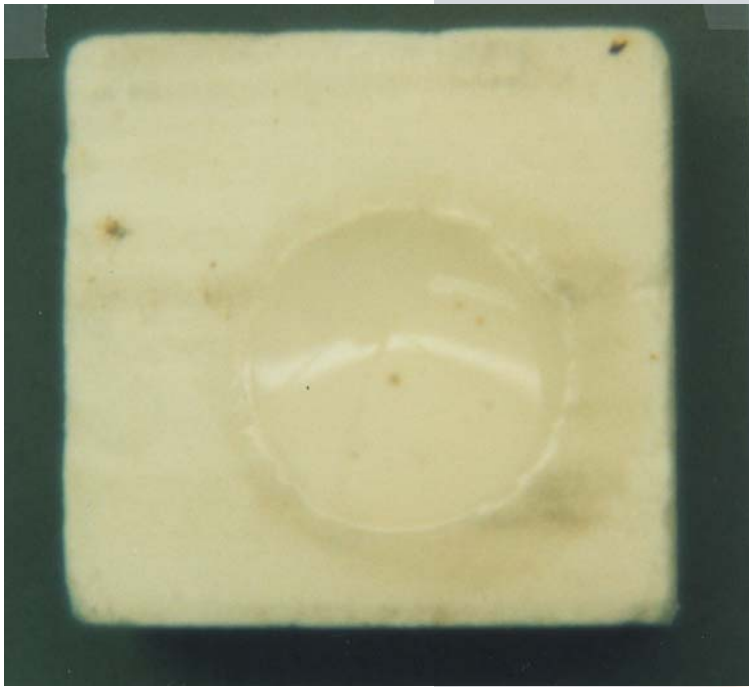
# Zero Net Gravity for Viscous Material



Centrifugal Force at 6 rpm for 1" Diameter Cavity=  $5 \times 10^{-4}$  g



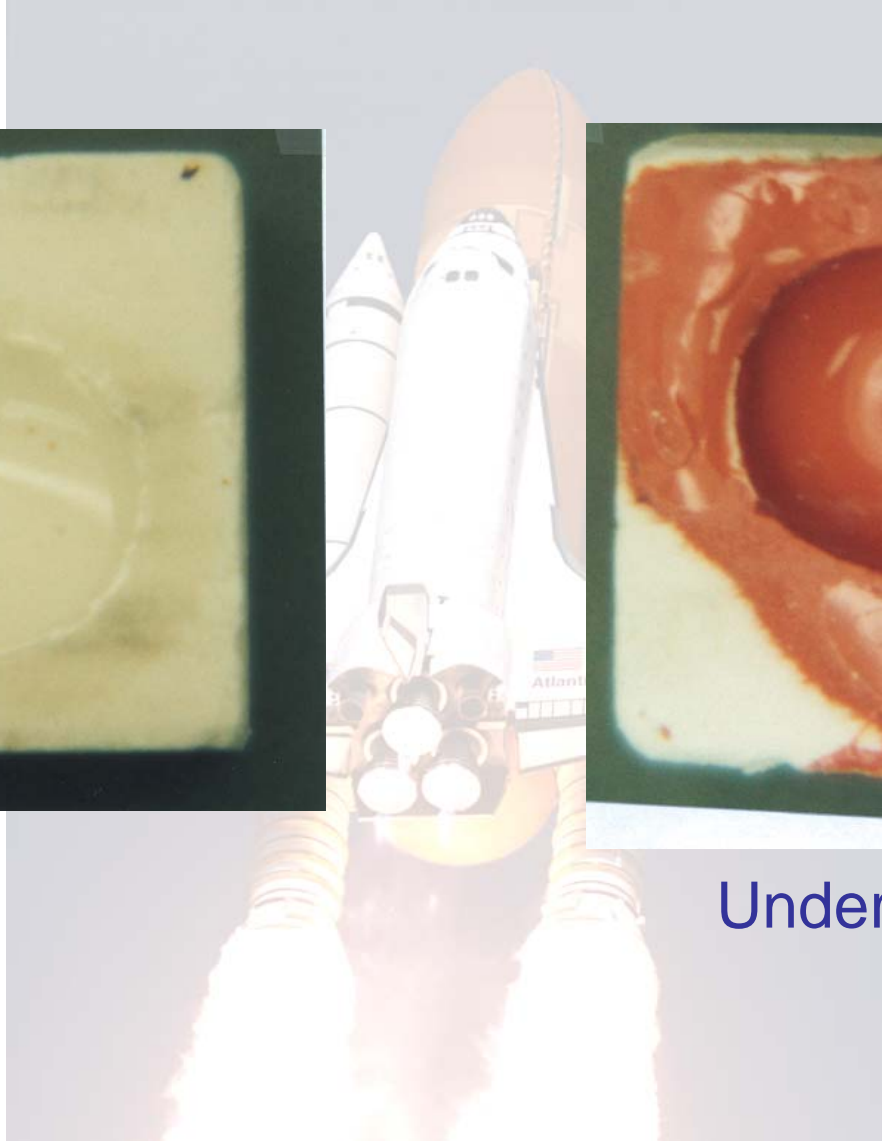
# Effect of Dispensing Environment on RTV



In Air



Under Vacuum





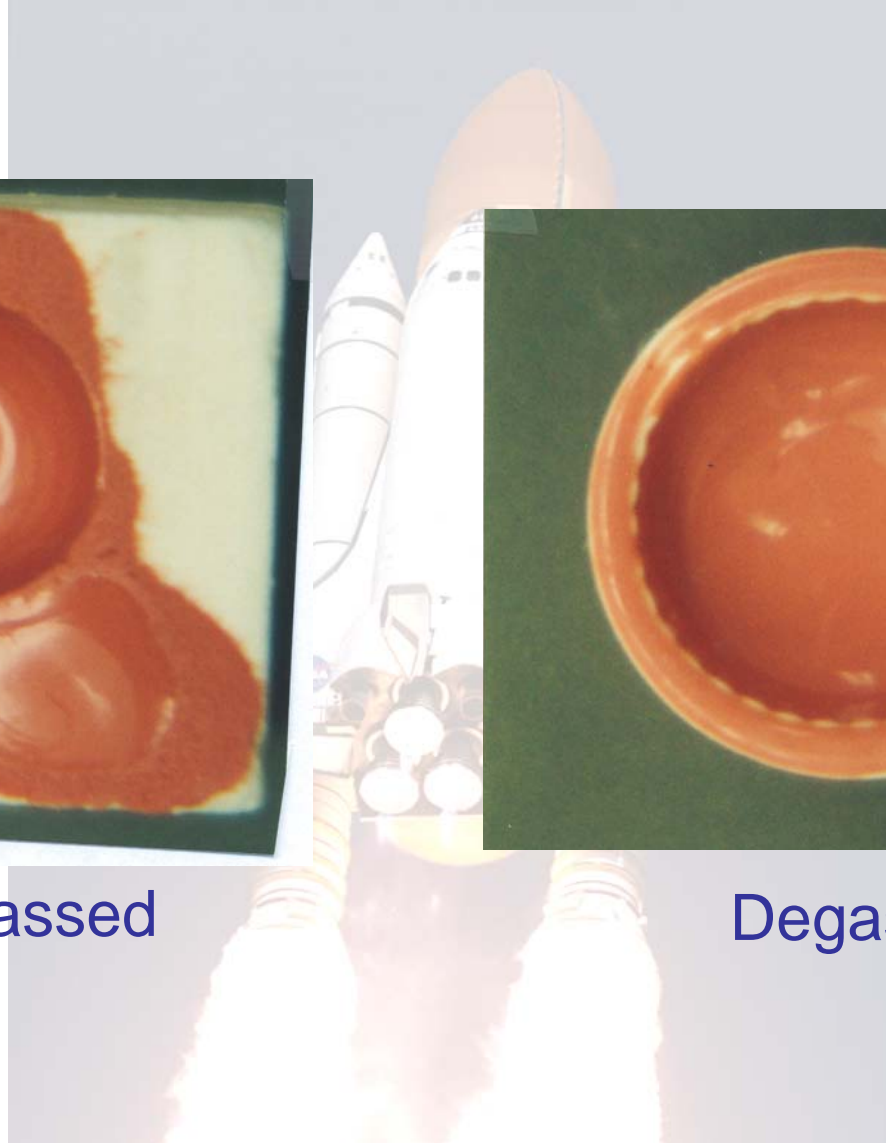
# Effect of RTV Pretreatment on Behavior Under Vacuum



Not Degassed



Degassed





# Effect of Entrained Air on Injection into Damage Cavity



Mixed in Air



Mixed in Vacuum



# Effect of RTV Pretreatment on Application

Material	Resin Degassed	Pre-Mixed	Post-Mixed Degassed	Bubbles
Phenyl Methyl Silicone	Y	Y	N	Y
Vinyl Silicone	N	Y	N	Y
Phenyl Methyl Silicone	Y	Y	Y	Y
Vinyl Silicone	N	N	N	N





# Effect of Vacuum on Application

Material	Vacuum	Mass in Cup (gm)	Dripped Mass (g)	% Retained in Cup
Phenyl Methyl Silicone	N	--	--	100
Vinyl Silicone	Y	1.4	5.4	20
Phenyl Methyl Silicone	Y	9.0	11.4	43
Vinyl Silicone	Y	4.1	6.3	35



# Summary and Conclusions

- Unique test facility at NASA Langley Research Center can simulate combined vacuum and net zero gravity effects on on-orbit tile repair application
- Short term outgassing can be detrimental to tile repair patch application
- Repair material pretreatment can mitigate application difficulties

