Technique	When designing robotic systems for removal and application of thermal protection materials, pay close attention to support fixture indexing, precision positioning, optimum sequencing, and protection against robotic cell environmental conditions. By integrating proven hardware and software practices with equipment and facility design and operation, the effectiveness of robotic systems is ensured.

ROBOTIC REMOVAL AND APPLICATION OF SRB THERMAL SYSTEMS

Use robotic systems to improve productivity of the launch vehicle refurbishment process

Benefits	Adherence to proven robot cell design and operational practices will result in improved consistency, speed, safety, precision, and reliability and increased cost-effectiveness of robotic systems over manual or semi-automated processes.
Key Words	Robot, robotic removal of insulation, robotic application of insulation, robot cell design, and robot operational practices.
Application Experience	Space Shuttle Solid Rocket Booster (SRB)
Technical Rationale	SRB refurbishment operations at KSC have resulted in the successful robotic insulation removal and application of 68 SRB aft skirts and other SRB elements. The facility schematic depicted in the description shows the SRB aft skirt in its most environmentally critical operation, insulation removal. This facility has been in operation for 5 years and, under routine maintenance, has been operational since its inception. Similar reliable operation has been experienced in the robotic application of insulation.
Contact Center	**Marshall Space Flight Center (MSFC)**

Robotic Removal and Application of SRB Thermal Systems
Technique OPS-3

When the SRB is recovered from the ocean, disassembled for refurbishment, and reused on subsequent Space Shuttle flights, several layers of insulating materials and protective coatings must be removed and then re-applied. Experience has shown that the use of robotic systems for insulation removal and application will improve productivity in most operations by a factor in excess of 10 to 1. Originally, the application of the SRB insulation was a semi-automatic operation. The nine ingredients (see Table 1) were measured by hand, placed in a large blender and mixer, and mixed to a uniform consistency required for spraying. This mixture was pressurized and delivered to the spray gun, which was attached to a pedestal mounted robot in the spray cell. The SRB structures were prepared by hand, i.e., sanded, cleaned, inspected, and areas masked that did not require insulation. The SRB structure was mounted on a portable turntable, which was coordinated with the operation of the robot and spray gun. Then the SRB structure and the turntable were positioned into the spray cell. A technician (with breathing air and protective equipment) was required in the spray cell during actual spraying to take thickness measurements, assist in unplugging the spray gun, and remove the wet insulation, if it did not meet specifications. The cured insulation had to meet a flatwire tensile test of 50 to 100 pounds and a toleranced thickness requirement. Adjustments were made to the delivery system and the insulation reapplied until it met specifications. Preparation of the structure for spraying and insulation required many man-hours.

Table 1. Ingredients in the SRB Insulation

1. *2215 Adhesive parts A & B**
2. *Ground Cork*
3. *Glass Ecco Spheres*
4. *Phenolic Micro Balloons*
5. *Chopped Glass Fibers 1/4 inch long*
6. *Milled Glass Fibers 1/8 inch long*
7. *Bentone 27*
8. *Ethyl Alcohol*
9. *Methylene Chloride/per Chloroethylene*

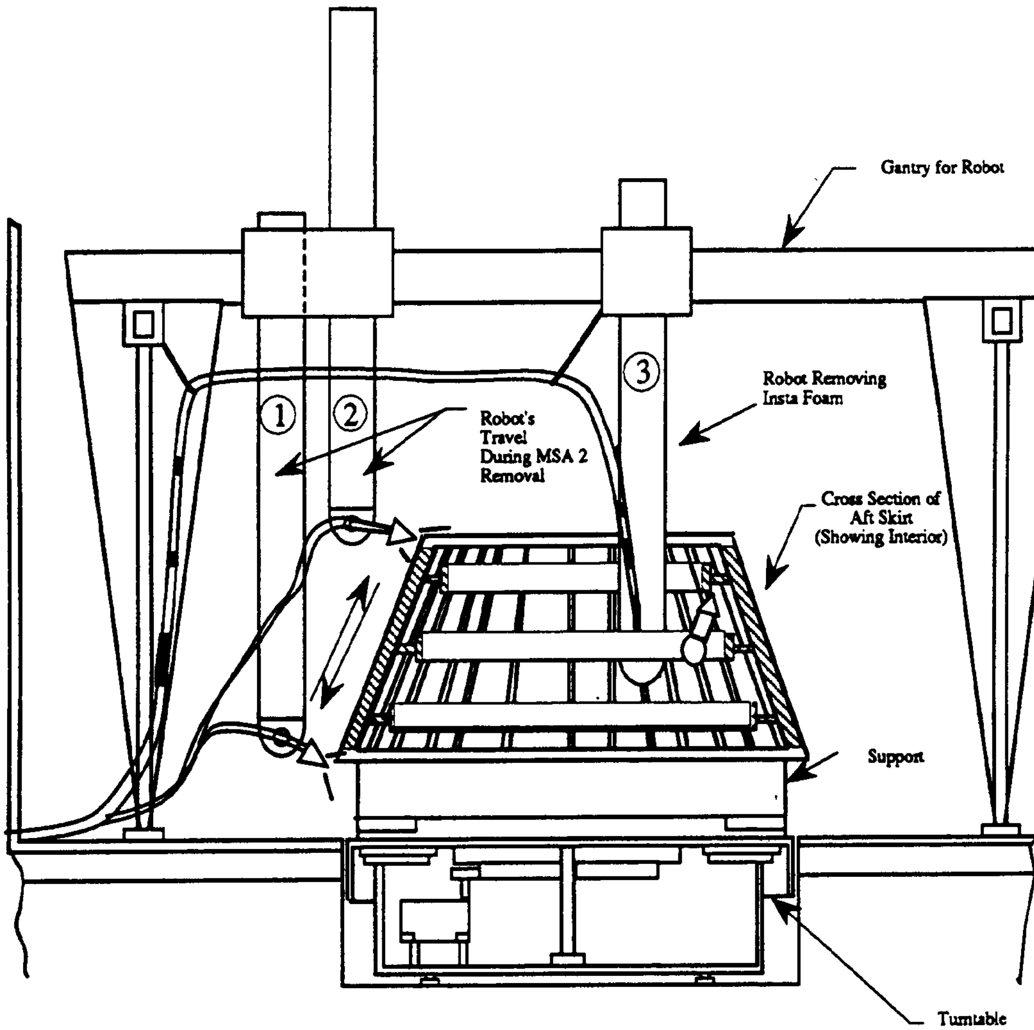
* *The original adhesive that contained shell z Catalyst was a carcinogenic*

After automating and robotizing the application of the insulation, the insulation ingredients are automatically measured, blended, mixed, pressurized and delivered to the spray gun, which is mounted on a gantry robot. The gantry robot allows spraying inside the structures without the need to rotate the structure for access. The robot is programmed to automatically attach an end-effector to perform the following operations: sanding, cleaning, inspection, masking, spraying, and thickness measurements. Automating and robotizing the application of insulation eliminated the need for a technician in the spray cell and eliminated many of man-hours of hand work.

At the start of the SRB refurbishment program, the insulation was removed manually. This required a technician to manually hold a hydrolaser pressurized to 8,000 to 10,000 psi. This created a backwash of 72 pounds force that the technician had to overcome using two 2-men crews rotated every 15 minutes. Any insulation left after this operation was removed by hand using nonmetallic chisels and mallets. Manual removal of the insulation from the two aft skirts required approximately 400 man-hours.

Procedures for Robotic Removal

Robotizing the removal of the insulation reduced the man-hours for two aft skirts to approximately 64 man-hours. The hydrolaser is mounted on a gantry robot which is located in the removal cell. The pressure to the hydrolaser has been increased to 12,000 to 15,000 psi. Technicians have been eliminated



① Robot Arm Position for External Insulation Removal (MSA-2)
② Robot Arm Position for External Insulation Removal (MSA-2)
③ Robot Arm Position for Internal Insulation Removal (Insta-Foam)

Figure 1. Example Robot Facility: SRB Insulation Removal

from the hazardous environment. The robot is controlled by computer. A turntable (also controlled by computers) is mounted flush with the floor. After removal of the insulation, the robot is programmed to clean the hydrolaser cell.

Table 2 lists typical reasons for using automated robot cell to apply and remove SRB insulation. Table 3 is a list of the 13 best practices in the design of robotic systems for removal and application of insulation. The most predominant consideration was the high pressure water spray and debris environment encountered in the hydrolaser insulation removal process. Operational maintenance, as well as design, is important in maintaining a safe and efficient operation. Potable water is used to reduce corrosion in the pumps, valves, and lines. The use of de-ionized water should be considered in areas where the water has a high mineral content. Since the water used in the insulation removal process is recycled, the water must be filtered prior to reuse to prevent erosion and corrosion of pumping and spray equipment.

Table 2. Typical Reasons for Using Robots

1. ***Man out-of-the-loop for hazardous and toxic environments.***
2. ***Efficient; robot does not get tired.***
3. ***Will do whatever it is programmed to do and will do it repeatedly.***
4. ***Will handle various end effectors for sanding, cleaning, inspection, spraying, and thickness measurements.***

For the SRB insulation system removal, the water is filtered to contain particles no greater than 5 microns. On a quarterly basis, or every 100 operating hours, high pressure water pumps are inspected and overhauled if necessary to repair or replace the pump head, pistons, or brass sleeves. Preventive maintenance is performed regularly.

Table 3. Best Practices for Robotic Systems

1. ***Gear Specifications to the environment and the application (i.e., adaption to a solvent or water spray and debris-laden environment).***
2. ***Pay close attention to the ergonomics for operators (i.e., convenience of controls, visibility, manual override, and teaching procedures).***
3. ***Provide sufficient space in robotic facilities for support equipment, mechanisms, personnel, and operational control stations.***
4. ***Design-in automated shutdown to be activated in the event of excessive flow, pressures, temperatures, or inadvertent ingress of personnel.***
5. ***Consider the use of vision systems for alignment, completion status, inspection, and thickness measurements.***
6. ***Provide overload sensing and tactile feedback for delicate operations.***
7. ***Retain manual capability for emergency and backup operations.***
8. ***Establish precise automatic indexing of fixtures with workpiece and robot to minimize setup time.***
9. ***Provide electrical grounding of all system elements.***
10. ***Purchase over-rated equipment. Use only 75% or less of the capacity in the initial design to provide growth potential and operational/maintenance margins.***
11. ***Protect robot elements from solvents in the environment to ensure continued robot lubrication.***
12. ***Train and use dedicated personnel for robotic operations.***
13. ***Establish preventive maintenance requirements during the design phase based on designed-in ease of maintenance features (i.e., proper panel access, calibration test ports, equipment clearances, etc.).***

Facility Requirements

A robotic facility of the type used for SRB insulation removal and application must allow operator visibility of the process and careful design for personnel safety and access provisions. During the noisy removal process, personnel within a 50 ft. radius are required to wear ear protection. Operators entering the area during or immediately after spray operations are required to wear protective suits with self-contained breathing apparatus to prevent inhalation or contact with toxic fumes.

Facility design must be carefully coordinated with robot design and robotic operations planning. A concurrent engineering approach is desirable in the design of robotic systems to ensure use of the correct robot, operating in an optimally designed facility, for the target application. A team of engineers and technicians representing all applicable disciplines should be assigned full time to the project throughout design and operations. Three levels of drawings of the robot/facility complex representing: (1) components, (2) subsystems, and (3) the integrated system should proceed through 30, 60, and 90 percent design reviews. Three-dimensional solid modeling simulations using computer-aided design techniques will dramatically speed up the design process. (See the MSFC Guideline titled, “Concurrent Engineering Guideline for Aerospace Systems,” in NASA TM 4322, "NASA Preferred Reliability Practices for Design and Test"). The facility must contain support equipment, pumping systems, material storage, control stations, and personnel dressing and clean-up.

Particular attention should be paid to debris handling. Sloped concrete subfloors provide for easy debris collection and clean-up. Automated cell clean-up techniques should be considered for material removal operations.

Special Design Considerations

Robotic systems lend themselves to the effective application of automated emergency shutdown, automatic end-effector changeout, overload sensing, tactile feedback, and manual override. These features should be designed into the robotic system at the outset with participation of the robot vendor. Setup time can be minimized by providing pre-engineered or automatic indexing and relative positioning between the work piece, support tooling or equipment, and robot. While mechanical systems should be over-designed for extra margins of safety against wear and malfunctions, care should be taken not to grossly overdesign control system memory, particularly if a bubble memory is used. This could result in slower robot control system operation.

References

1. Rice, Robert: *Process Report on the Automated Hydro Removal of TPS,* Report # USB-ATG-003, USBI Booster Production Company, Inc., NASA/MSFC contract # NAS8-36300, January 1986.

2. Loshe, Thomas: *Hydrolyzing Operations in High Pressure Wash Facilities*, Maintenance Manual # B8598, USBI Document Prepared for Kennedy Space Center, October 4, 1991.

3. Loshe, Thomas: *Solid Rocket Booster Thermal Protection Removal System Software Users Guide*, Document # 10MNL-0044, United Technologies, USBI, April 2, 1990.

4. Babai, Majid: *Robot Simulation and Manufacturing,* Aerospace Engineering, SAE, October 1992, pp 11-13.

5. Fertig, Alan R. and Tony S. Humble: *Robots Refurbish Space Shuttle Hardware*, TABES Conference Proceedings, Huntsville Association of Technical Societies (HATS), Huntsville, AL, 1987.

6. Special Government Publications:

MM B8601, *Preventive Maintenance Gantry Robot and Controller*

MM B8604, *Preventive Maintenance/ Validation Robot End Effectors*

MM B8611, *SRB Insulation Manufacturing Manual (Forward Assembly)*

MM B8616, *SRB Aft Skirt Assembly-MSA-2 TPS Operations Manual*

MM B8630, *MSA-2 Tunnel Cover Assembly Operations Manual STP 513, Cleaning Sprayable MSA-2 Insulation Spray*

STP 621, *MSA Control Room Operation*

STP 622, *Installation and Removal of Robot End Effector Adapters*

STP 634, *Sprayable MSA-2 Insulation Control Room and Mix Operations*

TP 741, *MSA-2 Spray System Preparation - ARF*

SESP (Safety Engineering Standard Procedure) 23405, *Safety Requirements for Robot Systems*