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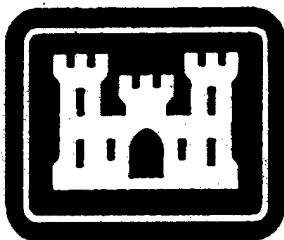# RESEARCH (CPAR) PROGRAM

Automated Thermal Spray Technology for Rehabilitation and Maintenance of Civil Works Infrastructure

by

Raphael Benary, Robert Ganertz, Herbert Herman, and Vincent F. Hock

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Lead-based paint is no longer used in the field, but repair crews, nearby communities, and the environment may be exposed to unacceptable levels of lead as older steel structures are abrasive-blasted before repainting. Onsite dust-containment enclosures used during surface preparation are either inadequate or expensive and cumbersome. Lead exposure problems may be mitigated by the application of long-lasting metal coatings, effectively reducing the frequency of the blast/recoat maintenance cycle. Automated technologies can address containment and metallizing needs while offering higher speed and lower labor costs. They also can protect workers from excessive physical strain, safety hazards, and exposure to toxic materials released during paint removal.

This report documents the design, construction, and field testing of a prototype Automated Thermal Spray System (ATSS) for surface preparation and coating of large steel public works structures. Using self-contained vacuum-blasting technology, a video inspection system, and a thermal spray system, the remotely operated device was able to remove lead-based paint from part of a steel bridge and recoat the metal with a zinc/aluminum coating. Initial indications are that ATSS base operating cost of $5.20 per square foot, for blasting and recoating combined, would be lower than the cost of blasting alone with environmental containment.

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1 Introduction

Background

It is well known that the condition of the United States transportation infrastructure has an important impact on the economy's ability to sustain itself and grow—and that it directly affects the nation's military defense and mobilization capabilities. Much of the U.S. transportation infrastructure has been in continuous service for more than half a century, however, and it is inherently subjected to a diversity of stresses that seriously erode and corrode structural steel and concrete reinforcement bars. Structures such as bridges are continually exposed to

- dry, marine, and industrial environments
- attack from deicing salts and other chemicals in the environment
- static and dynamic mechanical loading.

Among the nation's current inventory of 550,000 bridges, 28,000 are major steel truss bridges. The National Steel Bridge Inventory Service (NSBIS) currently lists 173 structurally deficient and another 141 functionally obsolete bridges with spans in excess of 100 m (300 feet). Estimated replacement costs for these 300-plus bridges tops $9.4 billion (Olsson and Bandel 1992).

Conventional corrosion protection of steel structures has usually involved the application and reapplication of lead-based paint (LBP), a material now known to be highly toxic and likely to find its way into the environment. LBP is no longer used in the field, but repair crews, nearby communities, and the environment may be exposed to unacceptably high levels of lead as the substrates of older structures are prepared for repainting during routine maintenance and repair (M&R) operations. Conventional dust-containment enclosures used onsite during surface preparation (abrasive blasting) are often inadequate. The most effective containment technologies, on the other hand, tend to be expensive and cumbersome. All of these factors make surface preparation and recoating slow, technically difficult, physically demanding, and hazardous to the worker and the environment.

Automated technologies have the potential to address all aspects of these interrelated infrastructure M&R problems. They can introduce new economies to many

kinds of projects, both by working faster and requiring fewer labor resources. They also can spare workers from the heaviest physical demands and safety hazards of such work. Furthermore, automated technologies offer great potential for limiting the worker's exposure to toxic chemicals or heavy metals released during paint removal operations.

Another M&R consideration can help to address the problems outlined above: longer-lasting coatings. Durable metal coatings can lengthen the amount of time between repainting cycles, which reduces resource input as well as the frequency with which blast wastes are produced. Thermal spraying is a well documented means for applying active metal corrosion protection to steel and steel-reinforced concrete, and is used frequently in Australia, Europe, North America, and Scandinavia (Morrow 1987; Manning 1990). In the United States, several state transportation authorities (e.g., California, Florida, Maryland, Ohio, Oregon, Virginia) have implemented or field tested thermal spraying for corrosion protection of steel and steel-reinforced concrete bridges (Carello, Parks, and Apostolos 1989; Birch 1986). There is a strong view among a number of transportation departments that automation will enhance the ease of application and economics of thermal spraying. Automation has been implemented in the thermal spray industry to provide greater process control, provide reproducible coatings, increase final coating quality, reduce costs, and increase the speed of fabrication. Commercially available spray cells integrate positioning systems together with spray equipment and surface preparation systems (Munjone and Irons 1993). Automation has been introduced into the field of infrastructure M&R to obtain the same benefits that other industries have realized. For example, the California Department of Transportation (CALTRANS) has developed and used an automated two-axis system for thermal spraying of zinc onto bridges (Apostolos, Parks, and Carello 1987). In Japan, construction corporations (e.g., Shimizu, Kajima Corp.) use robots to spray construction materials and inspect surfaces (Oppenheim and Skibniewski 1988). Articulated robots have been used for grit blasting bridges (*JPCL*, October 1990), and visual inspection equipment is used to inspect bridge undersides (*Olympus Industrial* 1992). While such examples demonstrate a gradual acceptance of automation in infrastructure M&R, there is no comprehensive technology available that integrates surface preparation, visual inspection, positioning, and surface coating equipment into one automated system.

Despite demonstrated successes in the field, many maintenance contractors tend to avoid using automated systems because of their high out-of-pocket cost, vulnerability to breakdown, and the high training requirements for equipment operators. These reasons are readily understandable, but they do not negate the growing need to automate infrastructure maintenance. Infrastructure maintenance

involves an abundance of relatively flat surfaces located in hard-to-reach places that are potentially dangerous to workers—a simple, reliable automated unit would therefore be a welcome alternative. Such a system would have to be transportable, easy to maintain and operate, and rugged enough for hard use in the field. It's purpose would be to work alongside a human crew, handling areas where repetitive motion is required while leaving intricate or complex work to maintenance personnel.

The U.S. Army Corps of Engineers is the proponent of Construction Productivity Advancement Research (CPAR), a research and development (R&D) program that leverages the resources of Corps laboratories, private industry, U.S. research universities, and appropriate government authorities to address construction productivity problems of national scope. Through CPAR, the U.S. Army Construction Engineering Research Laboratories (USACERL) entered into a CPAR Cooperative Research and Development Agreement (CPAR-CRDA) with the State University of New York at Stony Brook to design, construct, evaluate, and commercialize a prototype Automated Thermal Spray System (ATSS) for surface preparation and coating of large public works structures.

Objective

The objective of this CPAR project was to develop, demonstrate, and transfer to the technical coatings industry an automated thermal spray technology for field applications to civil works infrastructure. The CPAR-CRDA specified that the technology will:

- be capable of applying engineered abrasives for surface preparation of steel structures
- include thermal spray technology capable of spraying corrosion- and erosion-resistant metallic coatings onto blast-cleaned steel surfaces
- include a triaxial linear actuator system
- positional feedback sensors with a comparator for calculating positional error
- include a visual inspection system for remote monitoring.

The objective also included a requirement to prepare draft material and equipment specifications for consideration as industry standards.

Approach

This R&D project was divided into seven tasks:

1. laboratory evaluation (including bond strength evaluation) of coatings applied by selected thermal spray technologies, including two-wire arc, single-wire arc, and flame spray devices
2. environmental impact assessment of the technology, including regulatory zinc exposure limits, appropriate containment systems, and legal requirements related to lead-based paint abatement
3. design, fabrication, and laboratory testing of an integrated ATSS comprising a triaxial linear positioning system, an abrasive-blasting head, a thermal spray head, containment technology, and a visual inspection system
4. field testing of the ATSS on a bridge deck component specified by the New York State Department of Transportation and applicable local authorities
5. coating performance monitoring of the field test structure to verify coating quality and cost-effectiveness compared to application by conventional hand-held thermal spray equipment
6. preparation of technology transfer and commercialization plan, including draft material and equipment specifications submitted for consideration as industry standards by the Steel Structures Painting Council (SSPC) and the American Society for Materials and Testing (ASTM)
7. documentation of the project in a technical report.

Units of Weight and Measure

U.S. standard units are used in this report. A list of conversion factors for Standard International (SI) units is shown below.

1 in.	=	25.4 mm
1 sq in.	=	6.45 cm^2
1 ft	=	0.305 m
1 sq ft	=	0.093 m^2
1 lb	=	0.453 kg
1 gal	=	3.78 L
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32

2 Overview of Thermal Spray Technology

Protection Mechanism of Thermal Spray Coatings

Corrosion protection of steel with coatings works either by passivation or by electro-chemical means through the application of a conductive, active metal coating as provided through galvanizing or by a paint that is heavily loaded with metal (e.g., zinc). Long-term corrosion protection can be effectively achieved through the application of active metal coatings that are electrochemically anodic to the steel substrate. Corrosion tests of flame-sprayed coated steels conducted by the American Welding Society (1974) showed that sprayed zinc and aluminum coatings are highly effective over long periods of time in a wide range of hostile environments.

Thermal spray metallization is generally achieved by the melting and high-velocity air atomization of metallic wire or powder. The melt strikes a properly prepared steel surface, solidifies, and adheres principally through mechanical interlocking of the solidified, flattened particle (or "splat") and the grit-blasted surface. The sprayed metal thus forms a strong, adherent coating by the rapid deposition of molten particles. A cross-section of such a thermally sprayed steel is shown in Figure 1.
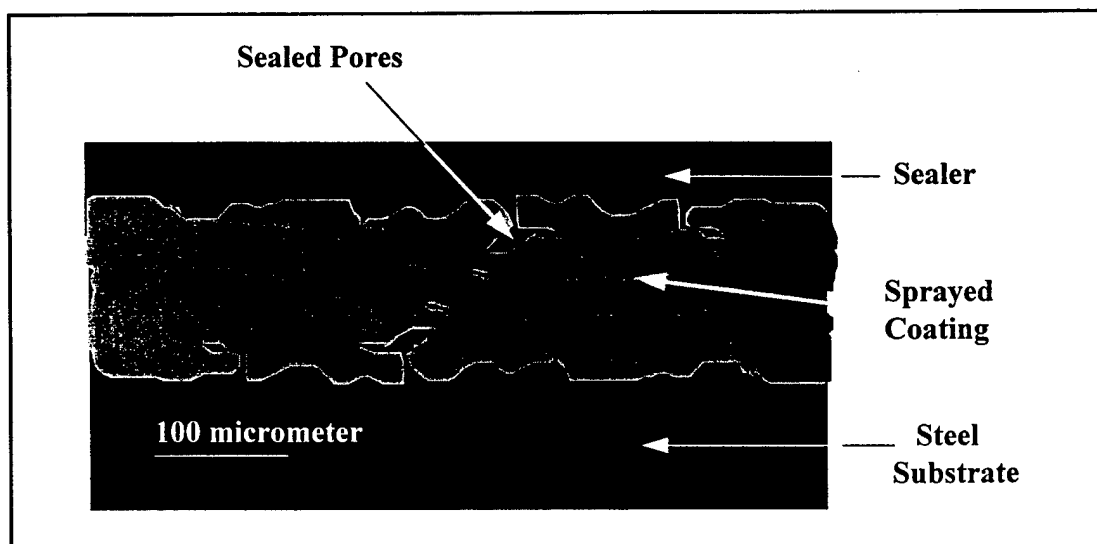
Figure 1. A cross-section of a typical sealed metallized coating.

While thermal spraying techniques vary, the essential features of the process are similar. The metallic wire or powder to be sprayed (such as zinc, aluminum, or combinations of the two) is melted and the molten material is accelerated by a blast of compressed gas (e.g., air) to the substrate. This process generally results in a porous coating containing some oxide but—of principal importance—having good electrical contact with the steel substrate. (Recent advances in processing techniques for thermal spray materials (TSM) result in less porosity, sometimes achieving nearly 100 percent density.) The electrochemical bonding of coating to substrate creates cathodic protection. According to the electrochemical series, the metals zinc and aluminum are anodic (less noble) to ferrous alloys, the latter being protected in a electrolyte through the dissolution of the active metal coating.

The main feature of this cathodic protection mechanism is shown in Figure 2. The galvanic coupling between the metal coating and the substrate steel should result in cathodic polarization of the latter and thus arrest anodic dissolution of the steel (Apostolos, Parks, and Carello 1987). In case of coating damage (such as occurs under abrasive conditions), the cathodic reaction will occur where there is exposed steel and the electrochemical circuit will be completed by the anodic dissolution of the coating at the edge of the failure region. The greater the electrochemical activity (or "throwing power"), the greater will be the area of the steel that can be safely exposed.

In the presence of electrolytes, zinc is more active than aluminum due in part to its tendency to form a surface film of corrosion products. Therefore, zinc coatings are sacrificed more rapidly than aluminum in sea water and greater thicknesses of zinc are needed to ensure adequate coating service life. However, this same characteris-
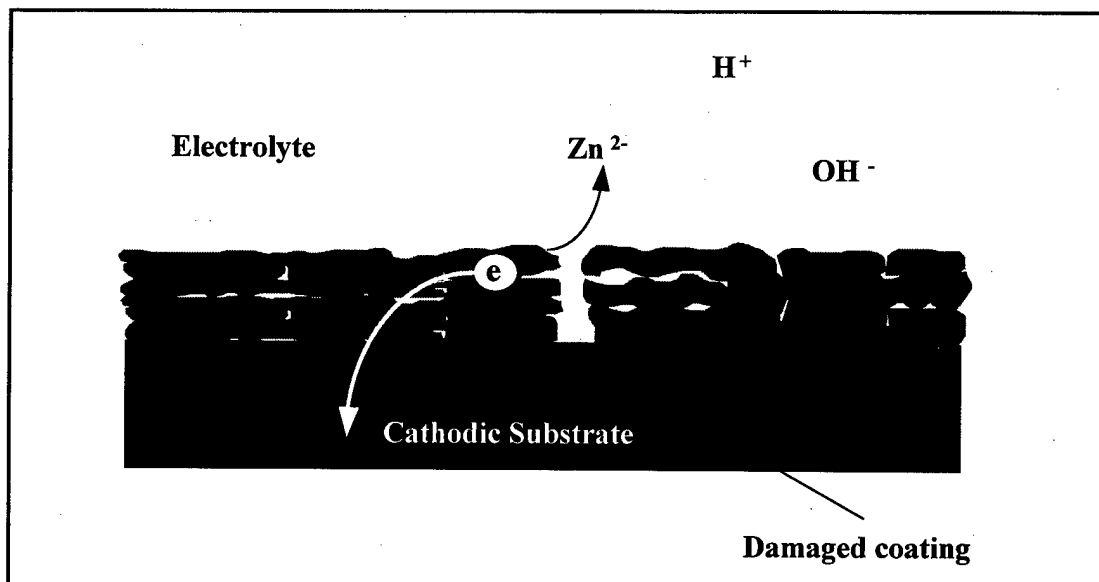
Figure 2. Mechanism of protection of the steel substrate by metallized coatings.

tic enables zinc to provide greater throwing power when coating failure exposes the steel substrate (Birch 1986). In order to combine the active potential of zinc with the lower corrosion rate of aluminum, alloys of the two metals have been produced. It has been found that an 85/15 Zn/Al alloy (percentages by weight) combines the optimum properties of zinc and aluminum coatings (LTC International, Inc., not dated). The alloy coating has a lower percentage of connected porosity than aluminum coatings, and comparable porosity to the zinc coatings.

Therefore, relatively thin coatings of this alloy (e.g., 150 micrometers [0.006 in.]) may be used.

The mechanical integrity of a coating depends on a number of factors: density; nature of the pores (which can act as stress risers); the nature of the inter particle bonding; and coating-substrate interfacial bonding. Corrosion can lead to undermining of the mechanical integrity of a coating both by localized attack between particles and at the coating-substrate interface (Carello, Parks, and Apostolos 1989). Erosion can combine both mechanical and chemical attack, causing greater possibility of failure in aluminum coatings with a volume porosity of about 10 percent. For zinc coatings, a volume porosity of about 4 percent will increase the possibility. If the coatings are sealed by mechanical means (e.g., rolling, shot peening), through sintering, or with sealers, the effects of erosion are significantly reduced. It is again important to note that the Zn-15 wt.% Al alloy fares best in erosion-corrosion conditions.

Environmental Advantages Of Thermal Spray Coatings

Environmental Containment Issues

There are increasing demands for absolute enclosures around any maintenance site to capture all hazardous debris for the protection of workers and the environment. Class A containment enclosures are cumbersome, difficult to erect, and they greatly increase the difficulty of any maintenance task, increasing both project time and cost. Therefore, it is highly preferable to use the longest-lasting protective coating available, which will not only decrease the number of maintenance cycles for a specific structure, but also minimize the level of effort required. Furthermore, thermal spraying can be applied at any ambient temperature, thus eliminating the need to cease work during the winter.

When the environmental impact of traditional maintenance and repair (M&R) techniques is analyzed, many factors are overlooked because their affects on the

environment are indirect. When any infrastructure maintenance program is to be undertaken, it is imperative to consider surface preparation. Regardless of the protective coating to be applied, the steel substrate must be cleaned to the "white metal" cleanliness stage (SSPC-PS-XMET01X-89). This preparation requires abrasive blasting or chemical etching. The use of Class A containment in the field reduces the chance of debris escaping into the environment, but does not eliminate it (Olsson and Bandel 1992). Alternative technologies are being investigated as substitutes for enclosures, but few meet the strict guidelines set by the U.S. Environmental Protection Agency (EPA). Minimizing the effects of surface preparation can be also achieved by lengthening the maintenance cycle. In addition, the level of effort for recurring maintenance is greatly reduced when a thermal sprayed coating is used because the steel itself does not corrode, so the need for further blasting is eliminated. Maintenance for metal sprayed coatings often requires a simple brushing of the deteriorated topcoat followed by a new layer of metal, as shown in Figure 3. Thus the need for extensive blasting is eliminated along with its detrimental effects on the environment (e.g., the introduction of heavy metals into the water table through spent blast media and lead-based paint blast waste). Abrasive blasting, when not fully contained, also acts to decrease the pH levels in the immediate work area, and can therefore contribute to the creation of electrolytic compounds that attack steel.
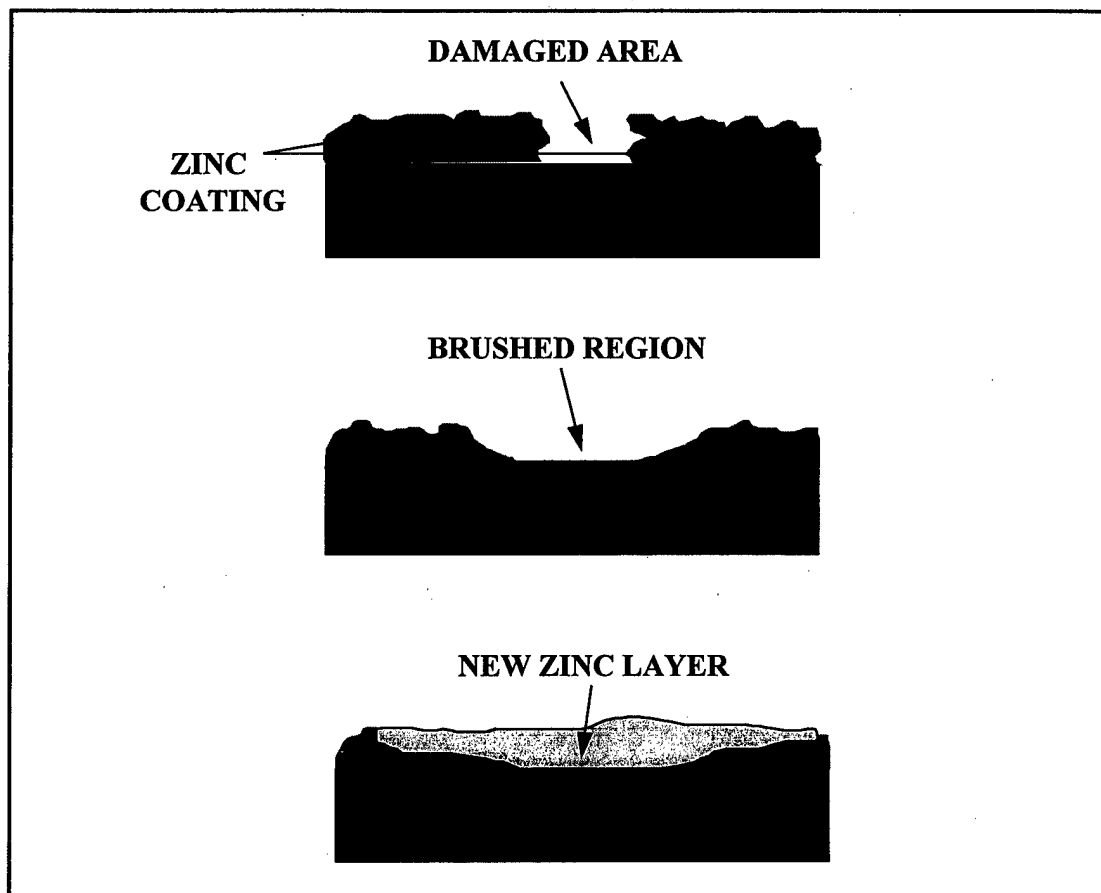
Figure 3. Repair process for a damaged unsealed zinc coating.

Lead Exposure Standards

The removal of lead-based paint from steel structures is impacted by the requirements of both 40 CFR 50 — the EPA's *National Primary and Secondary Ambient Air Quality Standards* — and the Occupational Safety and Health Administration (OSHA) *Lead in Construction Standard* (29 CFR 1926.62). 40 CFR 50 requires that lead emissions not exceed 1.5 microns per cubic meter as a quarterly mean. Containment structures must be put in place at the worksite to prevent the release of the waste into the environment. The ATSS system incorporates a fully enclosed vacuum abrasive blast system which fully contains the lead particulate generated during the removal of paints containing lead and other toxic pigments, and prevents the release of lead into the environment. The enclosed vacuum blasting system and the remote placement of the worker also greatly reduce or eliminate worker exposure to lead regulated under the OSHA standard (see Appendix A). Thus the ATSS facilitates compliance with the EPA and OSHA standards.

Volatile Organic Compounds

Recent changes in guidelines on the environmental impact of infrastructure maintenance have made it necessary for manufacturers to reformulate paints to comply with the lower volatile organic compound (VOC) emissions requirements. In complying with these new VOC standards, many paint systems have suffered an increase in required curing time and a reduction in long-term performance. A thermal sprayed aluminum/zinc alloy, with its proven long-term performance record, provides an excellent alternative to VOC-based coatings because the thermal spray process requires zero curing time and produces zero VOCs.

Zinc Exposure Levels

The threshold limit value (TLV) for zinc fume exposure is 5 mg/m^3 of air on an 8-hour time-weighted average basis (American Conference of Governmental Industrial Hygienists 1989). It is assumed that workers operating the ATSS will not be exposed to levels exceeding the TLV because the system is designed to be operated remotely, with workers remaining at a safe distance from the work surface. However, because NYSDOT granted an air monitoring waiver for this demonstration, no worker-exposure monitoring was conducted during the field test. Therefore, the presumption that workers would not be exposed to zinc fumes in excess of the TLV would have to be validated by quantitative exposure monitoring and analysis in future field testing.

3 Laboratory Evaluation of Thermal Spray Coatings

The configuration of any automated thermal spray system will heavily depend on the types and forms of feedstock material available, and the selection of equipment capable of delivering the coating material.

Automation of thermal spraying technology will not require any new types of forms of coating feedstock. Many available metallic materials are currently used to provide steel structures with corrosion and erosion resistance. Corrosion tests conducted and reported by the American Welding Society (AWS) validate the effectiveness of thermal spray aluminum and zinc coatings over long periods of time in a wide range of environments (American Welding Society 1974). The means by which these materials provide corrosion and erosion resistance is well understood and documented (Race, Hock, and Beitelman 1989).

The AWS C2.18 Guide (Sulit 1993) covers the application of thermal spray materials for the protection of steel with aluminum, zinc and their alloys, mixtures, and composites. The British Standards Institute Code of Practice (B.S. 5493:1977) for the corrosion protection of iron and steel provides service-life tables for coating materials used in various environments at given coating thicknesses. Based on the recommendations provided in these references and data from laboratory testing at SUNY, Table 1 summarizes the estimated service lives of zinc and 85/15 zinc/aluminum coatings for different types of exposure. The results of the laboratory investigation for automated thermal spraying are in agreement with the evaluation of abrasion-resistant metallized coatings for civil works applications conducted by USACERL during 1986 and 1987 (Race, Hock, and Beitelman 1990). The nominal feedstock spray rates and coverage are summarized in Table 2. Based on the data summarized in Tables 1 and 2, zinc alloy 85/15 Zn/Al was selected for the ATSS field demonstration.

Table 1. Estimated service lives of Zn and 85-15 Zn/Al coatings.

Type of Exposure	Coating Thickness Required for Indicated Service Life			
	5-10 yrs	10-20 yrs	20-40 yrs	>40 yrs
Rural Atmosphere	-	75-125 μm (0.003-0.005 in.)	150-200 μm (0.006-0.008 in.)	250-300 μm 0.010-0.012 in.)
Industrial Atmosphere	-	150-200μm (0.006-0.008 in.)	300-375 μm (0.012-0.015 in.)	350-400 μm (0.014-0.016 in.)
Marine Atmosphere	-	250-300 μm (0.010-0.012 in.)	300-375 μm (0.012-0.015 in.)	350-400 μm (0.014-0.016 in.)
Fresh Water Atmosphere	150-200 μm (0.006-0.008 in.)	250-300 μm (0.010-0.012 in.)	300-375 μm (0.012-0.015 in.)	-
Potable water*	190-250 μm (0.0075-0.010 in.)			
Salt Water Immersion	250-300 μm (0.010-0.012 in.)	350-400 μm (0.014-0.016 in.)	-	-

Table 2. Nominal wire feedstock rates and spray coverage.

Feedstock Material	Flame Spray (by wire diameter)			Arc Spray
	2.4 mm	3.2 mm	4.8 mm	Per 100 amps
	Spray Rate, kg/hr Coverage, m^2/hr/100 μm)			
Aluminum	2.5 (8.73)	5.4 (18.9)	7.3 (25.3)	2.7 (8.26)
Zinc	9.1 (9.44)	20 (21.2)	30 (30.7)	18 (11.0)
85/15 Zn/Al	8.2 (11.8)	18 (26.20	26 (38.0)	16N (9.68)
90/10 Al MMC	2.5 (8.73)	5.4 (18.9)	7.3 (25.3)	2.7 (8.26)

4 System Description and Development

Design Overview

Repetitive-motion systems offer many labor-saving solutions for public-sector and private-sector users alike. However, many design constraints need to be addressed for such systems to be practical. In the design of the Automated Thermal Spray System (ATSS), the main constraints were cost, machine size, and durability. Many automated systems available on the market offer precise motion control, multiple degrees of movement freedom, and long service life. While such systems are attractive to the designer, their cost is usually prohibitive (Oppenheim and Skibniewski 1988). For infrastructure maintenance—particularly the rehabilitation of large flat surfaces—only three axes of movement are necessary, and affordability is a major consideration for potential users. For this reason, ATSS designers chose linear motion actuators as the primary means of positioning, rather than more sophisticated technologies such as a gantry system or articulated arms.

Linear Positioning System Design

Thermal spraying of bridges and other infrastructure systems involves complex motion and requires flexibility in handling tasks such as abrasive blasting of large expanses containing hazardous materials. The ATSS positioning system is designed to eliminate many difficulties (e.g., physical demands on workers, surface inaccessibility) normally encountered in such work. A three-axis positioning system maneuvers a vacuum blasting head, thermal spray gun, and video camera to locations on the structure at the appropriate standoff distance for each component. Variable speed and acceleration is provided.

From an initial starting position, the system will traverse along the X-axis (horizontal) performing the required operation at set speeds and acceleration profiles. The system will move an incremental distance along the Y-axis, stop, and then traverse the X-axis in the opposite direction.

The system may be operated through remote control or can be programmed for specific motion. Remote operation will be required when the operator needs to

make required adjustments in cases when repeated motion cannot be performed. Control is provided through a joystick. Programmed actuation will be used for repetitive operations. Conventional bridge structures provide numerous opportunities for such work—large flat sections provide significant surface area for repetitive motion in vacuum blasting and thermal spray operations.

RACO LM3 belt-driven actuators (RACO International, Inc., Bethel Park, PA 15102) provide the required actuation. Each actuator consists of a guide rail, carriage, timing belt, motor, and gearbox. A high-stiffness, wear-resistant polyurethane timing belt drives an aluminum carriage along a track in a 3 in. x 3 in. square extruded aluminum body. The carriage provides the base for mounting the ATSS components.

Controls are located in a control station and integrated with the other ATSS operations. The control system provides motion in open- or closed-loop fashion while interfacing with programmable controllers and a computer. A digital motor controller is used to set drive assembly velocity, acceleration, and positioning. Microprocessors calculate actuator position and velocity from position-feedback sensors. The microprocessor contains motion-control algorithms for velocity, acceleration, and positioning. This information is converted to analog current commands amplified through a servo-amplifier to sufficient levels to drive alternating current (ac) servo motors. Controllers are available with input and output (I/O) channels, display field, program field, and power switch field. The I/O channels allow external hardware to be added, including ends-of-travel and home-position sensors. Figure 4 shows the connection layout for this type of control system.

An RS-232 serial port allows programs and data to be archived. Controller software allows off-line programming and downloading to the computer.

Linear Positioning Actuators

The X-axis actuator moves side-to-side at variable speeds and accelerations as specified for different stages of the repair cycle. The vacuum blasting and video monitoring stages require a slow, constant speed while the thermal spray process requires high velocities and high acceleration rates (to attain initial speed from standby). The X-axis actuator system consists of a driven unit (i.e., motor-controlled) and an idler unit with a maximum velocity of 91.4 cm/sec (3 ft/sec) and maximum acceleration and deceleration of 182.9 cm/sec^2 (6.0 ft/sec^2). The stroke length is 91.4 cm (36.0 in.) and is controlled by two proximity switches at the ends. The X-axis will support a maximum weight of 77 kg (170 lb) and has an overall
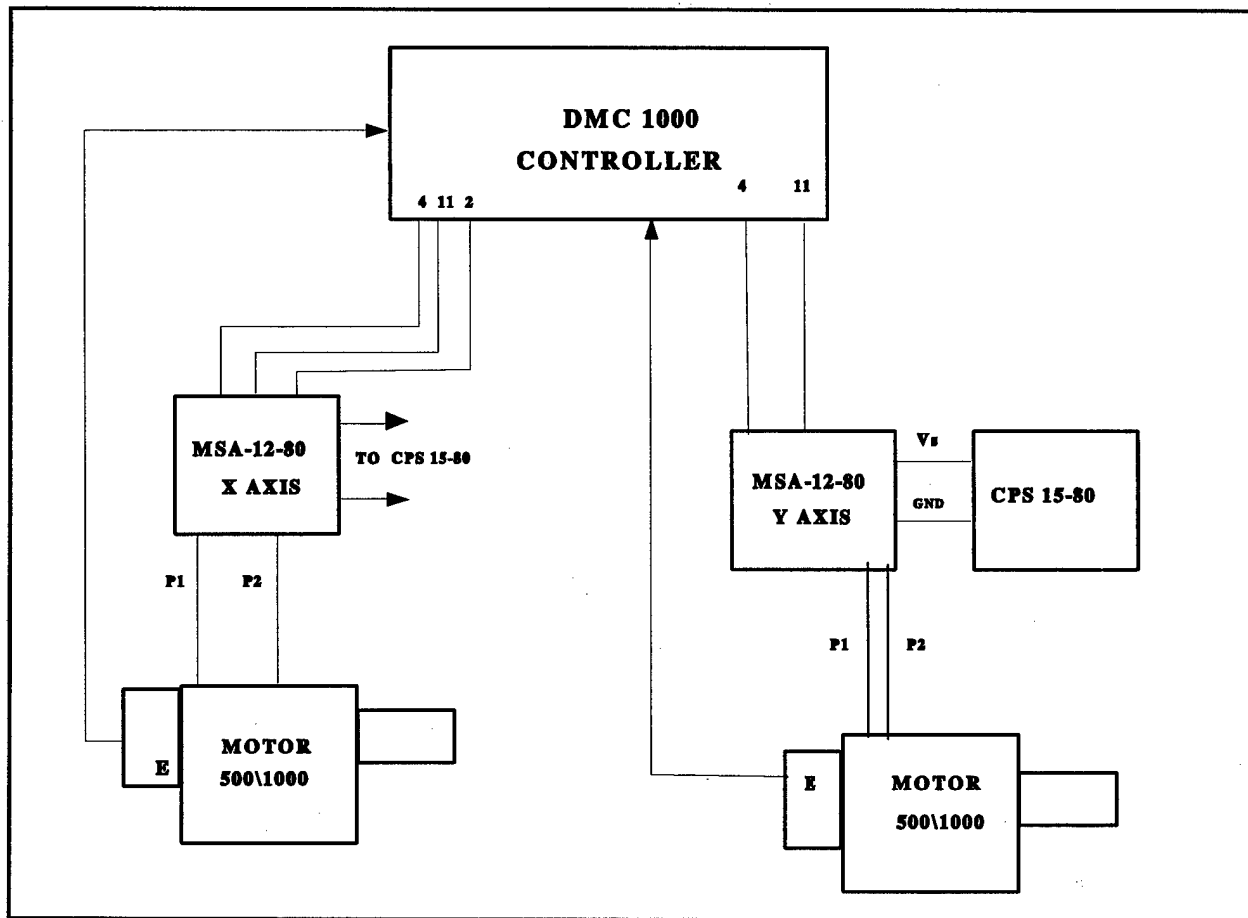
Figure 4. Schematic of the control system using the DMC-1000 controller.

length of 155.9 cm (61.4 in.). A servo-motor and a planetary gearbox with a ratio of 10:1 will drive the actuators.

The Y-axis actuator system controls vertical motion. Its acceleration and velocities are small relative to the X-axis actuator since the majority of motion in the vertical direction will be incremental displacements of about 2 to 3 cm (0.8 to 1.2 in.). Its two actuator units provide a maximum velocity of 5.08 cm/sec (0.17 ft/sec) and a maximum acceleration and deceleration of 10.2 cm/sec^2 (0.33 ft/sec^2). The vertical system has a 91.4 cm stroke (36.0 in.) and is controlled and monitored by two proximity switches, two end-of-travel switches, and one home position switch. The Y-axis system will support a weight of 127 kg (280 lb) and has an overall length of 155.9 cm (61.4 in.). Servo motors and planetary gearboxes with gear ratios of 20:1 drive the actuators.

The Z-axis actuator adjusts the distance between the loading plate and the substrate.   The specified standoff distances for each component can be accommodated within its 30.5 cm (12.0 in.) stroke length. The actuator supports a maximum weight of 59 kg (130 lb) and has an overall length of 94.9 cm (37.4 in.).

Maximum velocity is 5.08 cm/sec (2.0 in./sec) and maximum thrust is 440 kg (200 lb). The Z-axis actuator can control the position of the loading plate to within 0.05 mm (0.005 in.)—an important feature since the efficiency of the vacuum blasting system depends on the nozzle head being flush to the substrate. Figure 5 shows the configuration of a three-axis actuator system that has a driver and slave actuator in the Y-axis, a driver and a support track in the X-axis, and a single actuator in the Z direction.

Support Frame

Conceptual Design

Any frame for an automated system calls for a design that will be able to perform the basic function of supporting the moving actuators while not interfering with their motion. The most important design criteria were low weight, high strength, and the ability to allow for flex. Such specifications were weighed against longevity and durability in field conditions. Three options were examined to determine the optimal design for the support frame.

Design Option 1. The simplest design option for a support frame was a unit that rests on a flat horizontal surface and must be manually moved and placed against the working surface (Figure 6). One advantage of such a frame is that no attachment method would be needed to keep the automated system against the
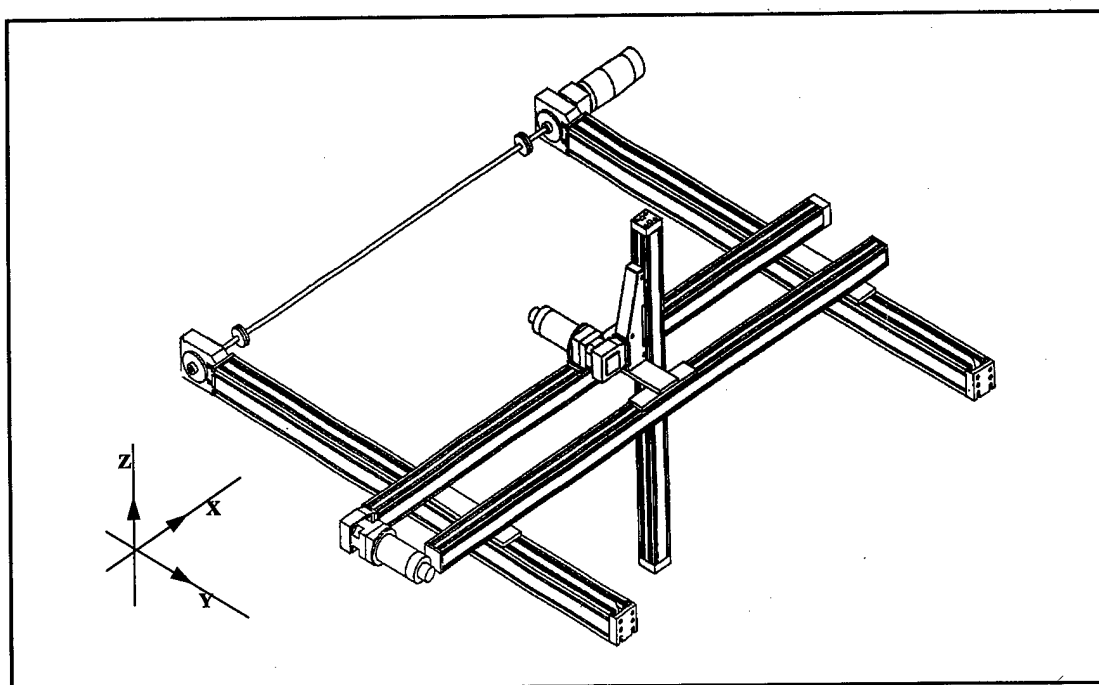
Figure 5. Triaxial ATSS support frame with Raco LM-3 linear actuators.
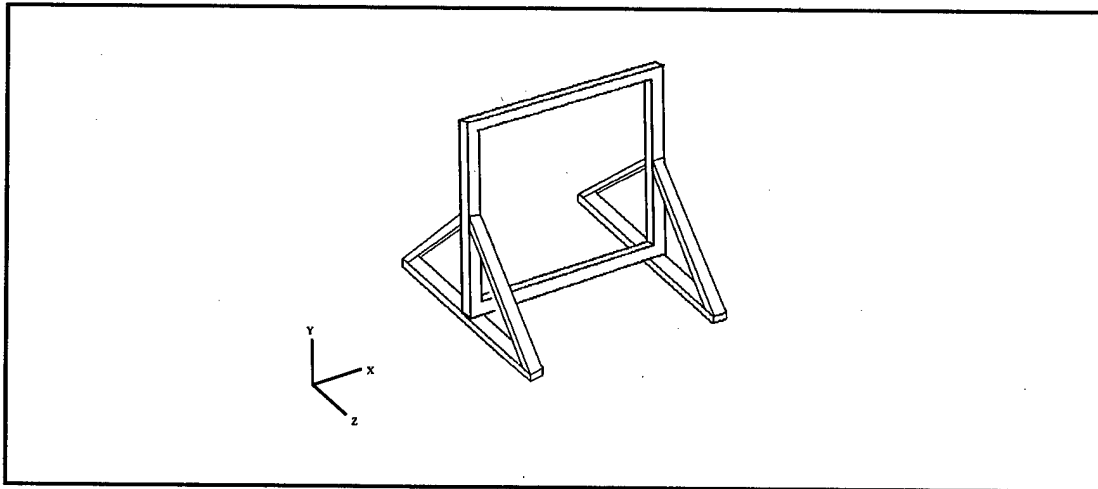
Figure 6. Design Option 1.

substrate. Such a unit could simply be placed on a scaffold and be moved from one section to the next when the maintenance cycle is finished. While such a design is straightforward, it could tend to be unstable when the automated equipment is operating.

Design Option 2. Using two separate frames, the ATSS could be supported on both sides during the maintenance cycle (Figure 7). This option is versatile and allows for the frame to be easily connected to the substrate while also allowing for easy transport to and from the work site. However, Option 2 has one serious flaw: it does not provide full support to the automated unit, and could buckle during actuator operation.

Design Option 3. The third design option—the most conventional of the three—is permanently attached to the ATSS. The frame uses four electromagnets to attach to the substrate (Figure 8). While it is cumbersome and heavy, this option provides the best support for the actuator system and allows for optimum maintenance quality. The legs at the four corners of the frame place the maintenance tools at a
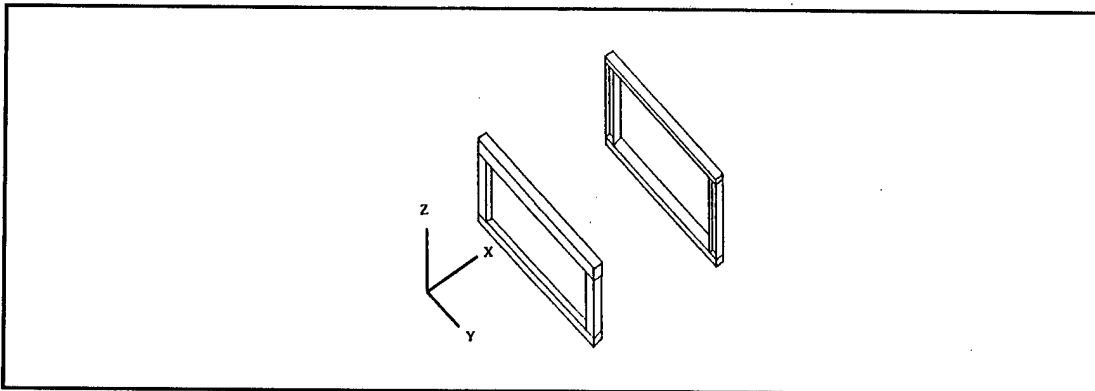
Figure 7. Design Option 2.
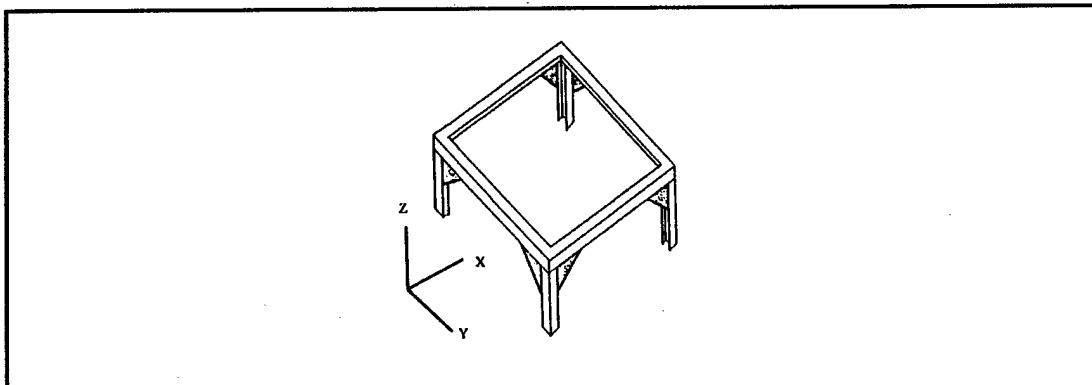
Figure 8. Design Option 3.

Table 3. Rating of design optimization factors.

Criterion	Importance	Design 1	Design 2	Design 3	Max.
Strength	1.0	9	2	8	10
Weight	1.0	5	8	8	10
Durability	0.9	9	2	8	10
Cost	0.9	8	9	8	10
Simplicity of Design	0.9	4	9	8	10
Simplicity of Mfg.	0.8	4	8	7	10
Transport	0.8	4	7	7	10
Stability	0.8	4	3	8	10
Flexibility	0.7	4	9	9	10
Ease of use	0.5	9	5	9	10
Setup	0.5	9	4	8	10
Storage	0.3	7	8	6	10
Maintenance	0.2	8	8	8	10
TOTAL		58.0	57.2	73.4	130

correct distance from the substrate while allowing the frame flexibility needed in working conditions.

The different design options were examined according to the criteria listed in Table 3 and rated on a numerical scale of 1 to 10 (10 being the best score). The criteria were then weighted according to importance on a numerical scale of 0 to 1 (zero being the lowest priority). The combined score for each design is a multiplication factor of the two numerical scales, followed by the addition of all scores for every criterion. Each individual option is weighed and the total score is compared with all other choices in order to establish the optimum design. Table 3 presents the scores for each design option.

The combined scores in the last row of the table clearly indicate that the third design option best supports the given criteria. Therefore, it was selected as the design for the prototype.

Frame Stress Calculations

When calculating stress on any rigid body, it is always more convenient to divide that body into smaller sections and calculate stress and load conditions on those sections. Because of the frame's design load and the fact that four electromagnets support the legs at the ends, it is easy to calculate the loading conditions on the top member of the frame and on the individual protruding legs. From the type of loading and the symmetrical way in which the frame is held, it is clear that the top cross-member and the legs are the only sections of the frame that support load. In order to determine whether the frame members can withstand the load placed on them, detailed loading, moment, and shear diagrams had to be made. The data from these diagrams were then used in the load bearing calculations. A safety factor of 2 was used in the calculations to ensure that no catastrophic failure will occur. The diagrams and calculations follow.

Top Supporting Member

The load on this member occurs mainly when the frame and the automated system connected to it are hoisted by a boom or crane. With a total length of 50 in., and with the crane supports placed 10 in. from either end, there is a symmetrical loading condition. The weight of the system is 400 lb which implies a 200 lb load at either end of the section. To find the value of the forces at the crane supports, a force diagram was drawn (Figure 9) and calculations for equilibrium were carried out as follows:

$$\Sigma F = -200 + F1 + F2 - 200 = 0$$
$$\rightarrow F1 + F2 = 400 \qquad \text{[Eq 1]}$$

and

$$M_{by} = 0 = 10 \times 200 + 30 \times F2 - 40 \times 200$$
$$\rightarrow 30 \times F2 = 30 \times 200$$
$$\rightarrow F2 = 200\text{lb} \qquad \text{[Eq 2]}$$
$$\rightarrow F1 = 200\text{lb}$$

where F = Force (lb) and M = Moment (lb-in.).
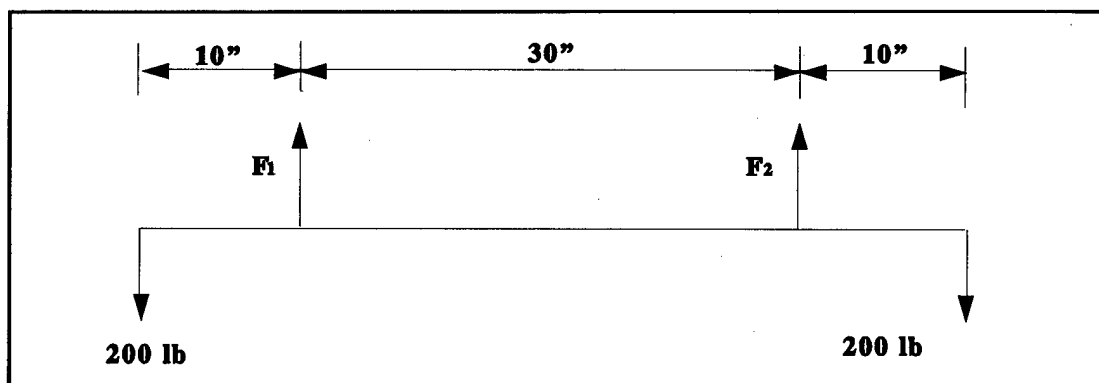
Figure 9. Force diagram on top frame section.

After all forces acting on the top support member have been calculated, the loading diagram can be used to obtain the shear and bending moment diagrams that are needed to find the highest bending moment value (Figure 10).

The bending moment for this type of loading (M_b) is determined to be -2000 lb-in, which is used to calculate the maximum bending stress that the aluminum section can carry safely. As noted previously, a safety factor of 2 is incorporated into the calculation. In order to find the maximum bending stress for this particular section, the moment of inertia of the member must be calculated as well as the coordinate axis (it is assumed that the beam is in pure bending). To calculate the coordinate axis, the three parts of the U-section must first be considered separately (Figure 11). The overall value of the coordinate axis, or $\bar{y}$, is calculated as follows:

$$\bar{y} = \frac{\Sigma \bar{y}_i A_i}{A} \qquad \text{[Eq 3]}$$

where:

$$\bar{y}_1 = b + \frac{3t}{2} \qquad \text{[Eq 4]}$$

$$\bar{y}_2 = \frac{b}{2} + t \qquad \text{[Eq 5]}$$

and

$$\bar{y}_3 = \frac{t}{2} \qquad \text{[Eq 6]}$$
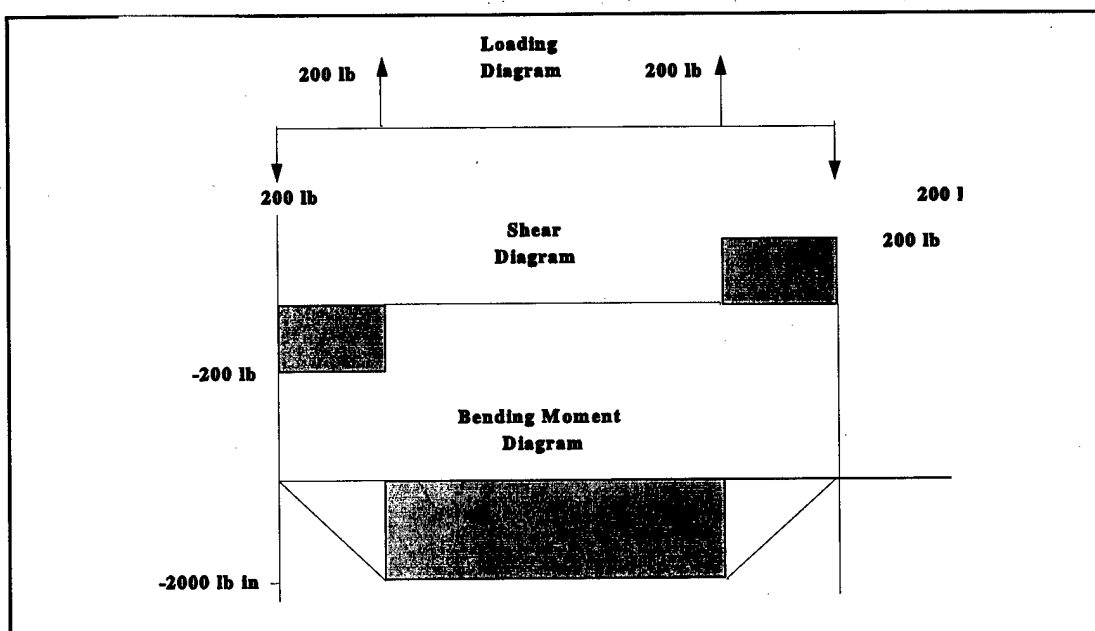
Figure 10. Loading, shear, and bending moment diagrams for top frame section.
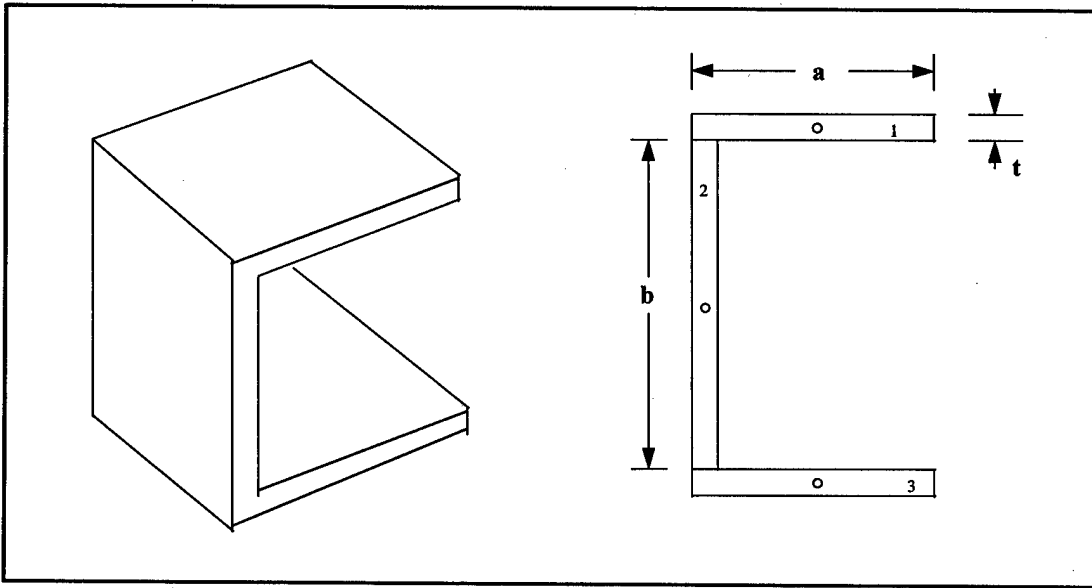
Figure 11. Cross section of U-channel.

The value for the coordinate axis becomes:

$$\bar{y} = \frac{at(b + \frac{3t}{2}) + bt(\frac{b}{2} + t) + at(\frac{t}{2})}{2at + bt} \qquad \text{[Eq 7]}$$

Rearranging gives:

$$\bar{y} = \frac{ba + 2at + b^2/2 + bt}{2a + b} \qquad \text{[Eq 8]}$$

The moment of inertia for the cross section is obtained by taking the moment of inertia of the rectangle containing the cross-section, and subtracting the inside area that is empty, as expressed by

$$I_{zz} = a(b + 2t)^3 - (a - t)(b)^3 \qquad \text{[Eq 9]}$$

When simplified, the moment of inertia becomes:

$$I_{zz} = tb^2(b + 6a) + 4at^2(3b + 2t) \qquad \text{[Eq 10]}$$

Once the coordination axis and the moment of inertia were obtained, the maximum bending stress was calculated as follows:

$$\sigma_{max} = \frac{Mb\bar{y}}{I_{zz}} = \frac{2000\left(\frac{ba + 2at + b^2/2 + bt}{2a + b}\right)}{tb^2(b + 6a) + 4at^2(3b + 2t)} \qquad \text{[Eq 11]}$$

The dimensions for the cross-section are as follows:

a = 1.5 in.
b = 3.0 in.
t = 0.25 in.

Therefore, the value for σ_{max} is 139.1 pounds per square inch (psi).

The particular U channel used for the frame is rated at over 2000 psi, thus the safety factor exceeds our assumed factor of 2.

Support Legs

The four supporting legs can be treated as cantilevered beams that support one-fourth of the applied load because the electromagnets hold one end of the leg against the wall while the other end hangs free. This approach to the analysis is not entirely accurate, however, because each leg is supported by the cross-members of the top frame. Nevertheless, the cantilever approach is used here since it represents the worst-case scenario: an unsupported leg carrying maximum load. The loading (a), shear (b), and bending moment (c) diagrams are shown in Figure 12.

Figure 12. Loading, shear, and bending moment diagrams for frame support legs.

In this case, M_{max} is calculated to be -2100 lb-in. The coordinate axis and the moment of inertia retain their values because the same U channel is used and the loading is applied on the same cross section. It follows then that the bending stress on the support leg would be expressed as the value for the maximum bending stress observed by the supporting leg is then:

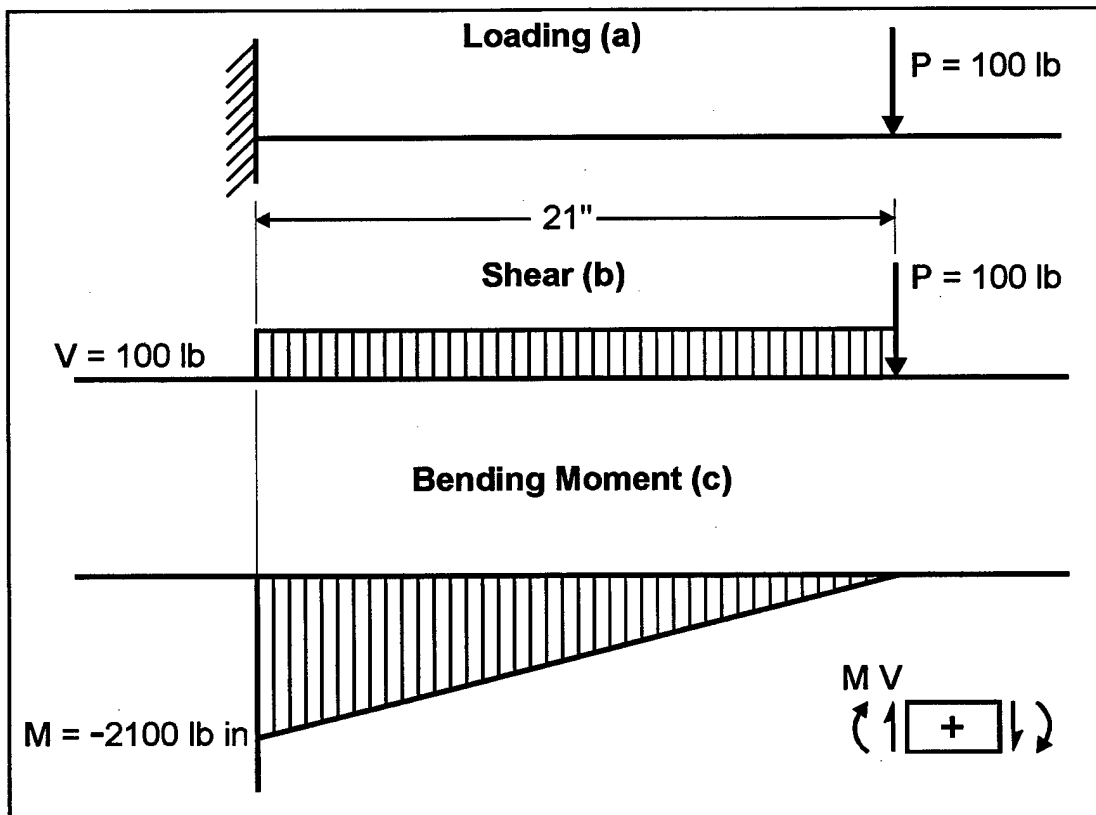$$\sigma_{max} \frac{2100 \left(\dfrac{ba + 2at + b^2/2 + bt}{2a + b} \right)}{tb^2(b + 6a) + 4at^2(3b + 2t)} \qquad \text{[Eq 12]}$$

σ_{max} = 146.1 psi which again exceeds the safety factor of two.

Electromagnetic Connectors

The frame that carries the ATSS attaches to the substrate by four electromagnets, each of which is connected at the end of a support leg. The magnets are held in place by a flat aluminum plate (flange) that is welded to the end of the leg. For the electromagnets to be most effective they must be placed flush with the substrate, but it is assumed that the substrate in the field will not be perfectly flat most of the time. The aluminum frame is not flexible enough to allow for such surface variances, so a rubber pad was placed between the electromagnet and the aluminum flange. When bolted through, as shown in Figure 13, the rubber will allow the magnet to move several degrees and ensure proper contact with the substrate. The rubber pad chosen is a flat motor mount for a 3.9 liter V-8 automobile engine which, according to its specifications, can allow two to three degrees of movement.

The electromagnets used in this design are rated for loads of up to 227.3 Kg (500 lb) so each individual magnet could support the system by itself in case the other three were to fail. The electromagnet control box requires 110 V ac, which can be taken from a standard wall outlet. The current passes through a rectifier unit inside the control box to provide conversion to direct current (dc), the latter of which is also rated at 110 V. A two-lead power cable is connected from the magnet control unit to a power distribution box mounted on the frame. Each magnet is connected to the distribution box in parallel so a power failure to one magnet would not disable the others. Figure 14 shows the connection schematic.

The ATSS is connected to a boom at all times in case of a total power failure to the magnets or the control box. This safety measure is necessary since a power failure in the box or the magnets would cause the frame to detach from the substrate.
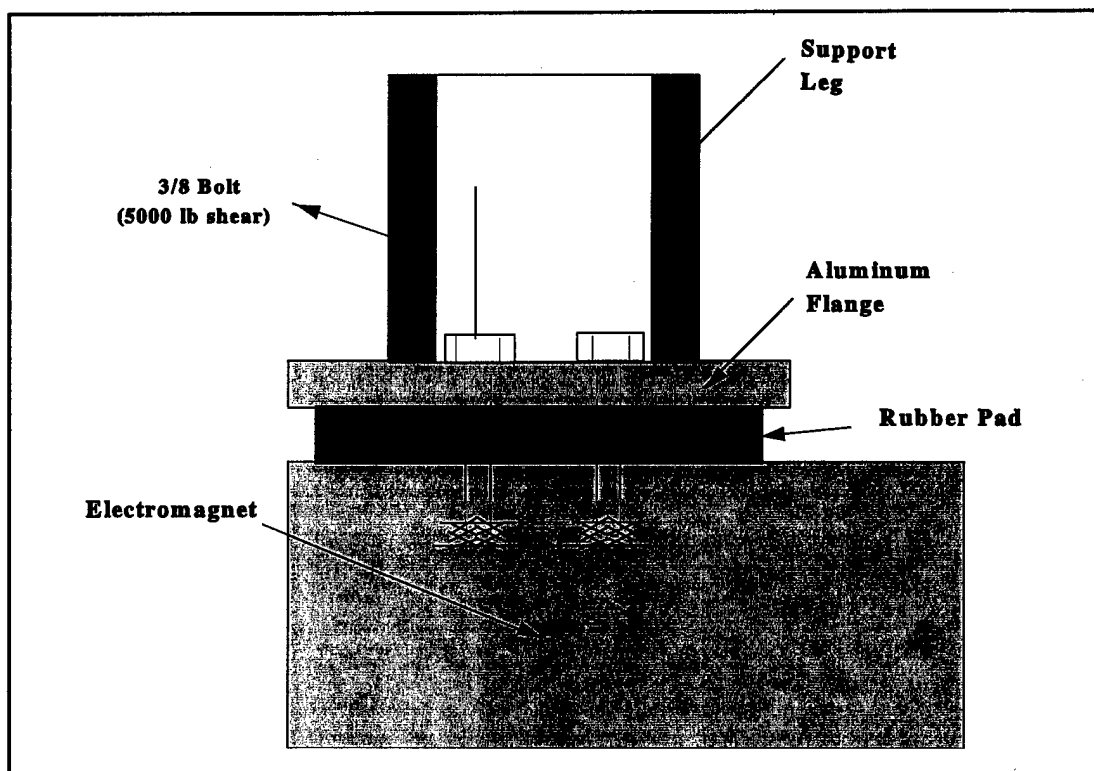
Figure 13. Schematic of connection joint.
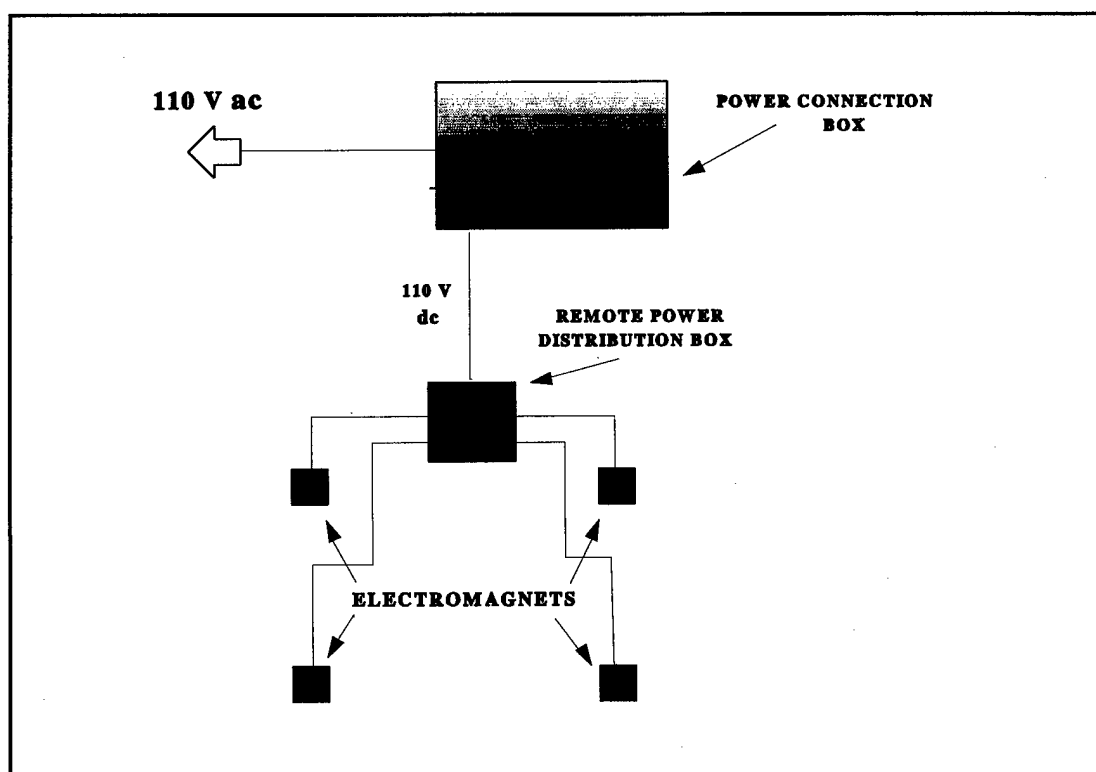
Figure 14. Electromagnetic-power connection configuration.

Infrastructure Service Platform

Thermal Spray Gun System

A two-wire electric arc thermal spray system (Hobart-Tafa Arc Spray Model 9000, Tafa, Incorporated, 146-T Pembroke Rd., Concord, NH 03301) was chosen for depositing alloy coatings onto the structures. The theory of operation behind the two-wire arc spray process is relatively simple. Two metal wires, located on spools in the control console, are fed through Teflon® conduits into the nozzle of the gun. The wires are subjected to a large electrical potential difference—one wire with a positive charge, the other with a negative charge. When the wires are fed through and reach the tip of the nozzle, a connection is made and a short-circuit occurs. The high voltage applied melts the wires instantly. The droplets of molten metal formed by the process are then atomized and propelled toward the substrate using compressed air fed through a pressure conduit to the nozzle tip. The molten droplets are accelerated toward the substrate and solidify upon hitting the surface. The bonding mechanism between the flattened droplets, or splats, and the substrate is physical. Therefore, the substrate surface must be abraded to the proper roughness. Figure 15 shows the operation of the two-wire arc gun.

Criteria for selecting this type of system were quality of the coatings produced, deposition rates, automation capability, logistical support requirements, materials sprayed, and operating costs. Two-wire electric arc systems have had a notable record of success in the thermal spraying steel and reinforced concrete bridges.

The spray parameters control particle size, coating density, and surface roughness. Reproducible coating characteristics are obtained by controlling amperage, air pressure, nozzle diameter, and wire diameter. The gun is an instant on/instant off device. It begins to spray when the wire feed switch is activated, causing the electrically charged wires to make contact. The fineness and density of the coating

Figure 15. A schematic of a two-wire arc spray gun.

are adjusted through the nozzle diameter and air pressure. The gun weighs 2.9 kg (6.4 lb) and is machine-mounted on the actuator to maintain the recommended distance (i.e., 20 cm for zinc) from the substrate. In a stationary position, the gun can spray an area of either 2.1 cm (0.83 in.) x 4.4 cm (1.73 in.) or a 2.1 cm (0.83 in.) x 5.0 cm (1.97 in.) area. Voltag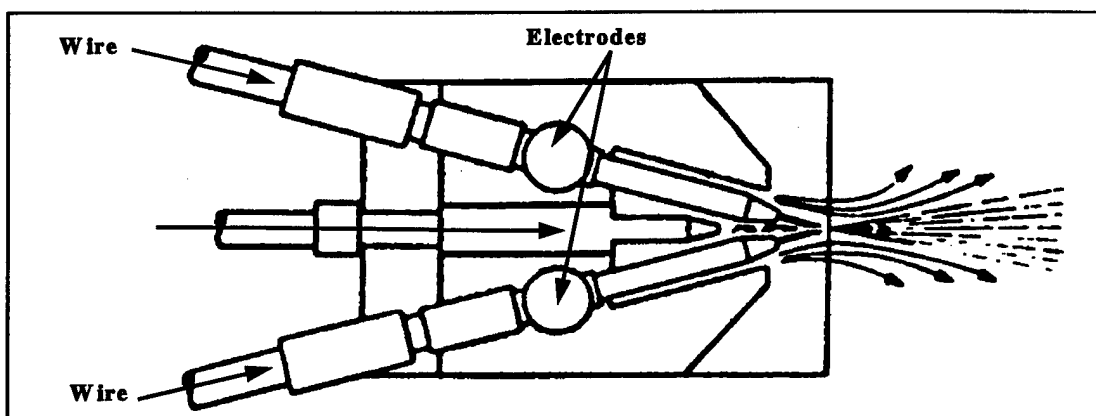e, amperage, and air pressure are remotely controlled from the console, and the wire feed is controlled by 2 closed-loop programmable logic controls (PLCs).

The wire drive motor is electronically synchronized with an auto feeder, which both pushes the wire from the control console and pulls it with servo motors in the gun itself. The operator can remotely adjust the wire feed rate between 0 and 25 cm/s (3000 ft/hr) to control the deposition rate and deposit thickness. An electric drive motor supplies 1.6 mm (1/16 in.) wire to the gun as far as 15 m (50 feet) away. The desired feed rate depends on the traverse rate of the gun and the desired coating thickness per pass. Compressed air delivered at up to 75 scfm will be provided to the control panel at 0.28-0.55 MPa (40-80 psig). A power supply unit weighing less than 109 kg (240 lb) will provide between 40A and 350A to the gun. The deposition rates for spraying zinc and aluminum are 6 lb/hr/100A and 24 lb/hr/100A, respectively. The gun is attached to the loading plate using a special mount that allows the manual trigger to be bypassed while the gun is in use, enabling accurate remote control of the system and ensuring control of the spray parameters.

Vacuum Blasting System

The service life and adhesion strength of a protective coating depends on the cleanliness and roughness of the substrate material. Many coating failures can be traced to improper surface preparation. Surface preparation must remove old coating materials, rust, dirt, and debris according to Steel Structures Painting Council (SSPC) specification SSPC-SP5, White Metal Cleanliness. Many paint removal systems meet these requirements. The primary method used is direct-pressure blasting, which provides high blasting rates but does not contain the resulting residue, debris, and grit. As noted in Chapter 2, a major concern associated with the deteriorating infrastructure is health hazards due to high levels of lead released from painted structures under frequent repair. The vast majority of older bridges (upwards of 90 percent, according to the New York State Department of Transportation, or NYSDOT) were coated with lead-based paints for corrosion protection. EPA and Occupational Safety and Health Administration (OSHA) requirements complicate the surface preparation of structures coated with lead-based paint.

Containment technologies for hazardous materials have evolved in recent years from simple and partial containment methods (i.e., tarps) to elaborate enclosures

that meet local, state, and Federal environmental regulations. Negative airflow is provided in such enclosures to prevent dust and debris from escaping into the atmosphere. Such containment technologies are effective but are also very expensive and labor-intensive. They also present logistical difficulties that can cause major disruptions in the day-to-day traffic on the bridge.

To avoid the necessity of using expensive full-enclosure technologies, a vacuum blasting system (LTC 1060-B, LTC Americas, Inc., 22446-T Davis Dr., Sterling, VA) was chosen for surface preparation. Vacuum blasting has a record of success in meeting local, state, and Federal regulations while performing at an adequate rate. Testing by North Carolina State University on a North Carolina Department of Transportation (DOT) bridge, whose coatings contained 18.4 percent lead by weight, demonstrated the effectiveness of the system by removing and containing the lead. Appendix A shows the Summary of Results from these North Carolina tests. All paint chips were contained by the machine, and 99.95 percent of the lead dust generated by the process was contained (Leming 1991). Results indicated that air quality standards were met downwind of blasting, and the residue collected was at hazardous levels. The recycled grit collected did not qualify as hazardous waste under current guidelines. In a 1990 test conducted by the Illinois DOT along the Dan Ryan Expressway in Chicago, the system was shown to be effective on a production scale; it was both cost-efficient and safe in removing and containing lead-based paints. Plate girders, cross frames, stiffeners, and diaphragms were blasted with a total surface area of 929 m^2 (10,000 sq ft) (Olsson and Bandel 1992). Federal Highway Administration Report FHWA RD-94-100 documents that no dust emissions were visible during two paint removal projects. The averages for these two projects were 7 µg/m^3 and 5 µg/m^3, measured over 8 hours (Smith and Tinklenberg 1994). The OSHA action level requirement is 30 µg/m^3, and the use of a respirator is required over 50 µg/m^3 (McPhee and Waagbo 1992).

The LTC 1060-8 system is fully pneumatic and integrates both abrasive blasting and containment. The blasting portion comprises a double-chamber pressure vessel, a 1.4 liter (0.5 ft^3) abrasive storage hopper, and a nozzle with a 30.5 m (100 ft) hose assembly. A 250 scfm capacity air compressor with a maximum working pressure of 0.79 MPa (115 psi) at the work head delivers high-velocity 7 mesh grit to the structure. A suction head, vacuum pump, material recovery drum, and dust filter collect the grit, residue, and debris and recycles the abrasive. Reusing the grit greatly reduces the amount of waste generated. The workhead includes a venturi nozzle and suction head that provides a 5 cm (2 in.) blast width. The workhead is connected to the loading plate and positioned flush against the substrate as it traverses the structure. While not accepted by all state departments of transportation as a substitute for the Class A enclosures currently specified for environmental

protection, the LTC 1060-B can provide the level of dust containment required by the EPA. The maximum cleaning rate is on the order of 24 m^2/hr (258 ft^2/hr) depending on the condition of the existing surface and the complexity of the structure. This rate is comparable to other cleaning methods currently available.

The vacuum blasting equipment provides the hose lengths needed to reach the suspended actuator frame from the ground, making it well suited for automated use. Another key feature is that it can prepare the surface for thermal spraying with a surface roughness of 75–100 micrometers (0.003–0.004 in.), which is ideal for receiving thermally sprayed coatings of zinc and aluminum.

Video Inspection System

Video inspection equipment is currently used to inspect bridges and its use is well documented for inspection in automated industrial systems (*Olympus Industrial* 1992). This type of equipment, which is reasonably easy to integrate into the ATSS, can be used to inspect substrate surface conditions before and after thermal spray operations. The operator will compare the prepared surface to the SSPC finish standards to ensure proper surface conditions. After thermal spraying, the operator will inspect the finished surface to evaluate coating quality and consistency.

Video technology will initially be used for a pass/fail inspection. The operator will visually compare the surface shown on the monitor with accepted standards. Image analysis technology is currently being investigated for future implementation. It is envisioned that, in the future, operators will be able to download real-time images from the video system and compare them digitally to selected images representing standards for proper surface preparation. Image processing hardware and software (e.g., *Image*, National Institutes of Health, Research Services Branch, Bethesda, MD) will be used to acquire, display, and analyze surface conditions. The images will be expressed as two-dimensional arrays of pixels, represented by 8-bit unsigned integers, ranging in value from 0 to 255, displayed on the monitor as white for zero-value pixels and black for a value of 255. However, throughout initial system development, the operator must make a qualitative judgment based on visual comparison of the displayed surface image with photos of surfaces prepared according to industry standards.

The major components of the ATSS video inspection system are a camera, environmental housing, video monitor, zoom lens, lens controller, video board, power supply, and software. A solid-state 2/3 in. high-resolution black and white camera (Vicon Model VC2400-24, Vicon Industries, Inc., 525-T Broad Hollow Rd., Melville, NY 11747) with a charged-coupled sensing device (CCD) will be used to provide

high-resolution images. The camera has a motorized zoom lens to 10X magnification, with auto iris (Vicon Model 11-110AC) to facilitate detailed remote inspection. The motorized zoom lens controller has a six-button control for zoom in/out, focus near/far, and iris in/out. Video amplitude is adjusted by the operator as it appears on a 9 in. black and white monitor (Vicon Model VM 5092) or in an automatic mode with a servo motor driving the iris. The camera will be protected by a dustproof enclosure that contains a heater, blower, and thermostat assembly to provide proper environmental conditions during ATSS operations. The monitor, power supply, and zoom lens controller are located at the control station.

The ATSS operator can also record the image obtained by the video camera on a standard video cassette recorder. These images can be used later to reference the type of damage to the steel, and can also help the operator review a section of the substrate to determine the effectiveness of the cleaning.

Loading Plate Conceptual Design

For the vacuum blaster to effectively contain all harmful debris generated by the grit-blasting process, the nozzle head must be kept flush against the substrate. Many bridges and dam floodgates are curved slightly and thus present a technical challenge for ATSS because the linear actuators cannot compensate for this curvature. A simple solution to this problem was found by designing a spring-mounted loading plate that can be compressed by moving the Z-axis actuator closer to the steel substrate. As the springs are compressed the mounting plate pushes against the substrate ensuring an acceptably tight tolerance between the nozzle and the steel. In the event that the substrate is curved, the springs push the mounting plate forward to maintain proper contact. This self-adjusting mounting plate can move up to 10 cm (4 in.) to accommodate curvature of the working substrates. It also has an attachment for the thermal spray gun nozzle. The plate is connected to the Z-axis via special aluminum wedges that fit inside grooves machined into the axis itself. These wedges ensure a proper orthogonal placement of the mounting plate against the substrate.

An important aspect of the loading plate design is its role in preventing abrasive blasting wastes from entering the environment. Dr. C. Chou of the Materials Research Group, NYSDOT, evaluated the design as an alternative to Class A containment. As a result of this evaluation and his observation of abrasive blasting tests in the laboratory, Dr. Chou determined that air monitoring would not be necessary during the field test.

Vacuum Blaster Nozzle

Loading Plate

Springs
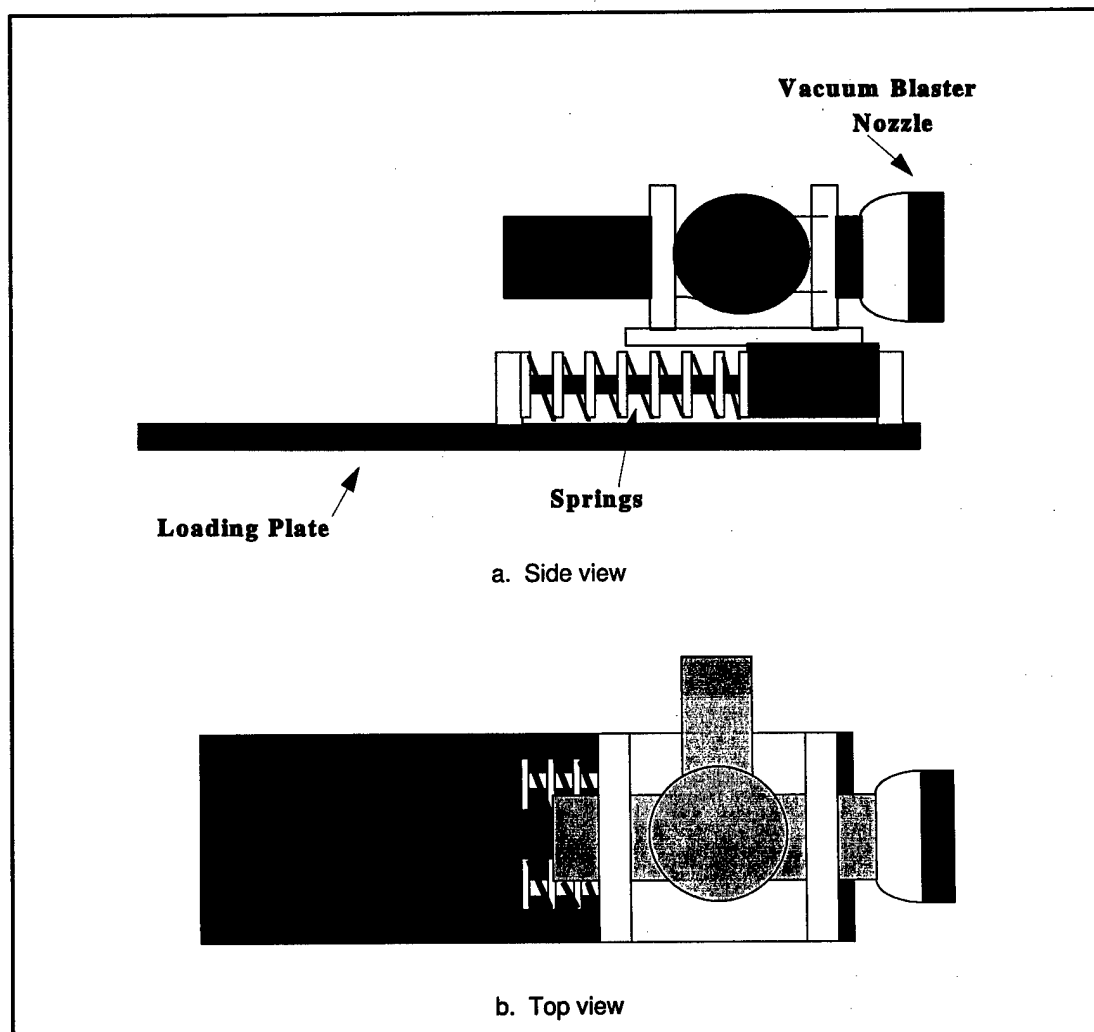
a. Side view

b. Top view

Figure 16. Loading plate schematic.

Figure 16 illustrates the design of the self-adjusting mounting plate.

Final Prototype System Configuration

Specifications for the ATSS as field tested with the New York State Department of Transportation in December 1994 may be found in Appendix B. Photographs of the fully integrated ATSS are presented in Chapter 5.

5 Demonstration of Prototype ATSS

Site Selection

In recent years, increasing limitations have been put on bridge maintenance projects due to growing public awareness of the potential adverse environmental consequences of such projects. The direct result of such limitations has been a considerable increase in the cost and duration of even relatively uncomplicated infrastructure maintenance tasks due to, for example, the requirement to use full Class A containment for lead-abatement projects. The prototype ATSS addressed all specifications presented by NYSDOT and the EPA without the need for Class A containment. Vacuum blasting was preapproved by NYSDOT and a field test was scheduled to evaluate the concepts of vacuum blasting and thermal spraying in public infrastructure applications and to specifically test the field-effectiveness of ATSS. NYSDOT waived the requirement for onsite environmental monitoring for this demonstration only, based on the findings reported in FHWA RD-94-100 and previous investigations of air quality standards related to the use of the LTC Model 1060 Air/Vacuum Blasting Machine (see Appendix A). The waiver of environmental monitoring allowed the field testers to focus on system setup, operation, and teardown, and to avoid the additional costs of air monitoring. However, it is acknowledged that environmental monitoring must be conducted in future field testing to collect quantitative data pertaining to operation of the equipment in the specific ATSS configuration demonstrated here.

On 9 December 1994 a general field test of ATSS was performed on bridge No. 1056230 over County Route 58 near Riverhead, Long Island. The test included a field setup procedure, grit-blasting to remove lead-based paint from part of the structure, and thermal spraying of the exposed steel substrate. Both the grit-blasting nozzle and the thermal spray gun were mounted on the ATSS as described in Chapter 4 and controlled from the ground.

Roles Of CPAR Partners in Demonstration

This demonstration required the active participation of NYSDOT Region 10, which is responsible for all road and bridge work on Long Island. The Bridge Maintenance
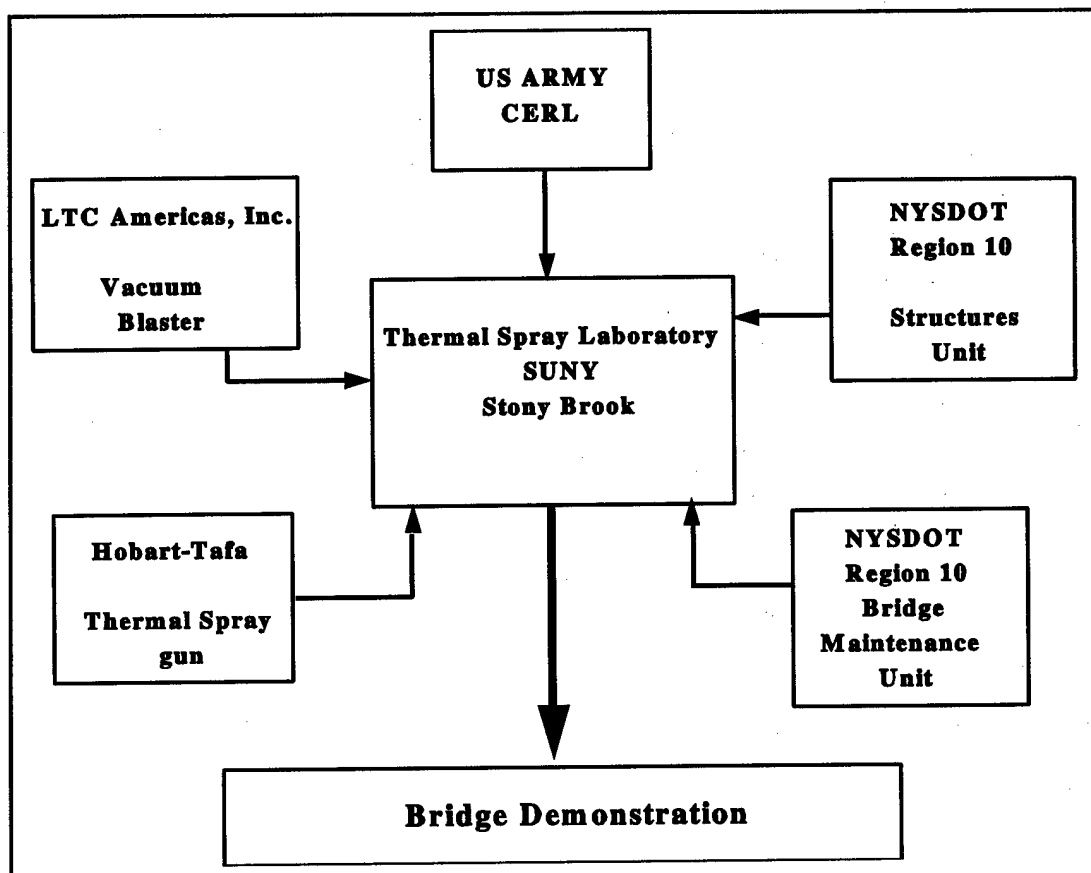
Figure 17. Interagency participation diagram.

Division of Long Island provided all technical support including workers and state vehicles as required. An agency responsibility list was drafted to ensure full participation by all CPAR partners while avoiding duplicated efforts. The agency participation diagram is shown in Figure 17.

Thermal Spray Laboratory at SUNY

The Thermal Spray Laboratory (TSL), in collaboration with USACERL, was responsible for the design of the ATSS and for the coordination of the demonstration. The first step was to contact NYSDOT and present a detailed description of the automated system and its possible benefits. Once it was shown how the demonstration would benefit the state, the Army, and TSL, Region 10 was contacted. A timetable was set up and the Bridge Maintenance Division of Long Island was asked to provide technical assistance. The following list details TSL's tasks for the ATSS demonstration:

1. Coordinate support services with participating parties
2. Provide ATSS equipment operator
3. Provide ATSS technical support
4. Set up system in the field.

NYSDOT Region 10

The ATSS maintenance tools and automated platform required a sizable electric generator and air compressor. ATSS also required a boom to hoist it to the desired location. Transportation to the site was the responsibility of the Region 10 bridge maintenance group, and included two flatbed trucks that carried ATSS equipment, and a welding truck carrying a 110 Vac generator. The compressor and the three-phase ac generator were carried on trailers hitched to the flatbed trucks. At the site, the bridge maintenance group set up mobile scaffolding, as shown in Figure 18, to ease access to the ATSS after it was hoisted to the bridge plate. All traffic was routed away from the right lane to minimize hazards to personnel and passing motorists. The main responsibilities of NYSDOT Region 10 were as follows:

1.   Identify suitable test site
2.   Transport workers and equipment to and from the site
3.   Position the boom
4.   Provide one 240 V three-phase ac generator and one 120 V ac generator
5.   Provide one air compressor (115 psi @ 250 scfm)
6.   Provide traffic control
7.   Erect mobile scaffolding.

LTC Americas, Inc.

The vacuum blasting unit was rented from LTC Americas on a daily basis and included the services of a technician. The unit consisted of the blast media injector and the vacuum unit, which were mounted in a truck. These were connected to the nozzle by rubber hoses attached to the ATSS tether line with cable ties. LTC's task list was to:

1.   Provide vacuum blaster unit, including air dryers, filters, and blasting grit
2.   Deliver the system
3.   Provide technical support for onsite testing
4.   Provide pressure fittings for hoses and connectors.

Final Control Checklist for All Participants

When field setup was complete, the following checklist items were examined to ensure the proper function of all hardware:

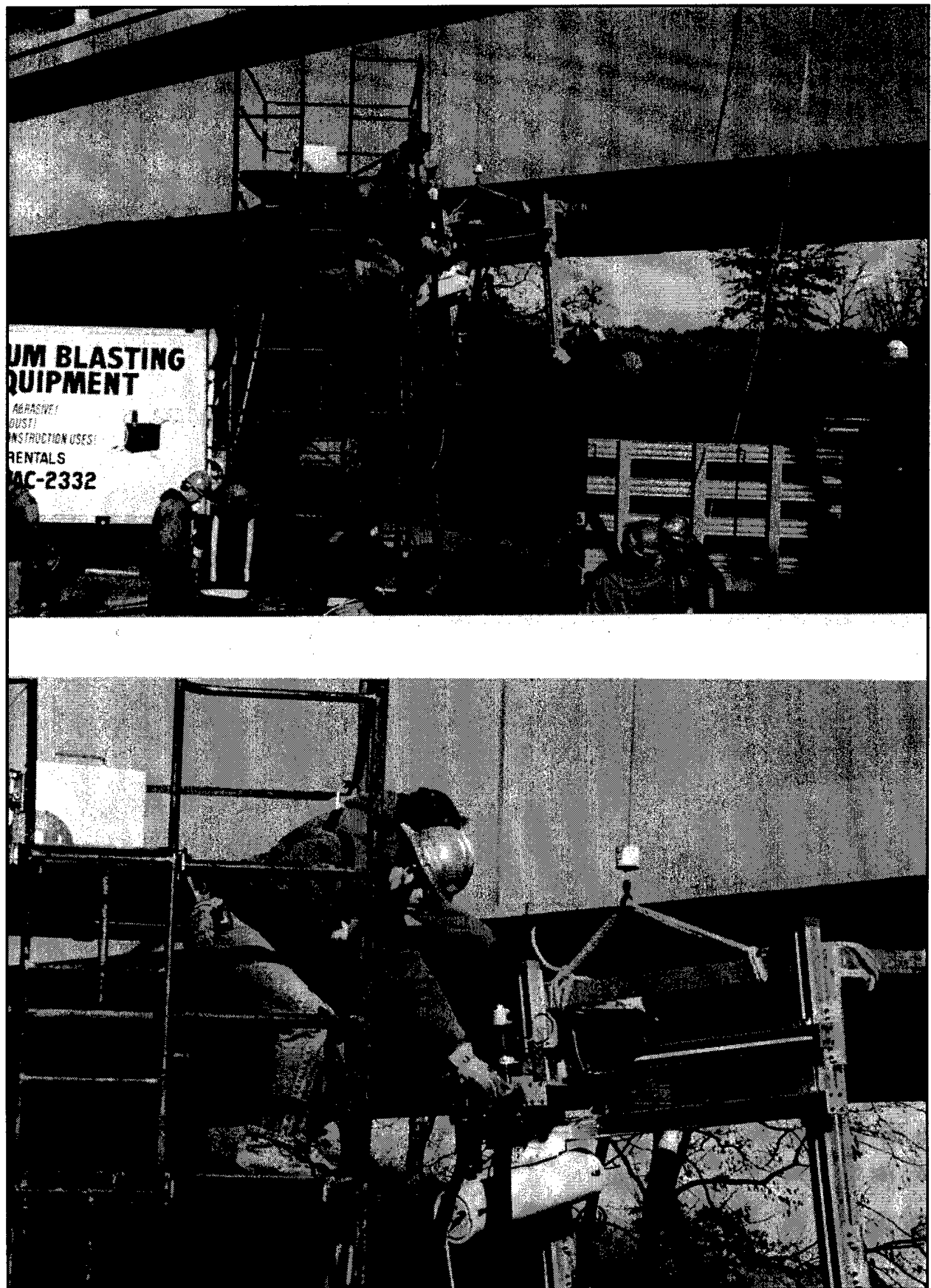1.   All power is connected to various elements

Figure 18. Onsite setup procedure.

2. All pressure fittings are secured
3. ATSS power is connected and motors are locked
4. All cables are secured
5. Computer is on and communication with the robot is working
6. Electromagnet system is operational
7. Crane is secured to ATSS
8. All control consoles and other equipment are far enough away from test site
9. All maintenance crews are far enough away from test site
10. All axes are in their proper starting positions.

Field Test Configuration

The schematic in Figure 19 shows how the diverse power requirements of ATSS were supplied by the two power generators positioned next to the test site. The 240 V ac three-phase generator powered the electromagnets and the thermal spray device. The generator cable was routed to a power connection box, into which 2 four-conduit power cables were connected in parallel. One cable was hard-wired to the spray gun control console while the other was connected to the electromagnet control box.

For the computer, video inspection system, and motor control, the 110 V ac generator was used. This generator was mounted on the truck that carried the crane. A power cable was routed to a power conditioning box which was in turn connected to a conventional power strip. This was done to eliminate power surges and harmonics that could affect motor operations or compromise the integrity of the ATSS electronic systems. Table 4 summarizes the onsite power and compressed air requirements.

Table 4. Field test power and air pressure requirements.

Subsystem	Power Requirements	Air Pressure Requirements
Computer Control	110 V ac	none
Motor Control	110 V ac	none
Inspection System	110 V ac	none
Electromagnets	240 V ac	none
Thermal Spray Gun	240 V ac 3 phase	75 psi @ 125 scfm
Vacuum Blaster	none	125 psi @ 375 scfm
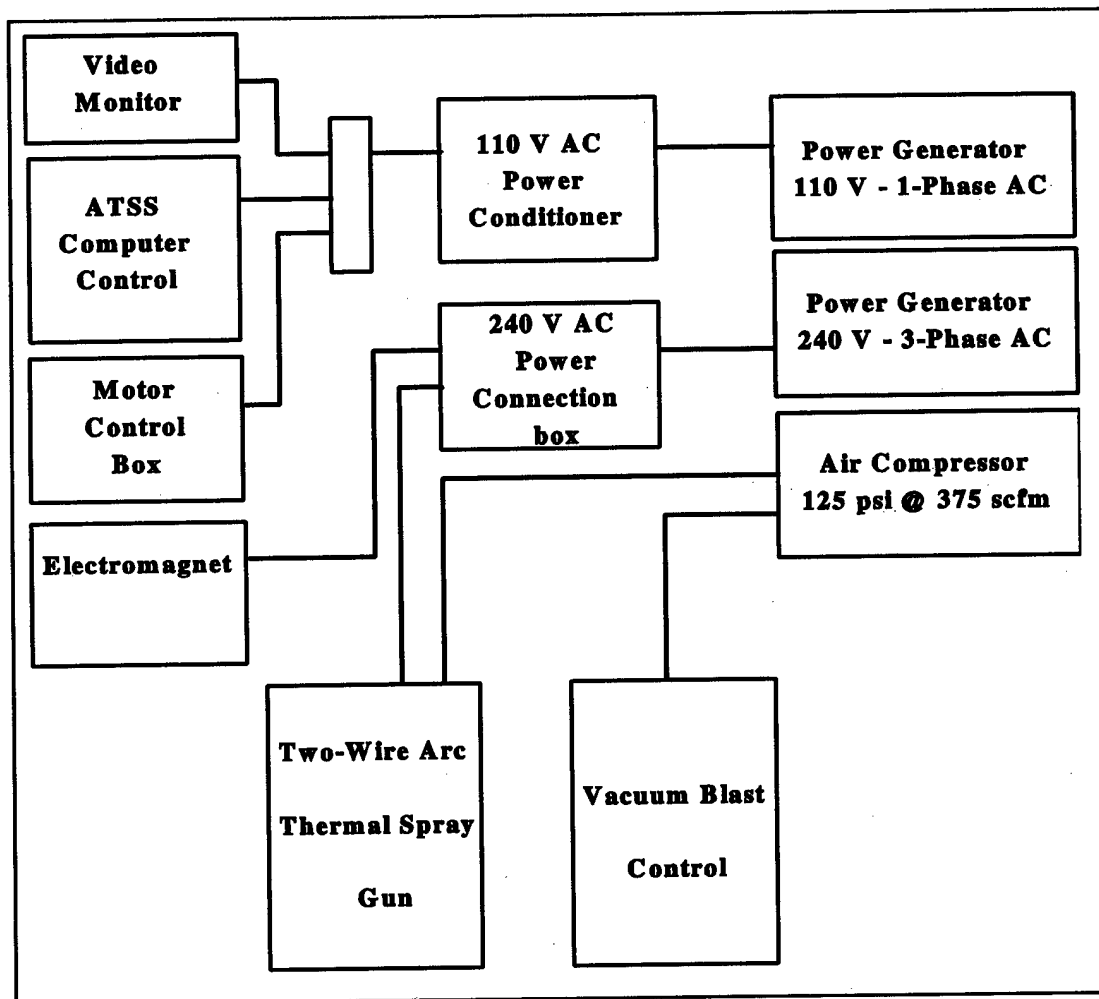
Figure 19. Onsite setup of automated system elements.

Test Procedure

All vehicles and trailers were positioned to allow ready access to every unit. The compressor and generators were connected to the control unit and the thermal spray gun. A truck carrying the crane positioned itself on top of the bridge so it could lift the ATSS to a new position after a blasting/coating cycle was completed. The vacuum blasting unit was mounted on a truck that positioned itself to allow the vacuum hoses to be connected to the ATSS. A portable scaffold unit was set up next to the test site to provide direct access to the ATSS.

Once all power and air couplings were connected, all generators were powered up and the connections verified in order to ensure that each system was running. At this stage, the ATSS was hoisted up to the bridge plate, shown in Figure 20, where it attached itself via the electromagnets.

After final connections were made (Figure 21) the two-wire electric arc gun was tested and a problem with the wire-feeding motors was discovered. The problem was traced to a faulty power cable connection. When the problem was resolved, the test procedure began. A diagram of the test site is provided in Figure 22.

First the bridge substrate surface was cleaned and prepared for spraying. When ATSS was in its starting position (Figure 23) the system began its pre-programmed movement sequence with a side-to-side traverse speed of 5 in./sec and the vacuum blasting unit was activated (Figure 24). When the demonstration blasting cycle was completed ATSS had produced a rectangular area of bare white metal approximately 2.5 square feet in area. The thermal spray gun was then positioned to the correct spraying distance. The same preprogrammed movement sequence was repeated as the thermal spray gun was activated, as shown in Figure 25. The side-to-side traverse velocity for the spraying stage was somewhat slower than it was for blasting—about 1.5 ft/sec. The layout of the spray gun and blast nozzle on the service platform made it necessary to leave a
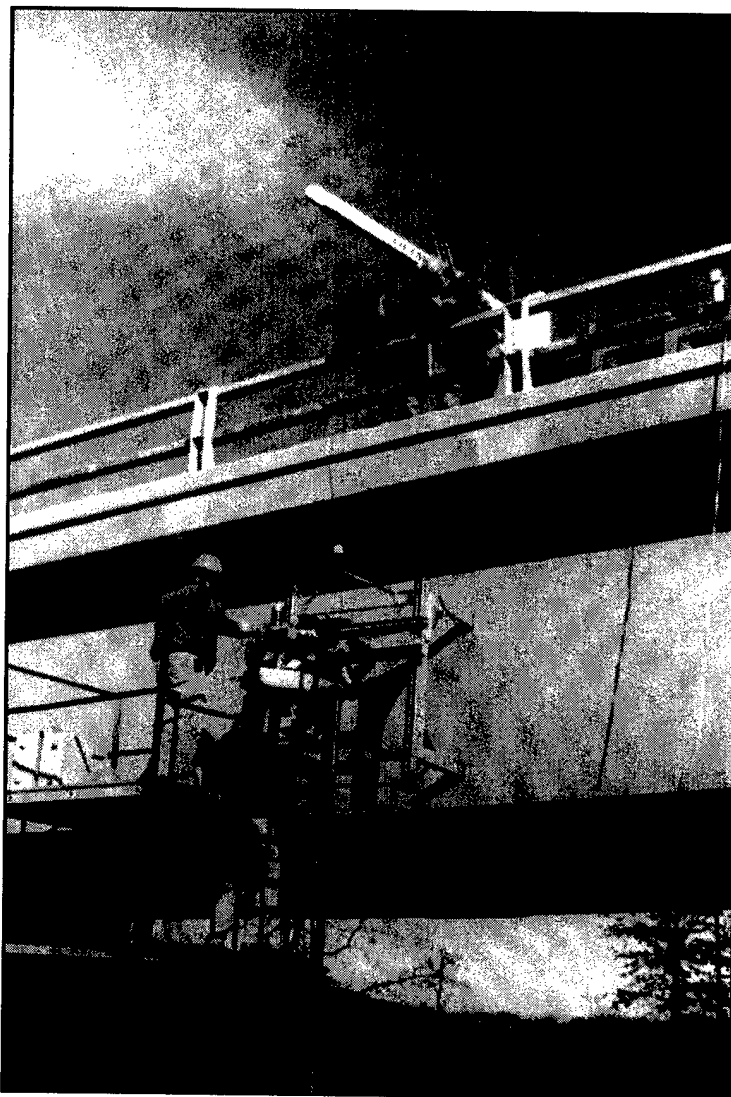
Figure 20. ATSS being positioned on the bridge plate.
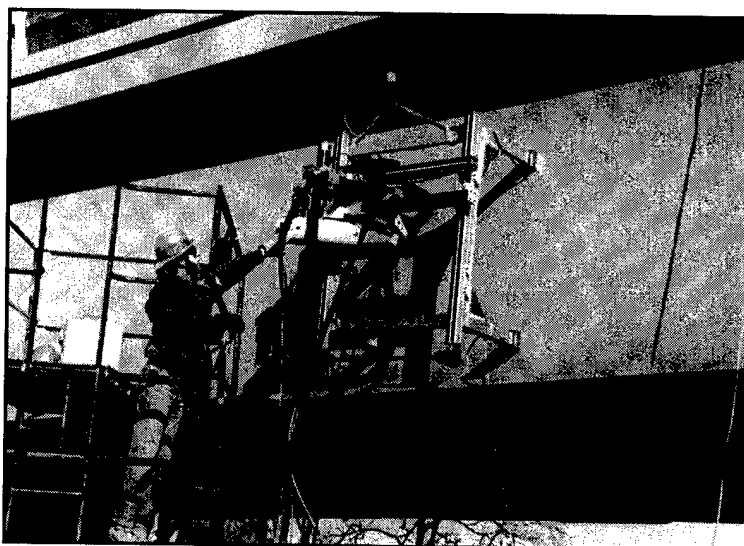
Figure 21. Final connection of infrastructure maintenance tools.

service platform made it necessary to leave a gap of about 1.5 in. between the blasted edge and the coating. This gap poses no corrosion problem for the bridge plate because of the galvanic corrosion resistance provided to the bare metal by the zinc alloy, as described in Chapter 2.

It is noted here that logistics, traffic-control requirements, and the limited availability of NYSDOT maintenance personnel to conduct the field test all created constraints on how much live demonstration time was available. The crew was able to execute one complete cycle of site setup, ATSS positioning on a bridge I-beam (stringer), automated surface preparation, automated thermal spraying, remote monitoring, and equipment removal.
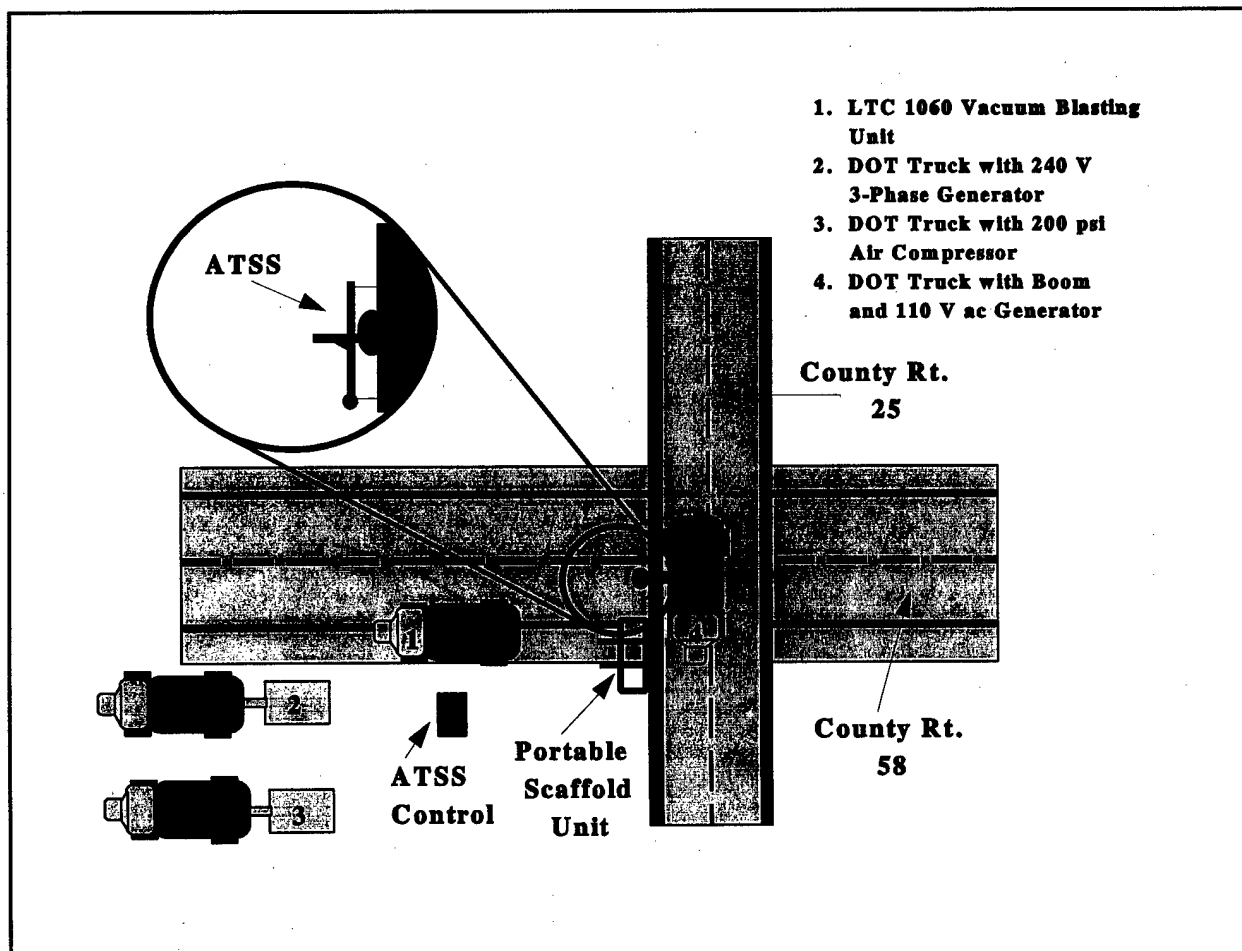
Figure 22. Layout of all equipment at test site.
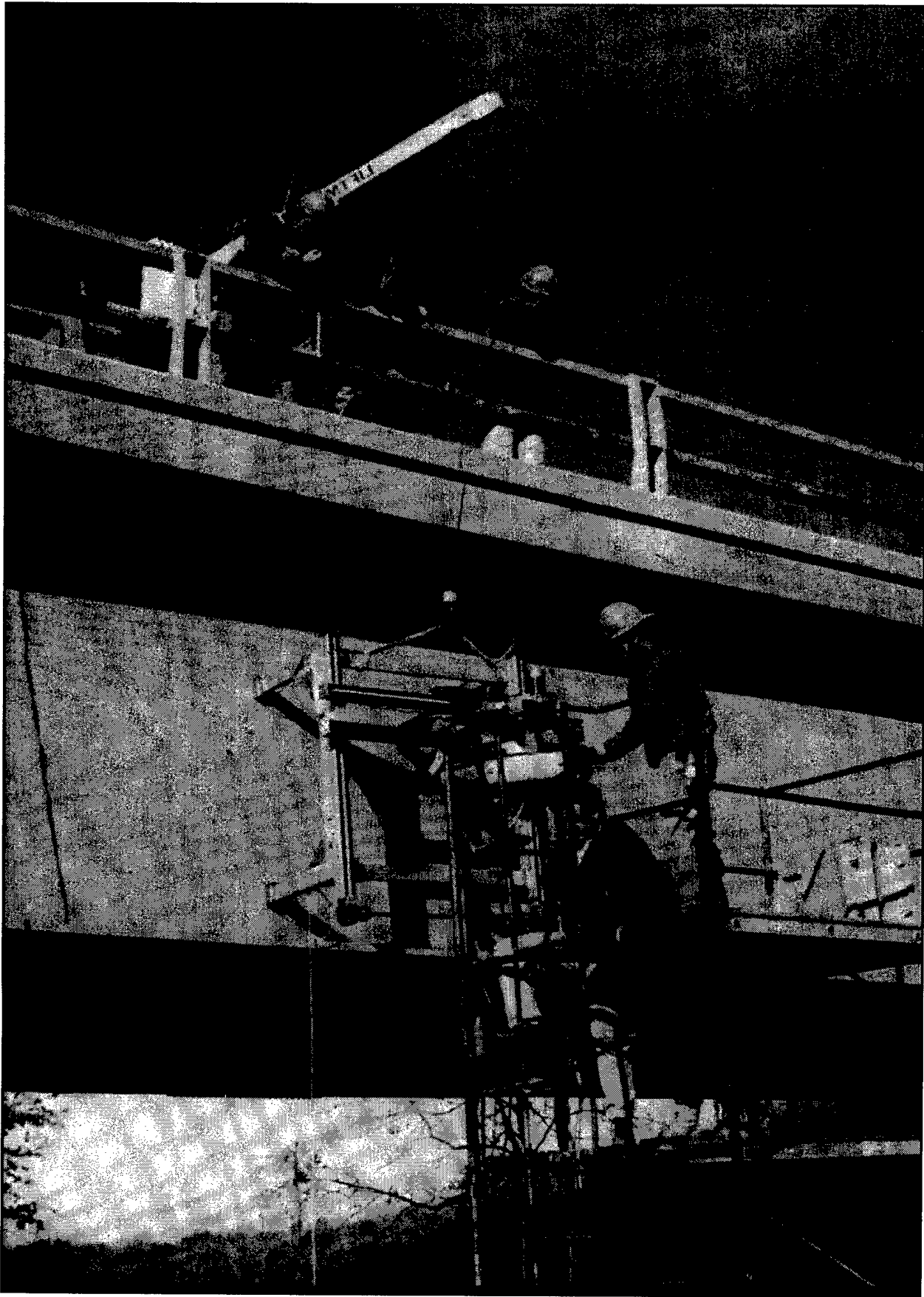
Figure 23. ATSS in final position, ready for maintenance cycle to begin.
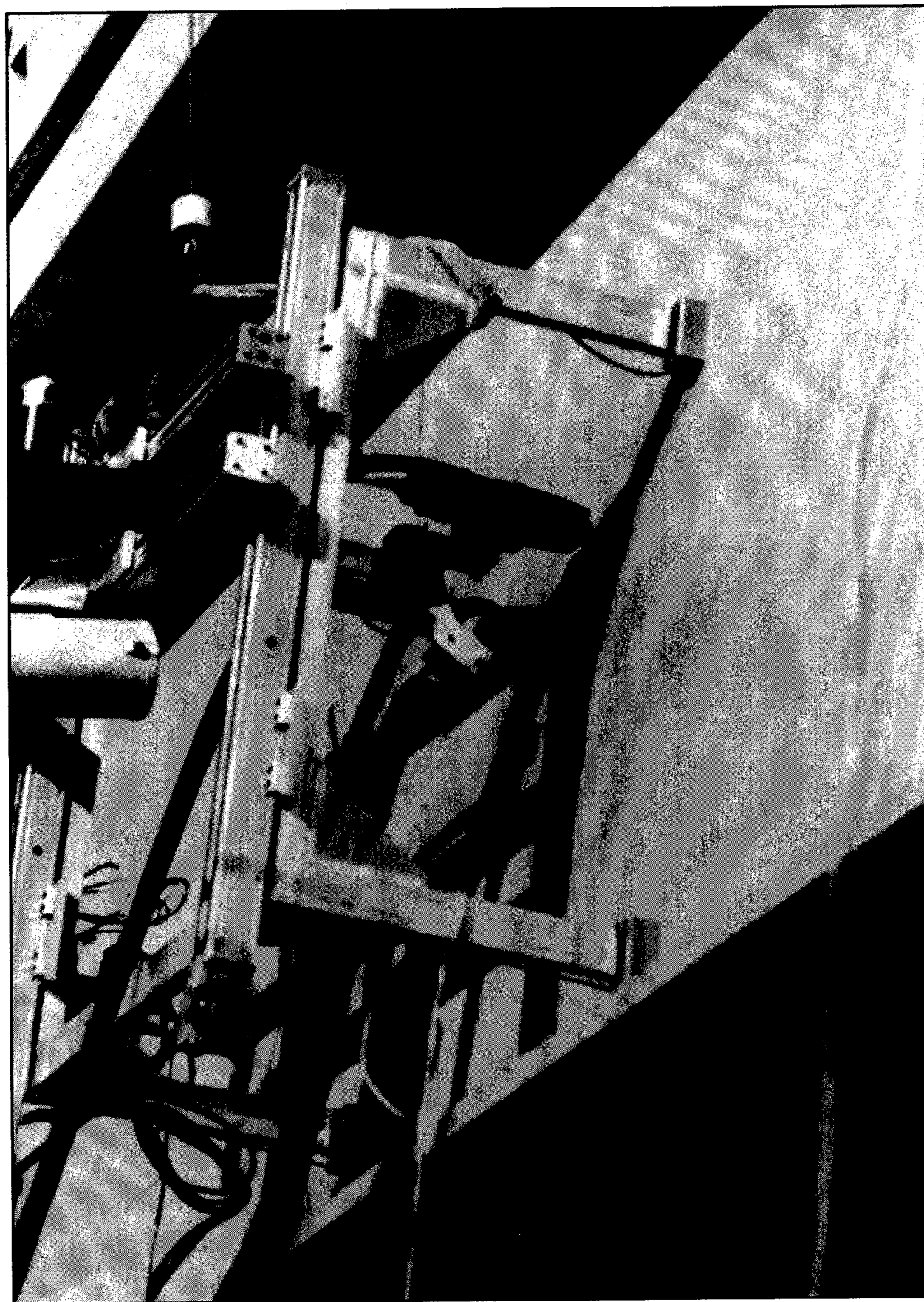
Figure 24. ATSS during vacuum blasting stage.
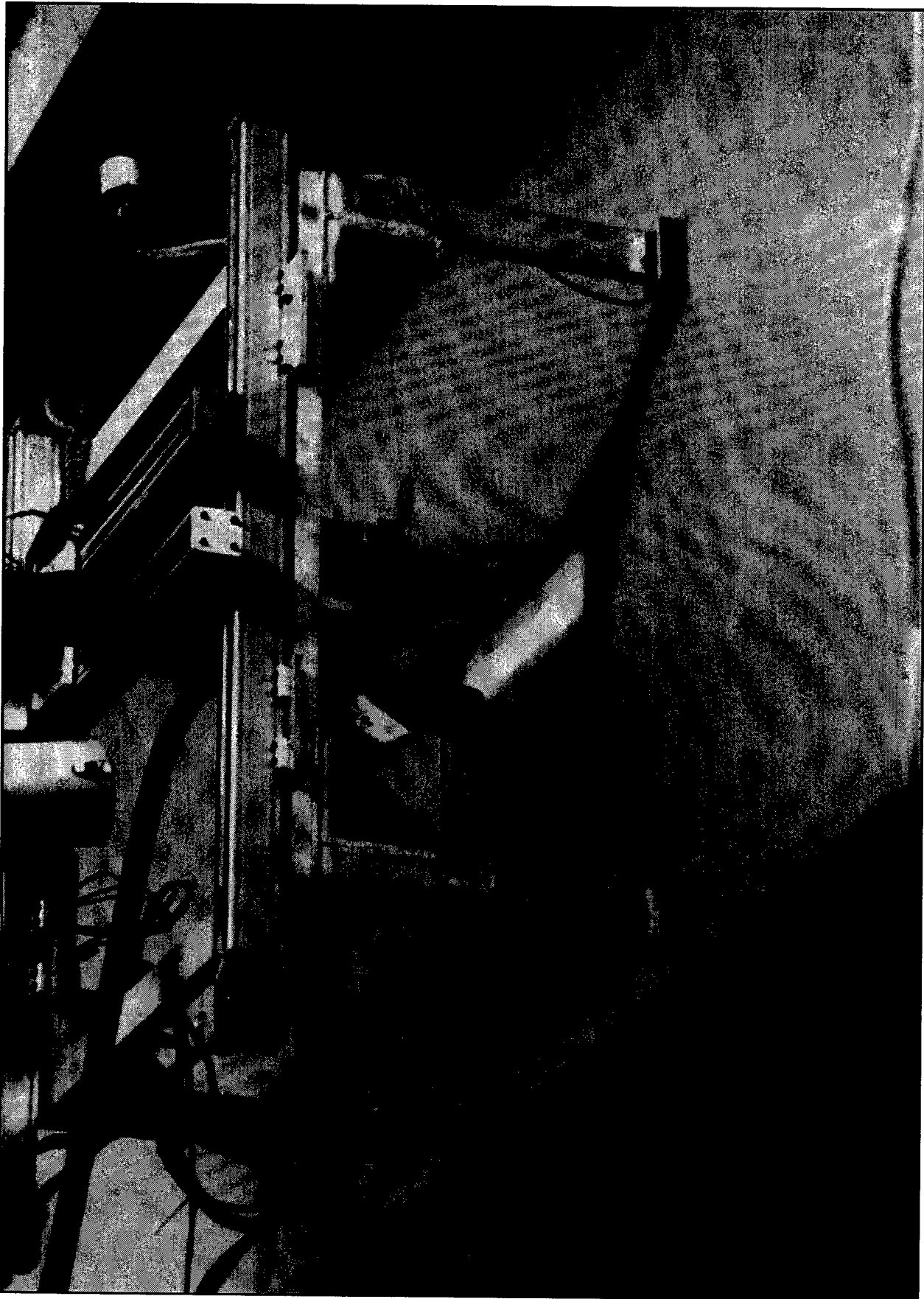
Figure 25. Thermal spray application of metal coating over grit-blasted steel substrate.

Discussion of Field Performance and Economics

System Performance

The prototype ATSS successfully blasted painted steel and recoated it with a therm-ally sprayed deposit of zinc/aluminum alloy. Engineers from USACERL and TSL judged the coating to be acceptable for corrosion-protection purposes.

Because this was the first-ever use of ATSS in the field, some problems were encountered with logistics and equipment operations as part of the crew's learning curve. For example, blasting was interrupted several times to ensure that paint residues were completely contained by the vacuum system. A number of such interruptions made it difficult to log the actual times elapsed for a single blast-ing/coating cycle and moving ATSS to its next position. Cost estimates given in the next section are based on the expert opinions of engineers and other personnel on the scene from USACERL, SUNY, and the participating transportation authorities.

The demonstration made it clear that the prototype ATSS required at least a three-person crew to function as intended. The small work area of the ATSS and its modest ability to navigate complex geometries (i.e., 4 in. girders) limited the scope of the demonstration. However, the demonstration results do prove the feasibility of using an automated platform for blasting and thermally coating steel substrates in field conditions. An important aspect of the test was successful demonstration that lead-based paint can effectively and safely be removed without using costly, cumbersome containment systems. Although the field crew was not equipped with environmental monitoring equipment, it was able to blast a portion of the bridge surface to white metal without any visible release of waste into the environment.

Coating Performance

After 12 months of exposure and again after 24 months of exposure, SUNY project personnel visited the site to visually assess performance of the thermal spray coating. No coating deterioration was observed (SUNY quarterly project reports to USACERL, December 1995 and December 1996).

Economic Considerations and Prospective Follow-up Testing

ATSS will have to be used in a full-scale rehabilitation project before comprehensive data can be compiled on the system's economic benefits. However, a few points are clear as a result of the demonstration: the largest part of demonstration costs are dedicated to traffic rerouting, scaffold erection, and onsite configuration of the

required power generators and air compressors. Therefore, the resources dedicated to site setup could be greatly leveraged if the next ATSS field test were to comprise a full-scale maintenance project that is already in the state's M&R queue. After all support elements (e.g., air compressor, power generator, elevation hoist) are in place, ATSS requires only a three-person crew for operation.

Engineers observing the demonstration estimated that a three-person crew with a few days of ATSS experience could set up a site in 1 hour and change the location of the system in 5 minutes. Assuming that all equipment is operating properly, the work crew could average 6 hours of continuous ATSS operation per day. Based on the specifications for the ATSS linear actuators and abrasive blasting head (LTC Americas,

Table 5. ATSS estimated base operation cost.

Element	Cost
3 Man Maint. Crew ($25/hr)	$600/day**
Wire (400 lb)	$800/day
Consumables*	$50/day
Grit Blast Media	$50/day
Price $/sq ft	$5.20
* Thermal spray gun caps, fuel, etc. **Based on the average NYSDOT worker salary billed to TSL for this demonstration.	

Inc., March 1994), the average coating time for 4 sq ft would be about 5 minutes. Therefore, the maintenance crew could cover more than 288 sq ft per day. The cost for coating this area, based on out-of-pocket materials costs and labor charges (estimated using the amount NYSDOT billed TSL for state workers participating in the demonstration), averages at $1548, or $5.20/sq ft. Table 5 lists estimated ATSS operating costs, including all materials and consumable parts. It is important to remember that this cost covers everything in the rehabilitation cycle, including cleaning and preparing the substrate, thermal spraying, and complete inspection of the results, but does not include the cost of any environmental protection that may be required. The ability to accomplish all maintenance tasks in rapid succession makes ATSS economically attractive. The best demonstrated lowest-cost abrasive blast technology for removing LBP from steel bridges has been documented at $5.00 to $5.50 per square foot. Therefore, if the ATSS can achieve both paint removal and recoating for approximately $5.00 per square foot, the life-cycle cost improvement makes ATSS an attractive M&R option.

Use of ATSS or a system of similar capabilities for a complete rehabilitation project is feasible as long as the system's limitations are understood and accounted for. Due to its limited capabilities, the ATSS can only perform its tasks on large, relatively flat expanses. A conventional crew would be required to work alongside ATSS to handle complicated sections of the structure. Once any structure is set up for a major maintenance project and all the technical support is in place, the specific cost for using the ATSS will decrease significantly, as shown above. A reduction in the time required for rehabilitation can be achieved readily since ATSS handles all tasks in the maintenance cycle in a single pass.

Using automation in the thermal spraying of bridge sections ensures uniform coating quality, which will increase the longevity of both coating and substrate. A well applied thermal spray coating can provide total protection for decades, even in harsh environments.

6 Conclusions, Recommendations, and Commercialization

Conclusions

The ATSS prototype developed in this research is a fully automated platform that includes a manipulator, positional feedback sensors, and a comparator to calculate positional error. The end effector is capable of holding and maneuvering any type of thermal spray device (either flame spray or two-wire electric arc technology), a paint-removal system (such as the LTC 1060 vacuum blasting system), and a visual inspection system. The ATSS design is appropriate for application to flat, curved, or non-flat structural steel elements such as girders and beams. Potential applications include structural steel on bridges and steel surfaces on civil works structures such as navigation lock gates, tainter gates, and wicket gates.

In the field demonstration, the ATSS self-contained vacuum blasting system successfully removed a coating of deteriorated lead-based paint from a steel I-beam (stringer) on a bridge located on New York County Road 58 near Riverhead, Long Island. The ATSS then applied a thermal-sprayed zinc/aluminum coating over the blasted white metal surface, and allowed workers to inspect the as-applied zinc/aluminum coating using an integrated video monitoring system.

The successful field demonstration confirms that the ATSS is capable of automated remote removal of hazardous lead-based paint.

The ATSS estimated base operating cost of $5.20 per square foot is lower than the best demonstrated lowest-cost technology for removal of LBP and recoating (or metallizing) of a steel structural components such as bridge stringers or lock and dam gates. (Base operating cost may vary depending on contractor overhead and profits.) A recent demonstration of LBP technology that required 85 percent wind screen containment for dry abrasive blast technology cost $5.00 to $5.50 per square foot for LBP removal only. Considering base operating costs, the combination of coating removal (including LBP) and recoating with metallizing makes the ATSS a very attractive alternative technology. Furthermore, the ATSS exceeds the application requirements of Corps of Engineers Guide Specification (CEGS) 05036,

Metallizing: Hydraulic Structures, by removing the need for human operators near the steel work surface.

Recommendations

It is recommended that the prototype ATSS evaluated in the field demonstration should be modified to include ATSS structure-to-weight reduction, operational power efficiency increases, and improvements in system ergonomics. It is important to note that the general ATSS design may be tailored to meet the requirements of individual applications much as highway infrastructure, civil works infrastructure, and industrial infrastructure such as storage tanks and vehicles.

It is recommended that a draft specification for design, operation, and maintenance of the ATSS be prepared by SUNY, reviewed by USACERL, and submitted to the Steel Structures Painting Council (SSPC) for review and possible adoption.

It is recommended that additional field testing be conducted to document the ability of ATSS to operate in compliance with applicable environmental and worker exposure standards without the use of full environmental containment or worker protection systems.

It is recommended that USACERL and SUNY apply to patent the ATSS. The patent application should detail the form and fit of the ATSS platform, and its ability to remove human operators from hazardous or difficult working conditions during paint removal and recoating of steel structures.

Technology Transfer and Commercialization

SUNY Post-CPAR Development

The field test documented in this report was a significant milestone in the ATSS development plan. After the demonstration, various state departments of transportation were asked to evaluate the ATSS prototype for operational effectiveness and cost efficiency. An important question that arose from this inquiry involved the ATSS's level of dependability in field environments. To address these concerns as well as the results of the CPAR demonstration, SUNY conducted ATSS follow-on testing on the SUNY – Stony Brook campus. After this testing, the ATSS prototype was deconstructed and modified to make it more rugged and user-friendly for actual field operations.

Production Plans

Cost-cutting approaches will be introduced for both system construction and materials. The intention is to achieve per-unit production costs of less than $10,000. Modifications incorporated into the production-design ATSS include weight reductions, operational power efficiency increases, and enhanced system ergonomics. It is important to note that production details will ultimately depend on the actual intended end use for which devices based on the ATSS are intended. For example, specific production details must be developed depending on whether a production version will be used on marine navigation infrastructure, rail transportation structures, highway infrastructure, industrial infrastructure, etc.

USACERL recently (April 1997) transferred ATSS prototype plans and specifications to a U.S. Department of Energy contractor in Oak Ridge, TN. The contractor's goal will be to fabricate an ATSS system for removing radioactive coatings from steel storage tanks and recoating the tanks using metallizing technology. USACERL has referred the contractor to contact the CPAR Partner (SUNY) about fabrication of the ATSS.

Marketing Plan

Discussions have been conducted with three manufacturers: Flame-Spray Industries, Inc.; Sulzer-Metco, Inc.; and Eutectic-TAFA. Flame-Spray Industries, Inc., has indicated willingness to develop and deploy an ATSS-based operational platform for the company's proprietary single-wire plasma spray technology system as well as for other conventional thermal spray technologies.

The results of this project have been communicated to industry peers in three presentations before the American Society of Metals (ASM):

- *Challenges and Applications for Thermal Spray Technology in the U.S. Army Corps of Engineers*, National Thermal Spray Conference (NTSC '94), 20–24 June 1994, Boston, MA (ASM International, Material Park, OH)
- *Automated On-Site Thermal Spraying for Corrosion Control*, National Thermal Spray Conference (NTSC '93), 10 June 1993, Anaheim, CA (ASM International, Material Park, OH).
- *Automated Thermal Spray Technology for Rehabilitation and Maintenance of Civil Works Infrastructure*, United Thermal Spray Conference, 15–18 Sept. 1997, Indianapolis, IN.

In addition, an invited article published in *Hydro-Review*, vol XVI, No 1, February 1997, describing the results of the demonstration and the potential benefits of ATSS technology to the North American hydroelectric industry.

References

"A Statement of Qualifications for the Removal of Lead-Based Paint With LTC Blasting Machines" (LTC Americas, Inc., March 1994).

Apostolos, J.A., D.M. Parks, and R.A. Carello, *Cathodic Protection Using Metallized Zinc: A 3.5 Year Progress Report*, Paper 137, Corrosion 87 (San Francisco 1987).

B.S. 5493:1977, *Code of Practice for Protective Coatings of Iron and Steel Structures Against Corrosion* (British Standards Institute, London).

Benary, Raphael, "Design of an Automated Thermal Spray System," master's thesis (State University of New York at Stony Brook, May 1995).

Birch, J.R., "Zinc Metallizing Protects a Bridge," *Welding Design & Fabrication* (October 1986).

Carello, R.A., D.M. Parks, and J.A. Apostolos, *Development, Testing, and Field Application of Metallized Cathodic Protection Coatings on Reinforced Concrete Substrates*, Report No. FHWA/CA/TL-89/04 (California Department of Transportation, Sacramento, 1989).

Code of Federal Regulations, title 40, part 50.

Code of Federal Regulations, title 29, part 1926, section 62.

"Connecticut Snooper Sees More Now," *Olympus Industrial*, vol 10 (Lake Success, 1992), p 2.

Corrosion Tests of Flame-Sprayed Coated Steel: 19-Year Report, C2.14-74 (American Welding Society, 1974).

Leming, M.L., *Investigation of Blasting Machine Residual and Air Quality Standards for Lead Contamination Potential Using the LTC Model 1060 Air/Vacuum Blasting Machine*, Technical Report (Dept. of Civil Eng., North Carolina State University, Raleigh, NC, 1991).

Technical Specifications—LTC Model 2000, 990-991, pamphlet (LTC International, Inc., Sterling, VA, not dated).

Manning, D.G., "Cathodic Protection of Concrete Highway Bridges," *Corrosion of Reinforcement in Concrete*, K.W.J. Treadway and P.B. Bamford, eds. (Elsevier Science, Essex, 1990), pp 486-497.

McPhee, W., and S. Waagbo, "Evaluation of Abrasive Recycling Characteristics of Several Abrasives in Vacuum Blasting," *Proceedings of the SSPC's 5th Annual Conference on Industrial Lead Paint Abatement and Removal* (SSPC, 1992).

Morrow, H., "Economics of Thermal Spraying for the Long-Term Corrosion Protection of Steel Structures," *J. Prot. Coatings & Linings (JPCL)*, 4, pp 39-47 (1987).

Munjone, F., and J. Irons, *Thermal Spray Coatings: Research, Design and Applications*, C.C. Berndt and T.F. Bernecki, eds. (ASM International, Materials Park, OH, 1993) pp 263-278.

"News from the Field," J. Prot. Coatings & Linings (JPCL) (Oct 1990).

Olsson, N., and H. Bandel, "Upgrading Steel Truss Bridges," *Modern Steel Construction* (March 1992), pp 16-20.

Oppenheim, I.J., and M.J. Skibniewski, "Construction, Robots in," *International Ency. of Robotics: Applications and Automation*, vol 1, R. Dorf, ed. (Wiley, New York, 1988), pp 240-248.

Race, T., V. Hock, and A. Beitelman, *Evaluation of Abrasion-Resistant Metallized Coatings for Civil Works Applications*, Technical Report M-90/06 (USACERL, February 1990).

Race, T, V. Hock, and A. Beitelman, "Performance of Selected Metallized Coatings and Sealers on Lock and Dam Facilities," *J. Protective Coatings and Linings*, 6[1], January 1989, 37-44

Smith, L., and G. Tinklenberg, *Lead-Containing Paint Removal*, FHWA RD-94-100 (Federal Highway Administration, 1994).

SSPC-PS-XMET01X-89, *Thermal Spray Metallic Coating Systems Guide* (Steel Structures Painting Council, Pittsburgh, PA, 1989).

Sulit, R.A., "AWS Guide for the Protection of Steel with Thermal Spray Coatings of Aluminum and Zinc and their Alloys and Composites," *NTSC Proceedings*, June 1993.

Threshold Limit Values and Biological Exposure Indices for 1989-1990 (American Conference of Governmental Industrial Hygienists, 1989), p 43.

Appendix A: North Carolina State University Summary of Results

North Carolina State University Tests

Summary of Results

Tests were carried out using a LTC 1060Pn machine included measurements in an enclosure, as well as on a full scale bridge belonging to the North Carolina Department of Transportation. The object of the tests was to confirm the effectiveness of the equipment in removing, and containing, lead based paints. A paint sample of the coating being removed had 18.4% lead by weight. The results of the tests can be summarized as follows:

1. **Effectiveness as Dust Free Operation.**

    The enclosure consisted of a Plexiglass box. This chosen to enable the operation to be observed close up and to determine if dust particles could be observed especially with very high static charges which would be present on the Plexiglass. NCSU's comment on this aspect is, "..It is significant to note that no dust was visible on the Plexiglass."

2. **Loss of Abrasive at the Blast Head.**

    The most realistic results were those measured on the full scale mock-up structure. The amounts of abrasive lost were very small. (see Note 1)

    The average lead content of samples collected was:
    - Lead content 0.19 %
    - Leachable Lead 4.01 mg/l

3. **Containment of Lead Removed.**

    The results of measuring the containment of Lead in paint removed form the full scale mock-up structure were: 99.95% containment.

4. **Lead Content in the Air.**

    The results of test related to blasting on the full scale mock-up structure were:

    - Machine Exhaust
        0.23 µg/m³

    - 60 ft. Downwind
        Less than detectable

    - 10 ft. Downwind
        Less than detectable

North Carolina State University Tests
Summary of Results
.....Page 2

- Operator's Throat
        20.8 µg/m³

- Blast Head
        1404 µg/m³

(Paint chips observed in sampler)

LTC Americas Comments

Note 1. Approximately 2% of the abrasive used was lost at the head. This percentage is calculated based on using 0.35 lbs/ft² of AL-Oxide when blasting with a LTC 1060 machine. This represents only 0.1% of the loss which occurs when open blasting.

Note 2. Despite the favorable results, as a prudent measure, operators should wear some type of respirator when actually blasting.

Note 3. It should be specially noted that tests were carried out, and the results achieved, with only the machine's primary air filter. This was prior to LTC having available a HEPA Kit. The present Kit enables the incorporation of an in-line HEPA filter. The standard minimum filter specification is an Acceptance Level A; Filters are tested at 99.97% efficiency on 0.3 micron particles using dioctylphthalate (DOP). Uniform size 0.3 micron smoke particles are generated with a Q 107 penetrometer. This test is conducted in accordance with U.S. Army Instruction Manual 136-300-175A. "A" level filters shall be made with "A" media.

Appendix B: ATSS Specifications

"X"-Axis Actuator and Motor and Controller Specification

A. "X" Axis Drive Unit
1. Drive system: Timing belt driven, wear resistant, high stiffness, with tensioner.
2. Body Material/Accessibility: Anodized aluminum body and carriage, 6063-T6. The sides of the body should provide removable covers to enable access to the carriage.
3. Carriage travel: Carriage shall contain wheels for travel.
4. Stroke length: 36 inches.
5. Overall length: Maximum of 62 inches.
6. Cross sectional dimensions: 3 inches x 3 inches
7. Loading: Maximum of 170 lbs.
8. Speed: Capable of maintaining a maximum constant velocity of 36 inch/second.
9. Acceleration/Deceleration: Maximum of 72 inch/sec.^{2}
10. Positioning accuracy: Minimum of .10 inches.
11. Maximum deflection of actuator: Maximum of 1/20 inch.
12. Gear box: Planetary Gear .
13. Gear reduction ratio: 10:1.
14. Mounting position: Horizontal (HS GL).
15. Accessories:
    a. Load Attachment Plate.
    b. Proximity Switches: 2-ends of travel, 1-home position .
    c. Tripping Plate.
16. Prime mover: AC Servo motor. Drive station shall provide zero backlash
    a. TP - 507 oz/in
    b. TS - 156 oz/in
    c. T - 127 oz/in
    d. N - 3K RPM
    e. P - 0.3 Watts
    f. PC - 1.62 KW/sec
17. Power supply: 72 volts, 36 amps continous.
18. Controller/Control System:
    a. The system shall be capable of both manual and programmable control.
    b. Remote control shall be provided through joy stick control.
    c. The control system shall provide a teach mode.
    d. The system shall be capable of varying the speeds.
    e. Capable of closed loop linear and circular interpolation in any two axis when this actuator is used in conjunction with the "Y" axis drive actuator.
19. Electrical cabling/connectors: Cable length of 75 ft. between motor and controller shall be provided. Cables and connectors shall be preassembled.
20. Power amplifiers:
    a. I_c - 12 amp
    b. I_p - 24 amp
    c. PWM - 72 VDC

B. "X"Axis Idler
1. Drive system: Timing belt driven, wear resistant, high stiffness, with tensioner.
2. Body Material/Accessibility: Anodized aluminum body and carriage, 6063-T6. The sides of the body should provide removable covers to enable access to the carriage.
3. Carriage travel: Carriage shall contain wheels for travel.
4. Stroke length: 36 inches.
5. Overall length: Maximum of 55 inches.
6. Cross sectional dimensions: 3 inches x 3 inches.
7. Loading: Maximum of 190 lbs.
8. Speed: Capable of maintaining a maximum constant velocity of 36 inch/second.
9. Acceleration/Deceleration: Maximum of 72 inch/sec.^{2}
10. Positioning accuracy: Minimum of .10 inches.
11. Maximum deflection of actuator: Maximum of 1/20 inch.
12. Gear box: None
13. Gear reduction ratio: None
14. Mounting position: Horizontal (HS GL).
15. Accessories: Load Attachment Plate.

"Y"-Axis Drive Actuator and Motor and Controller Specification

1. Drive system: Timing belt driven, wear resistant, high stiffness, with tensioner.
2. Body Material/Accessibility: Anodized aluminum body and carriage, 60603-T6. The sides of the body should provide removable covers to enable access to the carriage.
3. Carriage travel: Carriage shall contain wheels for travel.
4. Stroke length: 36 inches.
5. Overall length: Maximum of 62 inches.
6. Cross sectional dimensions: 3 inches x 3 inches
7. Loading: Maximum of 280 lbs.
8. Speed: Capable of maintaining a maximum constant velocity of 2 inch/second.
9. Acceleration/Deceleration: Maximum of 4 inch/sec.^{2}
10. Positioning accuracy: Minimum of .10 inches.
11. Maximum deflection of actuator: Maximum of 1/20 inch.
12. Gear box: Planetary Gear .
13. Gear reduction ratio: 20:1.
14. Mounting position: Vertical (VT GL)
15. Distance between centers: Maximum of 52 inches.
16. Accessories:
    a. Load Attachment Plate.
    b. Proximity Switches: 2-ends of travel, 1-home position .
    c. Tripping Plate.
    d. Clamping bars
17. Prime mover: AC Servo motor. Drive station shall provide zero backlash.
    a. TP - 1279 oz/in
    b. TS - 382 oz/in
    c. T - 311 oz/in
    d. N - 2780 RPM
    e. P - 640 Watts
    f. PC - 3.78 KW/sec
18. Control System:
    a. The system shall be capable of both manual and programmable control.
    b. Remote control shall be provided through joy stick control.
    c. The control system shall provide a teach mode.
    d. The system shall be capable of varying the speeds.
    e. Capable of linear and circular interpolation in any two axis when this actuator is used in conjunction with the "X" axis drive actuator
19. Electrical cabling/connectors: Cable length of 75 ft. between motor and controller shall be provided. Cables and connectors shall be preassembled.
20. Power amplifiers:
    a. I_c - 12 amp
    b. I_p - 24 amp
    c. PWM - 72 VDC

"Z"-Axis Actuator and Motor and Controller Specification

1. Drive system: Timing belt driven, wear resistant, high stiffness, with tensioner.
2. Body Material/Accessibility: Anodized aluminum body and carriage. The sides of the body should provide removable covers to enable access to the carriage.
3. Carriage travel: Carriage shall contain wheels for travel.
4. Stroke length: 12 inches.
5. Overall length: Maximum of 38 inches.
6. Cross sectional dimensions: 3 inches x 3 inches
7. Loading: Maximum of 130 lbs.
8. Thrust: 200 lbs.
9. Speed: Capable of maintaining a constant velocity of 2 inch/second.
10. Acceleration: Maximum of 72 inch/sec.^{2}
11. Positioning accuracy: Minimum of .10 inches.
12. Maximum deflection of actuator: Maximum of 1/20 inch.
13. Gear box: Planetary Gear .
14. Gear reduction ratio: 10:1.
15. Mounting position: Horizontal (HB GL)
16. Accessories:
    a. Load Attachment Plate.
    b. Proximity Switches: 2-ends of travel, 1-home position .
    c. Tripping Plate.
17. Prime mover: AC Servo motor. Drive station shall provide zero backlash
    a. TP - 507 oz/in
    b. TS - 156 oz/in
    c. T - 127 oz/in
    d. N - 3K RPM
    e. P - 0.3 Watts
    f. PC - 1.62 KW/sec
18. Control System:
    a. The system shall be capable of both manual and programmable control.
    b. Remote control shall be provided through joy stick control.
    c. The control system shall provide a teach mode.
    d. The system shall be capable of varying the speeds.
19. Electrical cabling length: Cable length of 75 ft. between motor and controller shall be provided.
20. Power amplifiers:
    a. I_c - 12 amp
    b. I_p - 24 amp
    c. PWM - 72 VDC

Electric Drive Arc Spray System Specification

1. Wire feed rates: 0 to 3000 ft/hr.
2. Automatic wire feeding: An automated wire feeder shall be capable delivering wire up to 50 feet from the gun meeting the wire feed rate specified above.
3. Power: Capability to 350 Amps, 100% duty cycle
4. Compressed air requirements: 75 CFM at 80 psig
5. Gun Weight: Maximum of 6.4 lbs.
6. Power unit weight: maximum of 235 lbs.
7. Air pressure range: 40 - 80 psig
8. Remote Operation: The system shall be capable of being remotely operated
9. Gun mounting: The gun shall provide for tool post mounting
10. Wire diameter: The system shall be capable of spraying 11 gauge, 2 mm, 16 mm and 0.045 inch diameter wire.
11. Programmable control: The system shall be capable of being controlled via programmable logic control (PLC) or computer system.
12. Spray pattern: The gun shall provide an oval or circular pattern
13. Dimensions: The system dimensions shall not exceed 20"W x 50"H x 40"L
14. Input Voltage: 110/220/440 VAC
15. Spray Rates:
    a. Aluminum: 6 lbs./hr./100 amps
    b. Zinc: 24 lbs./hr./100 amps
16. Spray aluminum wire meeting MIL-W-6712, Tb, II, aluminum, and meeting the following:
    a. Deposition efficiency: Minimum of 78%
    b. Bond strength: 4375 psi, blasted surface
    c. Tensile strength: 19,500 psi
    d. Hardness: 25-60 R_h
    e. Coating density: 2.51 gm/cc
    f. Coverage (wire consumption): 0.25 oz./ft^2/mil (approx.)
17. Spray zinc wire meeting MIL-W-6712B, Tb, II, Zinc, and meeting the following:
    a. Deposition efficiency: Minimum of 70%
    b. Bond strength: 1224 psi, blasted surface
    c. Tensile strength: 13,000 psi
    d. Hardness: 13 R_h
    e. Coating density: 6.36 gm/cc
    f. Coverage (wire consumption): 0.9 oz./ft^2/mil (approx.)

Closed Circuit Visual Inspection System

1. Camera: 2/3 inch black & white Charged Coupled Device, High resolution, 24 Volts AC.
2. Monitor: 9 inch black and white, 570 lines of horizontal resolution.
3. Power supply: Power supply to power 2/3 inch B&W CCD camera above. 24 V/20 VA, Plug-In.
4. Lens/Iris: Motorized zoom lens, with intraspot filter and auto iris, format 2/3 inch, 10X zoom range, F1.8, C-mount, 11/110 mm.
5. Controller: Motorized zoom lens controller to zoom lens/focus and auto iris lens containing 2/3 inch format, 10X zoom range. Six button control for zoom in and out.
6. Environmental Enclosure: Dust proof housing with slide-out camera platform.
7. Heater & Thermostat Assembly: Heater and thermostat assembly for dustproof housing, 120 VAC Operation.
8. Blower & Thermostat Assembly: Blower and thermostat assembly for dustproof housing, 120 VAC Operation.
9. Cabling: Coaxial cable, RG59U, 500 ft. spool.
8. Wire: 22 gauge, 4 conductor, stranded-shielded-jacketed, 500 ft spool.
9. Electrical connector: BNC connector, 10 per pack.
10. Console: Desktop console for mounting motorized zoom lens controller.

ELECTROMAGNET SPECIFICATIONS

1. Type: Flat faced, rectangular in shape
2. Required Holding Force: 500 lbs.
3. Control Unit: suitable for outdoor environments, manually controlled locally with
   option of remote, rectified 115 VAC, 12 volts D.C.
4. Electromagnet Voltage Input: 12 volts D.C., rectifier must be used for
   alternating current
5. Electromagnet Power: 6 watts
6. Width: 2-1/2 inches
7. Length: 4-1/2 inches
8. Height: 1-7/8 inches
9. Mounting: 2 inches
10. Location of Leads: 1-1/2 inches x 3/4 inches

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