

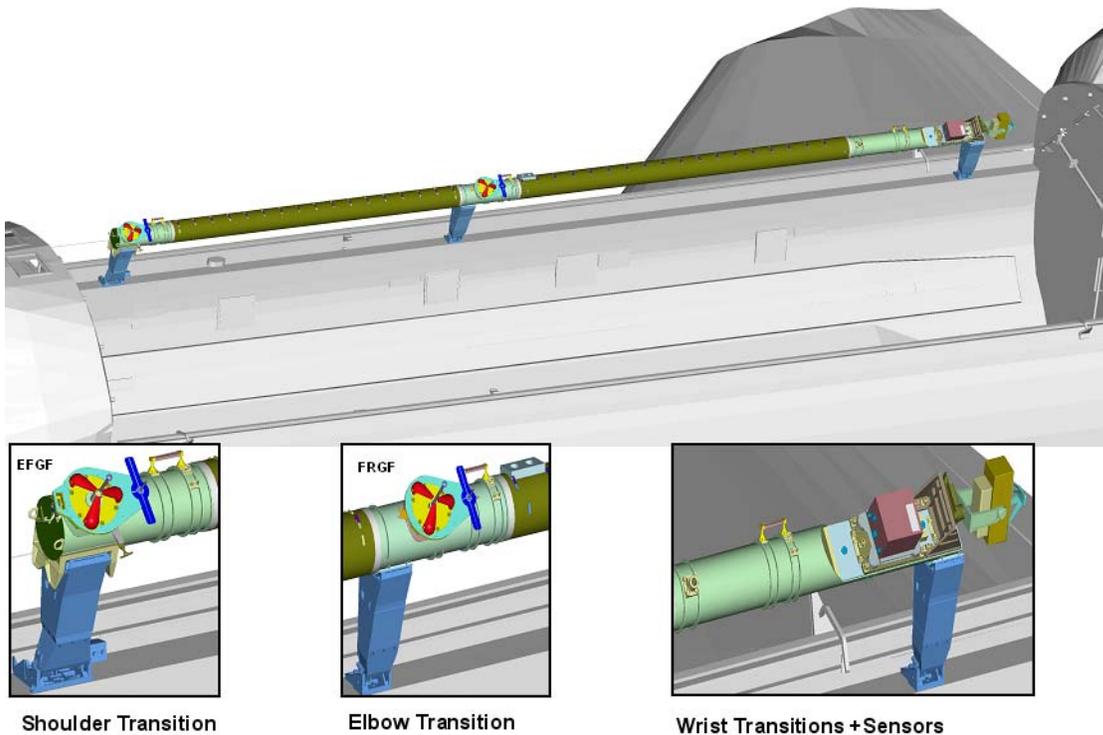
IN-FLIGHT INSPECTION AND REPAIR

In addition to improved cameras on the ground and on the Space Shuttle, Discovery's astronauts will conduct close-up, in-flight inspections with cameras, lasers, and human eyes.

The primary tool for on-orbit inspection will be a 50-foot-long Space Shuttle robotic arm extension and associated sensors, known as the Orbiter Boom and Sensor System (OBSS). While the Shuttle's remote manipulator system (SRMS) is capable of inspecting part of the thermal protection system on its own, the OBSS is needed to extend that reach to all critical areas of the Shuttle's wing leading edge and the Shuttle's belly.

The OBSS was assembled by MD Robotics of Brampton, Ontario, Canada, which

manufactures remote manipulator systems for both the Shuttle and the International Space Station. The OBSS combines two 20-foot-long graphite epoxy cylinders originally manufactured as Shuttle arm replacement parts. At one end of the boom is a modified electrical grapple fixture, and on the other end are the imagery systems. The upper and lower booms are joined by a rigid joining fixture, which has an attached modified flight releasable grapple fixture that will be used to hand the boom from the Station arm to the Shuttle arm during docked operation at the complex. Electrical and data cables run the length of the boom, providing power for the sensors while allowing imagery to be transferred through the Shuttle's wiring system to laptop computers and downlink systems in the crew cabin.



Orbiter Boom Sensor System Installed on Starboard Sill

For STS-114, the imagery systems will include a Laser Dynamic Range Imager (LDRI), a Laser Camera System (LCS) and an Intensified Television Camera (ITVC). The LDRI and ITVC are attached to the boom using a standard Pan Tilt Unit (PTU) that will allow them to be pointed at their targets. The LCS is hard-mounted to the side of the boom just behind the other two instruments.

Manufactured by Sandia National Laboratories, Albuquerque, N.M., the LDRI is comprised of an infrared (not visible to the human eye) laser illuminator and an infrared camera receiver. The LDRI can be used to provide either two- or three-dimensional video imagery data; the two-dimensional imagery may be seen by the Shuttle crew on orbit, but three-dimensional data will need to be processed on the ground after being downlinked via the Shuttle's high-bandwidth Ku antenna system that transmits the video through the Tracking and Data Relay Satellite System (TDRSS).

The ITVC is the same low-light, black-and-white television camera used in the Space Shuttle's payload bay. The two imagery systems may not be used simultaneously.

The LCS, manufactured by Neptec of Ottawa, Ontario, Canada, is a scanning laser range finder developed for use aboard the Space Shuttle. The LCS can be used as a 3D camera or to generate computer models of the scanned objects, accurate to a few millimeters at distances of up to 10 meters. Unlike the LDRI, the LCS data is not video, but instead are files collected on a dedicated laptop.

The data is processed on the ground after being downlinked through the Orbital Communications Adapter (OCA) - a high-speed computer modem that uses the Shuttle's Ku antenna system to transmit the data through the TDRSS.

During STS-114, Discovery is scheduled to rendezvous and dock with the International Space Station on Flight Day 3. As the Shuttle pursues the Station on Flight Day 2, the astronaut crew will conduct a thorough inspection of Discovery's wing leading edges and nose cone using the OBSS. Three crew members will take turns, working in pairs, to operate the Shuttle's robotic arm from the aft flight deck, unberth the OBSS from its cradles on the starboard side of the payload bay and conduct the inspection.

Since the LDRI and LCS distance to its target must remain within 10 feet to ensure image quality and because the arm and boom must not contact any of the Shuttle's surfaces in the process, the astronauts use a combination of automated and manual arm operation modes. The surveys are done using automatic mode with the astronauts monitoring its progress. The astronauts will use the manual arm operation mode to move the OBSS from the end of one sequence to the start of the next.

Mission planners expect the Flight Day 2 survey of Discovery's wing leading edges and nose cap to take about seven hours to complete, assuming a maximum scan rate of four meters per minute (2½ inches per second). The scans will be broken into 60- to 90-minute blocks, or sequences, corresponding with specific areas of the Shuttle's thermal protection skin. Engineering experts on the ground will review the data both in real time and after processing on the ground to identify any areas that need additional scrutiny.

Discovery's robotic arm is expected to be used without the boom on Flight Day 2 to conduct video inspections of the upper tile surfaces using the arm's end effector camera. The next day, during the Shuttle's rendezvous with the Station, as Discovery reaches a point 600 feet below the Station, the crew will perform a Rendezvous Pitch Maneuver, a three-quarter-foot per-second backflip, so that its underside faces the Station. The Station crew will use digital still cameras

with 400 and 800 millimeter lenses and a detailed plan to photographically map the Shuttle's underside for about 90 seconds before it continues on to docking. The images will be sent to Earth for inclusion in the collection of data that will be used by the Mission Evaluation Room (MER) and Mission Management Team (MMT) to evaluate the condition of the thermal protection system. That data will be part of the compilation of imagery to allow mission managers to make decisions on how the mission should proceed.

After docking and welcome ceremonies are complete, Shuttle and Station crew members will work together, lifting the OBSS out of the cargo bay using the Space Station Remote Manipulator System (SSRMS) and handing it to the Shuttle arm for use in additional surveys the following day. The Station arm, also known as Canadarm2, will be brought into play because the geometry of the combined Shuttle-Station configuration results in obstructions that prevent the Shuttle arm from maneuvering the OBSS out of its cargo bay cradles. The STS-114 flight plan identifies Flight Day 4 as an additional day for docked surveys, if required, using the OBSS, either to complete parts of the survey that time would not allow on Flight Day 2, or to supplement the survey with "stop-and-stare" scans of sites of potential interest. Some of Discovery's crew will reserve time for these detailed inspections for the last half of Flight Day 4 while other crew members are making preparations for the first spacewalk, which will, among other things, test thermal protection system techniques, tools and devices.

After the in-flight data, images and personal reports from the crew are relayed to the ground, engineers and imagery experts will process and integrate the information with that recorded during launch and the climb to orbit. The Space Shuttle Program's Systems Engineering and Integration Office (SE&I) will work closely with the MER to review and evaluate the information and provide separate damage assessments for

tiles and the Reinforced Carbon-Carbon panels of the wing leading edges and nose cap. Their evaluations and assessments will be presented to the MMT, which is expected to decide by Flight Day 6 whether a spacewalk is needed for an up-close, in-person inspection that could be followed by a hands-on repair.

At this writing, spacewalk designers are actively evaluating a variety of options for placing astronauts close enough to allow detailed inspection and repair of suspected thermal protection system damage. Several different challenges need to be met to enable a spacewalker to perform these tasks.

THERMAL PROTECTION SYSTEM ON-ORBIT REPAIR TECHNIQUES

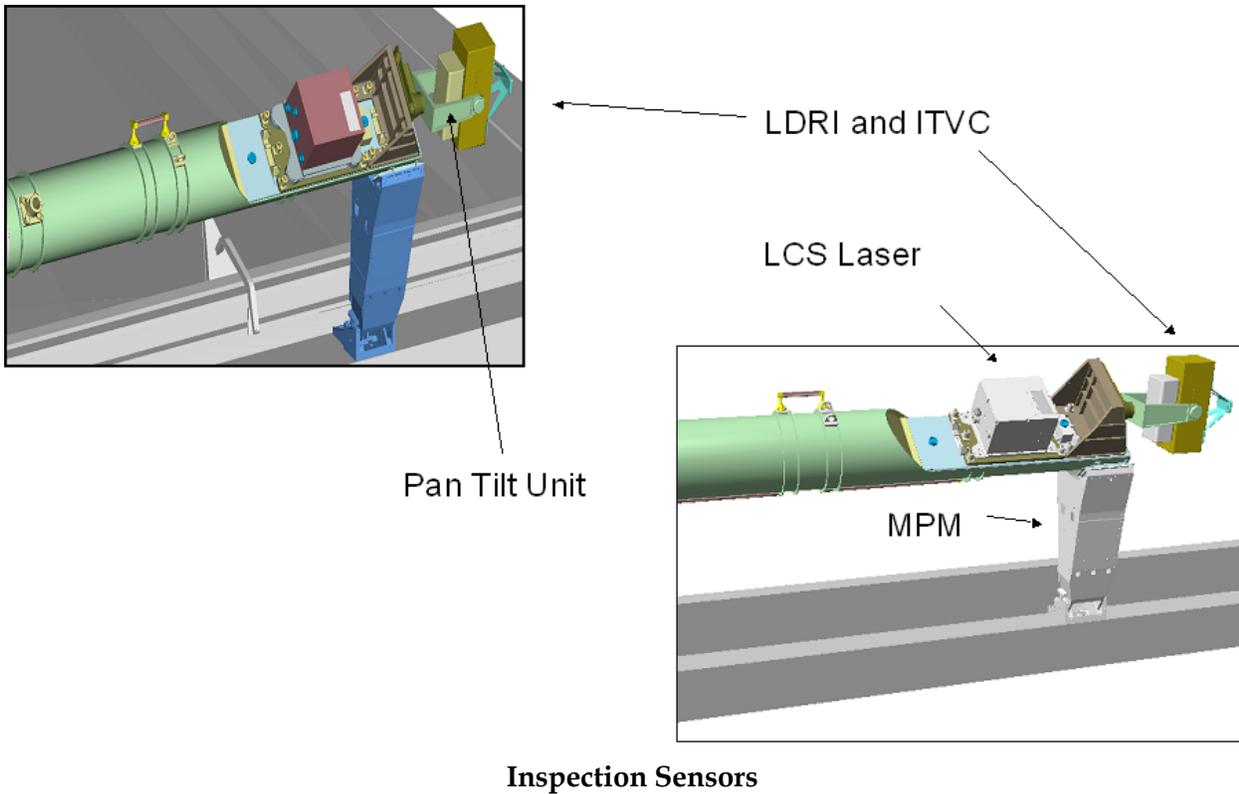
Prevention is NASA's first line of defense against damage to the Space Shuttle's TPS, which defends the vehicle and its occupants against the 3,000-degree, Mach 25 buffeting of re-entry. But quelling debris from the External Tank and Solid Rocket Boosters cannot eliminate all the threats to the Shuttle's tiles and reinforced carbon-carbon wing leading edge panels. On orbit, orbital debris (or space junk) and micrometeoroids also are capable of causing damage.

Although the STS-107 crew had no tested tools or materials available to address the type of damage inspectors have deduced was present during Columbia's re-entry, NASA lost little time in the months following the accident beginning work on viable repair strategies. A Vehicle Inspection and Repair Orbiter Flight Techniques Panel "tiger team" of experts from the TPS engineering, mission operations and extravehicular activity organizations at JSC, working in collaboration with their counterparts at other NASA centers and with contractors, made significant progress in identifying the issues that needed to be addressed, and in devising means of addressing them. The tiger team was able to define preliminary criteria for damage that must be repaired on orbit, identify all critical areas that

must be reached for inspection, identify candidate on-orbit repair materials capable of withstanding the stress of entry, and design initial tools and techniques that would allow spacewalkers to repair critical damage to both tiles and reinforced carbon-carbon segments.

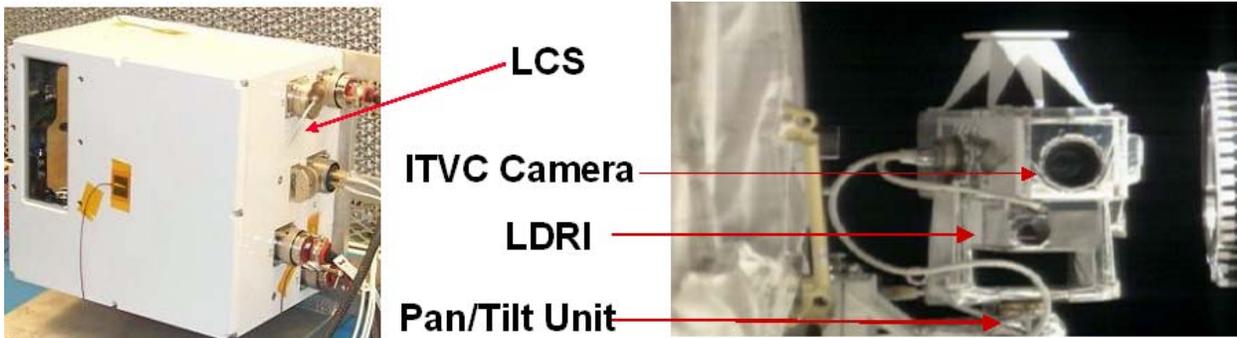
In November 2003, direct responsibility for leading these development projects was assumed by the Space Shuttle Program. The Space Shuttle Program divided and assigned this work to four separate but interactive project teams in its

Orbiter Project Office. These teams were given responsibility for managing design and development of an orbiter boom and sensor system, a set of wing leading edge sensors, a tile repair system, and an RCC repair system. The work of all these teams is ongoing, and is divided into two phases: systems that can be ready to meet the CAIB recommendations in time for the Shuttle's Return to Flight, and long-range projects that have the potential to further enhance the detection and repair needs if given more time.



The TPS repair systems developed to date fall into two basic categories, mechanical or chemical, and each type has advantages and disadvantages. Mechanical systems rely on prefabricated materials and fasteners that connect them to the Shuttles' existing protection systems. Chemical systems rely on materials that are applied in a raw form and develop a chemical adhesive bond when applied to the existing protection systems; these must cure in place before being subjected to re-entry conditions. Mechanical installation methods can be tested and validated on Earth, while chemical methods will require testing in

space to validate application techniques and material hardening. A Detailed Test Objective (DTO) for tile repair is being designed for the STS-114 mission, and will test those tile repair tools, techniques and materials that are mature enough in orbit. This DTO will use a series of task boards in the aft section of the Shuttle's cargo bay. The task boards will be returned to Earth for inspection and tests of their ability to withstand the stresses of entry. At this time, three repair methods are scheduled to be tested on STS-114 – two outside the Shuttle in the cargo bay and one inside the crew cabin.



- Neptec Laser Camera System (LCS)
- Triangulates 3D position with a small diameter scanning laser beam
- Sandia Laser Dynamic Range Imager (LDRI)
- Illuminates the FOV with modulated laser light. Images on a camera CCD are processed to provide depth information.
- Designed & flown as an integrated package with an ITVC and pan & tilt unit (PTU)

TILE

Space Shuttle Program managers recently reviewed the progress of tile repair development teams and selected three options for continued short-term evaluation.

The first is a design revived from incomplete 1970s work to develop an ablative material that could fill gaps caused by tiles that were lost or damaged during launch. Ablative materials, like those used on heat shields that protected early space vehicles in the Mercury, Gemini and Apollo programs, are meant to burn away partially during atmospheric re-entry. Engineers revived the '70s formula for a silicone-based, cure-in-place ablative material and further refined it to fill cavities in tile or to substitute for missing tiles.

The silicone-based material, now known as Shuttle Tile Ablator-54 (STA-54), is manufactured in two parts – a base material and a catalyst – and mixed together during application using a Cure-In-Place Ablative Applicator (CIPAA). This applicator system consists of an EVA backpack with tanks to separately contain the base and catalyst components under pressure, paired hoses to transport the components to the damaged area, and an applicator gun that uses a static mixer to combine the materials as they are extruded into a cavity. Astronauts apply the material – which has a consistency similar to cake frosting when dispensed -- using the CIPAA. Since the material is sticky and intended to adhere to tile, tools such as foam brushes and tampers are used to smooth the repair material without sticking. In addition, the ablative material expands when heated, so astronauts will under-fill cavities to protect against excessive expansion that could disturb the normal plasma flow across the Shuttle's tile surface. The STA-54 material cures and hardens over a period of 24 to 48 hours.

The second method is known as emittance wash application, which uses a repair material being developed primarily for shallow tile damage but also is useful as a primer to improve STA-54 adhesion to tile substrate. The silicon tiles used in the Shuttle's thermal protection system both reject heat and insulate. The white silicon substrate provides insulation, while the black reaction-cured glass (RCG) coating rejects heat. The ability of a material to reject heat is measured in terms of its "emissivity." The RCG coating on tiles has a high emissivity value, while the white substrate has a lower emissivity value, especially as temperatures rise. The science behind the emittance wash repair involves replacing a damaged tile's coating to restore its ability to reject the high temperatures of atmospheric entry.

NASA has developed and will test on STS-114 an emittance wash, which is fine-grit silicon carbide (SiC) granules mixed with a room temperature vulcanizing (RTV) material. Using a dauber-like applicator, the emittance wash can be applied to exposed tile substrate. The emittance wash wicks into the tile substrate, providing a strong adhesive bond, and a high emissivity, or heat rejection value. For small, shallow areas of damage, replacing the RCG coating with the emittance wash will restore enough heat rejection capability for safe entry. For larger or deeper gouges, the emittance wash may be used as a primer for STA-54. Its ability to wick into the tile substrate encourages a stronger bond between the tile and the STA-54 repair material, as well as protection along the edges of the repaired area when they are underfilled to allow for ablative swelling.

The third method is a mechanical repair that uses insulating blankets to fill cavities that are then covered by an overlay of carbon silicon carbonate installed using augers that penetrate directly into healthy tiles. The overlay system consists of Saffil insulation blankets, pre-packaged in a variety of shapes and sizes, which provide radiant heat

protection when installed in the cavity. A thin (0.03 inches) overlay cover made of a high-temperature resistant, flexible material such as carbon-silicon carbide -- which can hold its shape as a shield against plasma flow -- is installed over the damaged tile and insulation blanket using augers screwed directly into adjacent healthy tiles. Around the edges, between the overlay and the existing tile, a fabric gasket is used to prevent hot gasses from penetrating beneath the overlay.

The materials and tools for applying either repair system are continuing to be evaluated in laboratory tests, simulated zero-gravity tests and human-thermal vacuum tests. While tests of

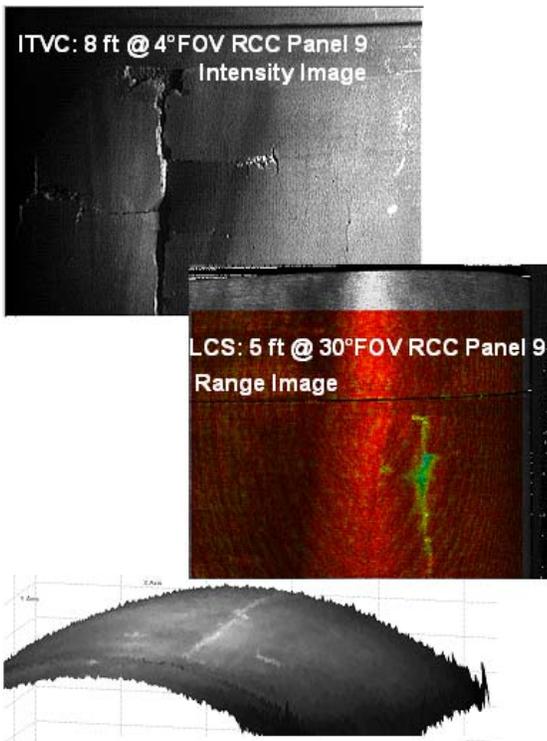
STA-54 at ambient atmospheric pressures and temperatures went as expected, the material exhibited a tendency to bubble when applied in a vacuum and temperatures approximating those of space. Materials tests are continuing to evaluate whether STA-54 can be applied in a manner that allows for relatively uniform bubble sizes and distribution throughout a given repair. Both STA-54 and the overlay system have passed preliminary tests in Arcjet facilities that can mimic the heating and dynamic pressure of atmospheric re-entry, but additional testing is continuing.



In the Orbiter Processing Facility, STS-114 Mission Specialist Charles Camarda looks closely at the tiles on Discovery. At left is Cindy Begley, lead EVA flight controller. The tiles are part of the Thermal Protection System on the orbiter.

REINFORCED CARBON-CARBON

Space Shuttle Program managers recently reviewed the progress of RCC repair development teams and selected two options for continued short-term evaluation. One option is a pre-ceramic polymer designed to repair small cracks and coating losses on the exterior of the RCC panel, while the other is mechanical in nature, designed for repairing holes that penetrate through an RCC panel.



- ITVC
- Good flexibility as a general survey tool
- Low resolution, inherent image defects
- Able to detect small defects under specific conditions
- LCS
- Provides very detailed 3-dimensional information
- Shown to operate while translating
- LDRI
- Valuable performance as both a 2D & 3D imager
- Picture shows an intensity image laid on top of range image, although it appears fuzzy to the untrained eye, it gives a wealth of data

The crack repair option uses a pre-ceramic polymer sealant impregnated with carbon-silicon carbide powder, together known as NOAX (short for Non-Oxide Adhesive eXperimental). It is designed to fix the most likely type of damage caused by small pieces of foam coming off the redesigned external tank. NOAX can be used at any RCC location, and does not require any physical modification of the RCC before affecting a repair. It is expected to repair cracks or coating losses up to .02 inches wide and 4 inches long, but cannot be used to repair holes. The repair procedure for this material may require a separate heating capability for application and/or curing. This could be accomplished by an astronaut installing an EVA heater to the damaged area of the RCC to prepare the surface for application of the repair material. A selection of hand tools similar to putty knives would be used to work the material into the crack and to smooth the surface of the repair. Early testing on the ground has shown promising results that heating the damaged area and the material may not be required to achieve the desired result.

The mechanical “plug” option consists of round, thin (0.03-inch), flexible 7-inch-diameter carbon-silicon carbide cover plates that are designed to flex up to 0.25 inch to conform to the shape of the wing leading edge RCC panels, and a hardware attachment mechanism similar to a toggle bolt, known as TZM. Twenty to 30 unique plug sizes and shapes are needed to provide coverage for all possible RCC panel damage locations. If the hole is not as large as one inch, the astronauts would use a Pistol Grip Tool (PGT) and special bit to drill out the hole. Astronauts would select the appropriate cover plate at the work site, connect the plate to a TZM bolt, and then insert the folded bolt through the hole. By tightening a fastener that extends through the cover plate to the TZM bolt, the astronaut will unfold the toggle inside the RCC panel and tighten it until the cover plate conforms to the exterior shape of the RCC



In the Orbiter Processing Facility, members of the STS-114 crew take a close look at the Reinforced Carbon-Carbon on the wing's leading edge on Discovery.

panel. After ensuring any gap between the cover plate and the RCC panel is within tolerances, the astronaut would apply a thin bead of uncured NOAX sealant around the edge of the repair as extra protection against plasma infiltration. The plug concept has the potential to repair damage up to six inches in diameter.

ACCESS

Access to damaged sites will be accomplished through a variety of means, depending on whether the Shuttle is at the International Space Station.

On Station missions, techniques are being developed that will allow robotic arm operators to undock and reposition the Shuttle for a Station-based spacewalk repair. Spacewalkers would be positioned at the work site by the Station's robotic arm using a Portable Articulating Foot Restraint (PAFR).

For non-Station missions, access may be gained through the use of the Shuttle's robotic arm or the arm and its 50-foot boom extension, or through use of the Shuttle Aid for Extravehicular Rescue (SAFER). A variety of candidate work platforms are in preliminary stages of development and continue to be evaluated.

FUTURE WORK

Several other repair concepts have been proposed for both tile and RCC repair. These include flexible adhesive patches and small area repair plugs for RCC, and hardening of the existing tile system coating. Researchers at a variety of NASA centers and contractor laboratories are continuing to develop these approaches for possible use in the next several years.