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AUTOMATED LASER DEPAINTING OF AIRCRAFT SURVEY OF ENABLING TECHNOLOGIES

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NOTICE

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The requirements needed to integrate a laser depainting system into the Oklahoma City Air Logistics Center Depainting Facility were identified and evaluated to determine if the enabling technologies were available to reasonably expect a large robotic laser depainting system could be made and operated in a production environment. Robotic, Laser, Sensor, and Computer control systems were examined, tested, and evaluated.

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1.0 Introduction and Summary

1.1 Purpose of Study

This final report presents a summary of work performed by Arthur D. Little and its subcontractors in fulfillment of the obligations of Contract Number F33615-87-C-5236.

The purpose of this project is to identify and evaluate the enabling technologies required to fabricate an automated laser paint stripping (ALPS) system.

Specifically, we were tasked to:

- Define, investigate, and evaluate elements/components required to form complete automated laser depainting systems capable of stripping large strategic or transport aircraft in current USAF inventory.
- Review the current state of development of laser depaint systems/components and develop system/component performance criteria to be used in their evaluation. These systems/components included:

  CO-2 Laser system
  Laser Head System with beam delivery components as required
  Paint/Substrate Discrimination Sensor System
  Automated real time control system
  Robot system
  Paint residue scavenge/reclamation system
  Environmental and safety systems.

- Examine available technologies supporting each system/component, compare their capabilities (including safety, reliability, and maintainability) against system/component performance criteria, and assess the suitability of the technology to support their development.

- Report the findings, conclusions, and recommendations of the work.

The purpose of this study is not to design or perform concept work for a laser paint stripping system. Rather, the intention is to determine the enabling technologies for the system and ascertain the level of development and compare it to the required level for each enabling technology. During this study, it was inevitable to form some ideas and generalizations regarding an ALPS system configuration. This was done for the purpose of identifying the required technology and organizing the associated workload. The possible system configurations shown should not be considered the best or desired system, but rather a generic layout used to structure this study and illustrate enabling technologies.

1.2 Summary of Key Findings

The following elements/components are required to form a complete automated laser depainting system: airframe preparation system; operator control and monitoring system; laser system; beam delivery system; sensor system (paint and color); supervisory control system; robotics system; training, testing, initialization, and calibration; quality control and maintenance; residue reclamation system; environmental and safety and security system; and ancillary systems.

The robot represents the largest element of the ALPS system. It will be responsible for moving the work head over the surface of the aircraft. The size of the work envelope and accuracy required makes this an extremely ambitious robot application. We believe that no off-the-shelf robots exist that can provide the required work envelope.

One of the more attractive potential robot systems would employ a mobile vehicle such as a standard flight line transport tug with a telescoping boom to position the work head around the aircraft. Advantages of employing this technology include no facility impact and transportable between facilities. There is some risk associated with all components to be integrated are based on existing technology.

Available laser technologies include: Lumonics, a high-pulse energy system with relatively low average power, 50 W; Raytheon - the GS600, which operates at 200 Hz and produces up to 2 kw of peak power for a 200-microsecond pulse; Coherent-General, which manufactures a 3-kw laser system, based on the enhanced axial flow technology; UTILs Laser System, which has a triggerable, pulsed version of their SM series line of high-power cw lasers; the Avco Laser System, which puts out 10 kw in pulsed mode at 10 Hz, and the pulse width is about 30 microseconds.

Beam delivery systems for high-power CO_2 laser systems are common for industrial and material processing applications, such as cutting, welding, and hardening of metals. The extension of this technology to very long path lengths (over 100 meters), if required, will not be straightforward. The risk here is related to the ability to determine an appropriate design rather than to develop new technologies. The development risk here is categorized as moderate to high.

The work head is used to shape the beam just before hitting the target. Several key areas exist for development of a practical work head system. Successful development of this system hinges on the sensor system. The development of a paint-identifying sensor is still in the early stages, and applicability to a large-scale, field-usable system must still be proven. While it is technologically realizable, the demands of the signal processing and control system, as well as the laser requirements of such a system may not be easy to integrate into a workable system.

Performance requirements dictate that an extensive sensor system be used. The following capabilities are required of the sensor system: collision avoidance/

obstruction detection, surface contour following/standoff control, color/substrate discrimination, global positioning, and surface mapping.

Complete air reclamation will require a system with the ability to remove particulate matter through some form of mechanical filtration and to remove gases by either chemical methods or incineration. A number of combinations using the systems mentioned can meet these requirements; however, a better understanding of the gas stream composition is required. This should include analyzing a gas stream from an ALPS system to determine the types of aerosols and gases present, their relative concentrations, and the particle size distribution.

Numerous controllers were identified, and through a trade-off analysis, several were determined to be adequate.

The tug robot concept was examined for technical risk evaluation. Two enabling technologies are projected for this system: one is the process itself, and the other is the color discrimination system.

The specific technical risks include: robot arm - low-medium, tug - low, beam delivery system - medium, controller - low-medium, software - low-medium, sensor - low, color discrimination sensor - medium-high, mapping sensor - low, global positioning sensor - low-medium, laser - low, process - medium-high.

2.0 Overview

2.1 Paint Stripping Background

Paints were initially applied to aircraft in order to protect them from deterioration and corrosion, provide camouflage and identification markings, and reduce drag by improving surface finish. Today, various types of paints and coatings are applied to reduce radar return signatures, to serve as ablative rain-erosion protection and to reduce IR emissivity. Both topcoats and primer coats must be periodically removed to inspect the aircraft skin, change the camouflage profile or identification markings, and to perform other maintenance/repair procedures.

Until recently, aircraft were almost entirely covered with metal skins, primarily aluminum. The advances made in the materials field have produced a large number of aircraft that use significant amounts of organic matrix composite material for skin panels. These composites need to be treated very carefully during paint stripping to prevent damage to the composite. Indeed, the principal objectives of the concurrent program by Arthur D. Little and described in WL-TR-91-4025 are to identify paint removal processes and protective coating systems which will reduce or eliminate the damage to the composite when paint layers are removed.

One present method for stripping paint from military aircraft involves the application of chemical stripping agents to the painted surfaces. Both the application and removal process present severe personnel and environmental hazards because of the toxicity of the chemicals in the stripper. Other paint removal processes also have severe limitations. Abrasive sanding is very slow and labor-intensive and can result in damage to surfaces, especially near joints. Media blasting using plastic particles requires precise operator control and can cause fiber breakage and delamination in composites when the gel coat is removed. These are some of the reasons the Air Force would like to replace their present stripping system with another that is significantly less hazardous to workers and the environment and less damaging to the surfaces, but which can still compete in terms of cost and time to strip aircraft.

2.2 Paint Stripping Systems

The Air Force has investigated a number of different approaches to removing paint from aircraft. Recent research examined a variety of abrasive techniques, including mechanical sanding, cryogenic sanding, and wet abrasives. Other work examined included blasting approaches using water jet, walnut shells, ice, sodium bicarbonate, plastic media blasting (PMB), and dry-ice blasting. Irradiation processes using high-intensity flash lamps, as well as CO_2 and excimer lasers have also been studied.

The USAF has also sponsored programs employing automated paint stripping. Ogden Air Logistics Center, Hill AFB, Utah, has procured a robot system to remove paint from fighter aircraft, using plastic bead media. The Southwest Research Institute robot was scheduled for installation in January 1990, but is on indefinite hold due to funding according to Hill AFB officials. The Air Force Laser Application Working Group selected Warner Robins ALC as the lead site for the removal of paint from radomes using lasers. Radomes from the C-141, C-130 and F-15 are currently hand-sanded and chemically stripped. The planned system would have incorporated a small overhead gantry with a three-axis wrist; however, the system was never installed. Avco performed a laser paint stripping study, resulting in a conceptual system for removing paint from fighter aircraft. In that study, Spar Aerospace developed a conceptual robot design.

2.3 Laser Paint Stripping

Under controlled conditions, lasers have been shown to be effective at removing paint from a variety of substrates. In order to remove paint from a surface, the laser must generate a critical fluence level (energy per unit area) high enough to energize and decompose organic material.

Critical to the idea of using a laser to remove paint is the establishment of an operating window that allows for sufficient energy delivery to create a plasma, yet not damage the substrate. The likelihood of establishing this window is discussed in more detail in the section on lasers. Past research has shown that the CO_2 is ideally suited for paint stripping, since its operating wavelength is situated in the middle of the region of high paint absorption. This means that the wavelength of the CO_2 laser is such that it is readily absorbed by a painted surface. The ability of the paint to absorb as much energy as possible is fundamental to efficient coating removal. Pulsed lasers remove surface coatings in a more controlled manner than continuous wave (CW) because of their ability to deliver a short-duration, high-intensity pulse. This allows a fraction of the paint layer to be removed without charring the paint or excessively heating the substrate. Such a system will eliminate the corrosion initiation and the debonding of repainted surfaces associated with other removal techniques.

Laser paint stripping thus offers the potential for little or no surface damage, the generation of very little hazardous byproducts, and the potential for automation using sophisticated robotics in place of operators. For these reasons and others, the automated laser paint stripping is of keen interest to the Air Force.

3.0 Performance Requirements

The performance requirements section is divided into requirements for aircraft type, size, process, facility, safety, and manufacturer's certification. The process requirements section includes robot, sensor, and operations guidelines.

Requirements were developed from information obtained in the literature study, from preliminary requirements supplied by the USAF, from experience at our subcontractor USBI (a division of United Technologies) in the areas of large-scale robotics and paint stripping, and from visits to the National Institute of Standards and Technology (NIST) and to Tinker AFB. The purpose of the visit to NIST was to evaluate current state-of-the-art research being performed in the areas of sensors, robotics, controls, kinematics, and mechanics. The purpose of the trip to Tinker AFB was to inspect the designated facility and specified aircraft.

General system level requirements are presented as follows:

- An operational availability of 85%
- A goal of 90% has been set for chemical quantity reduction.

A new facility at OC-ALC is planned for a large aircraft paint removal system. This was announced in the CBD in December, and the RFQ is to be released in early 1991.

3.1 Aircraft Types and Characteristics

The designed robotic system shall provide laser depainting capability for the following strategic and transport aircraft in the USAF inventory.

Boeing B-52. The main Strategic Air Command (SAC) versions are the B-52G and B-52H. The USAF plans to retain B-52Gs and B-52Hs in SAC units well after 1990.

Boeing C-135. The C-135 is slightly smaller than the Boeing 707 and is used for cargo and refueling duty.

Rockwell B-1. This strategic bomber became combat-ready in 1987.

The aircraft characteristics include aircraft dimensions, surface elements, surface types, surface materials, surface coatings, surface protective coatings, and dimensional inconsistencies.

Aircraft Dimensions. The work envelope of the aircraft is defined by the length (tail to nose), width (wing tip to wing tip), height (ground to vertical stabilizer top) and low point (belly height). These aircraft and their work dimensions are shown in Table 3.1. The overall required horizontal reach is approximately 26 feet. The required vertical envelope dimension is 35 feet. In order to access the exterior surfaces of these aircraft, a work envelope measuring 161' x 185' x 35' (LWH) is needed. With the B-1, there is a significant dimensional variation because of structural modifications during production.

Table 3.1 Aircraft Dimensions

	Boeing B-52	Boeing C-135	Rockwell B-1
Wing Span	185'-0"	130'-10"	136'-8"
Length	160'-11"	134'-6"	150'-2"
Tail Height	40'-8"	41'-9"	33'-7"
Tail Span	52'-0"	≈43'-0"	≈48'
Wheel Tract	11'-4"	22'-1"	≈20'
Fuselage Height	17'-5"	17'-10"	≈20'
Belly Height	4'-3"	≈3'-8"	≈10'
Fuselage Width	9'-10"	12'-0"	≈10'
Engine QTY	4	4	4
Engine Location	Under wing	Under wing	Wing
Stabilizer Location	Low	Low	Mid

Surface Elements. The system must be able to accommodate the following surface elements on the aircraft:

A. Skin panels
B. Hard points
C. Rivets
D. Concave and convex geometries
E. Access panels and caps
F. Knife-edge geometries
G. Windows and openings
H. Control surfaces and associated interfaces
I. Position and anticollision lights
J. Sensors and transducers.

The systems must be able to distinguish between the various substrates used as skin material. This becomes important because the ability to withstand the laser energy is not the same for all substrates and knowing the surface material will allow for maximum paint removal with minimum chance for substrate damage. Furthermore, the system must be able to distinguish between 12-18 shades of topcoat and primer. Finally, the system must also be able to handle clear materials (glass, polycarbonate, etc.) decals, rain erosion coatings, etc.

The specific surface types are:

A. Aluminum (8-10 shades)
B. Titanium (1-3 shades)
C. Paint (12-18 shades)
D. Decals (various colors)
E. Glass
F. Composite material (2-4 shades).

The B-52 and C-135 are largely composed of aluminum. The B-1 is a combination of aluminum, titanium, and composite surfaces.

The laser shall be required to remove the following types of paints:

A. Epoxy resin primers (Mil-P-23377)

B. Polyurethane topcoats (Mil-C-83286).

While other paints are still being used, these are the principal paints being used on Air Force equipment, and they are the most resistant to paint removal by any method.

Surface color will be changed by age, as well as exposure to weather, fuels, oils, exhaust, etc. The laser paint system must be able to adapt to all of these variations.

3.2 Processing

Stripping operations are currently performed on B-1, B-52, and C-135 aircraft in Building 2122 at Tinker AFB. These are the only aircraft to be considered for processing. The vertical stabilizer of the B-52s and C-135s are removed before processing, significantly reducing the required work envelope. The B-1 is pulled into the hanger, the C-135 backed in, and the B-52 "crabbed" in diagonally, as shown in Figure 3.1. B-1 wings are maintained in the swept-back position while the aircraft is on the ground. The tail area of the B-1 contains about 20% of the total area of the aircraft, and only about 5% of the total surface area for all three aircraft. It may be that systems which are height-limited (e.g., less than 25-foot high work envelope maximum) could be acceptable to the USAF.

Stripping and painting operations are not performed in the same hanger. Painting operations are performed in a more modern facility (1976) which utilizes six overhead bridge cranes to support man-platforms. These platforms extend down from the ceiling 30-35 feet. Processing time for stripping ranges from five days for a C-135 to nine days for a B-1. The chemical processing plant at Tinker AFB is not capable of handling the amount of waste generated by the process and the EPA is applying constant pressure. Forty C-135s, six B-52s and four B-1s are scheduled for stripping during 1990 at Tinker AFB; 100 total aircraft are projected for 1991 operations.

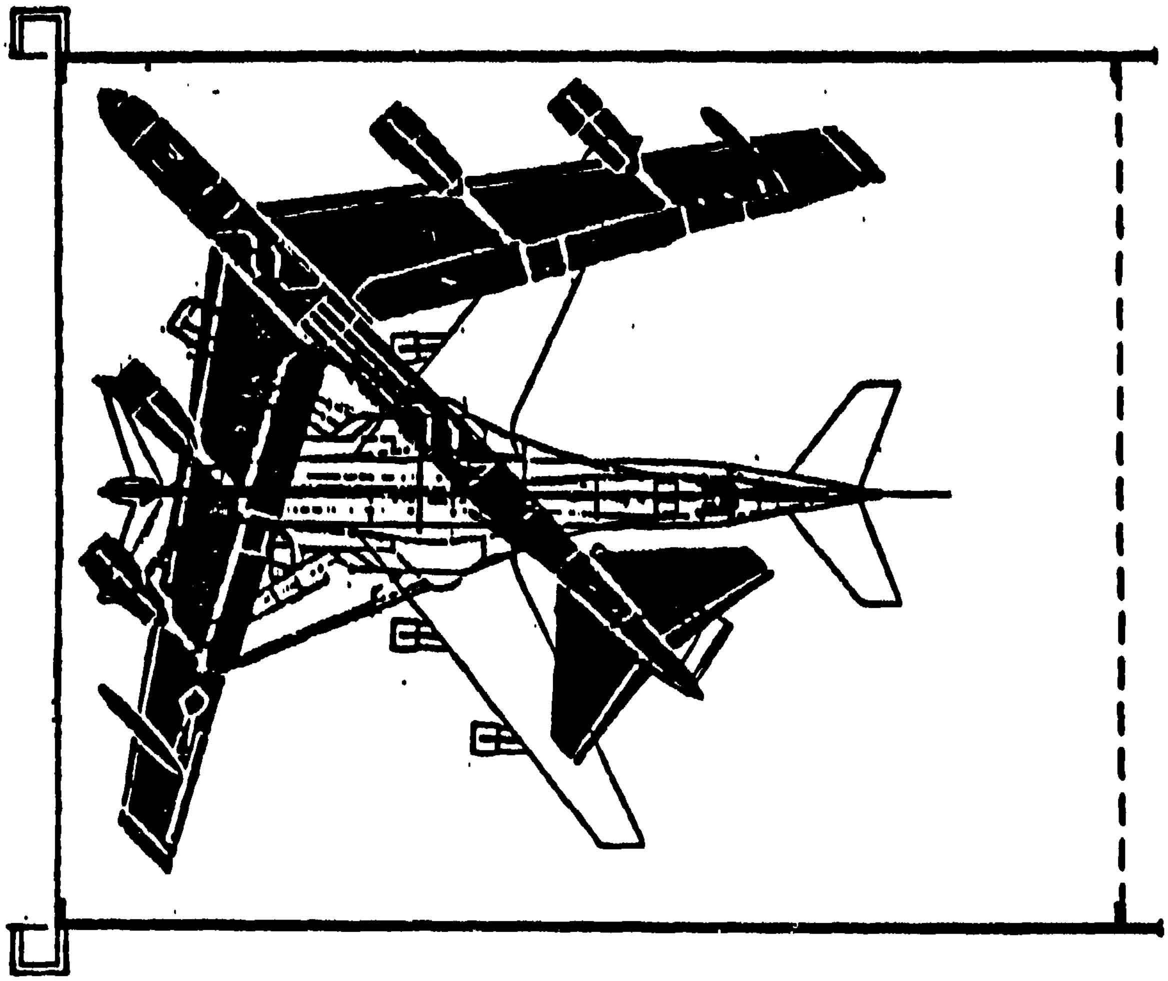


Figure 3.1 Aircraft Positioning Scheme

The impetus for a laser paint stripping system is to replace chemical paint stripping with a process that does not present the hazardous waste disposal problems or the toxicity dangers caused by workers exposed to the stripping agents. Despite the drawbacks inherent to the present system, chemical paint stripping has become the baseline paint removal system by which competing systems are compared. As a result, issues, such as time to strip an aircraft and cost to strip, are derived from the present process.

Process requirements for the ALPS system are as follows:

A. The robotic system shall not damage the aircraft through physical contact or overexposure to the laser.

B. Stripping shall take less than one week.

C. A removal rate of 2-4 ft^2/minute shall be achieved.

D. The system shall accommodate a laser pulse rate of 300 pulses/second.

E. Based on the pulse rate and average number of pulses required, a sensor feedback rate of 1/30 second shall be provided.

F. The robot shall be capable of transmitting the laser beam to the surface of the airplane and then of positioning the laser so that the pattern, over which the laser is incident differs from the target pattern by less than 0.040 inches at all points.

G. The robot shall accommodate a payload capacity of 100 lbs.

H. The robotic system shall be capable of paint stripping, partial paint stripping, and surface inspection.

I. Global positioning and relative positioning shall be provided.

J. A standoff distance of 12 inches shall be maintained during stripping.

K. The stripped area shall be at least 90% of the total surface area.

L. The system shall be able to differentiate between stripped and nonstripped surfaces.

M. Composites shall be stripped to primer only.

N. Metal surfaces shall be stripped to bare substrate.

O. A user-friendly programming language shall be used.

P. The robot controller shall be capable of receiving inputs from all sensor systems.

3.3 Facility

Building 2122 at Tinker AFB was built during the 1940's, originally designed as a bay for the chemical stripping of aircraft. The floor is steeply crowned to facilitate waste removal. It is likely that the floor would have to be replaced (leveled) before a system could be operated inside the hangar. Chemical contamination of the earth below the floor may necessitate its removal regardless of other issues. The air handling system was recently refurbished to provide faster air exchange and improved filtering. There are no windows in the hangar. Illumination is provided by overhead sodium lamps. No information was available at the time of the Arthur D. Little tour about the utilities supplied to the hangar. It is likely that they are insufficient for an ALPS system.

The Air Force has designated the west bay of the facility to receive the ALPS system. Any design must be sensitive to the size and structure constraints imposed by this building. The centerline headroom is 35' and 20' on the sides because of the duct work. Since the vertical stabilizer of the B-1 stands almost 34' tall and is very difficult to remove, there is insufficient space for any overhead robot designs. Also, the superstructure of both the walls and roof is unsuitable for any type of robot mounting.

Since it is not presently known whether a new floor will be installed in this facility, two sets of design constraints have been generated: one for the bay with the existing floor and a second set if a new floor were installed. The design constraints are as follows:

Existing Facility (Current Floor). The following requirements exist for the current facility:

A. Maximum workable ceiling height shall be 35 feet.
B. The robot structure shall fit around the current aircraft positioning scheme.
C. The robot system shall be capable of moving about on the existing floor, characterized by mild slopes, drain gates, and mottled finish, if applicable.

D. The robot system shall be capable of negotiating the existing duct work on the north and south walls of the facility. This duct work starts approximately 22 feet from the floor and extends out from the walls approximately 15 feet.

E. The robot system shall not prohibit aircraft from moving through the west hangar to the center hangar.

F. The facility shall provide laser-safe walls.

Existing Facility (New Floor). The following requirements exist for a new floor in the current facility:

A. The floor must provide drainage to the reclamation system.

B. The robot system shall be capable of moving about on the new floor, if applicable.

C. The robot system shall be capable of negotiating the existing duct work on the north and south walls of the facility. This duct work starts approximately 22 feet from the floor and extends out from the walls approximately 15 feet.

D. The robot system shall not prohibit aircraft from moving through the west hangar to the center hangar.

E. The facility shall provide laser-safe walls.

3.4 Operator Safety/Environmental Impact

The ability of the system to provide a high level of safety to both the aircraft and the personnel in the area is probably the most critical performance requirement. The safety threats to both man and aircraft come from several sources. The robot structure presents a collision hazard to anything and anyone within its reach envelope. Another potential danger is contact with the laser beam, either along its transmission path (optical train), at the work head, or as a result of reflection from shiny surfaces. Also, there is the danger of ignition/combustion of substances in the vicinity of the beam. These substances may include fuels and oils on and around the aircraft surface, and perhaps the volatiles generated during the paint removal process.

Another requirement is to provide adequate waste handling capabilities for removal of paint byproducts (after having been removed with laser energy). The overwhelming environmental problems associated with chemical paint stripping has sensitized the Air Force to the need to require any replacement paint stripping process to be environmentally acceptable. The EPA provides the necessary emission requirements for discharge into air, water, and earth.

The following environmental and safety requirements shall be met:

A. All OSHA and EPA regulations pertaining to this system and its processes shall be met.

B. The system shall produce no explosive fumes. The main safety hazard results from the high voltages used to excite the laser discharge.

C. Adequate operator shielding shall be provided. An acrylic or polycarbonate shield, interlocked to the system controller, should be used.

D. No operator shall be allowed in the work envelope during stripping activities.

E. The robot shall have emergency stop capabilities.

4.0 Elements/Components and System Configuration

The various elements and components necessary for an automated laser depainting system include the following:

Laser System
Beam Delivery System
Sensor System
Control System
Robotics System
Residue Reclamation System
Environmental and Safety System.

Prior to being configured into a total system, these components were analyzed through the process of functional decomposition, which separates the system into discrete elements.

4.1 Functional Decomposition

The following represent the series of functions that will be an important part of the ALPS.

Airframe Preparation System

- Positioning and visual inspection
  - positioning of airframe
  - global correlation with airframe topographic model
  - global coordination of airframe surface model
  - identification of critical areas of mismatch and notification of operators
- Surface and substrate testing

Operator Control and Monitoring System

- Human interface
- Control and operator feedback
- Error recovery
  - presentation of problem situation
  - feedback of solution from operator.

Laser System

- Laser
  - output
  - columnation
  - pulsing
- Low-power laser for manual training.

Beam Delivery System

- Deliver the laser beam from the laser source to the end effector or beam direction system
- Input
  - joint position
- Output
  - mirror and support position
  - laser direction
- Kinematics
- Safety

Sensor System (paint and color)

- Paint identification and measurement
  - input
    - expected paint types for aircraft
    - paint properties
    - location of surface contour features for surface region

- output
  - paint type location in image form.

Supervisory Control System

- Supervisory system
  - coordination
  - condition analysis and response
- Gross (initial) path planning for laser depainting
- Coordination between surface and material sensing
  - calculate the laser position from data from the surface and material sensors
- Calculation of position adjustment
- Database handling
  - truthing
  - storage
  - matching
  - access
- Subsystem monitoring
- Communication control within cell
- Communication control to external systems
- Network management
- Error recovery

Robotics System

- Tool-to-surface measurement
  - Global (open loop) positioning of the robot will not be sufficiently accurate for laser depainting. Measurement of the relative position between the end effector and the airplane's surface will be required.
  - input
  - output
    - surface map in global coordinates

- Rigid platform for sensors and lasers
  - physical position of the sensor and lasers
- Laser direction system (under beam delivery system)
  - laser control from known relative position
    - input
      - beam characteristics
      - tool relative location, speed, direction and path
    - output
      - positioned laser
      - laser beam
      - laser position, speed and power
- Global navigation
  - the initial depainting path will likely need to be modified in the light of information from the various sensors
  - this could be accomplished within the robot function or within the supervisory controller function
- Collision avoidance
  - The robot will need to be protected from potential collision with unexpected objects.

Training, Testing, Initialization and Calibration

- Training of sensors
- Training of robots
- Calibration.

Quality Control and Maintenance

- Global positioning accuracy
- Emergency training, positioning.

Residue Reclamation System

- Reclamation
- Air quality testing.

Environmental and Safety and Security System

- Security barriers
- Power interlocks
- Temperature sensors
- Robot shut down
- Computer security
- Physical site security.

Ancillary Systems

- Programming/training system.

4.2 System Configuration

The selected system configuration is shown in Figure 4.1. This configuration was established based on the requirements documented in Section 3.0 and the function decomposition described in Section 4.1.

Host Computer System. The host computer system will provide the following capabilities:

A. Monitor all process variables and parameters.

B. Control on/off operations of all equipment.

C. Interface with the selected robot controller.

D. Store base programs for the three aircraft.

E. Receive inputs from sensor systems as necessary.

F. Provide a user-friendly operator interface, allowing control of all equipment at one location.

G. Coordinate cell operations.

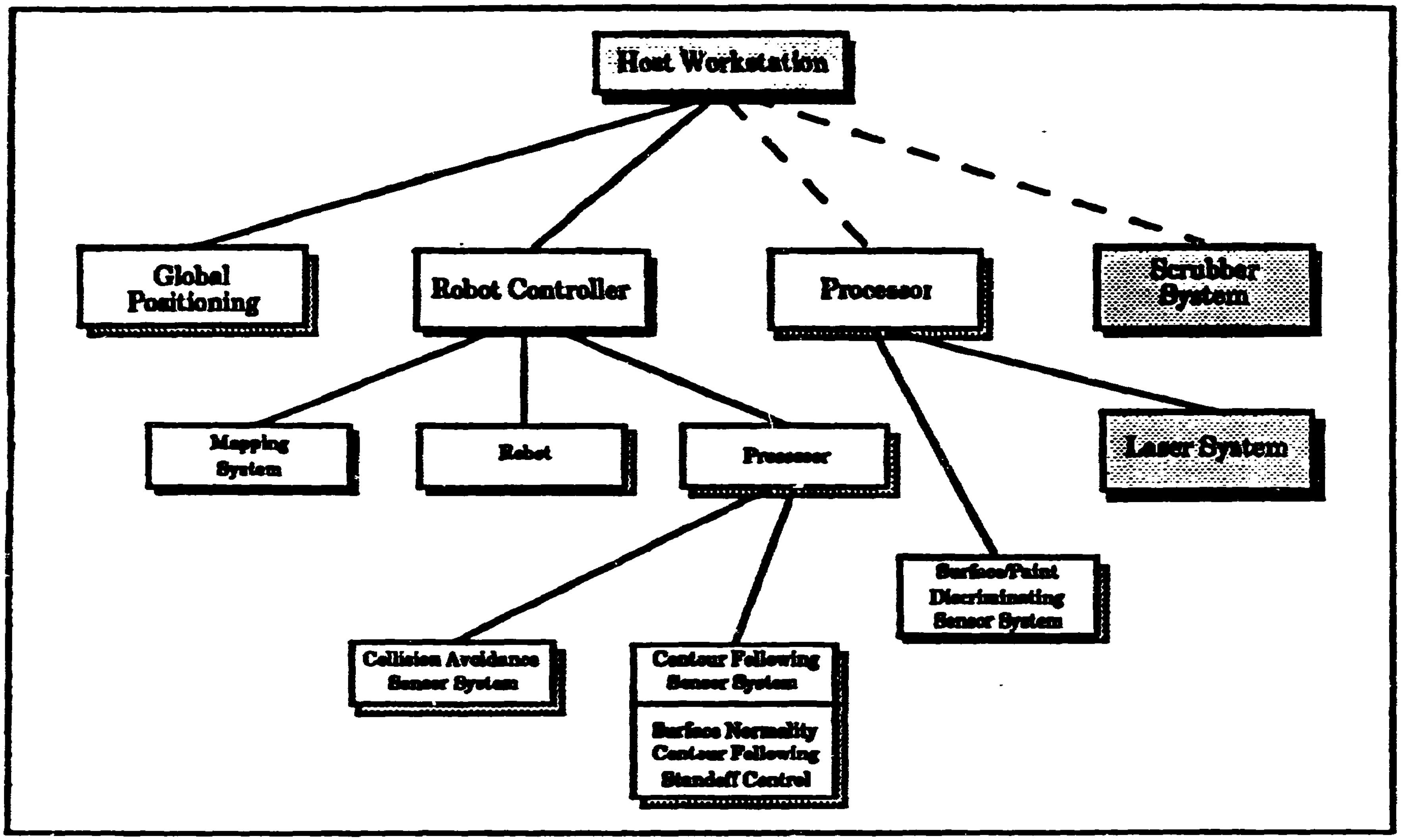


Figure 4.1 System Configuration

Robot Controller. The robot controller will control the robot, receive inputs from the mapping system (if incorporated), the surface contour sensor, and the collision avoidance sensors. The robot controller will also be capable of interfacing to the host computer system.

Laser System. To meet the near-term requirements of the Air Force at Tinker AFB no more than two of the selected laser systems will be used in order to minimize costs.

Scrubber System. A facility vacuum system will be needed to recover the waste particles of paint. After recover, the particles will be filtered and disposed of properly.

Sensors. From the requirements, it was determined that the system will need to incorporate the following sensor system functions depending on the operational scenario selected:

A. Collision avoidance/obstruction detection - This sensor system is needed to prevent the robot arm or work head from hitting the aircraft surface.
B. Surface contour following/standoff control - This sensor is needed to maintain the optimal process standoff during depainting operations.
C. Color/surface discrimination - This sensor system is needed to distinguish between the stopping color and the paint color.
D. Global positioning - The global positioning function is needed to orient the robot to the aircraft. The underlying assumption here is that the aircraft will not be positioned in the same exact location every time.
E. Surface Mapping. - A surface-mapping procedure may be necessary. One of three methods of path processing will be used:
    1. The surface area would be mapped using a mapping sensor system which inputs data points into a path program. This program is then used to guide the robot through its motions.

2. A prewritten path program would be used based on off-line CAD data of the airplane. The robot would then follow this off-line program with sensors adjusting for variances between aircraft.
3. Real time surface following and collision avoidance techniques would be totally responsible for the robot path.

In all three cases, collision avoidance and contour following sensors will transmit data to the robot controller during processing.

5.0 Available Technologies

5.1 Robot Technologies

The robot represents the largest element of the ALPS system. It will be responsible for moving the work head (containing sensor system, air reclamation system, and laser beam) over the surface of the aircraft. The size of the work envelope and accuracy required makes this an extremely ambitious robot application. These two critical qualities (size and positional accuracy) are completely antagonistic.

Our subcontractor, USBI, has worked with many of the leading robot manufacturers on the design of robotic systems. USBI has also developed large-scale systems for several marine and aerospace applications. From this experience and recent contacts, it is apparent that **no off-the-shelf robots exist that can provide the required work envelope.** Several related developments were identified, however. Among these are:

A. Laser Machining Incorporated (LMI) has developed a closed beam delivery system for heat treatment applications, using a Cincinnati Milacron gantry robot (40 feet x 20 feet x 12 feet). A 0.25-inch x 1.5-inch beam head 1.1-kw system is used. LMI has worked previously with Cimcorp on laser-processing robotic systems.

B. The USAF has installed and activated an n-ray inspection facility-mounted gantry robot at McClellan AFB, California. This Cimcorp system provides a work envelope of 85 feet x 75 feet x 16 feet with a repeatability of ±0.25 inches and is used on tactical aircraft.

C. SwRI has developed the previously mentioned plastic media blasting robot to be used to remove paint from fighter aircraft at Hill AFB.

D. The U.S. Navy is in the process of procuring two air-bearing mobile robot systems from InTA (and SwRI) for removing paint with lasers from fighter aircraft.

E. In addition to the system installed for the USAF, Cimcorp provides custom-engineered robotic systems to match specific requirements. Several large-scale units are in use in the nuclear and hazardous materials handling industries.

F. USBI, teamed with AKR Robotics, has recently received a contract award to install a painting robot system for a large aircraft manufacturer. This system uses cylinder-mounted scara positioners to move smaller pedestal robots. The cylinders are to be installed in the floor of the facility.

Robot Systems

The following 10 robot configuration concept classes were evaluated:

1. Overhead gantry system
2. Facility bridge crane system
3. Side gantry system
4. Hill AFB type system
5. Pedestal robot system
6. Pedestal robot lift system
7. Mobile vehicle system
8. Suspended robot (NIST-type) system
9. InTA system
10. "Mushroom" system.

Robot concepts were evaluated on the basis of facility impact, schedule, flexibility, technology risk and the ability to meet the system requirements presented in

Section 3.0. To quantify the evaluation, a weighted value was attached to each requirement, as shown in Figure 5.1. The requirements were then compared to the 10 alternatives. If the concept did not meet the requirement, a score of "0" was assigned. If the requirement was not applicable to the robot system, no score was recorded. Weight values were summed by concept for every zero entry. The concept with the lowest total score would theoretically be the best system.

Cost was not evaluated on a quantitative basis, but qualitative assessments were made. Relative cost rank is noted at the top of the chart. Requirements not met by the concept are noted in italics and parentheses in the following sections. Combinations of the above system concepts are also discussed.

The most attractive system for the existing facility is the wheeled mobile vehicle with a telescoping boom. It will accommodate the current floor in Building 2122 and will not impact the facility. For a new floor in Building 2122, the selected concept would be adequate, although other leading concepts would require reconsideration. However, the selected concept is compatible for either scenario. The details of each system are described in detail in the following section.

5.1.1 Overhead Gantry System.

This concept class representative is shown in Figures 5.1.1-1 and -2. This free-standing system would utilize a telescoping or pivoting z-axis to move around the aircraft. At the wrist of the z-axis, an additional arm would be attached for reaching under the wings and fuselage. The gantry would provide a span of 150-160 feet and a length of approximately 190 feet. The bridge section would be required to be self-supporting across the work envelope width. At 20 foot centers, 9-10 legs would be needed on each side. To allow for aircraft to be positioned in the middle hanger, no legs would be permitted to support the end span rails.

Facility Impact. The existing floor in Building 2122 would need to be evaluated to see if the loads delivered by the leg bases could be supported. The surface finish of

	Requirement	Weight	(1) Overhead Gantry	(2) Bridge Crane	(3) Side Gantry	(4) Hill AFB	(5) Pedestal	(6) Pedestal Lift	(7) Mobile Vehicle	(8) Suspended Robot	(9) IWA System	(10) Mushroom
	Facility Impact		Medium	High	Low	High	N/A	Low	Low	High	High	High
	Schedule		3 years	3 years	2.5 years	3 years	N/A	1 years	2 years	2.5 years	3 years	2.5 Years
	Flexibility		Medium	Medium	Medium	Medium	N/A	High	High	Medium	Medium	Low
	Technology Risk		Medium	Medium	Medium	High	N/A	Low	Low	Medium	Low	Low
	Qualitative Low Cost Ranking		6	7	5	9	2	1	3	8	4	10
	Requirement	Weight	Meets or Exceeds									
2.1.1	Reach all areas of a B-52	10	0	1	0	1	0	0	1	1	1	1
2.1.2	Reach all areas of a C-135	10	1	1	1	1	0	0	1	1	1	1
2.1.3	Reach all areas of a B-1	5	0	0	1	0	0	0	1	0	1	1
2.3A	No damage to the aircraft	20	1	1	1	1	1	1	1	1	1	1
2.3B	Less than one week to strip	5	1	1	1	1	1	1	1	1	1	1
2.3C	2-4 ft²/minute removal rate	5	1	1	1	1	1	1	1	1	1	1
2.3D	Accommodate a varied laser spot size	5	1	1	1	1	1	1	1	1	1	1
2.3E	Accommodate a square laser spot	5	1	1	1	1	1	1	1	1	1	1
2.3F	Accommodate an average pulse number of 10	5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3G	Accommodate extra number of pulses	5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3H	Accommodate 200 pulses/second laser pulse rate	5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3I	Provide sensor feedback rate of 1/60 second	10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3J	Provide less than 10° sway (arm swing)	5	1	1	1	1	1	1	1	1	1	1
2.3K	Accommodate UTIL laser	5	1	1	1	1	1	1	1	1	1	1
2.3L	Provide 0.040" accuracy	5	0	0	0	0	1	1	0	0	0	0
2.3M	Provide 100 lb payload	10	1	1	1	1	1	1	1	1	1	1
2.3N	Provide NDI/NDE capability	5	1	1	1	1	1	1	1	1	1	1
2.3O	Provide global and relative positioning	15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3P	Provide 3" inside diameter beam tube	5	1	1	1	1	1	1	1	1	1	1
2.3Q	Provide 7" diameter servicer hose	5	1	1	1	1	1	1	1	1	1	1
2.3R	Provide 12" standoff	5	1	1	1	1	1	1	1	1	1	1
2.3S	Strip 80% of total area	5	0	1	0	1	0	0	1	1	1	1
2.3T	Differentiate between stripped and non-stripped	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3U	Strip composites to primer	15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3V	Strip metal surfaces to bare substrate	15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3W	Move between facilities (optional)	5	0	0	1	0	0	1	1	0	0	0
2.3X	User friendly programming language	10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3Y	Controller inputs from all sensor systems	10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3Z	Accommodate 10.6µm laser	5	1	1	1	1	1	1	1	1	1	1
2.3AA	Provide purged air beam delivery system	5	1	1	1	1	1	1	1	1	1	1
2.4.1A	Work under ceiling height of 30'	20	1	1	1	1	1	1	1	1	1	1
2.4.1B	Work around current positioning scheme	15	0	1	0	1	1	1	1	1	1	0
2.4.1C	Be capable of moving on existing floor	15	N/A	N/A	1	N/A	N/A	N/A	1	N/A	0	N/A
2.4.1D	Work around existing ductwork	15	0	0	0	0	0	1	1	0	1	0
2.4.1E	Allow aircraft to move to center han.	10	1	1	1	1	1	1	1	1	1	1
2.4.1F	Provide laser safe walls	15	1	1	1	1	1	1	1	1	1	1
2.4.2A	Allow for drainage in the new floor	10	1	1	1	1	1	1	1	1	1	1
2.4.2B	Be capable of moving on the new floor	15	N/A	N/A	1	N/A	N/A	N/A	1	N/A	1	N/A
2.4.2C	Work around existing ductwork	15	0	0	0	0	1	1	1	0	1	1
2.4.2D	Allow aircraft to move to center hangar	15	1	1	1	1	0	1	1	1	1	1
2.4.2E	Provide laser safe walls	10	1	1	1	1	1	1	1	1	1	1
2.5A	Meet OSHA regulations	15	1	1	1	1	1	1	1	1	1	1
2.5B	Emit no explosive fumes or gases	10	1	1	1	1	1	1	1	1	1	1
2.5C	Provide shielding for the operator	10	1	1	1	1	1	1	1	1	1	1
2.5D	Do not allow operator in work envelope	10	1	1	1	1	1	1	1	1	1	1
2.5E	E-stop	10	1	1	1	1	1	1	1	1	1	1
2.6	Be manufacturer certified	15	1	1	1	1	1	1	1	1	1	1
	TOTALS (Sum of 0 entry weights)		70	40	65	40	60	30	5	40	20	20

The lowest score reflects the most suitable candidate concept

1=yes
0=no

Figure 5.1-1 Trade-off Analyses

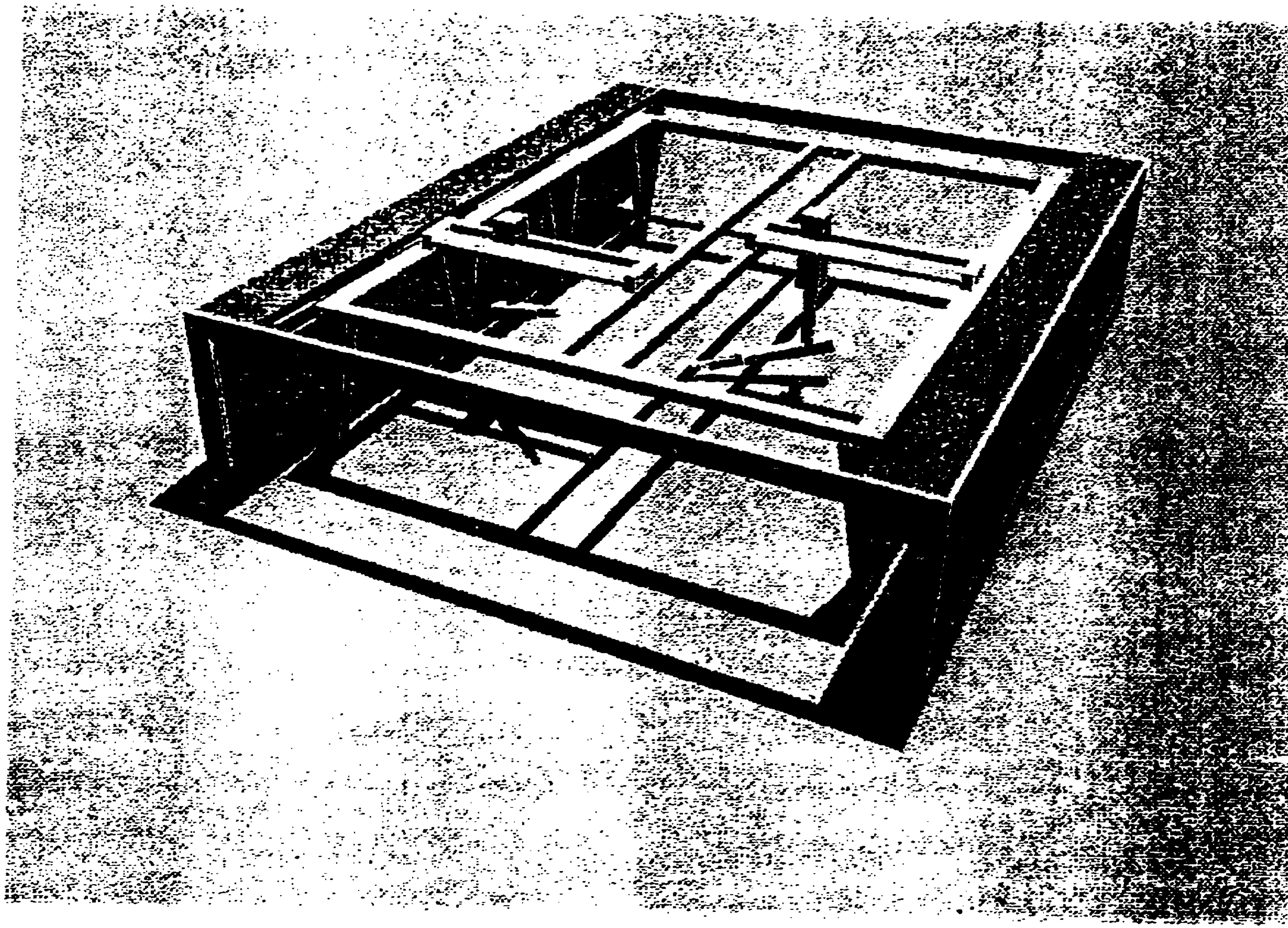


Figure 5.1.1-1 Overhead Gantry System in Building 2122

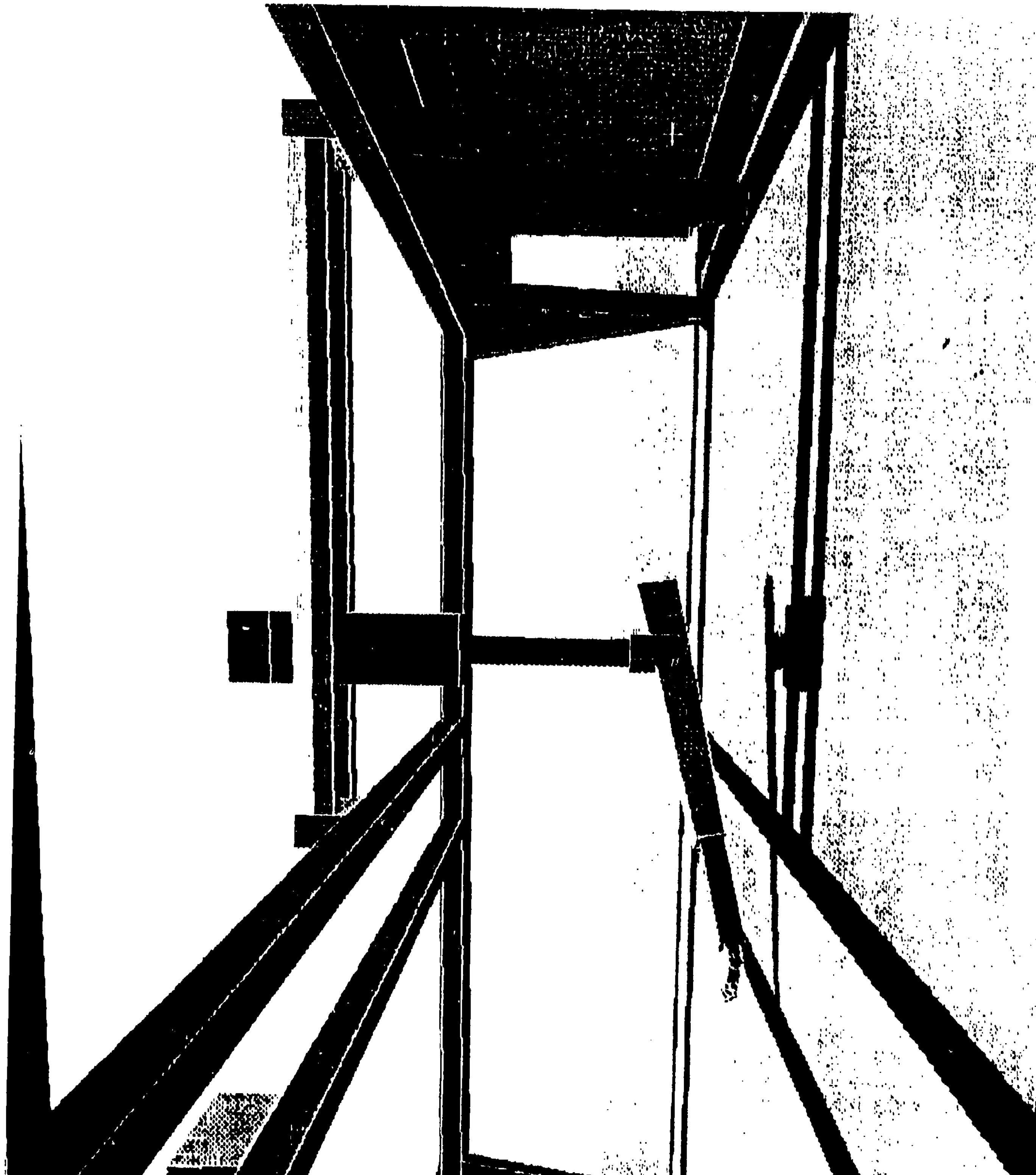


Figure 5.1.1-2 Overhead Gantry System

the current floor would require some modification for leveling purposes (the floor level differs by approximately 1 foot from the north side to the south side). If a new floor was installed in Building 2122, the necessary floor provisions could be made.

The existing duct work along the side walls of Building 2122 would interfere with the gantry structure, reducing its width and/or height capability. The workable ceiling height would limit the height of the gantry structure if a telescoping z-axis is incorporated. The telescoping member requires space above the gantry structure of 5-10 feet.

Schedule. Design, fabrication, and installation of this system into Building 2122 is projected at approximately 3 years. While gantry technology is quite advanced on a small scale, large systems such as this do not exist. Significant design effort would be required, long-lead items identified and fabrication activities started as early as possible. Software development would require not only kinematic formulation but would need to account for structural deflection across such a large span.

Flexibility. The system could provide other operations, such as NDI/NDE. The system is not transportable between buildings.

Technology Risk. Some risk is associated with developing a system of this size. Risk is reduced by the fact that the gantry's basic technology is already proven. Beam delivery methods are also proven for gantry systems.

Meeting System Requirements. Non-compliance areas for this concept are as follows:

- **Aircraft** - Owing to facility limitations caused by the ventilation duct work and ceiling height, it does not appear that the nose and left wing tip of the B-52 or the upper sections of the B-1 tail could be reached.
- **Process** - The spans required would introduce a significant structural deflection into the system. The accuracy requirement of 0.040 inch could not be met

without adaptive control (2.3L). Surface area percentage stripped would not meet the 90% requirement. (2.3S)

- **Facility** - B-52 positioning in the facility would require more time and effort than is currently necessary, because of the additional structures along the walls (2.4.1B). Facility duct work would interfere with the gantry system (2.4.1D, 2.4.2C)

Qualitative Cost Issues. The cost of the structure is estimated to be higher than the cost of most of the other concepts. Facility modifications would be necessary whether it be slight modifications in leg base areas or a complete new floor.

Final Analysis. The overhead gantry system is feasible, but the cost of the system and its inability to reach all areas of the aircraft when positioned in Building 2122 make it unfavorable.

5.1.2 Facility Bridge Crane System

A concept representative of this class is shown in Figures 5.1.2-1 and -2. This system is similar to the gantry but would be integral to the facility walls for support (similar to the Cimcorp System at McClellan AFB). This concept incorporates an enlarged industrial bridge crane spanning the 160' building width. Side rails are to be supported by the facility structure and/or additional supports attached to the facility walls. The bridge spans the rails similar to the gantry system. No end legs are provided on either end. A telescoping or pivoting arm is used with an additional arm mounted on the end for reaching under wings and fuselages.

Facility Impact. While no impact to the facility floor would be experienced, a significant amount of facility modification would be necessary particularly to the walls. From conversations with the facilities engineers at Tinker AFB, it appears that modification to the facility structure is not feasible.

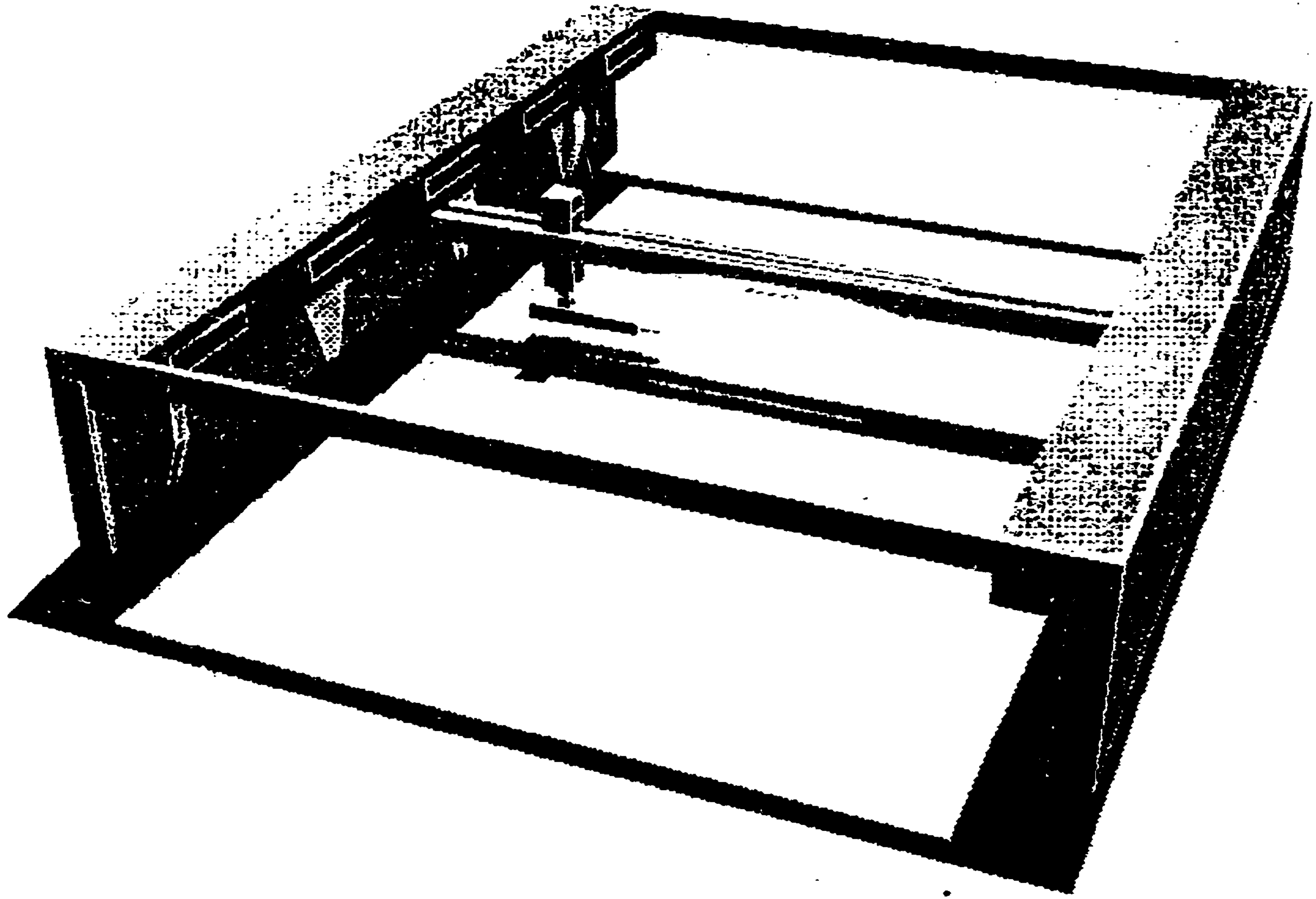


Figure 5.1.2-1 Facility Bridge Crane System in Building 2122

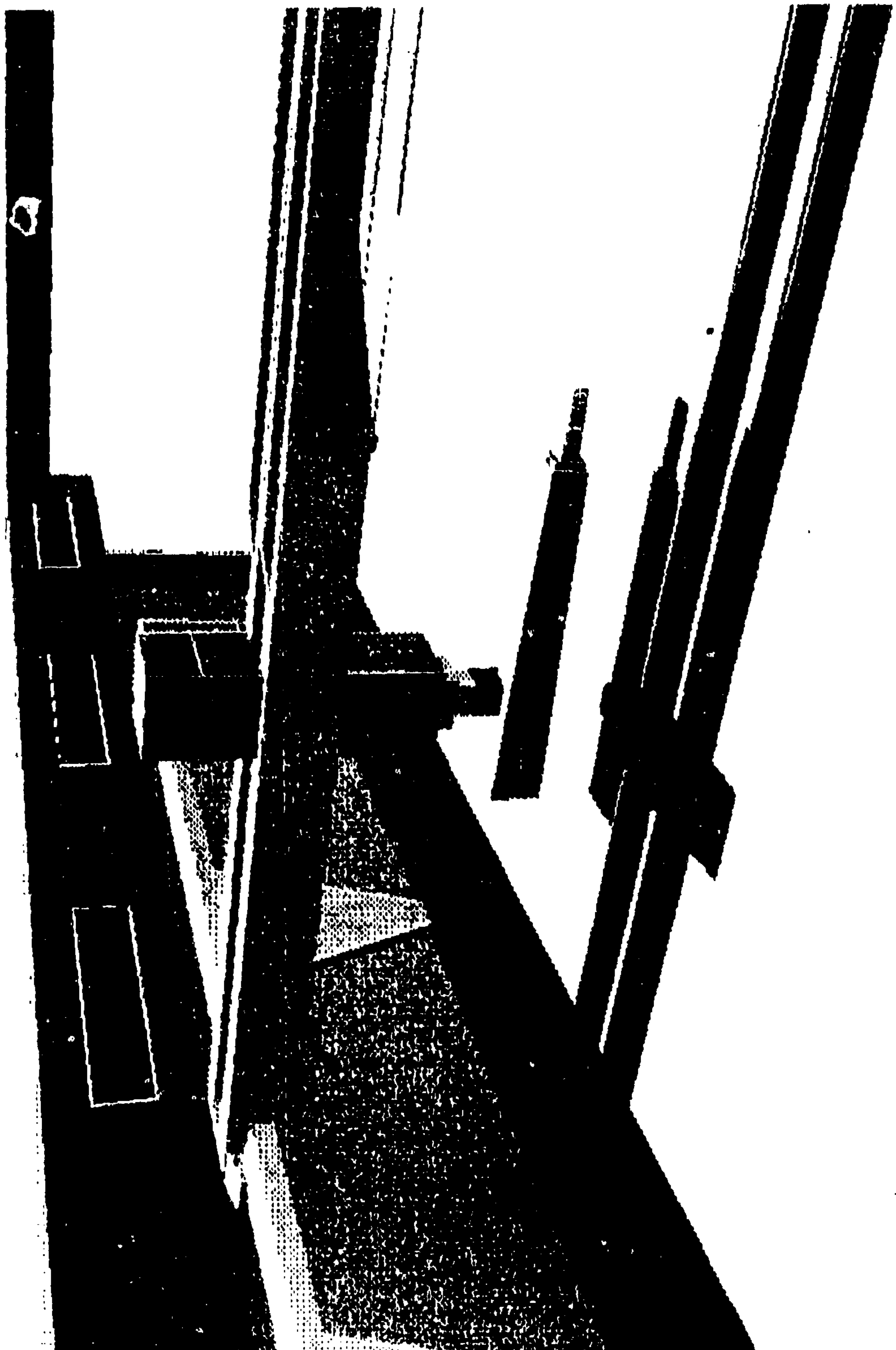


Figure 5.1.2-2 Facility Bridge Crane System

As in the gantry scenario, the existing duct work along the side walls of Building 2122 would interfere with the side rails. To raise the rails to the necessary height, the duct work would need to be relocated. If the rails were installed below the existing duct work, the required work envelope would not be met.

Schedule. The time for design, fabrication and installation of this system into Building 2122 is projected at approximately 3 years. A significant hardware design effort would be necessary to expand on crane technology. Major facility modifications would also be necessary.

Flexibility. The system could provide other operations such as NDI/NDE. The system is not transportable between buildings.

Technology Risk. There is moderate risk associated with developing a system of this size. Bridge crane technology is established on a smaller scale but would have to be expanded. Beam delivery methods would be similar to the gantry structure routing.

Meeting System Requirements. Noncompliance areas for this concept are as follows:

- **Aircraft** - The system could reach all areas of the aircraft except for the upper portion of the B-1 tail.
- **Process** - The system can not meet the 0.040 inch accuracy requirement, again because of the lengthy spans and inherent structural deflections.
- **Facility** - The floor issue does not affect this concept. Facility duct work would interfere with the crane system.

Qualitative Cost Issues. The cost of the structure and facility modifications would be higher than all other concepts. Modifications to the walls would be the major contributor to the cost.

Final Analysis. While the system is feasible, the amount of facility modifications necessary, the cost of the system and its incapability to reach all areas of every aircraft make it unacceptable.

5.1.3 Side Gantry System

A representative of this concept class is shown in Figures 5.1.3-1 and -2. This system would use a horizontal extension to position a smaller robot arm in the required work area. The system would be moveable within the facility on wheels. Air-bearing units would also be a possible mode of transportation, if an air-bearing finished floor were installed.

The end-of-boom robot used on the side gantry system would provide 5-6 degrees of freedom. The robot could be positioned in a normal upright position or upside down, as required to meet the reach requirements for the section of the aircraft being processed.

The robot would be mounted on a 22-foot in/out extension slide attached to a traversing track assembly. Lift platforms would first be moved to a set level, located and locked in position before any robot or in/out traversing motion is allowed.

Facility Impact. The existing facility structure would be required to support the loads placed on it by the weight of the side gantry. Foam-filled tires would be used in the existing facility. Some floor modification would be necessary to insure that the side gantry system could negotiate the slope grade. If a new floor was installed, air bearing motion capability could be considered. The varied positioning of the aircraft prohibits the use of rails or tracks in the floor.

The size of the side gantry system would require modification to the side roll-up door to allow entrance for operations on the front right side of the B-52. The height required to reach all areas of the aircraft would interfere with the ventilation duct work on the B-52 nose side of the building.

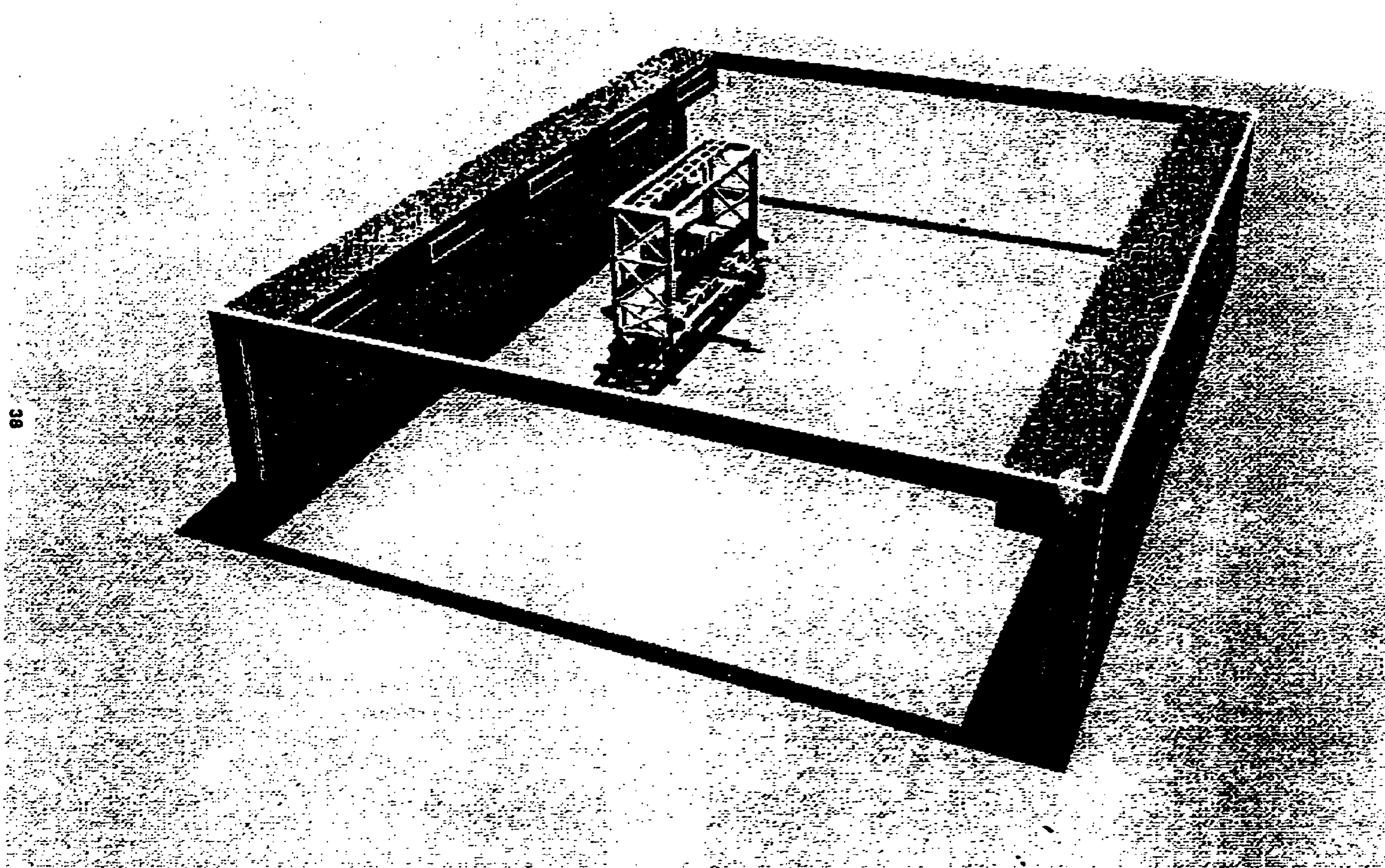


Figure 5.1.3-1 Side GantrySystem in Building 2122

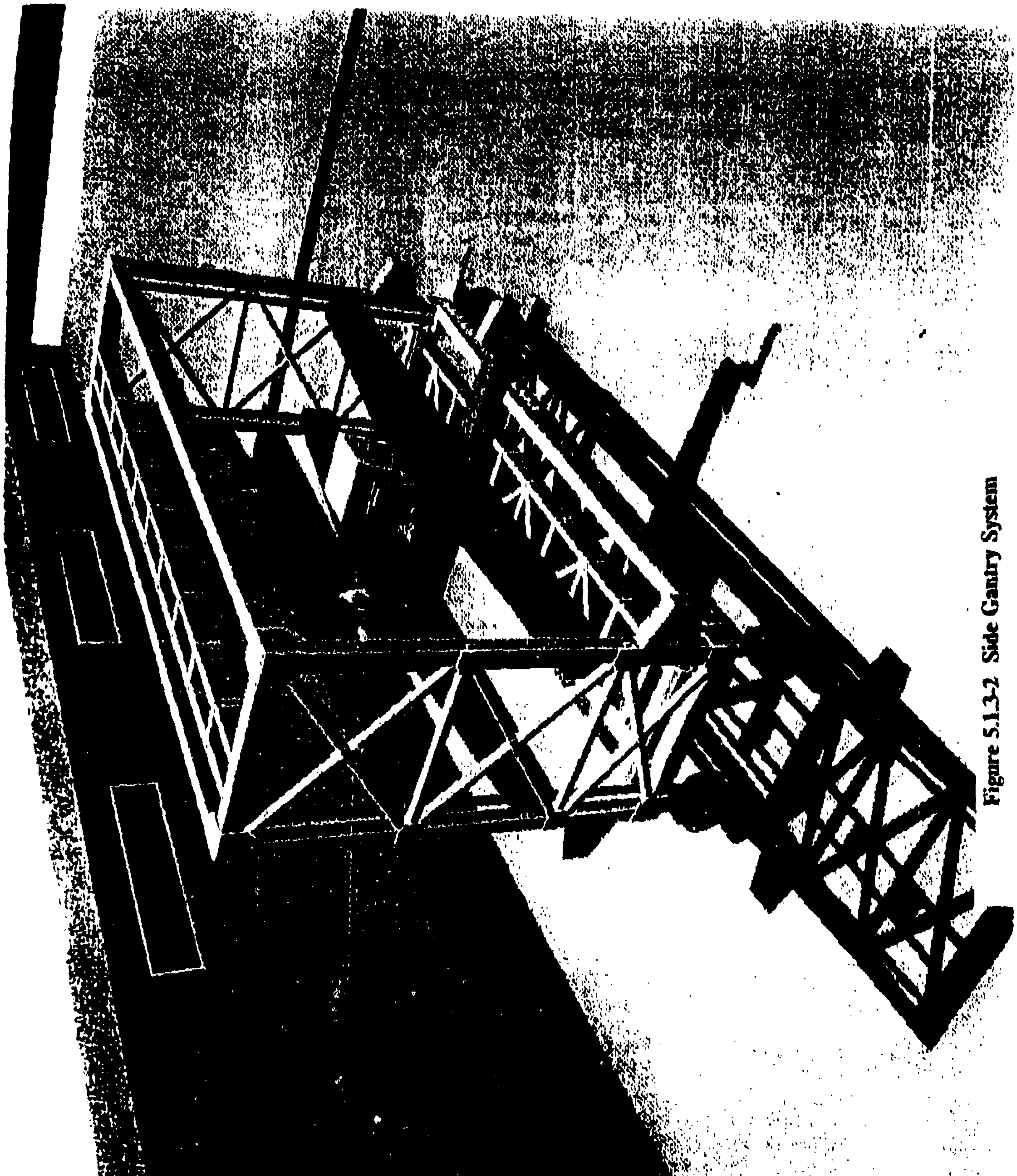


Figure 5.1.3-2 Side Gantry System

Schedule. The activation time period for this system is projected at 2-1/2 to 3 years. Being smaller than the previous two concepts and having a lower facility impact reduces the necessary activation time.

Flexibility. The system could provide other operations, such as NDI/NDE. Under tow or self-power, depending on the design, the system could move between facilities (tire version).

Technology Risk. There is some risk associated with this concept, as it is not used on a smaller scale and would require increased design effort. The required reach is reduced, however.

Meeting System Requirements. Noncompliance areas for this concept are as follows:

- **Aircraft** - It does not appear that all surface areas of the aircraft could be reached. Some thought would have to be given to moving around the B-52. The side gantry system might have to be moved outside the building to reenter through a side door. If the system were small enough to fit under the existing duct work, then it would not be large enough to reach all areas.
- **Process** - An accuracy of 0.040 inches can not be met by the system when considering the telescoping extension. The off-the-shelf pedestal robot on the end of the boom can meet the requirement, however. The surface area requirement of 90% cannot be met, and the system would probably not fit around the current positioning scheme.
- **Facility** - It does not appear that the system would accommodate the existing duct work.

Qualitative Cost Issues. The system would cost less than the first two concepts, because of its reduced size and lessened facility impact.

Final Analysis. The system is feasible. However, the side gantry height requirement, slight impact on the facility and process positioning scenarios make it difficult to accommodate.

5.1.4 Hill AFB Type System

A representative of this system, similar to the Hill AFB installation, is shown in Figures 5.1.4-1 and -2. This system would provide positioning of two smaller robot arms by two larger SCARA (Selective Compliant Adaptive Robotic Arm) type arms. Significantly longer reaches would be required for this system (on the order of 75 feet). The two larger arms would move the length of the building on tracks.

Facility Impact. The facility impact would be significant for this system. If the facility ventilation duct work is relocated, the top track can be located at workable ceiling height level. If the duct work is not relocated, the upper track would be located immediately underneath. With the existing floor, the two robot systems would not be identical (i.e., the floor elevations differ from one side of the facility to the other).

Schedule. Design, fabrication and installation time for this system into Building 2122 is projected at approximately 3 years.

Flexibility. The system could provide other operations, such as NDI/NDE. The system is not transportable between buildings.

Technology Risk. The system purchased by the USAF has established the basic technology. The expanded reaches demanded by this application would increase the risk substantially, however.

Meeting System Requirements. Noncompliance areas for this concept are as follows:

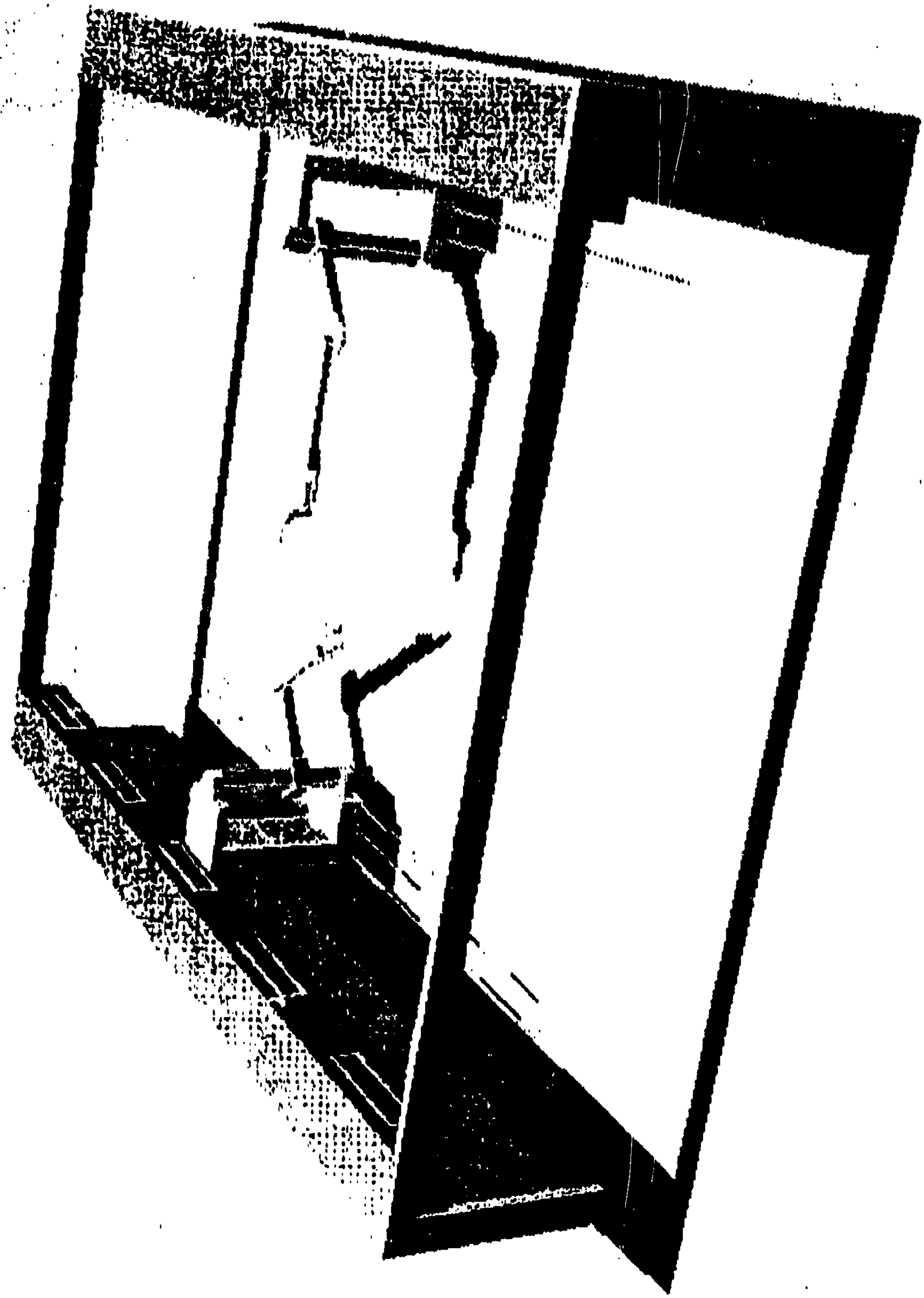


Figure 5.1.4-1 Hill AFB Type System in Building 2122

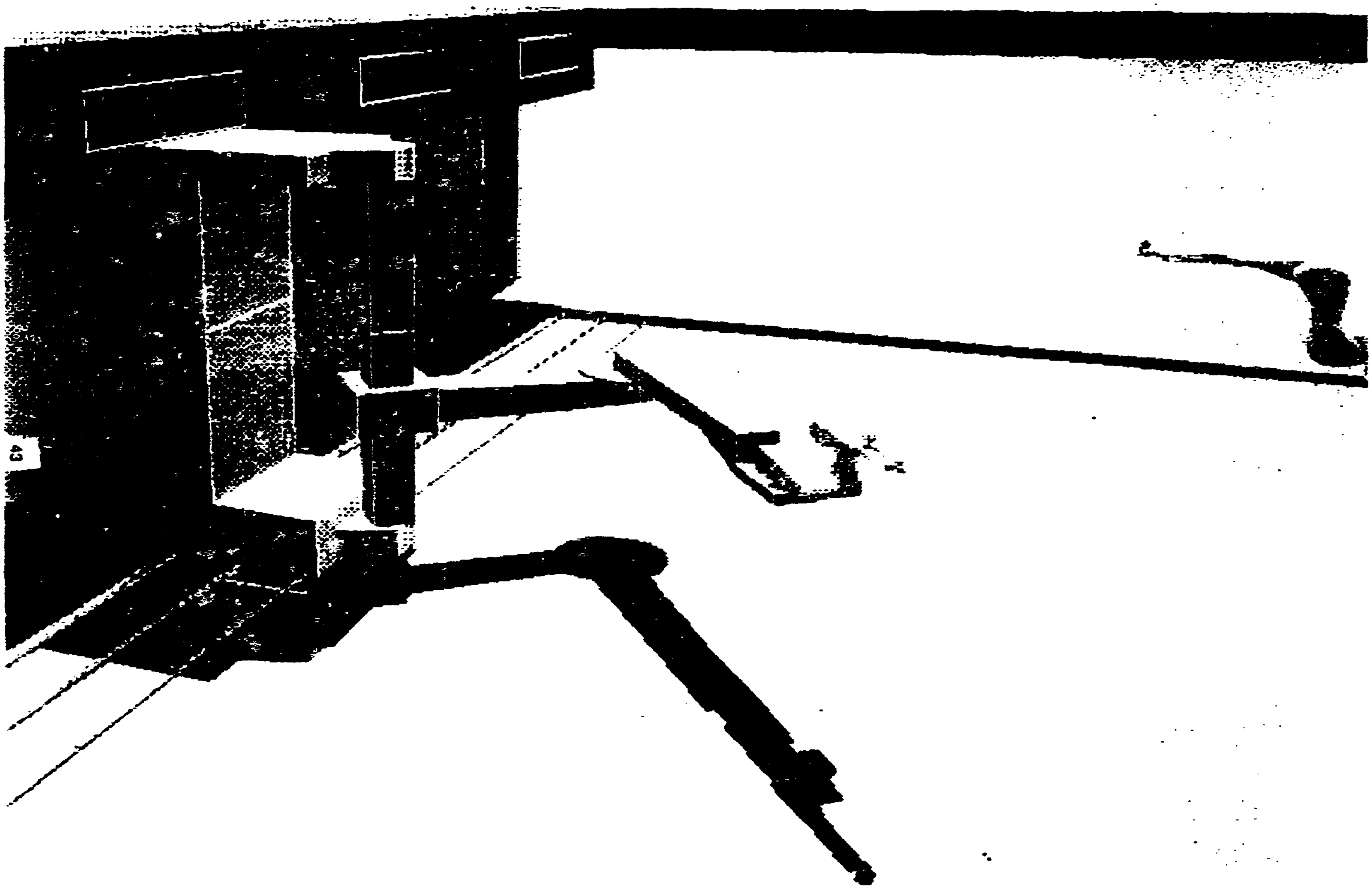


Figure 5.1.4-2 Hill AFB Type System

- **Aircraft** - The upper portion of the B-1 tail could not be serviced if the system is installed below the existing duct work.
- **Process** - The 0.040-inch accuracy could not be met by the entire robot system.
- **Facility** - The system would interfere with facility duct work if it was to meet the work envelope requirements.

Qualitative Cost Issues. Facility modifications and structural costs make the system one of the more costly of the alternative concepts.

Final Analysis. While this concept is ranked in the upper half, its substantial cost would prove prohibitive. The long reaches necessary would also prove to be a technical challenge.

5.1.5 Pedestal Robot System

This system would incorporate multiple off-the-shelf pedestal robots positioned on tracks around the aircraft around the outside shape of the various aircraft (preferred) or in a grid pattern. Clearly, this concept would not meet the reach requirements necessary. Even if the reach of the largest off-the-shelf pedestal robot was tripled, it would barely meet the necessary reach requirement. For this reason, the track-mounted pedestal robot alternative was excluded from further evaluation. Several robot manufacturers have been contacted about increasing the reach of their standard robots. None feel that this redesign is feasible. A symmetric grid track approach is shown in Figures 5.1.5-1 and -2.

5.1.6 Pedestal Robot Lift System

To investigate the use of pedestal robots, the concept of a pedestal robot on a mobile lift mechanism such as a scissor-lift or hydraulic cylinder-lift platform was evaluated. A sketch of a representative concept is shown in Figures 5.1.6-1 and -2.

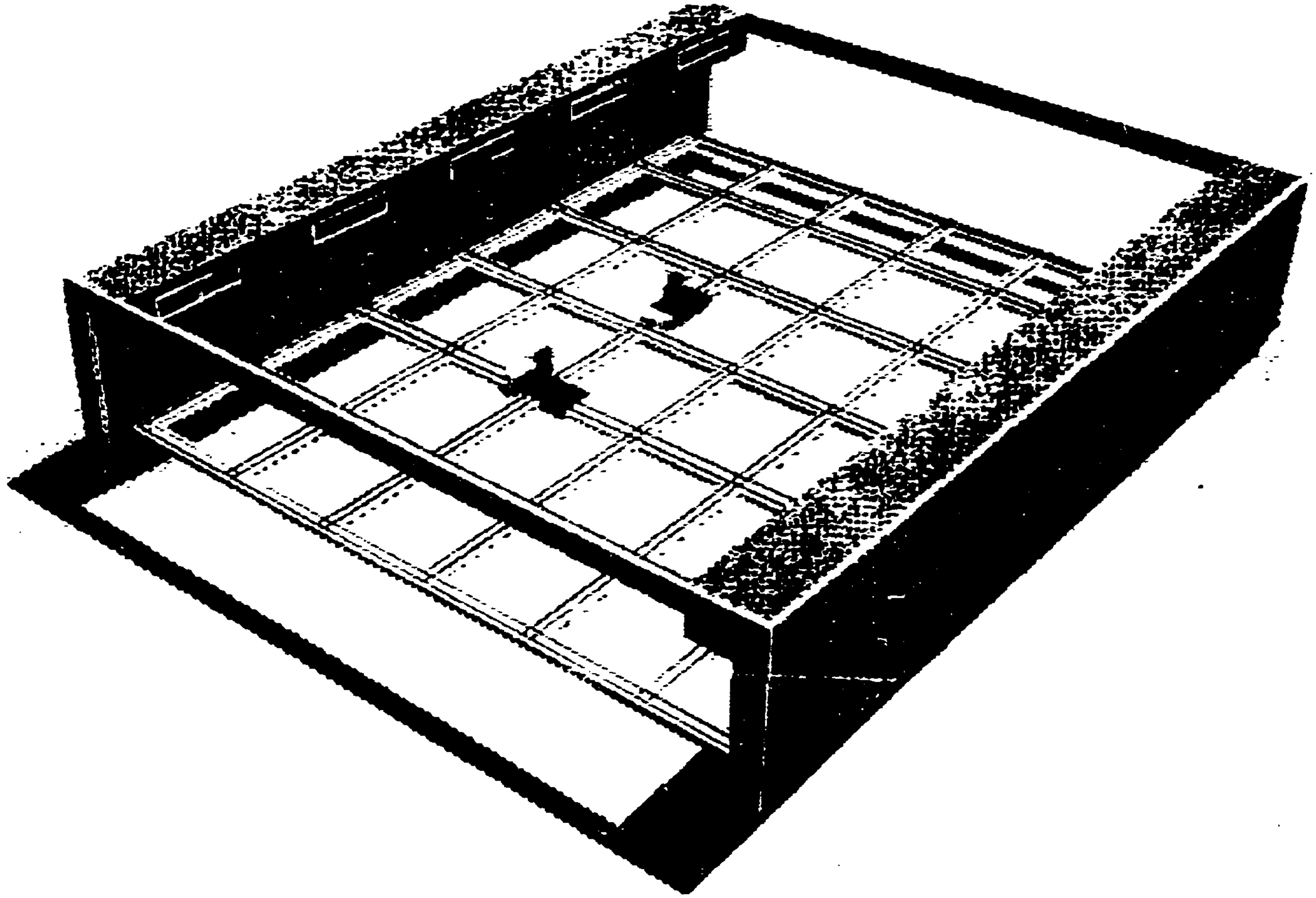


Figure 5.1.5-1 Pedestal Track System in Building 2122

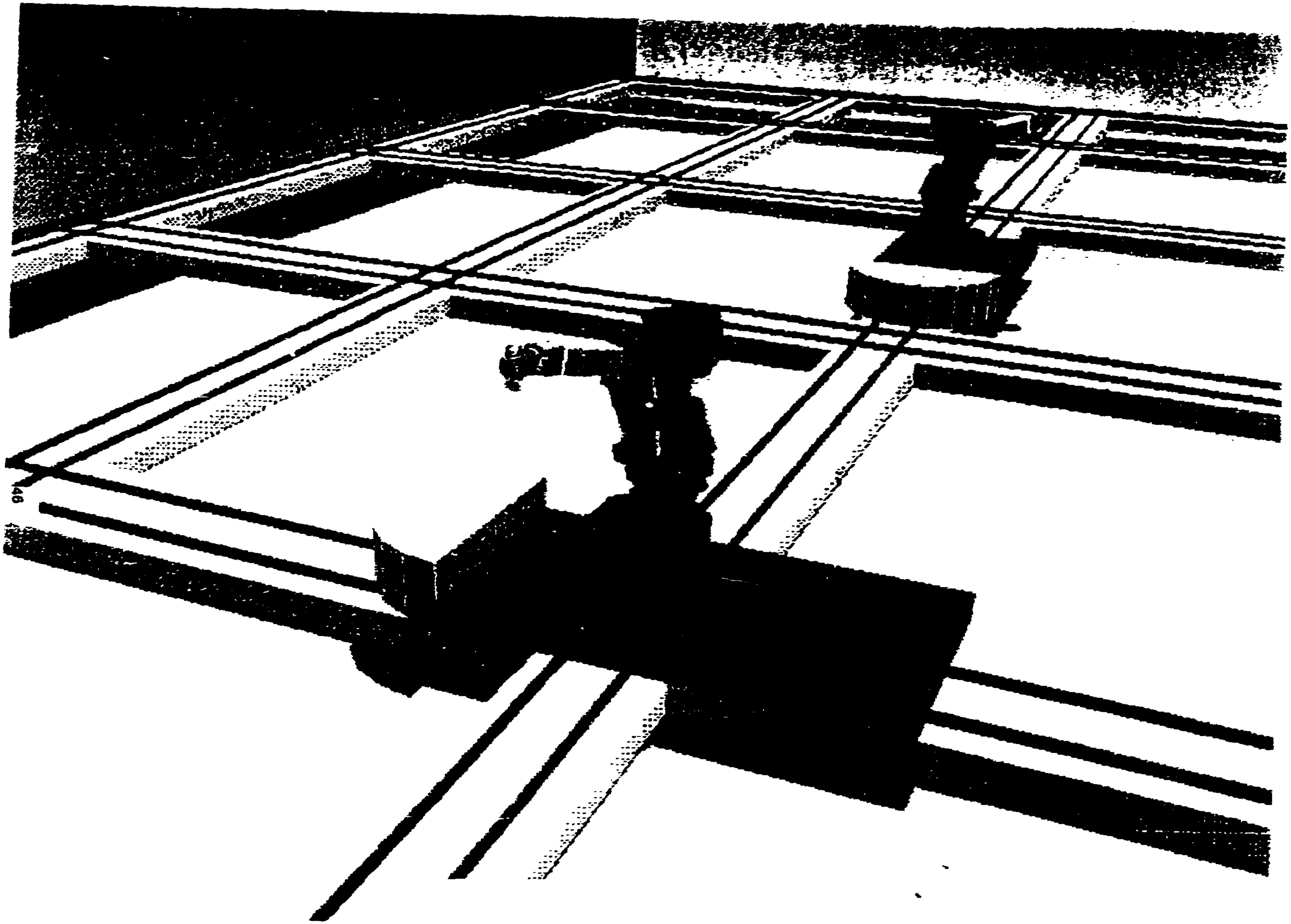


Figure 5.1.5-2 Pedestal Track System

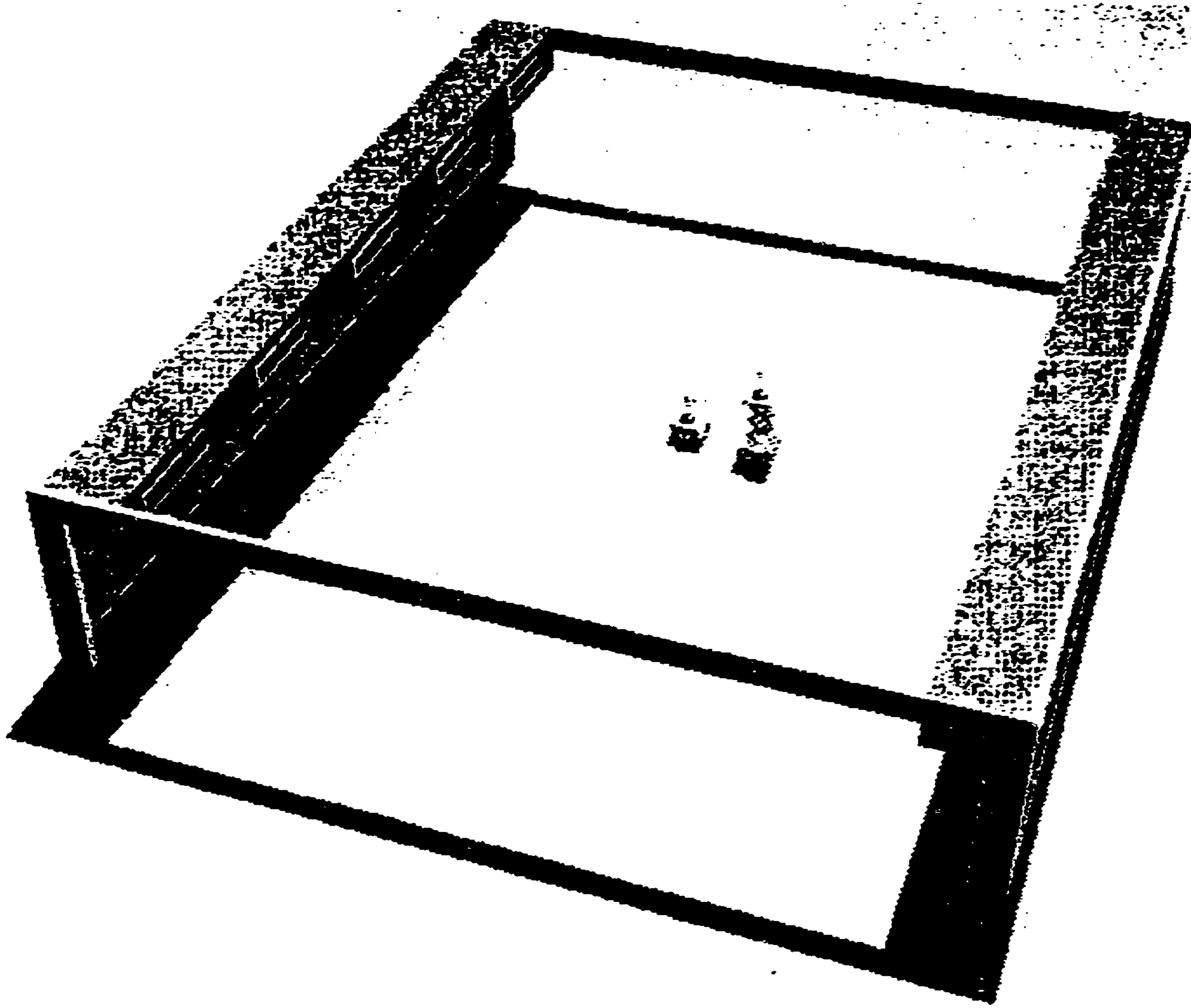


Figure 5.1.6-1 Pedestal Robot Lift System in Building 2122

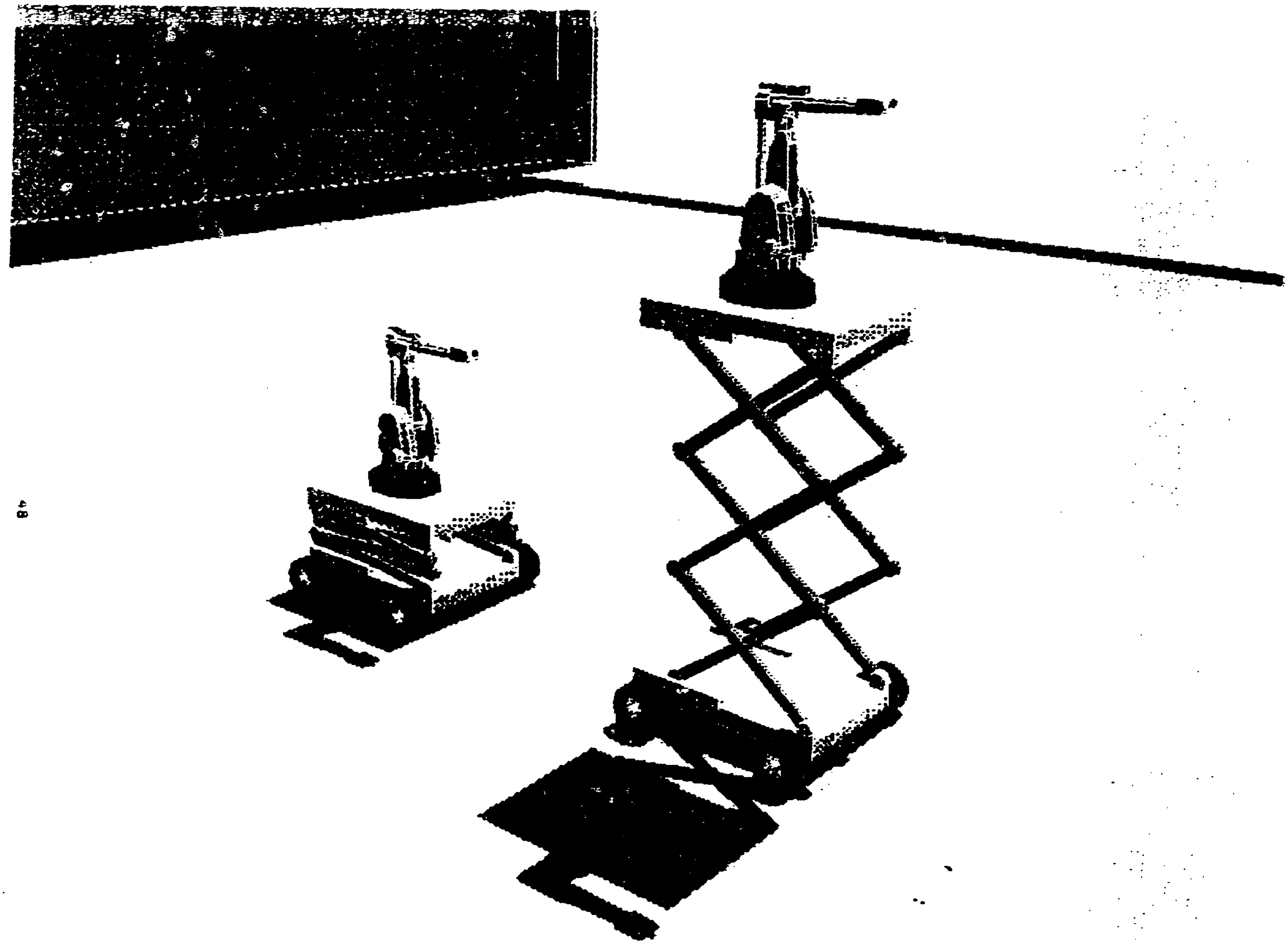


Figure 5.1.6-2 Pedestal Robot Lift System

Facility Impact. No facility impact would be encountered by this concept. Floor slope grades would need to be evaluated.

Schedule. The integration time for a pedestal robot and a scissor-type lift (or a platform-type lift) is projected at 2 years.

Flexibility. The system could provide other operations such as NDI/NDE and be transportable between facilities.

Technology Risk. These two items have not been integrated in the past. Individually, their risk is low; however, USBI has performed a preliminary design activity on this type of concept and found stability to be an issue.

Meeting System Requirements. Non-compliance areas for this concept are as follows:

- **Aircraft** - The system can not reach all areas of each of the aircraft. The system would not be capable of reaching completely under the wings or fuselage.
- **Process** - The system can not strip 90% of the total surface area of the three aircraft combined.
- **Facility** - All facility requirements are met by the system.

Qualitative Cost Issues. The hardware cost of the system would be one of the lowest.

Final Analysis. This is a concept that requires further attention. The major drawback of the system is its reach limitations.

5.1.7 Mobile Vehicle System

This system would utilize a standard flight line transport tug (a more stable base) with a telescoping boom to position the work head around the aircraft. This concept representative is shown in Figures 5.1.7-1 and -2.

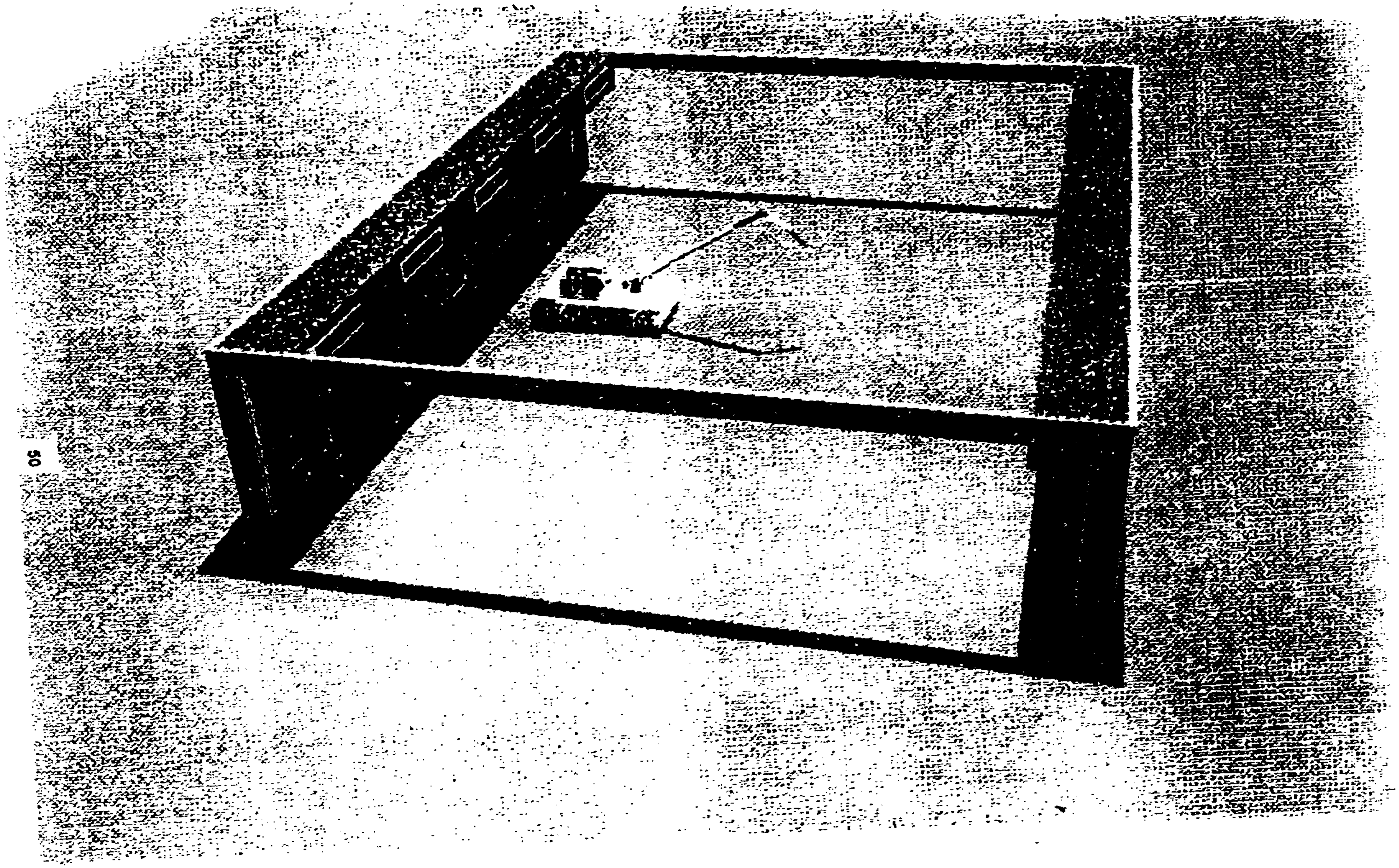


Figure 5.1.7-1 Mobile Vehicle System in Building 2122

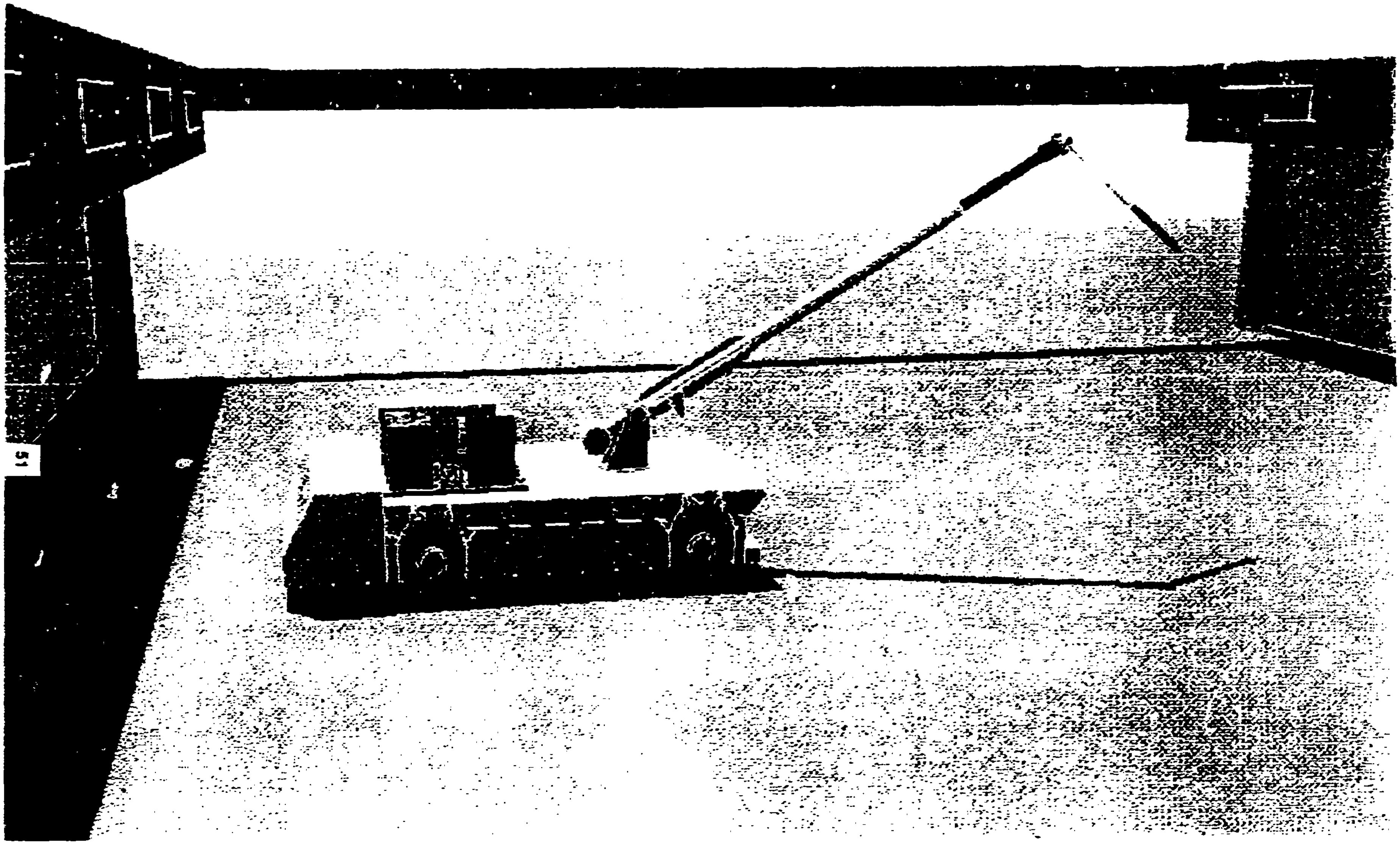


Figure 5.1.7-2 Mobile Vehicle System

Facility Impact. No facility impact is associated with this concept. The floor slope grade would require evaluation.

Schedule. System design, fabrication and installation time are projected at approximately 2 years.

Flexibility. The system could provide other operations such as NDI/NDE and would be transportable between facilities.

Technology Risk. From the integration standpoint, there is some risk associated with this concept; however, all components to be integrated are based on existing technology.

Meeting System Requirements. Noncompliance areas for this concept are as follows:

- **Aircraft** - All aircraft reach requirements are met by this system.
- **Process** - The accuracy requirement of 0.040 inches cannot be met by the system.
- **Facility** - All facility requirements are met by this system.

Qualitative Cost Issues. The cost associated with this system would be near the bottom of the concept list.

Final Analysis. This system concept class is not only feasible, but is evaluated as the best of the alternative candidates.

5.1.8 Suspended Robot (NIST-type) System

This system would incorporate technology developed at the National Institute of Standards and Technology, as pictured in Figures 5.1.8.-1 and -2. A pedestal robot would be suspended by cables from a moving platform.

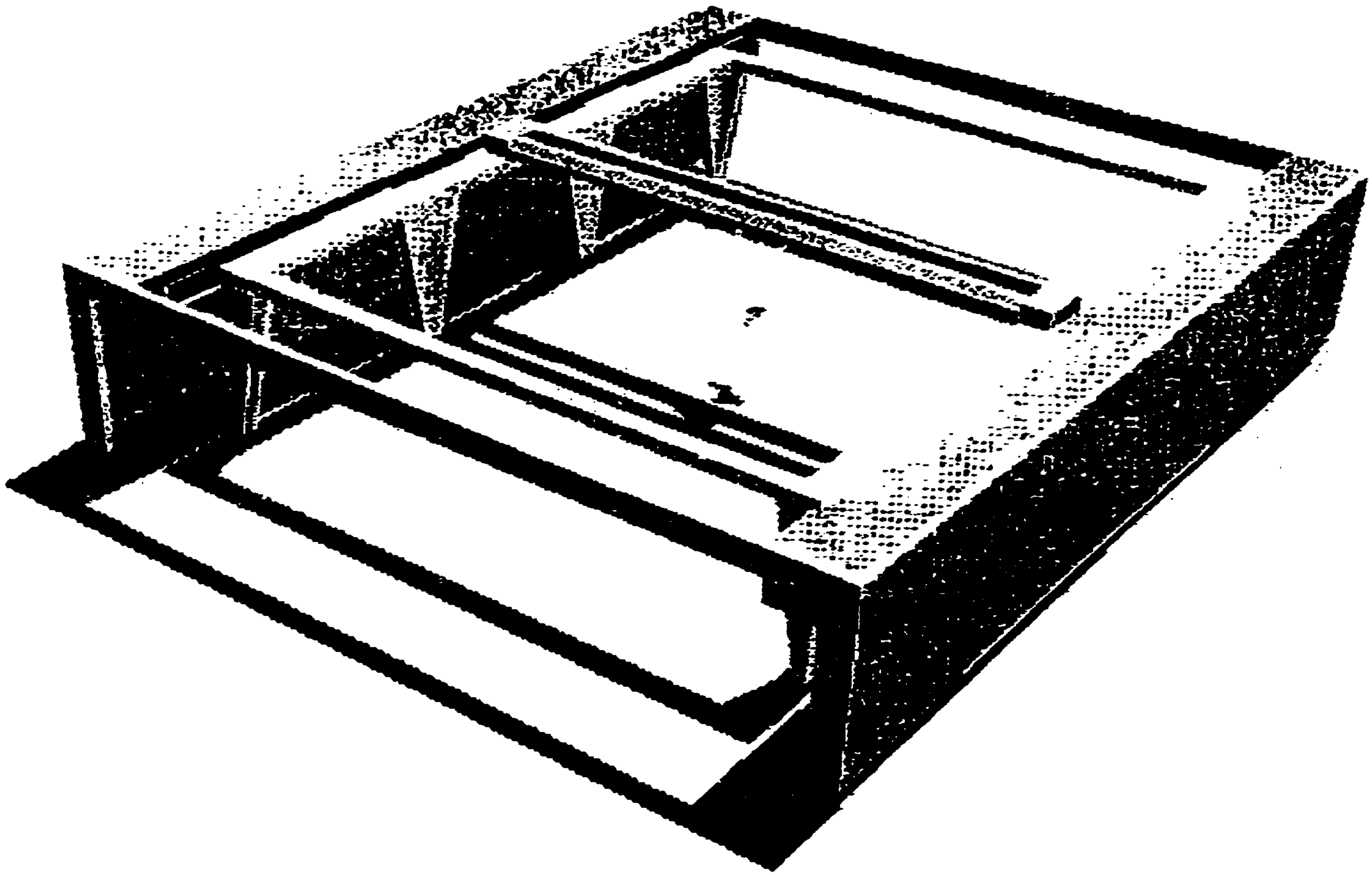


Figure 5.1.8-1 Suspended Pedestal (NIST Type) System in Building 2122

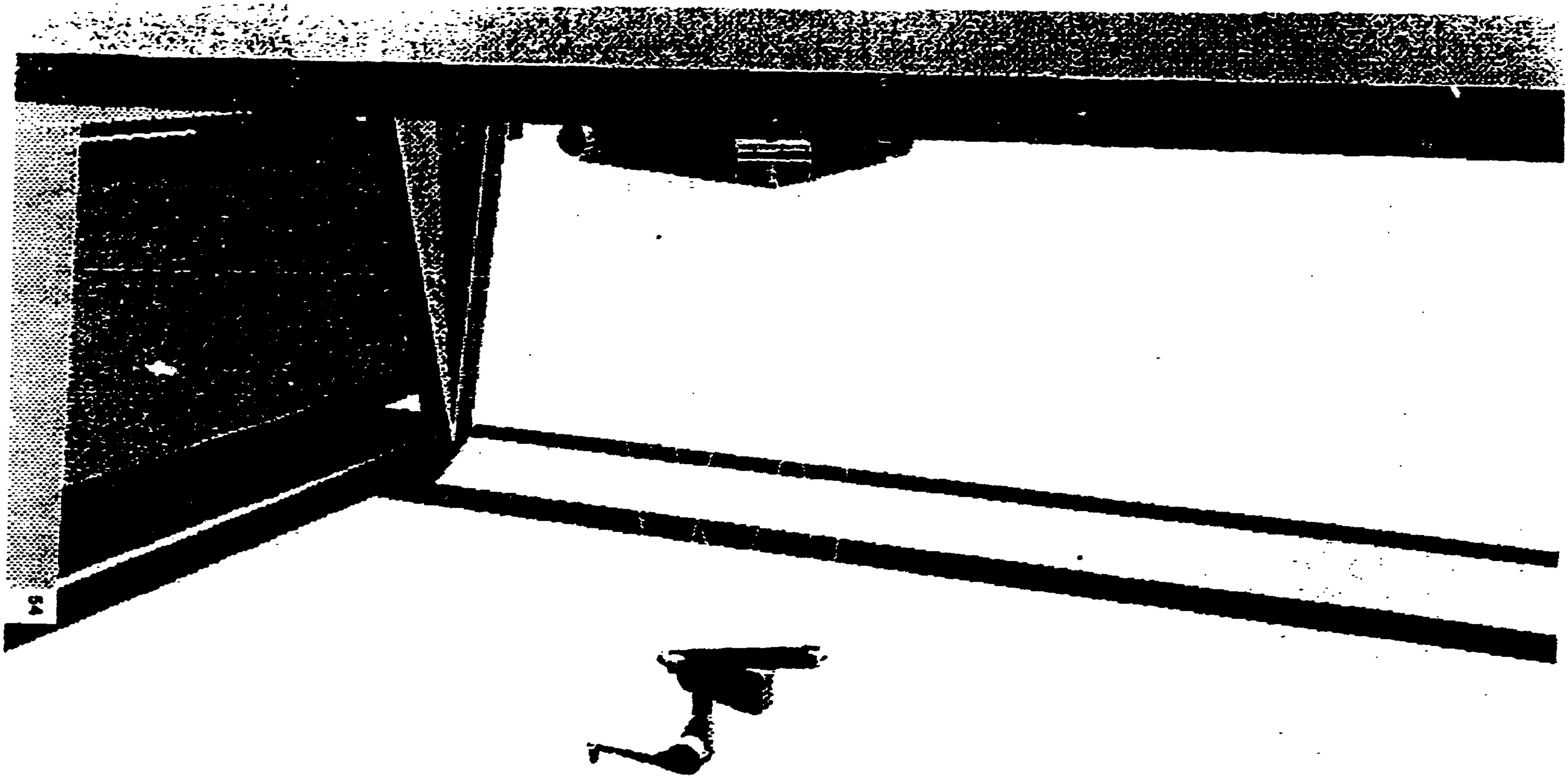


Figure 5.1.8-2 Suspended Pedestal (NIST Type) System

NIST's Robot Crane Technology Program developed kinematically constrained, dynamically stabilized robot cranes capable of lifting, moving, and positioning heavy loads over large volumes, capable of supporting fabrication tools and the inspection of large size and difficult-to-reach structures.

Facility Impact. This option would require a significant facility impact, similar to the crane concept (section 5.1.2).

Schedule. Design, fabrication and activation time for this system is projected at 2-1/2 to 3 years.

Flexibility. The system could provide other operations such as NDI/NDE but would not be transportable between buildings.

Technology Risk. There is risk associated with this concept. The basic technology has been proven at NIST, but only under laboratory conditions.

Meeting System Requirements. Noncompliance areas for this concept are as follows:

- **Aircraft** - The system would not be able to reach all areas of the B-1, because of the facility duct work location.
- **Process** - An accuracy of 0.040 inches could not be met.
- **Facility** - Facility duct work would interfere significantly with crane operations and/or limit the work envelope.

Qualitative Cost Issues. The cost of the system would rank among the top of the concept entries.

Final Analysis. While the technology appears well suited for the application, the facility does not lend itself to such a configuration.

5.1.9 InTA System

This system would consist of InTA's design as proposed to the Navy, with a modified reach capability. InTA's system uses SwRI developed arm similar to the system to be installed at Hill AFB. The system would be mounted on an air-bearing platform and follow a soft wire for each specific aircraft type on the floor. The robot arm provides a reach of 22.5 feet and is counterbalanced by the weight of the laser unit located on the air-bearing platform. A conceptual drawing is not available.

Facility Impact. The system, as configured, will not operate in the existing facility. A new air-bearing surface is required.

Schedule. The system currently being designed for the Navy is scheduled for activation in 3 years. Based on knowledge gained in the Navy program, this system could probably be installed in 2 years.

Flexibility. The system could provide other operations such as NDI/NDE but is not capable of moving between facilities.

Technology Risk. At the present, there is a significant amount of risk associated with the project. Based on the development of the Navy system, the risk could be reduced.

Meeting System Requirements. Noncompliance areas for this concept are as follows:

- **Aircraft** - The system could meet all aircraft reach requirements.
- **Process** - The accuracy requirements cannot be met.
- **Facility** - The system cannot operate in the existing facility.

Qualitative Cost Issues. The cost of this system is in the bottom third. The Navy's purchase price is reportedly under $10,000,000.

Final Analysis. The system is among the top candidates; however, its inability to be used in the existing facility severely limits it.

5.1.10 Mushroom System

This system is similar to a USBI/AKR Robotics team concept selected by McDonnell Douglas Aircraft in Tulsa, Oklahoma. A 6-degree-of-freedom robot is mounted to a scara positioner. The positioner is raised and lowered on a cylinder which is installed in the facility floor. This system is shown in Figures 5.1.10-1 and -2.

Facility Impact. The system would significantly impact the floor of the facility. A new floor would have to be installed and large pits provided for the cylinder and drive systems.

Schedule. System installation and activation would require 2 to 2-1/2 years.

Flexibility. The system could provide other operations such as NDI/NDE but is not capable of moving between facilities.

Technology Risk. Risk for this system would be reduced because of the installation of a similar system for McDonnell Douglas.

Meeting System Requirements. Noncompliance areas for this concept are as follows:

- **Aircraft** - Multiple robots could meet all aircraft reach requirements. A single system, however, could not meet the reach requirements.
- **Process** - The accuracy requirements cannot be met.
- **Facility** - The system cannot operate in the existing facility. Systems would also need to be positioned so that an airplane could move to the center hangar.

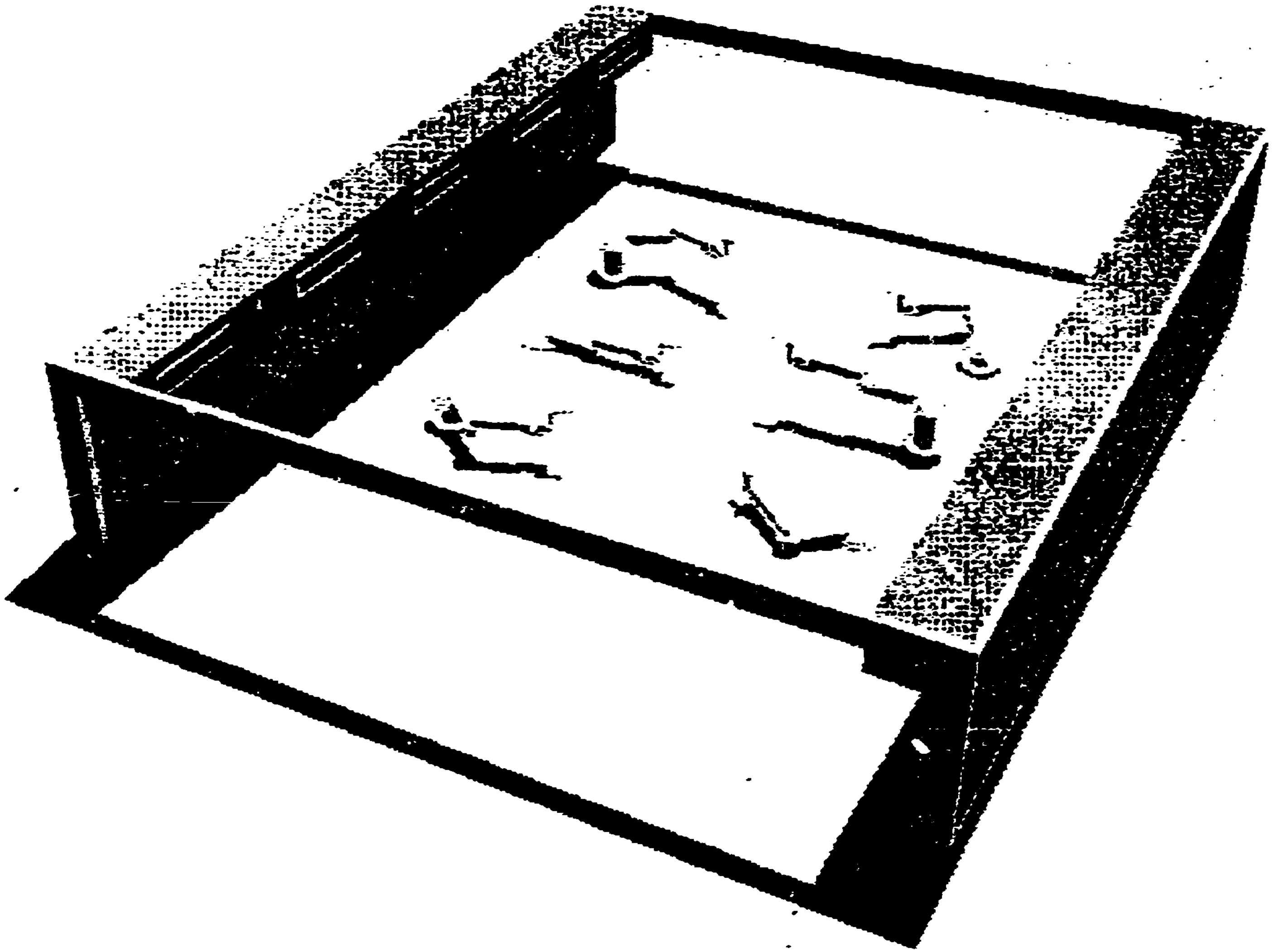


Figure 5.1.10-1 Mushroom System in Building 2122

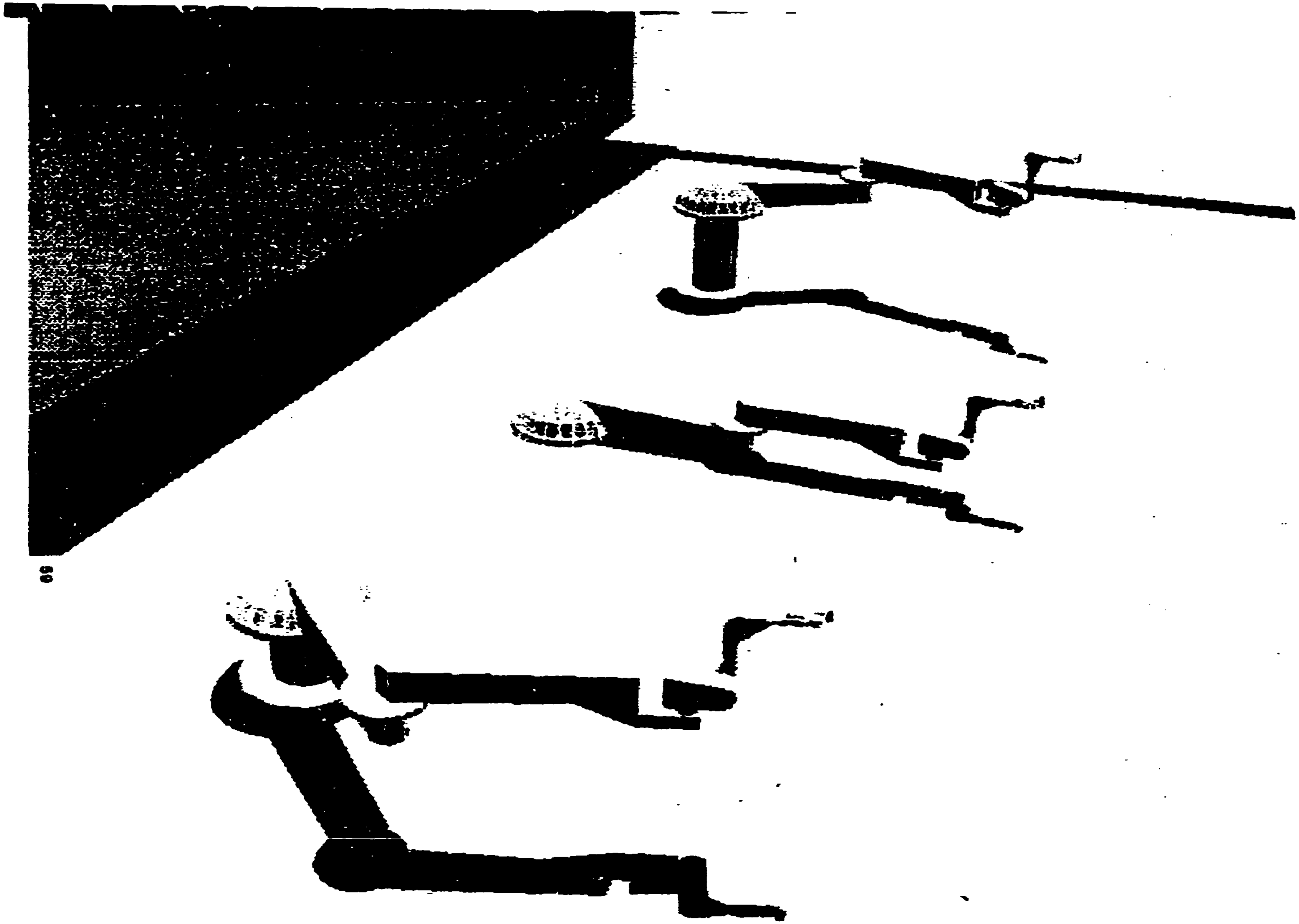


Figure 5.1.10-2 Mushroom System

Qualitative Cost Issues. The cost of this system would be high because of the facility impact and the number of robots required.

Final Analysis. The inability of the system to be used in the existing facility and the number of systems required severely limit its feasibility.

5.1.11 System Combinations

Some combination of the previously described systems should be evaluated. For example, one of the overhead concepts (5.1.8) can be used in conjunction with a mobile pedestal robot (5.1.6). Clearly, the advantages of such a system are:

- Reduced reach requirements for the robot systems
- Use of standard pedestal robots for both systems.

Disadvantages for this type of system would include:

- Facility impact associated with the overhead system
- Cost of the two laser systems over the cost of one system.

Because of the facility impact and cost of the additional laser systems, it does not appear that any hybrid system would meet the near-term requirements of the USAF for Tinker AFB. However, in a new facility this might prove to be a favorable approach.

5.2 Laser Technologies

5.2.1 Background Information - Materials Processing.

The laser is one of the most significant and versatile technologies of the second half of this century. Lasers ranging from tiny semiconductor devices to giant industrial systems are used in a wide variety of applications in manufacturing, R&D, medicine, telecommunications, computer peripherals, defense, and entertainment.

Materials processing with lasers can be more flexible, faster, and more precisely targeted than with conventional techniques. In some situations, laser processing is economically advantageous -- it increases productivity and product quality and reduces processing cost. In other situations, lasers allow new processing tasks that are not possible by other means. Together with robotics and automated process control and inspection, lasers can enhance flexible manufacturing and maintenance systems.

About 17,000 industrial laser systems are installed worldwide, with over 3,100 systems installed in 1988 (Table 5.2.1). The laser component itself typically accounts for only one-sixth of the value of the total system, which includes the means of laser beam delivery, parts handling, control, and monitoring.

The automotive industry, one of the first mass-production industries to use laser technology, accounts for about one-quarter of laser materials processing applications. The principal applications are welding, cutting, and drilling. The aerospace and electronics industries each account for about one-sixth of the application, and the remainder ranges across numerous industries, from garment making to shipbuilding.

Factors that have limited the growth of lasers are:

- The high initial costs of large laser installations
- Uncertainty of the costs, performance, and benefits of laser technology relative to well-established alternative technologies
- Continuing advances in competitive materials processing technologies.

Table 5.2.1 **Installed Base and Sales of Industrial Lasers (1988)**

	Units	Total Installed
Carbon Dioxide	1,900 (60%)	8,800 (52%)
Neodymium/YAG	1,200 (38%)	8,000 (47%)
Excimer	60 (2%)	200 (1%)
Total	3,100	17,000

Lasers are sources of electromagnetic radiation in the optical (ultraviolet, visible, and infrared) regions of the spectrum. Conventional light sources produce radiation by spontaneous (random) emission. In contrast, lasers generate their output by stimulated emission within the lasing medium, which may be a solid, a liquid, or a gas. Confined within a reflective resonator, the radiation is amplified by successive passages through the medium and emerges as a powerful, concentrated, coherent beam.

Excitation of a gas-lasing medium is usually achieved by initiating an electrical discharge within the laser resonator, while solid and liquid (dye) media are "optically pumped" by means of high-intensity lamps or a secondary laser. In semiconductor lasers, the recombination of holes and electrons in the semiconductor material gives rise to the coherent optical emission.

The laser output beam has three main attributes that are valuable in industrial processing:

- The beam's high radiance (brightness) and the use of focusing optics together can produce very high levels of irradiance (power density) at the workpiece.
- Its directional nature permits remote, flexible, localized, and efficient processing.
- Its monochromaticity (narrow spectral bandwidth) allows strong yet selective absorption into the target material.

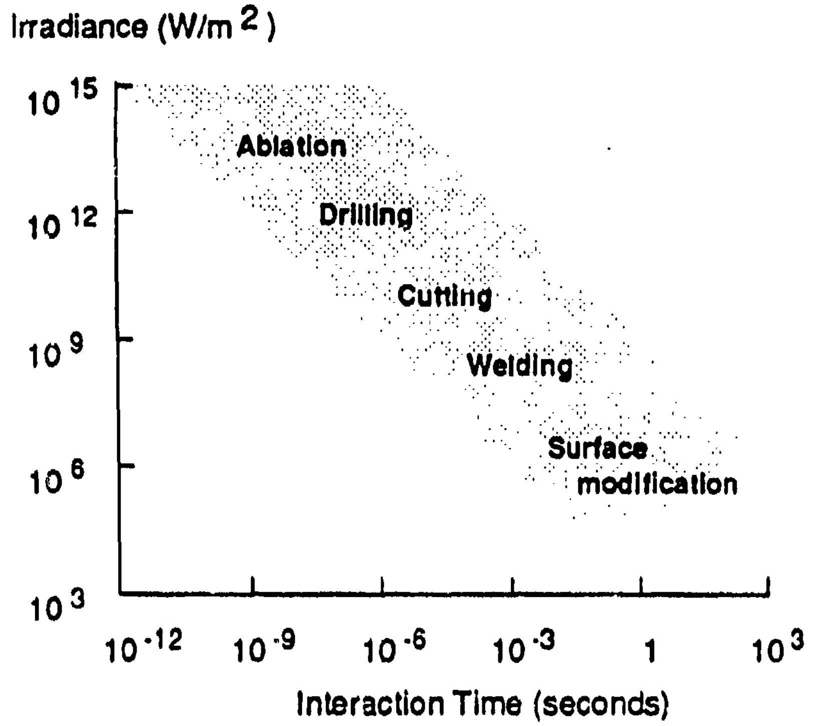
Although conversion efficiencies from electrical input to optical output are never high, the entire output can be applied to the process, yielding overall process efficiencies that are often competitive with those of conventional techniques.

Laser-Material Interactions

Most industrial laser processes are thermal, that is, they depend on the high temperature generated by absorption of the laser beam into the material being worked. The irradiance (power density) and interaction time determine the temperature and the resulting effect (Figure 5.2.1). Progressively higher temperatures are required for surface modification, welding, cutting, drilling, and ablation. Ablation is the almost explosive removal of small quantities of material by pulsed laser radiation of high-peak power and short duration, so that material is vaporized and removed without harming the surrounding area.

Laser output power does not correlate directly with the temperature achieved because temperature is also affected by the incident beam area (spot size) and the processing speed (when there is any relative motion between the beam and the material, as in cutting, welding, and paint stripping). Very high power lasers are being used to speed up processing (thereby increasing productivity), rather than to achieve even higher temperatures.

Lasers can interact photochemically with organic substrates, as opposed to thermally. The incident laser energy interacts directly with the molecular structure of the material, breaking molecular bonds and inducing chemical change. Photochemical effects depend on total absorbed energy, not on energy rate. These effects require radiation at low wavelengths (in the ultraviolet) where the energy of the individual photons is relatively high. UV lasers are being used for the rapid curing of acrylic coatings, for ablative marking, and for hole drilling in printed circuit boards.



Source: Cambridge Consultants Ltd.

Spectrum, Advanced Materials

Figure 5.2.1 Irradiance Levels and Interaction Times of Different Types of Laser-Material Interactions

Industrial Laser Processes

The principal industrial laser processes are cutting, welding, marking, drilling, and surface modification. Although different than laser paint stripping, much of the technology is similar and is useful in considering available technologies.

Cutting

Laser cutting offers high accuracy, precision, and process speed, as well as minimal part distortion and the ability to cut intricate shapes and to reprogram patterns rapidly. Lasers can successfully cut many metals, including steel, stainless steel, titanium, and thinner sections of aluminum and copper. Lasers can also cut many nonmetals, including composites, plastics, paper, wood, rubber, leather, and certain low-expansion glasses. Cutting precision of 0.01 mm is achievable with lasers, although precision is sometimes limited by the work-handling system and by thermal distortion in the workpiece rather than by the laser itself.

Organic matrix composites and engineering plastics are increasingly replacing metals in many applications. Such materials are generally difficult to cut by conventional methods but can be cut accurately and productively using lasers. Complex contoured structures can be processed by combining the laser beam delivery system with a multiple-axis table or gantry arrangement.

Welding

Lasers can weld steel plates more than 25 mm thick in a single pass. High processing speeds, low distortion (which is important with thinner materials), narrow heat-affected zones, and strong welds in many metals are among the advantages of laser welding. In some materials, the mechanical properties of the weld can surpass those of the base material. Laser welding is particularly advantageous for materials such as magnetic alloys that are difficult to join by conventional welding techniques.

An inert gas flow shields the beam-focusing optics from sputter, removes the plasma (generated by metal-laser interaction) that would reduce the efficiency of energy coupling into the weld, and prevents oxidation of the molten metal. Like laser cutting, laser welding often requires very accurate motion systems, although seam tracking is often used in large-volume production where the manufacturing tolerances do not position the joint line consistently. Filler wire is sometimes used to increase the tolerance of laser welding to gap width.

The feasibility of using lasers for joining composites is under investigation by the Edison Welding Institute and other organizations. The automotive industry, among others, is already using lasers for cleaning the surface of composites to enhance bonding.

Marking

Laser marking technology is widely established globally. Two basic laser-marking techniques in use are mask marking and spot scanning. In mask marking, an expanded laser beam is projected onto the substrate through a stencil mask that defines the pattern to be marked. Commercially available systems using pulsed lasers can produce up to 50 marks per second in this way.

In spot scanning, a focused laser beam spot is scanned with a galvanometer mirror to "write" directly onto the surface of a material. Unlike mask marking, where a change of mask is needed to change the mark, spot scanning can be computer-controlled to produce an infinite variety of patterns.

Laser marking relies on a change of state at the substrate surface and is similar to laser paint removal. Pulsed Nd:YAG lasers are used most often, although CO_2 lasers are also employed. UV-emitting excimer lasers can also produce marks with high visual contrast and high resolution on many materials. Lumonics (Canada), now owned by Sumitomo Heavy Industries (Japan), pioneered the development of marking with excimer lasers. With some organic materials, excimer laser marking is a photochemical process rather than a photothermal one. Excimer ablation marking can be particularly useful with brittle materials, such as glass, because of the absence of thermally induced stress.

Similar laser-based techniques are also used for micromachining, surface etching, and semiconductor fabrication. Like ablation marking, these techniques all involve the controlled removal of minute amounts of material.

Drilling

The use of pulsed lasers to form small holes with great precision in thin-gauge metal is now well established. Flexibility, hole quality, and speed are the laser's main advantages. Recent improvements in laser design (especially beam shape) have allowed taper-free drilling even of thicker materials. Hard, brittle materials (such as ceramics and sapphire) that can be difficult to drill by other techniques can be laser-drilled successfully. The noncontact nature of laser drilling greatly reduced part distortion and eliminates the part contamination and drill-bit wear, breakage, and replacement that occur with conventional drilling.

Improved techniques for drilling holes as small as about 50 microns in diameter are being developed by Laser Fare and other companies. Such techniques would offer considerable advantages over conventional chemical etching by permitting faster and more accurate processing, which would be especially valuable in the aerospace industry for fabrication of critical engine components.

Surface Modification

Surface modification by lasers includes surface hardening and surface alloying. In surface hardening, a coating may need to be applied first to increase the laser beam's absorption. The laser energy heats the surface to above the phase-transformation temperature. Because the heating effect is localized, rapid quenching occurs by thermal diffusion into the surrounding unheated material. In ferrous metals, shallow, localized layers of hardness can thus be produced with minimal amounts of energy.

Laser surface alloying with cobalt, nickel, ferrous alloys, or carbides is used to improve corrosion resistance of surface wear characteristics. As with other laser surface modification processes, the uniform energy distribution required can be achieved by multimode laser beams, beam scanning, or specially designed optical beam integrators (which convert the inherent Gaussian distribution of energy into a more uniform one).

The principal benefits of laser surface modification are low distortion, reduced energy input, localized processing (restricted to those areas subject to greatest wear), and high production rates. Furthermore, this technique often eliminates the need for subsequent finish grinding.

Other Industrial Applications

In addition to the various materials-processing tasks reviewed above, in which the laser causes a permanent physical change in the target material, lasers of lower power are used for sensing, measurement, and inspection. These functions include interferometry; optical sensing of position, vibration, and temperature; optical profiling of complex shapes; machine vision; holographic recording of engineering structures; and chemical analysis by laser-based spectroscopy and fluorescence measurements. The key difference is that in these applications, the laser beam is used as an information carrier, as opposed to an energy carrier in materials processing.

Increasingly, however, combinations of low-power and high-power lasers are being used in the same process. Thus, optical monitoring by a low-power laser can provide feedback control of a task being performed by a high-power processing laser. Also, many high-power industrial laser systems incorporate a low-power visible beam (typically from a helium-neon laser) as an alignment aid.

The use of lasers for material synthesis and modification is also being investigated. In laser photosynthesis, the laser beam energizes a photochemical reaction (as opposed to effecting only a physical change). For example, a process developed at the Massachusetts Institute of Technology uses a 180-W continuous wave CO_2 laser to synthesize ceramic powders of very high purity and uniform submicron particle size. This process eliminates grinding, which is a troublesome source of contamination in conventional methods. Ceramic products made from these powders have superior mechanical properties and fewer defects than those made by conventional means.

Types of Industrial Lasers

Of the many different types of lasers that have been developed in the 30 years since laser action was first demonstrated in ruby, just two perform the vast majority of industrial laser processes: the CO_2 gas laser and the Nd:YAG solid-state laser (Table 5.2.2). Excimer lasers are much more expensive -- their capital costs are on the order of $1,000/W compared with $100/W for CO_2 and $150/W for Nd:YAG. Use of excimer lasers in materials processing is relatively limited at present but is expected to grow in specialized high-precision applications.

Carbon Dioxide Lasers

The CO_2 laser is established as the workhorse of industrial laser processing, largely for cutting, welding, and surface modification. CO_2 lasers offer high reliability with output power ranging from 500 W to 10 kW. The CO_2 laser utilizes a mixture of gases comprising CO_2 (the lasing medium) and usually two other gases, nitrogen and helium, to enhance efficiency. An electrical discharge within the gas mixture, produced by either direct current or radio frequency energy, initiates and sustains laser operation. CO_2 lasers emit in the infrared (at 9-11 microns, with the strongest line at 10.6 microns).

Sealed-tube lasers can be used for power outputs up to about 50 W, but gas circulation must be used for most industrial applications, where up to several kilowatts are often required. Earlier slow-flow systems have given way to either transverse-flow (TF) or fast-axial-flow (FAF) systems, both of which permit

Table 5.2.2 Major Types of Lasers Used in Industrial Materials Processing

Process	Type of Laser CO_2	 Nd:YAG	 Excimer
Cutting	X	X	
Welding	X	X	
Marking	X	X	X
Drilling		X	
Surface Modification	X		X
Paint Stripping	X		X

high-output power to be generated from relatively compact resonators. However, recent research at Heriot-Watt University (U.K.) suggests that more-compact sealed-tube or slow-flow systems of high power may yet become feasible.

Neodymium YAG Lasers

By contrast, Nd:YAG lasers are solid-state devices containing a crystal of yttrium aluminum garnet doped with neodymium ions to about 1%. Excitation (pumping) is accomplished optically, using high-intensity white-light lamps positioned around the crystal and focused on it. Emission in the near-infrared (at 1.06 microns) enables the output beam to be transmitted through optical fibers, permitting more flexible beam delivery and multiple workstations with rapid switching between tasks. Simultaneous spot-welding on the same component can also be carried out. Nd:YAG lasers may be operated in either continuous or pulsed mode, where peak powers of several megawatts are achievable, but maximum average or continuous powers are lower--currently just over 1 kW.

The main applications for Nd:YAG lasers are drilling, marking, and micromachining. Nd:YAG lasers' high-peak power makes them suitable for intermittent processes such as drilling, whereas CO_2 lasers' high-average power makes them useful for continuous processes such as cutting and welding. Because of their shorter wavelength, Nd:YAG laser beams can be focused more narrowly than CO_2 laser beams, thus permitting more accurate micromachining. In pulsed mode, Nd:YAG lasers can process aluminum and copper, something that can be difficult with CO_2 lasers because the surface reflectivity at 10.6 microns is high and because heat is transferred rapidly away from the point of impingement.

Significant advances in beam quality (through resonator design) and system reliability (through longer lamp lifetimes) have made it possible to drill deeper holes and reduce the surrounding heat-affected zone. Technical problems in growing larger crystals and in heat dissipation are the main limitations to achieving greater output power, although multiple crystals can be used to increase the volume of the active medium. Safety is seen as more of a problem with Nd:YAG because the threshold of eye damage at its wavelength is lower than with other types of lasers. Although continual improvement in Nd:YAG technology will strengthen this sector of the market, encroachment into the CO_2 lasers' preserve of high-speed metal cutting and welding is unlikely.

Excimer Lasers

The lasing medium in excimer lasers is a rare-gas compound, such as argon fluoride, krypton chloride, or xenon fluoride, that can exist only in an excited state (hence the name "excited dimer" or "excimer"). Excimer lasers' short pulse duration and high-peak power permit surface ablation that is highly controllable and causes no thermal damage to adjacent material. The very short emission wavelengths -- in the ultraviolet, which most materials absorb heavily -- provide much finer resolution than is possible with other lasers. In organic materials, excimer lasers can produce photochemical rather than photothermal effects.

The output beam from excimer lasers has a larger area and is more divergent than beams from other industrial lasers. This feature is advantageous in through-mask processing but limits focal-spot applications. Excimer lasers would be economically competitive only in specialized high-precision applications, not in bulk processing tasks.

Currently, excimer lasers are used primarily for exploratory or "mission" sales for assessing and developing new technologies. Emerging application areas are in micromachining, marking small parts at high speeds, photochemical processing (as in semiconductor fabrication), and hardening and annealing very thin layers.

In our companion study (WL-TR-91-4025), Arthur D. Little has shown that excimer lasers may be successfully used to strip paint from composites. Strip rates are currently low, and the high cost of excimer lasers will limit their use in this area.

Other Types of Lasers

Other types of lasers are used occasionally for specialized processing applications that require relatively low power but specific emission wavelengths for very selective absorption by the target material.

Ruby lasers are crystal lasers that are optically pumped in a similar way to Nd:YAG lasers and produce a red output beam at 0.694 microns. They are suitable for certain high-precision drilling operations, but their low-pulse repetition rate of about 1 Hz limits their usefulness.

Carbon monoxide (CO) lasers are being investigated for materials processing. Their output, which lies between those of Nd:YAG and CO_2 lasers, is absorbed more strongly in some metals than CO_2 lasers and can be delivered via optical fiber, as can the Nd:YAG's output. CO lasers offer greater output power and efficiency than CO_2 lasers, although cryogenic cooling of the laser cavity is required for optimum performance.

Free-electron lasers (FELs) are currently at the research stage. They produce an intense, coherent output through the interaction of an electron beam with an optical beam in a magnetic field that varies rapidly along the region of interaction. The FEL's main advantages over conventional lasers are tuneability over a wide range (and hence, versatility) and higher efficiency. The FEL's disadvantages include very high system costs (in the millions of dollars) large size, and limited availability--only about 10 FELs exist in the Unites States at present.

In the United States, the U.S. Department of Defense's Strategic Defense Initiative sponsors most of the R&D on FELs. In the United Kingdom, the University of Liverpool is developing a more compact FEL with emission in the far-infrared and microwave regions but with the potential for a lower wavelength (near that of the CO_2 laser).

Suppliers

About 1,500 companies participate in the industrial laser business worldwide. Roughly a thousand of them are contract laser processors (job shops), with approximately 400 in the United States and 300 each in Europe and Japan. Of the over 300 major equipment suppliers, 40 manufacture only the lasers, 70 make both lasers and complete processing systems, and 200 are system integrators. System integrators buy lasers from vendors on an OEM basis and incorporate them into their own systems for sale to end users.

Table 5.2.3 lists the world's principal industrial laser manufacturers, including suppliers of total systems, but excluding system integrators that do not manufacture lasers themselves. Other selected participants are listed in Table 5.2.4. The proportion of major laser system installations developed and supplied by system integrators is generally greater in Europe than in the United States.

Table 5.2.3 Principal Manufacturers of Industrial Laser Devices and Systems

Company (Parent or Full Name)	Base Country	Laser Devices			Laser Systems
		CO2	Nd:YAG	Excimer	
Alumor Laser	Israel	X			
Amada	Japan	X			X
Coherent General	USA	X	X		X
Electrox	UK	X			
Ferranti	UK	X			X
International Laser Machines (Cincinnati Milacron)	USA	X	X		X
Lambda Physik	W.Germany			X	
LISA (Laser Industries S.A.)	France	X			
LMI (Laser Machining, Inc.)	USA	X			X
Lumonics (Sumitomo Heavy Industries, Japan)	Canada	X	X	X	X
Matsushita Industrial Equipment (Matsushita Electric Industrial)	Japan	X			X
Mitsubishi Electric	Japan	X			X
NEC Electronics (NEC)	Japan		X		
Quantronix	USA		X		
Raytheon Laser Products (Raytheon)	USA	X	X		X
Rofin-Sinar (Siemens)	W.Germany	X			
Trumpf	W.Germany	X			X
United Technologies	USA	X		X	
XMR (Amoco)	USA			X	

Table 5.2.4 Selected Industrial Laser Manufacturers

Company (Parent or Full Name)	Base Country	Laser Type CO2	Nd:YAG	Excimer
Aldron Sources (Lectra Systemes)	France	X		
Advanced Laser Systems	USA		X	
Apollo Lasers (Patlex)	USA		X	
Baasel Lasertechnik	W.Germany		X	
CBL Optronics	Belgium	X		
Control Laser (Quantronix)	USA		X	
Diahen	Japan	X		
Electro Scientific Industries	USA		X	
Fanuc	Japan	X		
General Systems Research	Canada	X		
Haas Laser	W.Germany		X	
Hitachi	Japan	X		
Integrated Laser Systems	UK	X		
Lasag	Switzerland		X	
Lasercut	Switzerland	X		
Laser Dynamics	Australia	X		
Laser Electronics	Australia	X		
Laser Materials Processing	Switzerland		X	
Laser Nucleonics	USA		X	
Laser Photonics	USA		X	
Lasertechnik (Esab Held)	W.Germany	X		
Laser Valfivre	Italy	X	X	

Table 5.2.4 Selected Industrial Laser Manufacturers (continued)				
Company (Parent or Full Name)	Base Country	Laser Type		
		CO2	Nd:YAG	Excimer
Lee Laser	USA		X	
Line Lite Laser	USA	X	X	
Messer Griesheim (Hoechst)	W.Germany	X		
Micro Controle	France		X	
Miyachi Electronic	Japan		X	
MLI Lasers	Israel	X		
Munich Laser Systems	W.Germany		X	
PRC	USA	X		
Questek	USA			X
Soitaab	Italy	X		
Toshiba	Japan	X	X	
U.S. Laser	USA		X	

Note: Many companies also do business in countries other than their base country.

Technology Trends

Significant trends for industrial laser technology over the next 5 years include the following:

- Parts and complete products being designed specifically for laser processing to exploit laser technology's benefits fully, rather than simply using lasers as a replacement for conventional manufacturing techniques;

- A greater role for systems engineering, leading to more advanced laser processing and more effective implementation as part of the production process;

- More compact high-power CO_2 laser systems, through improvements in resonator design and gas-flow technology;

- Increasing use of sealed-tube CO_2 lasers at medium power (100-500 W).
- Very high power (as much as 25-50 kW) CO_2 systems, primarily for high-speed welding but also for cutting and surface modification;

- High-power (up to 2 kW) Nd:YAG systems with multiple crystal assemblies that have superior drilling capabilities and can perform some of the cutting and welding tasks currently done by CO_2 systems;

- Greater use of fiber delivery systems for Nd:YAG lasers, to increase processing flexibility and provide more freedom in the integration of laser systems in processing lines;

- More sophisticated beam delivery systems for CO_2 lasers, including beam-shaping and scanning systems, for optimal coupling of the laser radiation with the workpiece material;

- Multiple workstations from higher-power single laser units, using both Nd: YAG (with fiber delivery) and CO_2 systems;
- Greater reliability and better beam quality at higher power, through improvements in resonator and system designs, as well as in critical components, such as flashlamps, output couplers, and gas-circulation units.

5.2.2 Recent Laser Paint Stripping Activities. As previously noted, Warner Robins Air Logistics Center (WR-ALC) was the lead site for a laser paint stripping program bid on by InTA, Avco, and Battelle among others. The contract was not awarded.

InTA has received the authority to proceed on the two robotic depainting systems for Navy fighter-size aircraft laser depainting. InTA has five subcontractors , including Grumman, United Technologies Industrial Lasers (UTIL), and SwRI. The laser is a 6 kw-pulsed CO_2 system developed by UTIL, providing a 250,000-W peak during each pulse. Dr. Paul Lovoi of InTA states the optimal paint stripping laser should be in the 5-10 KW range and that despite the research into excimer lasers, CO_2 lasers are the optimal method. A sealed beam tube delivery system with mirrors is used.

The laser provides 5 J/pulse to remove paint at a rate 3 ft^2 per minute (180 ft^2 per hour). One hundred fifty to two hundred fifty microinches of paint are removed per pulse. At 1000 pulses per second (5 kw to the surface, 1 kw lost power), 1000 Hz is delivered per pass (one pass per second) over 1 square foot. Using 200 microinches of paint removed per pulse, 5 pulses will remove one mil of paint. Based on a thickness of 4.2 mils of paint for a typical aircraft coating thickness, 20 passes in 20 seconds results in 3 ft^2/minute. Various paint types, thicknesses and ages have been tested and successfully removed. Decals (3M type) have also been removed. With the spectroscopy system, even if the beam is out of focus, the system is still expected to perform to speci: .tions.

Several 2-inch x 4-inch samples were displayed at a presentation, given at Tinker AFB in 1990, as evidence of system success. The test samples showed only an 11-mm x 11-mm strip area. InTA states that the laser could be shot at ±60° from the normal with a depth of field range of 6 inches and still work. Speculation is that the small samples were done in a controlled environment with no deviation from the norm and the optimal depth of field held. Each spot is hit 5-15 times (pulses), depending on the substrate. A compliant hood vacuum system is planned.

Plasmatronics Incorporated has been researching paint removal using their 1-kw pulsed CO_2 laser. Several aluminum, steel, and plastic samples were supplied to USBI for evaluation. According to Plasmatronics, they are removing 1/2 mil thicknesses per pulse with a standoff tolerance of ±12 inches. A 1-cm square spot is used.

Two basic laser processes are used for material removal:

A. The laser beam melts the material and removal is accomplished by a gas jet.

B. The laser beam vaporizes the material and removal occurs by the expanding vapor.

5.2.3 CO_2 Laser System

Technology. As described in the background section, several laser systems can deliver the high energy densities required for the laser paint removal application including Nd:YAG, excimer and CO_2. Of these three laser types, CO_2 lasers operate with the highest power conversion efficiency, as high as 15%. Both CO_2 and Nd:YAG have been proven in widespread use in industrial material processing applications, with CO_2 systems being the most predominant. Although some applications have found improved material processing performance with the 1.06 μm wavelength of the Nd:YAG lasers, there are concerns with the flashlamp reliability and maintenance needed for these lasers at kilowatt power levels. Excimer lasers are currently in a transition state, moving from the laboratory into commercial use. The number of excimer lasers installed in factories is less than 5% of the number of CO_2

systems. From a practical standpoint, a CO_2 laser system is a reasonable choice for near-term laser paint removal development efforts. The Nd:YAG system may prove a viable alternative for future development efforts.

Even within the family of CO_2 lasers, there is considerable difference between the operation of different systems. Output powers and beam quality vary. Therefore, the paint removal laser should be carefully chosen by considering the requirements of the entire system. Below, some of the important operating characteristics of the laser system are discussed.

General. A laser requires a gain medium, an energy source to excite the gain, and an optical resonator to provide feedback. For the CO_2 laser, a gas mixture consisting of carbon dioxide, nitrogen, and often helium and other gases is used for the gain medium. Electrons in a gas discharge are used to vibrationally excite the nitrogen which transfer their energy to the carbon dioxide and also excite vibrational modes. When the molecule relaxes from one vibrational state to another of lower energy, the energy between vibrational modes may be given off as radiation at 10.6 μm. Therefore, a large population of excited carbon dioxide molecules acts a gain medium for light at 10.6 μm.

Laser Gas Systems. The exact composition of the gas mixtures vary from system to system. The molecules used depend on factors such as cost, and specific requirements for laser operation (e.g., high power or long-term stability). Though lower in cost, lasers without forced gas recirculation will be limited in repetition rate to a few pulses per second. High-repetition-rate, high-power systems require gas circulation by blower systems to replenish the gas mixture during operation.

The two most commonly used gas circulation methods are the fast axial flow (FAF), and the transverse flow. FAF lasers typically operate with output powers around 6 kw. FAF lasers use a Roots-type positive displacement blower to force the gas mixture through narrow discharge tubes centered on the optic axis. The high-velocity Roots blowers are commonly the cause of reliability problems in these systems. In transverse systems, the gas flows across the optical axis. Because the gas flow duct has a larger cross-sectional area than the FAF systems, lower flow velocities are used. Therefore, the fans are simpler, consume less power, and are more reliable than Roots pumps. One class of the transverse systems, the transverse-excitation atmospheric pressure lasers (TEA), is used for high-energy-density pulsing applications. The most common failure in DC TEA lasers is due to arching across the excitation electrodes. In general, the beam quality from TEA lasers is not as good as from the FAF lasers because of gradients across the gain. However, TEA lasers are more readily scaled up in power, and can achieve output powers as high as 25 Kw cw. They achieving very high peak powers (gigawatts) for short-duration pulses.

Because thermal excitation can excite the vibrational modes of the CO_2 and reduce overall efficiency, removing waste heat is an important consideration for operation of CO_2 lasers. In addition, thermal gradients in the gas causes nonuniformities in the output beam profile. There are two methods of cooling: conduction and convection. In conductive cooling the heat is transferred through the gas by conduction through the outer walls, which are usually actively cooled. The disadvantage of this approach is that the thermal conductivity of the gas is low, so heat transfer is not efficient. In convective cooling the gas flow itself carries the heat away. This is the most common cooling method for high-power systems.

Another consideration for laser operation in terms of laser output quality is acoustic and shock waves generated within the gain medium, which affect the mode profile of the laser. It is common in most high power laser systems to use baffles to eliminate or reduce the propagation of these waves.

Electrical Excitation. Electron sources used to drive the gain are either plasma or electron beam. Plasmas are generated either by DC or RF electrical excitation with

DC used most often. The advantage to using RF excitation is that the anode and cathode are placed outside the gas enclosure, which reduces wear on the electrodes and the problem of sputtering of the electrode metals that contaminates the gas. The disadvantages of the RF systems are radiation problems and the high cost power supply. The RF excitation is typically 5-50 MHz, much faster than the duty-cycle or repetition rate of standard pulsed systems.

The plasma has a negative resistance, so a positive resistive ballast is used in the power supply. Both hot and cold cathodes are used. Typical cathode materials include aluminum, tantalum, nickel and platinum cold cathodes, and tungsten or oxide coated hot cathodes.

Pulsed systems are often used to achieve higher peak power for short durations. Modulation of the laser output by control of the electrical excitation requires pulsing the high-voltage supplies used to excite the discharge.

There is a significant difference between a standard pulse laser system and a triggerable pulsed laser system. In a standard system, pulses of relatively constant pulse duration and repetition rate are continuously emitted from the laser. The system can not be rapidly turned on and off, because of limitations in both the electrical excitation circuitry, and the excitation of the gain medium. The turn-on time can be several milliseconds, seconds, or even minutes. In contrast, a triggerable system can be turned on and off within about a 500 nanosecond (ns) delay time. Triggered systems for high-power lasers are still in the developmental stages, though they have been successfully applied to lower power systems by UTIL.

Optical Resonators. The output beam from the laser system is dependent on the optics used inside the cavity. For applications which require focussing over long distances, the laser is typically operated in the lowest-order transverse mode, which results in a low-divergence, Gaussian-profile, beam. The mirrors are placed directly facing one another, and so a transmissive end mirror is used which causes distortions and can reduce reliability in high-power lasers. Typically, in-line apertures are used to force the laser to operate in the lowest order mode, significantly reducing the output power.

An alternative is to use an unstable resonator which uses all reflective optics and results in an output beam with an annular shape. At focus, or in the far field, the beam is close to a Gaussian shape but has additional outer rings.

The other common optical resonator configuration is a multi-transverse-mode resonator. These are effectively single-mode, stable resonators without the in-line aperture. They produce significantly more output power than the single mode systems. The incoherence of the beam (compared to the single-mode case) can reduce the coherent effects such as diffraction rings that occur from the edges of the finite sized optical elements, which may be an advantage. However, multimode outputs do not focus as well as the single mode output because the divergence of each of the modes is different. Mode hopping can result in short term instabilities in the laser output.

Most CO_2 lasers operate in multiple longitudinal modes. These modes beat together, which causes a temporal modulation on the output, at the characteristic frequency of the longitudinal mode separation. In a 3-meter-long cavity, this is around 50 MHz. For most applications, this modulation is not a problem, and the alternative, forcing single longitudinal mode operation, results in significant reduction in output power.

Output polarization from high-power industrial CO_2 lasers is typically randomly polarized. Particularly in cutting and welding applications, polarization can be a key factor in the shape and quality of the weld. Although the effects of polarization on paint removal are not yet clear, random polarization is probably desired for paint removal applications.

Application to Paint Removal. Experimentation on the laser energy requirements for optimum paint removal is still underway. According to the Avco draft report AFWAL-TR-84-4132, the energy density requirements for paint removal are about 25 J/cm^2 per mil. The energy may be delivered either cw or pulsed. While most proposals center on pulsed technology because of well controlled energy delivery, careful consideration should also be given to the cw systems, particularly if the work head optical systems for the pulsed technology have evolved to consist of moving optical elements anyway. Below, some of the characteristics required of cw and pulsed laser systems for paint removal are described.

Pulse Systems. To minimize damage to the substrate, it is desirable to use low fluences and multiple exposures to removal the paint. One way to achieve this has been to use a pulsed laser source. The Avco report claimed an acceptable pulse energy density is between 6-10 J/cm^2 per pulse. This figure has also been used by InTA. Therefore, to remove about 2.5 mils of paint, 60 J/cm^2 are required, so that 10 pulses would be used on each square. The typical pulse duration is about 20-30 μs. The damage to the substrate is related not only to the pulse energy, but also the repetition rate and the thermal conductivity of the aircraft surface and surrounding materials. Avco has determined that for 6 J/cm^2 pulses, the maximum repetition rate is limited to 10 pulses per second. Obviously, with variations in paint thickness, and the possibility of decals, etc. the total fluence incident upon the surface needs to be controlled. The following discussions of system performance criteria are based on the requirements discussed above.

One of the possible paint removal systems described by InTA requires the use of a triggered laser system. The laser would operate at 1000 Hz. By using high repetition rates, faster stripping will be realized. However, it is not possible to operate at 1000 Hz at one spot on the laser, because of damage. The laser will be shut off within one cycle should the sensor system determine the surface can not withstand another laser pulse. This concept has the advantage that the laser pulse repeatability is not crucial because the sensor checks the surface before each pulse.

However, it puts stringent demands on the electrical excitation system and discharge mechanism to allow triggerable, high-repetition-rate operation. Although this concept is not unreasonable for many lasers, triggered systems for high-power lasers are still under development. In fact, for high power systems, operation at 1000 Hz reliably over long periods is still unclear. The development of this type of system is underway at UTIL.

Another paint removal concept uses well controlled, constant pulses to produce a repeatable amount of energy at the target. Commercially available high-power lasers typically have about +-5 to 10% long-term power stability. This is marginally acceptable for paint removal applications, which indicates that a sensor system, and a feedback beam control system will be required, even if the paint thickness is completely uniform. The required sophistication of the sensor and feedback system (processing speed and number of processing operations) would be traded off with the requirements for stability of the laser output.

CW Systems. In the early development of paint removal, cw lasers were utilized. In particular, a demonstration in 1984 by Battelle demonstrated a 5-kw laser stripping at a rate of about 1 sq.ft./minute/(Kw of laser power) for single coats of paint. CW laser systems have the advantage of a track record of reliability because of their use in industrial material processing applications. The effects of thermal and acoustic variations are lessened because the electrical discharge is constant. There is still a constant gas flow through the system.

Particularly for use with composite skin materials, it is not possible to directly control the amount of energy delivered to the target. Therefore, a cw system requires a beam delivery and focusing head optical system that provides this control.

In the Battelle study, they used a spinning polygon scanner. This simulates a pulse system by limiting the time the laser beam illuminates a section of the target. In this case the dwell time and spot size are limited by the speed and configuration of the mirrors that direct the beam. The requirement on the laser system is to produce a stable, reproducible output, both beam profile and long and short-term temporal behavior. Output powers on the order of 5-10 kw would be required.

One disadvantage of the cw laser system that has been discussed is that substrate heating is higher. This is not the case when the cw light is used in a simulated pulsing arrangement. Although a cw laser system would require a stabilized rotation mirror arrangement, the positional accuracy required of the robotics would not necessarily be any greater than for a pulsed system as has been suggested. One potential substantive disadvantage of cw lasers is the lower peak power, which could reduce stripping speed. As an added consideration, InTA has suggested that cw beams will ignite surface contaminates such as oils and grease. In addition, cw systems would require the use of a mirror to direct the beam away from the delivery system as opposed to turning the system off and on electrically, because cw systems have a substantial lag-time between electrical excitation and laser emission. UTIL has developed a beam switching accessory that switches the beam path in less than one second.

Even with these potential disadvantages, the cw laser should not be overlooked as a candidate for paint stripping. The cw laser technology is more developed, and has been proven in long-term, high-duty-cycle operation. This advantage could overcome the disadvantage of using a moving work head optical system.

Beam Profile. For the paint removal application, with both cw and pulsed lasers, it is important that the beam profile be uniform at the aircraft surface. This is achieved either by specifying a uniform beam profile at the laser output, and maintaining beam quality during beam delivery via atmosphere control and appropriate optics, or by using a beam integration technique at the focus head to spatially average the beam pattern.

Obviously, the specific requirements on the laser output beam are strongly dependent on the beam delivery system and work head optical and sensor systems. Efficient, long beam delivery path lengths require low-divergence, large diameter beams from the laser. The maximum beam size is limited by the size of the optical elements used and the size of the beam enclosure system, if used. Typical designs proposed to date use 7- to 10-cm-diameter beams.

The sophistication of the work head impacts the required beam profile uniformity and stability. If a beam integration system is used, the beam profile can be less uniform. It is important, however, that the design of the work head optical system carefully consider the temporal stability of the laser system and how that impacts the design of the work head integration system. This is discussed further in a later section.

Available Technologies. Lumonics, an industrial laser manufacturer, produces a line of CO_2 lasers. The high-pulse-energy systems are relatively low average power, 50 W. For a 7-microsecond pulse duration, the pulse energy available is as high as 5 J with a repetition rate of 10 Hz.

Raytheon manufactures a high repetition rate system, the GS600, which operates at 2000 Hz. This is a fast-axial-flow type system that produces up to 2 kw of peak power for a 200-microsecond pulse duration in multimode operation.

Coherent-General manufactures a 3-kw laser system, based on the enhanced axial flow technology. This system operates up to 1 kHz. It comes with a 2-year, 4000-hour warranty.

Two different laser systems have been proposed for the paint removal application, one manufactured United Technologies Industrial Laser Division (UTIL) and one by Avco.

UTILs Laser System. The system proposed by UTIL would be a triggerable, pulsed version of their SM series line of high power cw lasers. The current cw technology is described below, followed by a discussion of the development required to achieve the triggered system.

The SM-series lasers operate at powers of 6 kw, 14 kw, and 25 kw (higher powers are achieved by increasing the number of gain modules). The system is closed-cycle, and the N_2, He, and, are circulated using vaneaxial fans. Gas pressure is typically operated around 0.1 atm, and may be as high as 0.25 atm for some applications (in general, higher pressures result in higher powers for CO_2 systems). All-copper, water-cooled heat exchangers are used to recondition the gas. The electrical discharge system is DC, and is perpendicular to both the gas flow and the laser propagation direction. A resistive ballasted power supply is used.

The optical system is an unstable resonator with magnification, M, where M=2 or M=4. Because the typical application of these systems requires a highly focusable beam, as opposed to a uniform, large diameter beam, the lowest order, single-mode optical output is used. The output beam has an annular shape. This beam is not, in general, uniform in intensity across the beam being subject to distortions generated by thermal gradients within the gain medium. For applications where a more uniform large diameter beam is required, beam integration techniques, or different laser cavity optics must be employed.

All mirrors are water cooled, and have gold reflecting surfaces. The output from the low-pressure cavity goes through a patented aerodynamic window. This eliminates the need for a transmissive optical element that introduces loss and aberrations. The forced air from the window is also directed through the enclosed output optical beam path and through the housing that contains the ballast and power supply. This slight over-pressure keeps impurities (oils, etc., commonly found in industrial factories) from building up on the optical elements and the ballast resistors.

Installation requirements.

Laser gas: 10-20 scfh, He, N_2, CO_2.

Shop air: 80 psig

Purified, dehumidified air: 80 scfh

Cooling water: 60 psig, 30 gpm/100 kw, <10C

Electrical service: 460 V, 3-phase, 60 Hz, 225 A

Floor Space: Approx. 150-200 sq. ft.

Performance.

Output power/pulse energy: CW output powers from 6 kw to 25 kw are available. Pulse operation is currently under development.

Output spectrum: Center wavelength is 10.6 micrometers, with multiple longitudinal mode operation.

Beam profile: Beam profile is dependent on the optical configuration within the cavity. Common: single-mode unstable resonator, annular shape.

Power stability: +- 5 % (long-term)

Reliability. The current SM-series cw laser systems manufactured by UTIL have demonstrated factory operation with 95% availability working three shifts for over 3 years. The most unreliable part of these lasers are the blowers.

Maintainability. The parts of the high-power lasers that require maintenance are the discharge elements and the optical elements. UTIL uses "long-life" cathodes which provide about 5000 hours of continuous service. At the end of life, these elements are replaced via easily accessible ports. The optical elements that direct the beam out of the laser are enclosed and kept in a slight over pressure. These gold-coated copper mirrors must be carefully cleaned if exposed to oil or metal particulates. A molybdenum coating is used on the final output mirror to provide a more rugged surface that is more readily cleaned.

Development. UTIL has also made, for special applications, pulsed, triggerable CO_2 lasers. The key to operation of these systems is the UV pre-ionization system. This system maintains a plasma, so that when the trigger is sent, a laser pulse is emitted within 500 ns of the electrical discharge. This triggered system was demonstrated in a low-power system in 1984. Operation at a 1-kHz repetition rate was demonstrated, although only for short time periods (less than 5 seconds) before the onset of arching. The operating time was believed to be limited by the build up of O_2 in the gas mixture because of a limitation in the catalytic reactor system. Operation for longer periods at this repetition rate would require an improved catalytic reactor. The other factor affecting the performance of high-repetition-rate high-power CO_2 lasers is the generation of shock waves within the gain medium by the discharge that interfere with beam propagation and result in poor beam quality. To avoid this, baffling is required to attenuate the shock wave.

Avco's Laser System. The laser system proposed by Avco research laboratories is their Series 300 CO_2 laser. It puts out 10 kw in pulsed mode. The repetition rate is 10 Hz, and the pulse width is about 30 microseconds. The gas flow system is a closed cycle, cross-flow type. There is a muffler system, and two heat exchangers, one down stream, and one below the blowers. Most of the waste heat is removed by the downstream heat exchanger.

The optical system is typically a multimode stable resonator, but could be configured as an unstable resonator if needed. The output beam is square. Output passes through a partially reflecting 1-cm-thick zinc selenide window. The output window cooling is caused by the reconditioned, cooled laser gas internal to the laser, and externally by the beam duct air. The optical elements within the laser are liquid cooled.

The excitation method is an ionizer-sustainer. In this system, an ionizer gun creates a 150-kV beam of thermionically generated electrons. The e-beam is pulsed at 10 Hz for a 30-microsecond duration. This e-beam is directed into the laser gas chamber, and ionizes the gas. The sustainer system, which is a lower voltage, higher current power supply than the ionizer, maintains a stable, sustained discharge across the gas, pulsed at a 10-Hz repetition rate with 33 microsecond pulses.

Installation requirements.

Laser gases. Laser gas is required to fill the evacuated laser chamber prior to use in an approximate ratio of 3:2:1 of He, N_2, CO_2. Supply pressure must be maintained at 90 psig.

Shop air. Air supply at 90 psig is required to operate pneumatic valves. Control air is typically used at 0.3 scfm.

Purified, dehumidified air. Required for maintaining an over-pressure within the beam delivery tube.

Cooling water. A (1:1) water glycol mix maintained at $<$20 C is used as a coolant. The closed-loop system requires 55 gpm of coolant at the primary source. An air-cooled chiller cools the cycled coolant. The system cools the ionizer, optics, electrodes, and both heat exchangers.

Electrical service. In addition to the electrical supply required to run the vacuum systems, and control systems, electrical service is required to run the high-voltage discharge systems, which require 480 V, 3-phase, 60 Hz,and 120 V, 1-phase, 60 Hz.

Floor Space. Unspecified.

Performance.

Output power/pulse energy. The Avco laser system produces 700- to 980-Joule pulses 20-30 microseconds in duration, with a repetition rate of 10 pps.

Output spectrum. The laser output wavelength is at 10.6 micrometers. Output spectrum is in multiple longitudinal modes.

Output mode profile. Depending on the optical configuration within the cavity, single transverse mode or multiple transverse mode operation is achievable. Beam diameter and profile is dependent upon the optical configuration of the laser. A 2-inch-diameter beam is typical.

Power Stability. +-5%

Run Time. Unspecified.

Reliability. Unavailable.

Maintainability. The filaments, foil, and cathodes in the electrical discharge system must be periodically replaced. The optics must be cleaned when contaminated.

State of Development. Currently unavailable.

Risk. The laser system portion of the laser paint removal system would be categorized as low to medium risk, depending on the level of development required over and above the existing, commercially available systems. Note that the level of development required is directly related to the other system issues: beam integration and beam delivery. Therefore, the risk of realizing a viable laser paint removal system should include consideration of the available laser technologies in the context of the proposed beam delivery and work head systems.

5.3 Beam Delivery Systems

The problem for robotics in laser systems is beam delivery. Most of the robotic systems are 5-6 degrees of freedom (DOF). Generally, it is easier when the part has the DOF, and the laser remains stationary. An accuracy equal to the focal point size is usually required. Beam delivery systems for robots are generally broken down into internal and external systems. CO_2 lasers can only utilize a mirror-type beam delivery system, and cannot use a flexible optical fiber-type system, as is possible with some other lasers. For 15-meter optical fibers, a 10% loss in power occurs. With the CO_2 beam delivery system, no loss occurs, because of path length.

Specially designed hollow-arm robots, with an inner-arm optical path, provide flexible optical guiding without added kinematic constraints. In 1986, Cincinnati Milacron introduced the first through-the-arm laser welding and marking systems. An example of through-the-arm beam delivery is shown in Figure 5.3.1. A typical external beam delivery system is shown in Figure 5.3.2. Additional mirrors are usually required for external beam delivery systems.

External, internal, and hybrid beam delivery systems were evaluated in this work. In any of these approaches, the number of mirrors necessary and the mirror control requirements will be significant.

5.3.1 External. External systems allow for ease of maintainability and simplicity of robot design. However, external delivery systems are usually maintained below or above the robot, but not both. The robot system required to work on aircraft must be capable of reaching above and below the aircraft. The beam delivery system must be capable of positioning itself above the robot arm while working on the top of the aircraft and below the robot arm while working below the aircraft.

5.3.2 Internal. Internal beam delivery systems eliminate the cumbersome tube delivery systems moving with the robot. Internal beam delivery systems must be

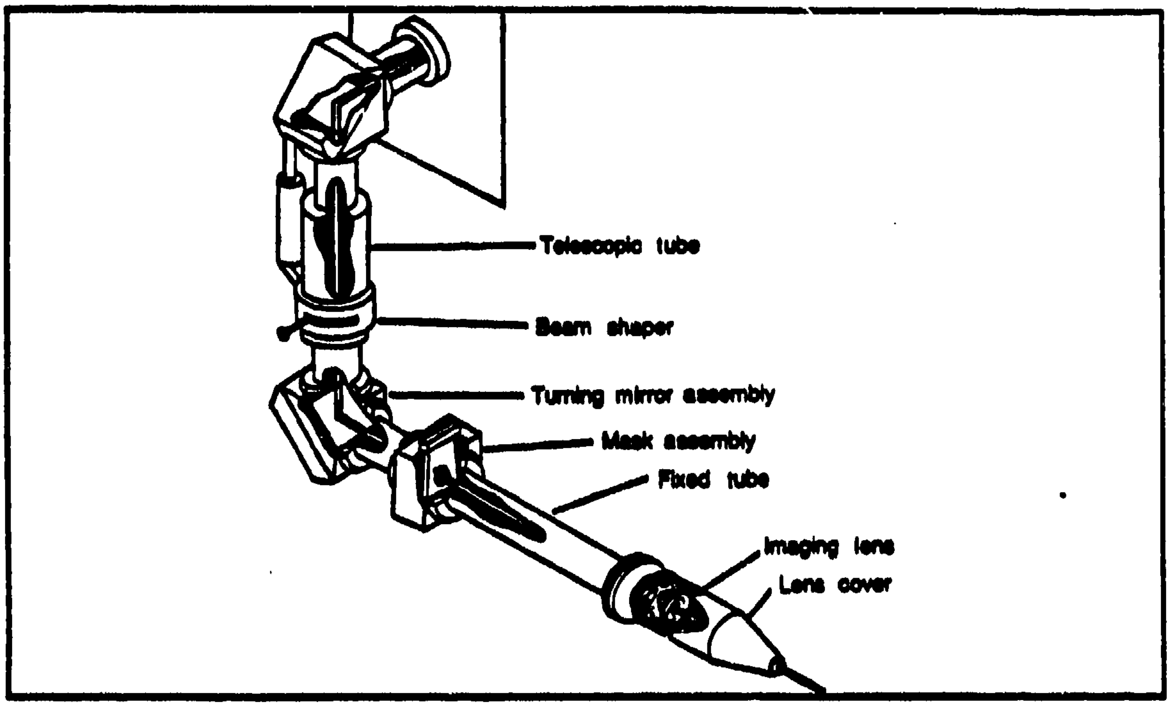


Figure 5.3.1 Through Arm Delivery System

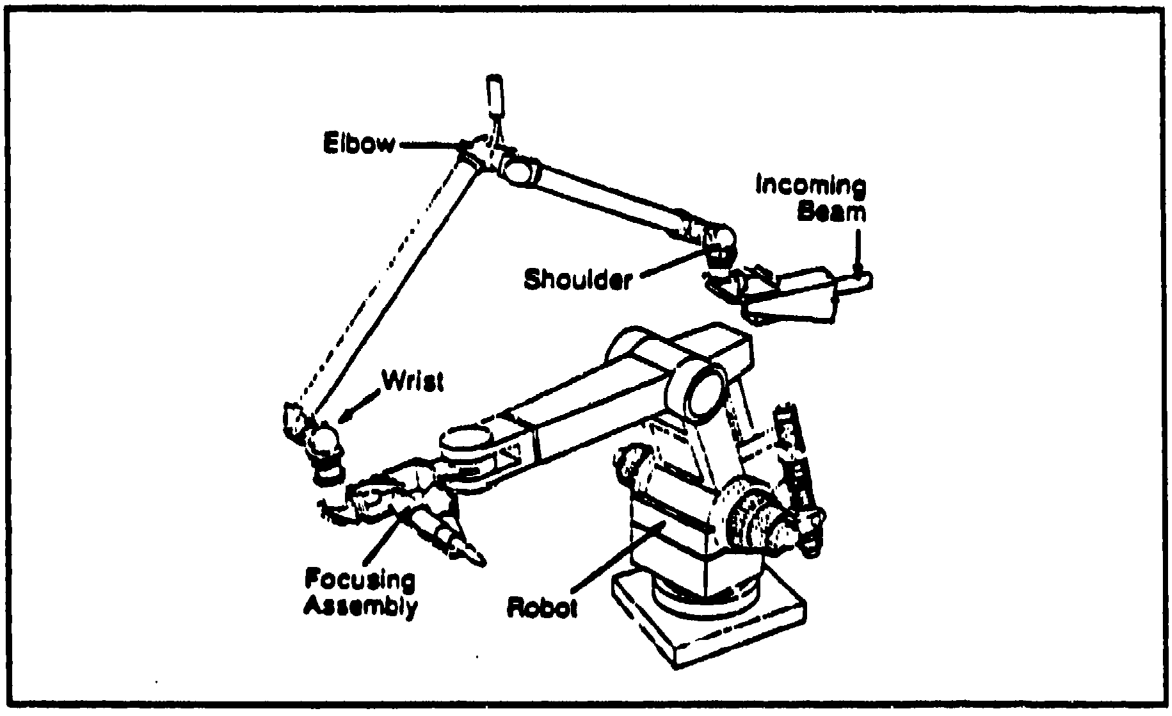


Figure 5.3.2 Tube Delivery System

designed into the robot arm, however, and must be provided with an adequate travel space.

5.3.3 Hybrid. It appears that some type of hybrid system would work best for this application. In areas where an internal system proved to be optimal, the beam would be routed through the robot. In areas where external systems were necessary, the beam would be transferred by a tube delivery scheme.

Beam delivery systems direct light from the output of a laser to a work head that does final beam shaping. In this section, the important characteristics of the component hardware needed for beam delivery systems are described. Then, the optical system design considerations for the laser paint removal application are discussed.

Components. A beam delivery system requires optical components and mounting hardware appropriately designed for the particular application. In the case of a dynamic system, controllable motorized mounts and control systems are required.

Transmissive Optics. For CO_2 lasers, the materials used for transmissive optics at 10.6 micrometers include silicon, germanium, potassium chloride, and zinc selenide. Of these, zinc selenide is the most useful for high power applications because it has a relatively low absorption and high thermal conductivity, reducing the possibility of thermal damage from high power laser beams. It is also somewhat transparent to visible light, so alignment may be verified using He-Ne laser light. However, although the absorption is relatively low, the transmission through a typical optical element is only about 70%. Therefore, if a large number of optical elements are used in the optical system, the accumulated loss will be high. As a result, reflective optics are often used.

Reflective Optics. Reflective optical materials include silicon, molybdenum, and copper. Silicon with a high reflectivity silver coating is an economical method to achieve a high reflectivity surface. Copper is used more often in high power applications because of the excellent thermal conductivity. Copper is soft, and the surface is sensitive to scratching, and are not suitable for use in dirty environments. Molybdenum is the most rugged CO_2 laser mirror surface. It has high reflectivity, about 98%, and is the easiest mirror to maintain in dirty environments.

For high-power applications, over 1 kw, it is advisable to use some sort of efficient heat sinking, or water cooling. This will improve the reliability of the mirrors, and reduce the effects of thermal effects that can distort the mirror surface and affect beam quality.

Additional Considerations. The optical elements and any coating applied must be able to withstand the high powers, and should be easy to maintain. Also, real-life optical components introduce aberrations.

The propagation of the light beams through lenses and off of mirror surfaces are predicted by the paraxial theory, which considers only those rays that propagate near the axis. Aberrations are deviations of the light rays from the predictions of the paraxial theory. Aberrations are classified into different types including spherical aberration, coma, field curvature, distortion, and astigmatism. Spherical aberration is the result of the off axis rays coming to focus at a slightly different point than near axis rays. This effect is reduced by using doublets that combine positive and negative elements. Coma is effectively different magnification from different parts of the lens. Curvature of field causes images to be sharper on curved, rather than flat surfaces. Astigmatism is the result of rays propagating through the two perpendicular planes that contain the object and the optical axis coming to focus at a different point. Astigmatism causes a elliptical blur around the image. One disadvantage of using off axis reflective optics for waveguiding applications is the resulting large astigmatism.

Mounting Hardware. Several manufacturers produce optical mounting hardware that can be controlled with motorized drivers. Often, specialized optical systems are machined from raw stock. Mounting hardware is typically manufactured from aluminum, although for special applications steel or superinvar (low-coefficient-of-expansion steel) are used. The important consideration in the design of mounting hardware is stability, accuracy, and precision. Moving optical mount design must address backlash, and additional vibration factors.

The mounted optical component diameters should be sufficient to capture the beam, but consideration must be given to the space available within the beam delivery tube. The optical systems will be bulkier with motorized mounting systems and cooling apparatus.

Optical System Design. The design of an effective beam delivery system must work with the types of output beams available with current high-power laser technology in terms of beam cross section, divergence, and uniformity. Beam propagation effects which impact the design include diffraction, thermal blooming, and the potential breakdown of air from a tightly focused beam. The design is ultimately determined by the desired depth of focus at the work head, the overall path length, and the difference in path length between the extreme positions of the work head in practical application.

Diffraction. Diffraction effects cause any finite diameter beam to diverge. In general, the larger the beam diameter, the smaller the divergence. Optical waveguide systems are used to control both the beam size and the divergence, but diffraction effects will limit the ability to maintain a small beam diameter. To illustrate, the divergence of two ideal Gaussian-profile beams is indicated in the graph of Figure 5.3.3, which shows the beam diameter (where intensity is down by 1/e from the peak) as a function of distance. The 0.5-inch-diameter beam has a significantly more pronounced divergence, expanding to 3.9 inches in just over 80 meters. The 2.0-inch spot, on the other hand requires a 300-meter path length to have the beam

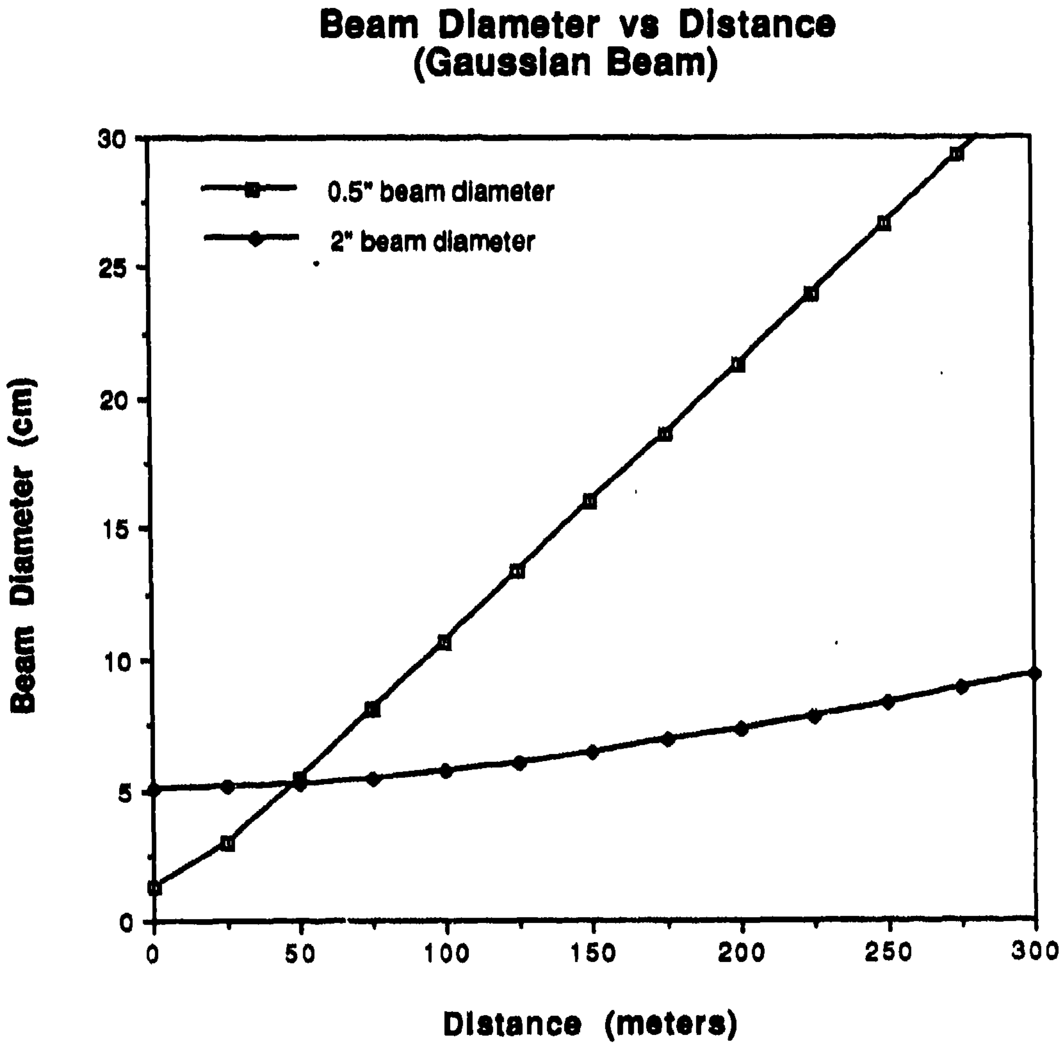


Figure 5.3.3 Beam Diameter vs Distance
(Gaussian Beam)

diameter reach 3.9 inches. This calculation indicates that a 2.0-inch-diameter beam can be transmitted over an 80 meter path before it expands up 10% of its original diameter. In addition, changes in path lengths on the order of 20 meters do not have a significant affect on the beam diameter.

The ideal Gaussian mode profile assumed for this calculation is only an approximation for the laser systems proposed to be used for this application. Different beam profiles propagate differently, and these effects must be carefully considered in the design of the beam delivery system, particularly in the design of a system which is adaptable to different path lengths.

Thermal Blooming. Thermal blooming is related to a change in the local refractive index of the air due to thermal effects. This region then acts effectively like a diverging lens and causes the beam to spread. It also causes distortions in the beam pattern. Thermal blooming is exaggerated by humid air, which absorbs the laser radiation more effectively and causes localized heating. This effect usually warrants operating high power laser beams within an controlled environment.

Air Breakdown. Another consideration for high-power laser beam propagation is the effect of air breakdown because of high electric fields. The electric fields of the laser radiation can exceed air breakdown (the practical breakdown field is related to the composition of the air) if a high-power, coherent laser beam is focused to a very small spot. Therefore, the beam delivery system should not require bringing the beam to a tight focus.

Path Lengths. For long paths (over 10 meters), a low-divergence beam out of the laser is desired. Even with a low-divergence beam, waveguide optics will probably be required to maintain the beam size at the work head. For short paths (under 10 meters), waveguide optics will be needed if the beam divergence restriction on the laser output is reduced.

For all paths, at each joint, a set of mirrors on a motorized mounts will be needed to change the beam direction. The motor controller must be controlled and tied into the robotic system controller. The control system must be able to control mounts on joints for each degree of freedom. For the beam delivery system, this could be as few as none, or as many as six depending on the flexibility of the work head system and the type of robotic system used. If curved mirrors are used, they can double as waveguide elements. Astigmatism is more pronounced for off-axis illumination however.

Depth of Focus. The focal plane of an optical system is determined by the focal lengths of the elements and their separation. Since the focal length of the optical elements is constant, the separation between the elements must be used to control the focal plane position. This also implies that as the path length from the laser to the target changes, the focal plane of the optical beam delivery system will change. Therefore, the beam delivery system must demonstrate the ability to compensate for these effects by changing the separation of the waveguiding elements. For a dynamic laser beam delivery system, the movement of the optical elements that adjust the beam waist must be able to respond within the time frame of the motion of the work head. Because of the time required to move these waveguiding elements, it is unlikely the beam delivery system could respond in the time frame of a laser pulse period. This points toward a system that moves a work head to one position, strips a set large region (approximately 1 square foot), then moves to another position. Alternatively, a slowly scanning system could overcome this problem.

The dependence on the focal plane position can be reduced by using a long depth of focus. The depth of focus is directly proportional to the focal length of the optical system. A long depth of focus produces a more constant diameter beam over longer distances. This type of beam is easier to accommodate at the work head, and would be advisable if substantial path length changes are anticipated. One disadvantage of the long depth of focus is that the beam will maintain a high intensity over long distances, which increases the hazard of the beam causing damage if it is accidentally directed away from its intended target.

Stability. Stability is an important factor for the beam delivery system. The longer the path length, the more sensitive the laser beam position at the end of the path is to small changes in the mirror position at the start of the path. A 0.1-mrad angular deviation causes a 1-mm shift in the beam center at a distance of 10 meters, and a 1-cm shift at a distance of 100 meters. Therefore, stability of the optical mounting hardware to a reasonable tolerance must be demonstrated. As discussed earlier, the mounting hardware and design have a significant affect on system stability.

Enclosed vs. Open Systems. One question that arises in the design of a beam delivery system for the paint removal application is whether to use an open or a closed beam path. This decision impacts the development of the robotic system.

From a functional standpoint, it impacts the safety, maintainability, and performance of the beam delivery system. From a safety standpoint, an enclosed system is desirable because the laser beam from this Class IV laser is available to the human eye, and there is the possibility that the beam could be interrupted by either personnel or equipment, causing significant damage in either case. To satisfy OSHA regulations, personnel must be isolated from the laser beam. Therefore, if personnel are allowed in the room during operation, an enclosed system is required.

Enclosed systems would allow an over-pressure to be maintained over the optical elements. This, coupled with the additional protection from debris provided by the enclosure, would lead to improved reliability and reduced maintenance for the optical elements. There would also be a reduction in the potential for thermal blooming effects, and a resulting improvement in performance. Note that accessibility of the optical components and mounting hardware will be required.

Over very long path lengths, unsupported enclosure systems are subject to droop, which would hinder beam propagation and must be accounted for in system design. This factor could ultimately lead to a path length limitation.

Development and Risk. Beam delivery systems for high-power CO_2 laser systems are common for industrial and material processing applications such as cutting, welding, and hardening of metals. These systems routinely cover path lengths of 10 meters, and often are adaptable to path length changes. Although these systems are relatively straightforward, the system must be carefully designed to maintain beam quality, and to produce the appropriate beam diameter at the material surface. **The extension of this technology to very long path lengths (over 100 meters) will not be straightforward.** Stability, and adaptability of the system are crucial. Additionally, if a control system must be developed to maintain the focus in the appropriate place as the path length changes, the risk would be even higher. However, the risk here is related to the ability to determine an appropriate design rather than to develop new technologies. The development risk here is categorized as moderate.

5.4 Work Head

The work head is used to shape the beam just before hitting the target. In most situations, the work head will also contain a sensor element that controls not only the work head optics, but the beam delivery system and the laser. In this section, beam integration methods are discussed. Then the performance requirements for paint removal are outlined. Some of the proposed work head concepts are described, and finally the development areas and risk are discussed.

Beam Integration. In systems utilizing lasers with outputs that are not uniform across the beam profile, optical systems may be utilized to improve the beam profile at the aircraft surface. Beam integration may be accomplished in several different ways including a static, spatial beam integrator, or scanning system. The basic concepts are discussed below.

Static Systems. Standard static spatial beam integrators use a multifaceted spherical mirror. Each facet, which is typically a planar surface, reflects a section of the beam, and these sections are directed to overlap at the focus of the sphere. The beam size is determined by the size of the facets. The number of facets, and therefore the beam size in the focal plane, is set by the desired level of integration. Typical industrial heating applications utilize between 16 and 36 facets. The focus is typically a few inches.

The depth of focus issue is important for the beam integration system. If beam integration is done within the work head, the ultimate depth of focus of the system is dependent upon the optics in the work head. In the case of planar facets, the divergence of the small beam section will be dictate either by the diffraction of the small beam size, or the divergence of the original beam, whichever is greater. The depth of focus of the spherical focussing element determines the distance over which the small beams remain overlapped. To obtain a large depth of focus, the integrating head must be large enough to accommodate long path lengths.

Scanning Systems. Scanning systems use time integration, sometimes in combination with spatial averaging to achieve a uniform distribution of light on a surface. These types of systems rely on scanning mirrors that direct the beam to different locations within a region on a time-scale short with respect to the total dwell time at that location. As a specific example, consider a rastering system that rapidly scans a 1-inch beam across a 5-inch strip. On average, each position within the strip sees every x-position of the beam, resulting in averaging over this one dimension. The other dimension is averaged in the same way. Note that edge effects must be dealt with separately. Timing, and raster-beam spot size must be carefully designed to achieve the appropriate level of averaging for a given application.

There are some other important issues to consider in the choice of a beam integration system. The integrated beam is no longer phase-coherent across the beam. Therefore, its propagation and focussing properties are not that of the Gaussian, or near-Gaussian beams that are incident on the integrator. In general, a spatially averaged beam will not focus to a small spot. There are also diffraction lines associated with the finite edges of the small facets.

Use in Other Applications. Beam integration systems are commonly used in industrial laser applications where beam profile is important. Heat treating is one major application area. UTIL incorporates Spar integrators, manufactured by Spar, Inc., in their applications which require uniform beams. UTIL also uses a beam spinner system that rotates the beam around its propagation axis just prior to the target. The rotation averages the beam profile around the axis, improving uniformity. Circularly symmetric patterns would not be averaged out with this method.

Alternatives. There are other methods to achieve a high quality beams that are parts of the laser system, rather than the work head. This includes beam paths which integrate over the gain medium, and master-slave oscillator type systems. UTIL has done significant development in this area for laser applications in laser radar systems. The applicability of the master-slave oscillator system to 15-kw systems has been demonstrated; however, significant alignment is required, and practical long-term operation may not be possible.

Performance Requirements. For paint removal applications, the beam profile must be uniform and repeatable to assure that the paint is completely removed, and the aircraft surface is not damaged. A practical work head system design will accommodate the available laser output parameters and produce a uniform exposure at the target. The tolerance to nonuniformity is dependent on the surface tolerance to laser fluence. Avco determined experimentally that the beam profile must be uniform to +/-10%.

Beam Shape. The beam size and intensity fall off will have an impact on the paint removal at the interface between two adjacent laser footprints on the surface. Effective exposure at the interfaces also requires careful coordination of the robotics or scanning mirror arrangement. For a Gaussian beam, the intensity profile is specified by the full width at half maximum (FWHM). For small FWHM, the alignment between two adjacent foot prints becomes more critical. Figure 5.4.1 shows the overlap of two adjacent Gaussian laser footprints with FWHM's of 1.7 cm and 5.0 cm. The solid line shows the sum of these two patterns which is the total energy density imparted to each spot after two laser pulses. In each case, the beam separation is set so the beams cross at the intensity-half-maximum. Figure 5.4.2 shows these two beams after a misalignment of 0.5 cm. It is apparent in the case of the 1.7-cm-FWHM beam that the integrated intensity at the interface has dropped below the 10% reduction limit, and therefore paint stripping will not be uniform. The 5.0-cm-FWHM beam is not sensitive to the 0.5-cm misalignment. These results are summarized in Figure 5.4.3, which shows the relative energy density at the interface (summed intensity) as a function of the misalignment of the beams. In this graph, a positive Delta-X indicates increased separation, negative Delta-X indicates decreased separation. The +/-10% deviation limitation is shown on the graph. Note that for the 1.7-cm-FWHM beam the deviations of less than 0.75 cm result in an

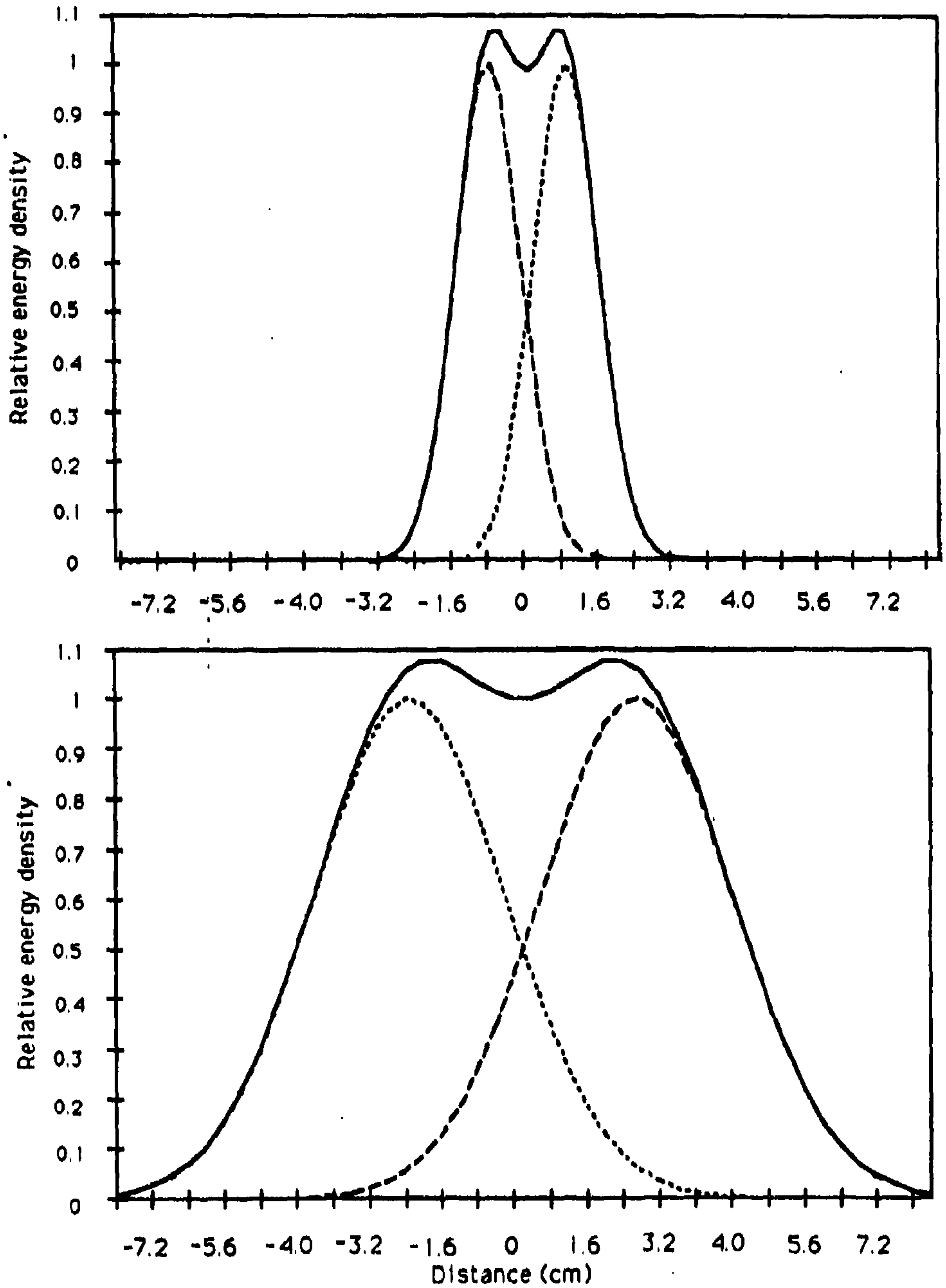


Figure 5.4.1 Laser Footprints
Top: FWHM = 1.7 cm
Bottom: FWHM = 5.0 cm

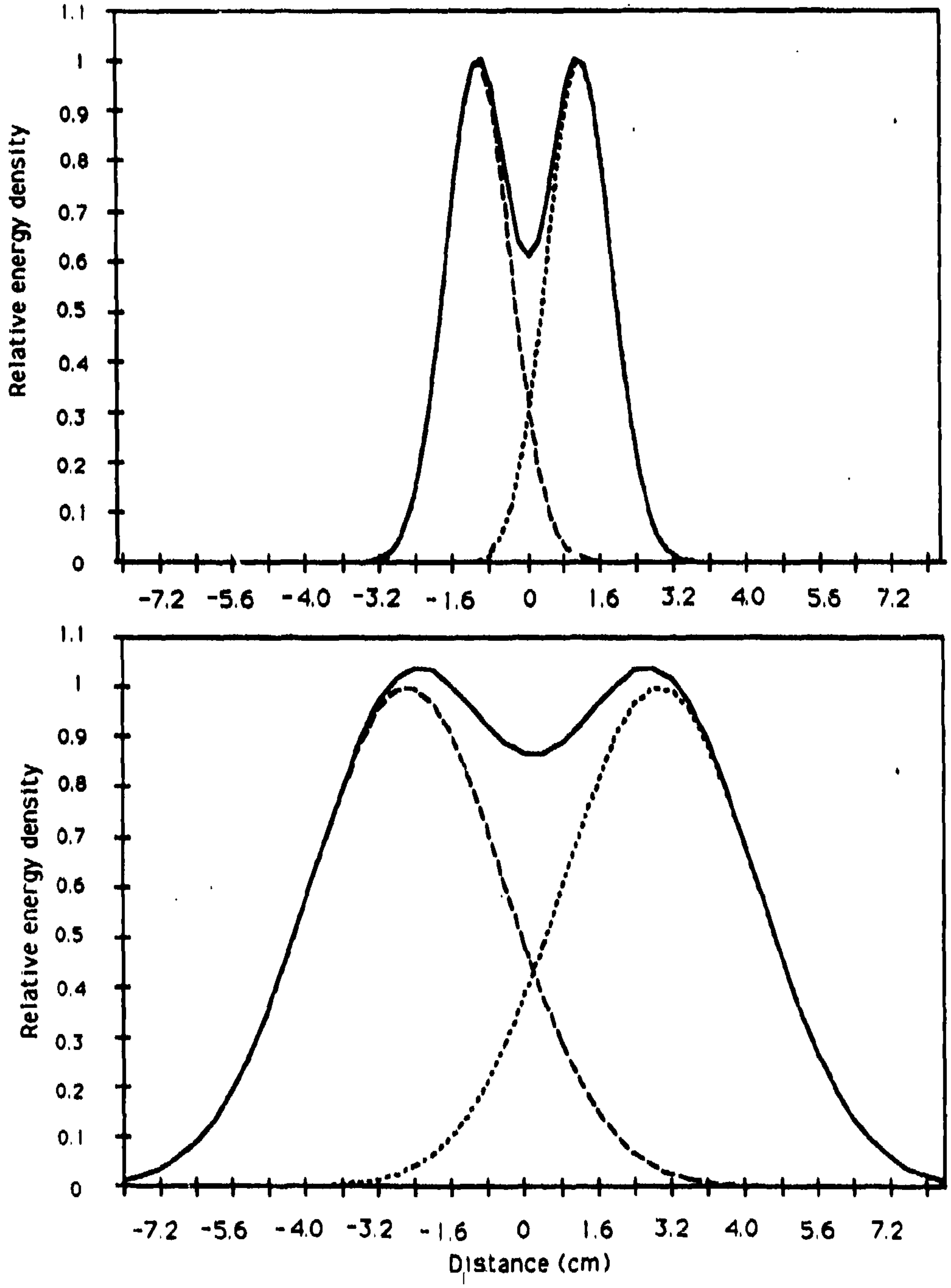


Figure 5.4.2 Laser Footprints
0.5 cm misalignment
Top: FWHM = 1.7 cm
Bottom: FWHM = 5.0 cm

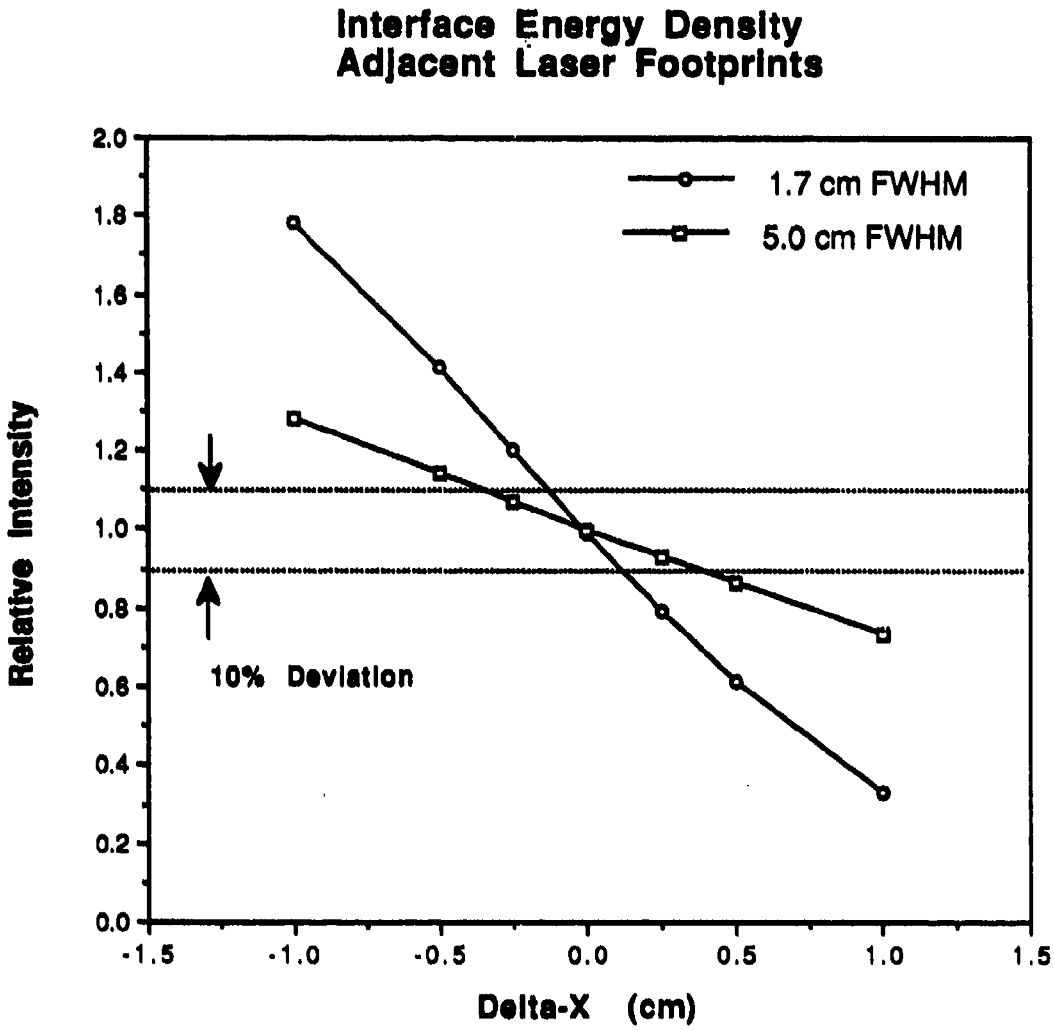


Figure 5.4.3 Interface Energy Density Adjacent Laser Footprints

overshoot of the energy density at the interface that exceeds the limit, and could lead to surface damage.

This analysis assumes a smooth Gaussian beam. The beam delivery system and focussing head optics dictate the exact intensity pattern. In reality, most beams will have diffraction side-lobes. The impact of this modulation on the paint removal is dependent on the intensity and spacing of these side-lobes. If the side-lobe spacing is small compared to the thermal diffusion length of the target, the modulation will be washed out and will not have an impact on the paint removal. If the fringe spacing is larger, however, the modulation will be evident in the thickness of the paint removed and/or the amount of damage to the aircraft skin.

Temporal Stability. The requirement for temporal stability of the laser power output and beam profile is determined by the integration technique that is used. Temporal variations in the laser power that are short with respect to the integration time will be averaged out. Longer-term variations must be accommodated by a feedback system that controls the exposure time of a certain area. In most cases, the temporal stability of the laser system will be a given, and the integration scheme must be engineered around this parameter.

Available Technologies

Rastering Concept. One technique which has been considered for paint removal applications is to raster a nominally 1-inch-square beam over a large area (1 square foot). The entire area is covered once every second. Beam integration is obtained by slightly displacing the center of the beam on each sweep. Sixteen sweeps are made to clean a nominally 2.5-mil-thick layer of paint. With the use of a spectroscopic sensor system, some of the 1-inch square regions will not be illuminated on a particular sweep if the sensor indicates the paint has been removed.

This particular system alleviates some of the requirements on the laser stability by using the sensor to judge and to control the exposure time. In this case, if the laser power suddenly increased on 1 sweep, this "overexposure" would be offset by not illuminating the section on the next sweep.

For the integration method to be practical, the beam uniformity at the aircraft surface must be quite good because only 16 pulses or fewer are used to average. In the case where the paint is thin in some area and only one or two pulses are used, nonuniformities may not be sufficiently averaged. The averaging system would be most effective if the sensor were also used to determine the averaging pattern. For this to be effective, however, the sensor spatial resolution must be much smaller than the beam size. The lower limit on the necessary resolution would be set by the thermal diffusion length of the target. Of course, higher resolution will necessarily require more processing and subsequent closed-loop control.

As mentioned above, the edges of the large area will not be sharp with this averaging method. This effect must be dealt with either by using a high-resolution sensor, or by keeping the integration protocol in memory, and recalling the protocol used in adjacent regions. Again, this adds to the computational complexity of the system.

Reliability, Maintainability, Safety. This work head system concept requires as a baseline motorized kinetic mounts, reflective optics, the sensor system, and associated control electronics. The work head optical system be capable of rigid and repeatable motion, which can be realized by current technology. While kinetic systems are not as reliable as fixed mounting systems, they are generally reliable if used within their specified operating load conditions.

The reliability of the optical components hinges on the adequacy of the reclamation system. The optical elements will be subject to fouling from debris given off by the paint removal process. The lifetime, as well as the maintenance of these elements depends on the reflective materials used. Molybdenum coated mirrors are recommended if fouling is likely because of their durability. Ready access to the work head optics would be essential for ease of maintenance.

It is important that the work head be able to tolerate the back reflection of the laser beam should it strike a highly reflective surface such as aluminum. Water cooling may be required to reduce heat build-up.

The sensor element would also need to be shielded from high-intensity reflections by some filtering or appropriate shielding. The reliability of the sensor system is as yet unspecified, but should be analyzed because it could be the reliability driver of the work head system.

The electronics should be realizable with standard off-the-shelf components, and do not pose a significant reliability or maintenance issue, though they should be accessible for repair.

Stationary. Another approach which has been suggested by Avco is a stationary beam integration system. Avco's modified beam integrator is similar to a Spar integrator, but uses convex mirror facets rather than the standard planar facets. These facets serve to expand the different portions of the beam, and reduce the path length needed within the work head to result in a 10-X-10-cm beam at the target.

This system has a short depth of focus. Depth of focus must be sufficient to accommodate the largest curvature of the aircraft that is stripped. Robotics accuracy must be high enough to accommodate the sensitivity of the focal plane. For a 0.5 inch depth of focus, +/-0.25 inch robotic accuracy is required perpendicular to the aircraft surface.

Reliability, maintainability and safety. This type of system would be very reliable particularly because there are no moving parts. The issues of reliability and maintainability of the optics are the same as in the previous system.

The short depth of focus is desirable from a safety standpoint, because the beam diverges rapidly.

Although a paint identifier sensor would still be advisable to accommodate variations in paint thickness over large scales, the resolution of the sensor could be fairly low, and the feedback control less complex. This reduction in complexity would provide the associated improvement in reliability and maintainability.

Additional Considerations. The weight of the work head system will impact the stability of the robotic system. The work head weight should easily be less than 100 pounds. The work head center of gravity may also be a consideration for the robotic system. Counter-balancing weights may be required.

Development/Risk. Several key areas exist for development of a practical work head system. It is possible in the design to trade off the complexity of the sensor and control system with the complexity of the optical system, as was alluded to in the above discussion. The key to an operational scanning-type system is a functional, high-level sensor system. This type of a system may be essential for paint removal from composites. Successful development of this system hinges on the sensor system. The development of a paint identifying sensor is still in the early stages, and applicability to a large scale, field usable system must still be proven. While technologically realizable, the demands on the signal processing and control system, as well as the laser requirements of such a system may not be easy to integrate into a workable system.

On the other end of the spectrum is a system utilizing a less sophisticated sensor system in conjunction with a laser and optical system that produces spatially and temporally uniform illumination at well defined, open- or closed-loop controlled, positions. This approach results in a simpler and easier to maintain system, but may not be adequate for stripping composite skins, particularly if the paint thickness is not uniform.

5.5 Sensor Systems

The sensor technology that accompanies the robotic system, including standoff and collision avoidance, are available off-the-shelf, and do not pose a significant development issue. A sensor system that adequately controls the laser and work head optical system, on the other hand, represents a significant development challenge. Even more difficult is the combination of the sensor technology with the robotics technology. It is difficult to combine the sensor with the robotics control system when the sensor window leads the paint removal window because the robotic control system must be able to ascertain the exact relationship between the sensor window and the laser beam window. This requires either *a priori* knowledge of the aircraft surface, or complicated sensor system and control circuitry. The integration of a sensor into the robotics window will require that the sensor be able to process the necessary data within the time allowed for the control signal to be sent. This could prove a difficult task if the sensor has to compare spectroscopic signatures with a known data base.

Several types of sensors are available, and have been proposed for use in the paint removal application. These include imaging systems, optical spectroscopy, acoustic sensors, and magnetic sensors. Imaging systems would be appropriate to determine the shape of the laser footprint. Depending on the resolution, imaging systems can require considerable electronic processing to produce a useful output. Imaging systems also require predictable illumination, because illumination changes cause significant changes in the video image. They would not be readily adaptable to the different surface curvatures for this reason. The CCD elements, though transparent to radiation at 10.6 μm, would still need to be protected from reflections and radiation that occurs from ignition of the paint and contaminants on the surface. Sensitivity to this stray light can be reduced by using monochromatic illumination and filtering systems. CCD cameras also have a characteristic persistence, which may cause a problem for very fast imaging requirements.

Optical spectroscopy has the advantage over imaging that the resolution may be lower. However, the amount of processing required for each pixel of spectroscopic information is significantly greater. Depending on the size of the library of paint absorption spectra, the matching procedure could prove cumbersome. USBI has determined that the spectroscopic system must identify the surface within 0.67 milliseconds and that a color sensor has not been found that can work on this time scale. It is possible that clever processing, and the use of some *a priori* information could reduce the processing burden. However, most spectroscopic gas identification systems have processing times on the order of several seconds. These systems only have a few isolated lines to identify. Furthermore, the data presented by InTA do not show readily identifiable spectral lines within the visible wavelengths interrogated. Spectroscopy instrumentation requires some calibration or referencing scheme to produce reliable results. The spectroscopic system could also be thrown off by the flash and the smoke and debris that accompanies the paint removal as well as any contaminants, dirt, or oil that may be present on the aircraft surface.

Ultrasonic measurements could be adversely affected by the acoustic signal that is generated by the laser paint removal process.

Electromagnetic sensor sensitivity would depend on the composition of the paint. Different paints have different dielectric properties. Some are good insulators, and others are conducting.

Contour following and collision avoidance, color discrimination and global positioning sensors were evaluated against the system requirements. Laser, ultrasonic and electro-optical methods are seen as the best methods. Magnetic methods are not effective on all types of substrates, as is the case with capacitive methods.

Performance requirements dictate that an extensive sensor system be used. The following capabilities are required of the sensor system. Each of the sensor subsystems are discussed in greater detail following their definition.

Collision avoidance/obstruction detection. Collision avoidance capability is essential to protect the aircraft and other objects within the work envelope.

Surface contour following/stand ↓f control. In order for the laser energy to be efficiently directed toward the aircraft surface, the beam must be normal to it. The work head must operate at a relatively constant distance from the surface in order to keep the focused portion of the laser beam in contact with the area to be stripped.

Color/substrate discrimination. The decision to pulse (strip) a surface is dependent upon the spectral response (color) of the material. Knowledge of the underlying substrate material allows for a more robust stripping algorithm.

Global positioning. An ALPS system requires the ability to orient itself with respect to the aircraft. The aircraft cannot be located in exactly the same location each time the stripping process begins.

Surface mapping. Some type of mapping capability is needed to allow the system to generate "tool" (work head) paths over the aircraft surface.

5.5.1 Collision Avoidance/Obstruction Detection. Collision avoidance is accomplished by ensuring that the robot arm does not come into contact with the aircraft during processing. Obvious deviations from the working CAD model of the aircraft will be detected during global location and accounted for during path planning.

Several methods could be used during processing: ultrasonic, laser, electro-optical, or vision (cameras). Any of these will provide the desired information. Since there will be a number of sensors and sensor processors incorporated into the conceptual design, it would prove beneficial to utilize another one of the sensor systems and its controller. Based on the fact that a vision system will be utilized for color discrimination and global locating, it appears that the best approach would be to use a camera to look ahead of the laser work head to the next robot arm position for obstacles which might be encountered during the next move. The vision system would use the same processor as the color-discrimination and global-locating functions, all tasks which are required, but are performed at different intervals.

First-level collision avoidance is expected to be handled by the controller and its software. It should be quite feasible to program the controller to prevent the robot from occupying the same space as the aircraft at any point in time. The ability to do this is predicated on the controller's knowledge of the space occupied by the aircraft, the space occupied by the robot at any instant in time and the ability to distinguish these two spaces.

The criticality of collision avoidance warrants a sensor-based redundant system to back up the controller. This system can be either a contact-type where a probe physically touches the aircraft (or other collision hazard in the work envelope) or a noncontact-type such as a sonar transducer that detects the presence of objects by the reflections of sound emitted by the transducer.

The Cimcorp robot used in the Air Force NDI system uses instrumented "bumper pads" around the robot arms. If the robot comes in contact with an object, the pad deflects to prevent damage to either the robot or the object (likely to be the aircraft) and shuts the system down to prevent subsequent damage. See the Appendix for more information concerning Cimcorp and the NDI system.

5.5.2 Surface Contour Following/Standoff Control. The specific requirements for surface contour following and standoff control will be different for each ALPS system concept. Any concept, however, can be expected to require some knowledge of the local surface normal and the distance to the surface. The InTA design only requires that the laser beam be within 60 degrees of the surface normal and within 5 cm of its average standoff distance. The Avco concept, on the other hand, requires that the beam be within 5 degrees of the surface normal. It must be remembered, however, that neither of these values have been verified and are subject to further refinement. In either case, the work head must be able to calculate the local surface normal and the distance to the surface. There are a variety of techniques to calculate this information.

Standoff Sensor Systems. Standoff sensor systems include contact and noncontact methods. Systems which consist of multiple sensors provide information about normal orientation to the surface, as well as standoff distance, for a three-dimensional perspective.

Contact Methods. Contact methods usually consist of touch probes. A probe, of specified standoff length, would remain in contact with the aircraft surface during processing. For two reasons contact methods are not deemed appropriate for in-process use and are not considered further. The first reason is the requirement not to damage the aircraft surface. The second is that the changing shapes of the aircraft surface and the fixed positioning of the contact probes could lead to inaccurate standoff control.

Noncontact Methods. Noncontact applications include magnetic, capacitive, laser, ultrasonic, and electro-optical.

Magnetic. Several types of magnetic sensors are used as proximity devices. Reed relays are one example. A fixed conductor and a reed tube, made of a magnetic material, are sealed in a glass tube. The magnetic reed is moved by the approach of a small permanent magnet which closes the electrical circuit.

Another magnetic sensor is the "Hall effect device" which utilizes the generation of a potential in a semiconductor plate. This plate carries a current in the presence of a magnetic field perpendicular to the plate. The potential difference generated between the two sides of the plate is orthogonal to the direction of both the current and the magnetic field. This is called the Hall voltage.

Capacitive and Inductive. Capacitive transducers have two parallel conducting plates. When the plates are displaced relative to each other, the capacitance changes so that the impedance to the passage of an alternative current (AC) varies.

Capacitive displacement/proximity sensors generally work only for small standoff ranges. These sensors respond to the presence of metal. Although the sensors are actuated by any type of metal, their sensitivity to nonferrous metals is sometimes only one third that of ferrous metals.

One noncontact capacitance clearance control system is designed specifically for laser operations. This system maintains an optimum focal point by measuring the clearance between the laser cutting nozzle and work piece. The system is incorporated into the laser work head with a copper nozzle used to act as an electrode. The nozzle electrode and the work piece provide a variable capacitance. Changes of clearance are detected by a high-frequency oscillator circuit. The shift of frequency is converted into an analog direct current (DC) signal.

Proximity sensing from nonferrous metals can better be accomplished with AC inductive sensors. The ability to differentiate between ferrous and nonferrous metals could be useful in this application.

Laser Gauges. The laser contour sensor used the basic geometric law of triangulation. The contour sensor contains a solid-state laser diode and camera mounted in a sealed, rugged protective housing. The solid-state photosensitive imaging array, high-resolution optical, and laser diode are generally factory prefocused and rigidly positioned in a monolithic mount precision-machined from a single block of material. Standard standoff ranges are available from 1 inch to 120 inches. Other fields of view and standoff distances can sometimes be custom-delivered. These sensors provide a remarkable ability to measure soft, wet or delicate surfaces because they do not destroy or alter the materials they measure. In addition, their small laser spot makes them ideal for measuring highly contoured parts. Laser contour sensor advantages are higher speed, more repeatable measurement data, and lower maintenance costs that are due to the noncontact approach.

Sensor data is usually processed real time (but can be stored in ASCII files and can be analyzed by most data analysis software or programming language). Most systems include a sensor head, connecting cables, a multiplexer driver box and an interface card. When measuring surfaces with little variation, the sensor can operate in fixed exposure modes, where exposure times are set, thus increasing measurement speed. For surfaces that vary in texture, color or reflectivity, the sensors can be set to automatic exposure in which exposure time is adjusted with each measurement to maximize accuracy.

Ultrasonics. Ultrasonic sensors use ultrasonic wave-reflection techniques to measure accurately distances through air or other gases. Ultrasound is generated at high frequency from the tip of a transducer, which senses echoes from a reflective surface. Time of flight is determined by the system, which converts the data to distance or thickness and displays it and/or sends it to the computer. Applications include thickness and distance measurements or other dimensional checking, edge location and robotic arm positioning. Accuracies of 0.1% of the measuring distance can be achieved. Measuring ranges generally vary from 1 inch to 60 inches.

A leading system incorporates state-of-the-art ultrasonic technology to provide measurement and control data. The system transmits narrow beam acoustic pulses at a user selectable rate, processes an echo reflected from a target within a defined range, and provides multiple control outputs, depending on the position of the target.

Almost all target shapes can be sensed, but generally, smooth flat targets, normal to the beam axis, are easier to sense than rounded targets. The displacement of a flat target can be detected at a greater distance than a round target. If a smooth flat target is inclined more than approximately 3% to 8% to the normal of the beam axis, part of the signal is deflected away from the sensor and the sensing distance is decreased. Ultrasonic sensors can be affected by humidity and air turbulence. Ultrasonic waves can also be sent through a stream of water. However, for this application, this is unacceptable.

Electro-optical. Electro-optical sensors detect surfaces by the use of a light source such as a light-emitting diode and a photosensitive cell. A lens is used to image the light source at a point in space where the light will be reflected from an object back through another lens to a photosensor.

This type of sensor is characterized by a modulated, infrared, noncontact device used to determine part presence, absence, or object position. Three distance zones are usually identified (NEAR, OK, or FAR). The OK zone can vary from 0.003 inches to 20 inches, depending on standoff. One system uses infrared triangular reflection with a single optical lens to detect whether an object is within an OK region. Dual-modulated IR emitters inside the sensor project a small spot on the object. The single lens and small spot size permit highly directional sensing. Reflected energy from the surface to a single detector then determines the object's range status. A built-in switching hysteresis is sometimes provided, and a response time of 10-20 milliseconds can be expected.

Similar systems use infrared (IR) light and a dual mirror configuration to measure distance over a wide range of reflective surfaces from diffuse to specular, including mirror or glossy paint surfaces. Analog output data are also available. The sensor is housed in an anodized aluminum case and employs integral air purge to minimize contamination of the glass optical surfaces in hostile environments.

5.5.3 Color/Substrate Discrimination

The decision to strip an area of paint is a function of the type of paint (primer or topcoat) and the substrate (aluminum, composite, etc.). At the present time, this decision is made based on color. While the human eye can easily distinguish color differences among the primers and topcoats used by the Air Force, this task is very difficult for an electro-optical vision system handle.

International Technical Associates (InTA) of Santa Clara, California, is in the process of developing a color discrimination system using an array developed by Lawrence Livermore National Laboratories. The theory of this system is quite simple, although its design is not. A painted surface is exposed to a light source containing a broad range of wavelengths, from IR to UV. This is slightly beyond the human visible range. The exposed surface reflects the light in intensities that vary with wavelength. Each paint apparently has a unique spectral response. The InTA system compares this response with a "library" of stored colors. Library colors have been previously stored in a similar manner.

Issues regarding camera performance:

- Can the array algorithm resolve colors with similar spectral responses (i.e., shades of grey)?
- Will the spectral response of a dirty, weathered paint be close enough to its corresponding library color for an identification?
- Will the system be fast enough to allow paint-type determination to keep pace with the laser?

Substrate discrimination is of importance from the standpoint of aircraft safety. The laser energy has the ability to damage the substrates. Aluminum can withstand (reflect) more energy than composite. In light of this fact, the ALPS system can strip aluminum surfaces to bare metal, while a layer of primer must be left on the composite to protect the epoxy resin. The whole issue of laser interaction (damage) with the various substrates is not, to date, well understood. Composites have a much lower threshold for laser energy damage than does aluminum.

If one limits substrate differentiation to metals and nonmetals, the property of conductivity (of metals) may be used to distinguish metallic substrates from composite. Eddy current sensors may be used for this applications.

Surface/Paint Discriminators. Color and material discriminating functions also employ contact and noncontact methods.

Contact. Contact methods of material sensing include the eddy current process. Typical eddy-current sensors work best with metal surfaces. Composite surfaces will not allow sufficient surface currents to be induced, and thus, will not alter the measured electromagnetic fields enough to get reliable measurements. Contact color instruments offer high accuracy and low sensitivity to varying ambient conditions but were not pursued since these methods are not compatible with either the processes or the speed requirements.

Noncontact. Noncontact methods are mostly electro-optical. One electro-optical system permits detection of up to 12 memorized colors and detects subtle color differences. It is capable of using an RS-232C communication port to send recognition results to an external computer.

For the light-receiving element, which is the heart of the sensor head, a special photo diode is utilized. It consists of three chips which incorporate a filter for one of the three respective primary colors and features high-color sensitivity and wavelength characteristics. Light reflected by the detected object is resolved into the three primary colors by this color resolution light-receiving element. After analog/digital conversion, they are analyzed at the microprocessor and are transmitted as color information to the control unit.

The controller allows a reference color to be stored into memory in advance. The microprocessor recognizes the color consistent with that stored in the memory from among the color information transmitted from the sensor unit. Subtle color difference recognition becomes possible by the process described above based on utilization of the high-capability color resolution photo diode and independently developed algorithms. Color recognition in 50 milliseconds is possible.

The Avco study of the InTA system shows that the visible reflectance spectra have a sufficiently unique signature for all encountered colors. They propose to measure surface reflectance between laser pulses, analyze the observed effect and then use the output to control the timing or special movement of the next pulse through the control system. InTA's product literature is included in the Appendix.

The process involves premapping of the aircraft surface prior to stripping by means of a 32 x 32 optical sensor array. The recorded data are stored in memory with paint and substrate source data that show how the reflectance varies through a range of energy pulses. A comparison of the source data and actual reflectance during stripping will tell the control system when the substrate or primer has been reached. Note that the dominant principle behind this control scheme is color differentiation and is based on work performed at Lawrence Livermore Laboratories.

The color sensor must determine when the desired base material-stopping color has been exposed so that the laser pulses can be discontinued. There are several critical issues surrounding this sensor, including feedback rate and the number of colors that can be accommodated.

The color discrimination sensor can either be taught all the colors that it may encounter or only the colors that require the laser to stop pulsing (base materials). An estimate of the number of colors to be encountered is shown in Table 5.5.3.

Table 5.5.3 Expected Color Quantities

Aircraft	Topcoat Colors	Primer Colors	Base Material Colors	Total
B-52	2-4	2	1-3	5-9
C-135	2-4	2	2-4	6-10
B-1	2-4	2	8-10	12-16

For the sensor to accurately access the changing color spot, the sensor field of view (FOV) must be the same as the laser FOV. The most reliable methods to achieve this is to use the same scanning optics and to switch between the laser and sensor on a shot-by-shot basis. Because of the vast difference in optical power levels, substantial protection must be provided to the sensor so that the detectors are not "blinded" by the laser. An alternative is to offset the sensor spot from the laser spot such that the sensor spot is one or more scan positions ahead of the laser spot, as needed to achieve the required feedback rate. This would decrease the amount of energy coupling from the laser to the sensor, and might allow simultaneous use of the scanning optics. By separating the two optical axes, both the laser and the sensor could utilize the scan optics for the full laser-blast time.

Considering the InTA color discrimination system, the following analysis was performed. Based on the 11-mm x 11-mm spot size presented by Dr. Lovoi, a 12" x 12" processing pattern will encompass 27.7 spots in each direction. For a 10% linear overlap, 30 spots are estimated in each direction, or 900 spots per square foot total. At the projected 3 ft^2/minute stripping rate, the work head (1 ft^2) will be moved three times in 1 minute. Estimating 5 seconds for each of the 3 moves and allowing for settle time, permits 45 seconds available for processing, or about 15 seconds/ft^2 for stripping.

Since there are 900 shot positions/ft^2 and up to 10 shots per position, the derived rate is now 9000 shots/15 seconds, or 600 shots/second, or 1.667 milliseconds/shot. Using a worst-case estimate of 0.4 inches/millisecond to clear debris from the sensors "view" (using the vacuum system),then the necessary tangential air flow is 23 mph (0.4 inches/millisecond). Under these assumptions, the color sensor must measure and classify into one of the 11-17 known base material colors in less than 0.67 milliseconds. That amount of time does not allow for settling time of the optics because of the scan motion. At this time a color sensor has not been identified that is fast enough to meet the InTA system requirements of 1.667 milliseconds, much less the reduced amount of time allotted.

Another issue with color discrimination sensors is the need for a uniform light source that is much brighter than the ambient. The light could be diffused or pulsed. A diffused light source to provide even lighting over the viewing surface would be more than 2 feet square (4 square feet). This light would prohibit movement around several areas of the aircraft. As an alternative, an array of pulse lights or strobe lights could provide for approximately uniform off-axis illumination for each individual spot position. In general, these could be made smaller, but would be less reliable.

5.5.4 Global Positioning. A CAD model of the aircraft will be used as a guideline to generate rough robot-path trajectories before processing. The global locating procedure will be used to orient the aircraft with respect to the robot's position and determine how much of the robot's work envelope can be utilized. Many machine camera-type vision systems exist today which perform similar functions.

5.6 Air Reclamation

The purpose of the air reclamation system is two-fold: remove the contaminated gas stream (from around the work head) and remove the byproducts of paint stripping from the gas stream. Removing the contaminated air and replacing it with clean air is necessary to prevent ignition of the byproducts generated by the laser, to prevent contamination of the surface, to prevent the escape of toxic materials into the atmosphere, and to provide a clear atmosphere for the sensor system to look through. Another function of the air reclamation system is to remove these potentially toxic paint byproducts from the gas stream and to collect them for environmentally responsible disposal.

Laser paint stripping research has shown the gas stream to be composed of two classes of material: aerosols and gases. The air reclamation system must remove both of these types of contaminates. Aerosols are (in terms of the gas stream produced by laser paint stripping) particulate matter in the form of carbon (soot), metallic oxides, metallic fumes, and paint particles. Specific characteristics are a function of paint composition and process conditions. Aerosols may be removed by a variety of mechanical methods. Common methods include filtration via a fabric filter in a bag house system. Another system, employing a scrubber, removes particles by entraining them in water and filtering the water. The trapped particles are collected and removed as wet filter cakes. Other techniques possible for this application are electrostatic precipitation or cyclone centrifugation.

The gaseous byproducts are found in the form of hydrocarbons (organics) and oxides (inorganics). These gases may be responsible for odors, irritants, and toxicity. There are two fundamental approaches for their removal: adsorption and incineration.

Adsorption is a chemical process in which the gases are adsorbed (chemically bonded) to the surface of a solid such as activated carbon. The solid is then replaced or regenerated by heating.

Incineration is the high-temperature burning (oxidizing) in the presence of an excess amount of oxygen. The byproducts are simple molecules such as H_2O, CO_2, and NO_x, which are released into the atmosphere. The system relies on some fuel, often natural gas, to produce a temperature of approximately 1300°F. As the gases are oxidized, they contribute to the burning and serve to reduce fuel consumption.

In some cases, such as situations where a large volume of air contains a relatively low concentration of volatiles, a combination of both adsorption and incineration is used. This allows the carbon bed to adsorb the gases from a large quantity of air. Subsequent heating of the bed drives off the gases in a higher concentration than in the original air volume. This higher concentration of volatiles is more efficiently incinerated (in terms of the Btu's expended). This type of system is not necessary for an ALPS application because of the relatively low volume of air required, 2000 SCFM.

Complete air reclamation will require a system with the ability to remove particulate matter through some form of mechanical filtration and to remove gases by either chemical methods or incineration. While there are probably a number of combinations using the systems mentioned above to meet these requirements, before the most appropriate system can be identified a better understanding of the gas stream composition is required. This should include analyzing a gas stream from an ALPS system to determine the types of aerosols and gases present, their relative concentrations, and the particle size distribution.

Cleaning the gas stream is well within the capabilities of the present technology. This is a well developed industry and should be well equipped to provide the Air Force with a system to adequately clean the gas stream. Waste reclamation rates of well above 99% are the norm.

5.7 Controllers

In this study, we conducted a trade-off analysis of controllers. The conclusion from that trade-off study is that a USBI design appears to be the most appropriate to meet large-scale system requirements. A summary of that effort is presented in this section. The USBI-designed controller was compared to products by other vendors. The Spar Aerospace controller is almost equally capable of meeting the design requirements and desired system criteria.

Initial candidates were screened against the system requirements. Each controller that passed this screening process was scored on its ability to accommodate the selection criteria. Definitions of selection criteria and their significance are also given. Once the alternatives were evaluated, a trade matrix was completed, and the best controller was determined.

The candidates for the trade-off analysis were:

A. Advanced Control Technologies
B. Allen Bradley-8200R and 8600GP
C. AMF - Versatran 600
D. BEI Motion
E. Cimcorp (GCA) - CIMROC 4000
F. Cincinnati Milacron
G. Cybosystems - RC-6 and RC-7
H. Datem
I. GCA - CIMROC 2000
J. GMF - Karel
K. Graco
L. Honeywell - DMCS 3000
M. ICC (Gould) - 3220 and 3240
N. Spar Aerospace - Search
O. USBI Design
P. Westinghouse - Unival

The following criteria were established as initial screening requirement set:

Analog/digital signals available. One digital I/O signal is projected. A 24V DC signal and a 110V AC signal are also seen as necessary. This criteria ensures the controller's capability of interfacing with required devices such as process equipment, sensors, and motors.

Axes of control. The ability to control a minimum of 7 coordinated axes with respect to a common tool point.

Configurability. The system must be modeled on a flexible body, not a rigid system. The operator must be able to adjust controller inputs to define link values and adjust ga: - in the control loop (inverse kinematics).

Emergency backup. Battery backup for memory is required to prevent loss of accuracy and position in the event of power loss.

Language. Mandatory utilization of a high-level, English syntax language ensures a user friendly operator interface.

Mass storage. Nonvolatile storage for programs in the form of bubble memory and hard disks are required for easy fact retrieval of stored data, minimizing program run time.

Meet need date. The controller must be built, delivered, and integrated with the robot system in accordance with an established schedule.

Multi-tasking capability/parallel processing. In order for the controller to perform advanced control algorithms, it must be able to execute multiple tasks concurrently.

Real time operating system. The robot controller must perform in real time.

Serial communication ports. A minimum of one RS-232 serial communication port is required for external device interface.

System storage (RAM). Every controller will have enough storage to execute the system software.

Candidates that passed the initial screening were scored according to their abilities to meet the following selection criteria.

Communication ports. Additional communication ports (more than one RS-232 serial port) are desired, accommodating expansion in the form of additional external devices.

Cost. The most reliable system at the least cost is the goal in choosing a controller.

Interface requirements. The controller should have the flexibility to interface with a variety of motors and feedback devices.

Internal memory. The amount of expansion that the controller is able to support (additional processes) depends upon its memory capacity; therefore, additional memory is a plus for the controller.

Language. Use of a high-level, English syntax language is a requirement for the robot controller. A standard language is more desirable than a highly specialized language. If software modification is necessary, no special training will be required for operator interface with the controller.

Local area networking. Robot controller ability to interface with communication networks, i.e., Ethernet, MAP, is a desirable option.

Maintainability. Replacement parts for the system should be readily available (i.e., a system that uses more off-the-shelf components is faster to service than a system which requires specialized parts).

Operating system. A real-time operating system is an initial screening requirement. A standard operating environment (DOS, VX Works, etc.) is more desirable than a specialized one.

System software. Minimal USBI software development is desired. The less software development required, the higher the score on this issue.

Technical risk. A company with the reputation of delivering a quality product is desired. The main consideration is whether the vendor has the experience to meet the development schedule at the quoted cost.

Vendor support. Ready availability of technical assistance from the vendor is desired in event of problems. An estimation of support availability can be based on the geographical location of the vendor, the size of the company and the vendor's reputation.

The candidates who met the initial screening criteria are shown below.

A. Cimcorp (GCA)

B. GMF

C. Spar

D. USBI design

These controllers were scored in the trade matrix based upon the desired system characteristics. A brief description of the analysis is presented in the following sections.

Additional communication ports. The Spar and USBI controllers are highly expandable because both implement a VME bus for the back plane. The Cimcorp is expandable to a maximum of 14 total serial communication ports.

Cost. The USBI designed controller is least expensive because it eliminates built-in middle-man profit, a cost which would be incurred if a controller were bought from an outside vendor. The Spar and GMF are less expensive than Cimcorp because those companies have more experience in building robot controllers; they would require less research and development time/cost.

Interface flexibility. The controllers all met this criteria.

Language. All controllers implement a high-level language. The Cimcorp uses a specialized language, while GMF and Spar software are written in a standard language such as C. The USBI-designed controller would also support a standard language.

Local area networking. The controllers all have the capability of interfacing with local area networks.

Maintainability. The difference in maintainability is not significant because the controllers are built from similar components.

Memory expandability. Two Megabytes of RAM, 40 Megabyte hard drive and a 3.5-inch floppy disk drive are standard in the Spar system. The USBI design and Spar systems both utilize VME busses, making their controllers virtually unlimited in memory-expansion capabilities. The GMF Karel controller is not as memory-expandable. The Cimcorp has the least capability to accommodate memory expansion.

Operating system. All robot controllers implement a standard operating system.

System software. Cimcorp, Spar and GMF provide applications software for their controllers. The USBI controller design would require that all software development be an in-house responsibility. Allowing software customization makes the USBI-designed controller the best choice for meeting this criteria.

Technical risk. Cimcorp and GMF are the lowest risk technically because of their experience in building controllers. Spar and the USBI design would require more research and verification time for design efforts.

Vendor support. The USBI designed controller would have an advantage in the availability of technical support because the design team would be involved in the installation, integration, and maintenance processes. Of the outside vendors, Spar is a larger company and would be able to provide more technical advice in the event of problems; however, a disadvantage for Spar is that they do not manufacture their own controller parts. Replacement parts might not always be readily available from a vendor. The Cimcorp and GMF are better equipped to provide service and replacement parts.

The trade matrix used to determine the best robot controller is shown in Figure 5.7.1. The trade matrix indicates that the USBI controller is the best choice. There is a marginal difference between the Spar and GMF controllers. Both the USBI design and the Spar controllers are capable of handling the system requirements and in meeting desired system specifications. The USBI controller also has the advantage of accommodating custom software.

Feature Required	Requirement sWeight	Cimcorp		SPAR		USBI		GMF Karel	
	1=Low 5=High	Score	Score x Weight	Score	Score x Weight	Score	Score x Weight	Score	Score x Weight
Additional Communication Ports	3	3	9	4	12	4	12	2	6
Cost Minimization	3	3	9	2	6	4	12	3	9
Interface Flexibility	4	3	12	3	12	3	12	4	16
Internal Memory	2	2	4	4	8	4	8	3	6
Language	4	4	16	4	16	4	16	3	12
Local Area Networking	4	4	16	4	16	4	16	4	16
Maintainability	3	3	9	3	9	3	9	3	9
Operating System	2	3	6	3	6	3	6	3	6
System Software	4	3	12	3	12	4	16	3	12
Technology Availability	4	4	16	3	12	3	12	4	16
Vendor Support	3	2	6	3	9	4	12	4	12
TOTAL			115		118		131		120

Figure 5.7.1 Controller Trade Matrix

6.0 Conceptual Design

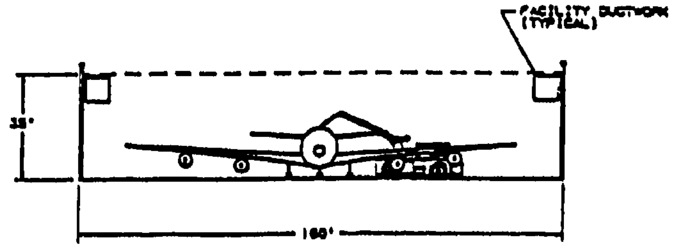
This section presents the conceptual design for the selected robot system, sensors, controller, laser, and operational scenario. The counterbalanced telescoping beam mounted on a heavy-duty tractor tug was selected as the most feasible representative candidate. Based on the trade-off in section 5.1, the robot would be controlled using an in-house designed VME-based controller. The UTIL Model SM11-6/6 kW CO2 Laser will be located forward of the robot arm.

The selected system for the existing facility is the wheeled mobile vehicle with a telescoping boom. It will accommodate the current floor in Building 2212 and will not impact the facility. For a new floor in Building 2122, the selected concept would still be proposed, although some of the subsystems would require additional attention. The conceptual design for the current floor in Building 2122 is presented first. The second section addresses any significant issues and impacts on this concept if a new floor were installed.

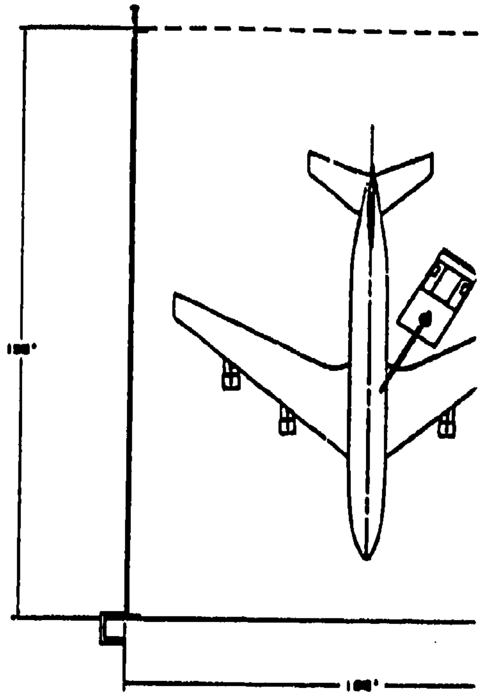
6.1 Building 2122 - Existing Floor

The following sections describe the conceptual design for Building 2122 as it exists.

6.1.1 Robot System. This system utilizes a standard flight line transport with a counterbalanced telescoping boom to position the work head around the aircraft, as shown in Figure 6.1.1. Ranges and travel speeds are projected for the mobile robot system (MRS) and are shown in Table 6.1.1.

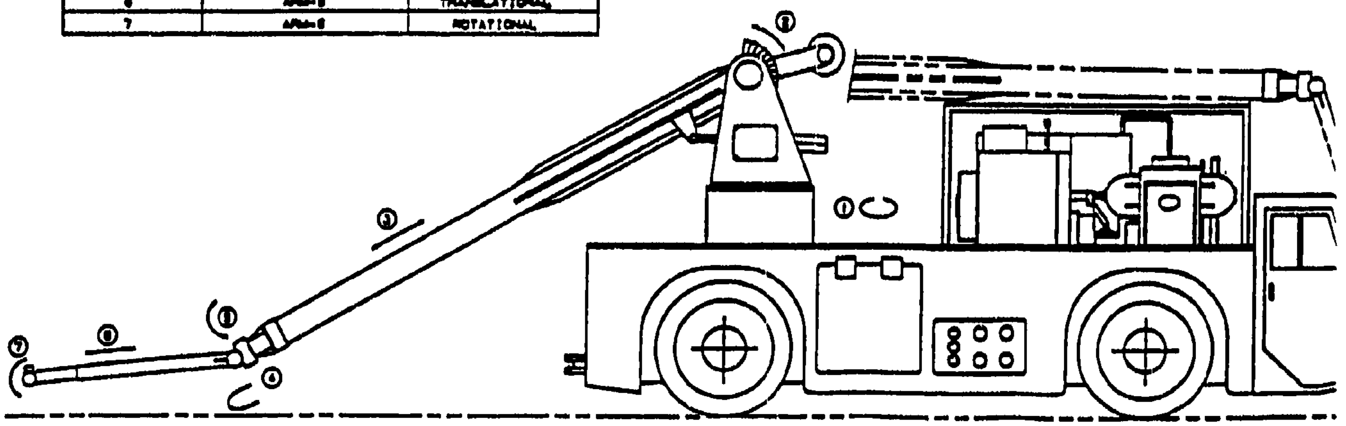


FRONT VIEW
C-135 IN BUILDING 2122
TINKER AFB, OKLAHOMA

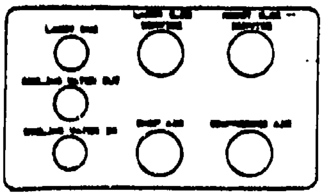


PLAN VIEW
C-135 IN BUILDING 2122
TINKER AFB, OKLAHOMA

AXES (DOF)	NOMENCLATURE	TYPE
1	BASE-1	ROTATIONAL
2	ARM-1	ROTATIONAL
3	ARM-2	TRANSLATIONAL
4	ARM-3	ROTATIONAL
5	ARM-4	ROTATIONAL
6	ARM-5	TRANSLATIONAL
7	ARM-6	ROTATIONAL



SIDE VIEW
MOBILE ROBOT SYSTEM FOR LASER DEPAINTING



UTILITY CONNECTION PANEL

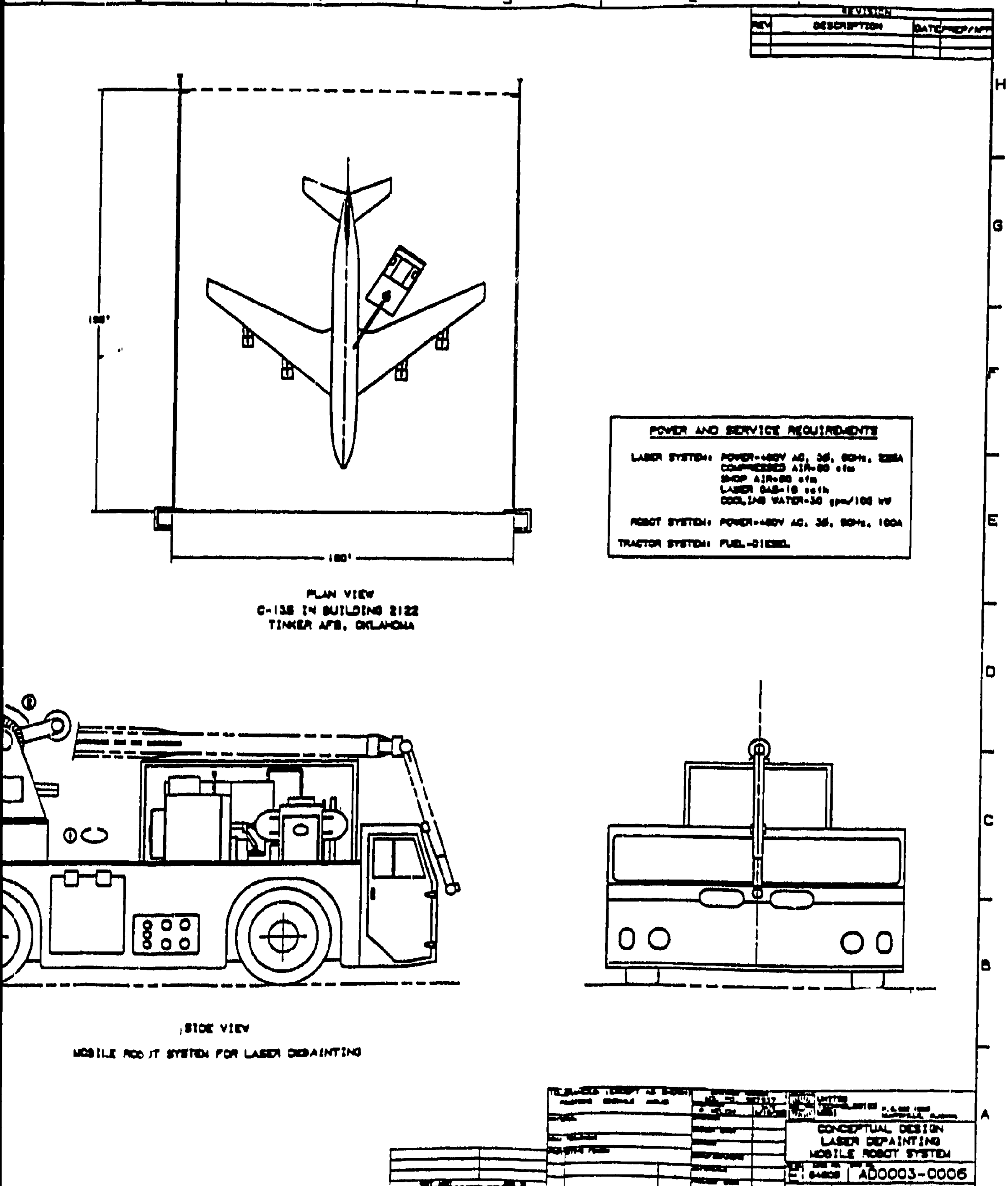


Figure 6.1.1 Mobile Robot System for Laser Depainting

Table 6.1.1 MRS Ranges and Travel Speeds

Axes	Name	Type	Range	Speed
1	BASE-1	Rotational	360°	0-24°sec
3	ARM-1	Rotational Pitch	200°	0-1°sec
4	ARM-2	Translational	20-30'	0-6"/sec
5	ARM-3	Rotational Yaw	180°	0-6°/sec
6	ARM-4	Rotational	180°	0-6°/sec
7	ARM-5	Translational	6-9'	6"/sec
8	ARM-6	Rotational Pitch	180°	0-1°/sec

With the boom extensions fully retracted, the reach of the robot is 26 feet. Axis ARM-2 provides an additional 10 feet of reach when extended; ARM-5 contributes an additional 3 feet of reach when extended. The highest reach required for the three aircraft is 35 feet measured from the ground. For this particular scenario, only the smaller 5-foot extension will be required.

Power requirements for the robot are estimated to be 480V AC, 100A, 60 Hz, 30 to support the controller and electric motors. The vehicle diesel power supply would need to be running to engage any of the drives unless an independent generator was used. Since it is not feasible to run the diesel engine inside the facility, an umbilical connection panel is provided on the side of the mobile robot system to be connected to facility power and services or to a trailer generator system which would be located outside the facility. The power and service trailer concept will allow the mobile robot to travel between facilities regardless of facility power availability. A stow position is provided for the robot arm during relocation.

The flight line tug is available from manufacturers such as Tug, Jetway Systems and FMC. The tug is designed for heavy-duty operations and provides steel section weldment unibody construction. Typical specifications are shown in Table 6.1.2.

Table 6.1.2 Typical Tug Specifications

Engine	
Model	8.2 liters turbo charged
Type	Four-cycle V8
Displacement	500 cubic inches
Horsepower	205 HP at 2800 RPM
Torque Rating	442 ft. lbs. at 1700 RPM
Fuel Capacity	34 gallons
Travel Speeds	0-15 mph

The beam delivery system method was not considered during the evaluation of the robot alternatives. Owing to the nature of the concepts (i.e., all would require a design effort), it was assumed that the beam delivery system could be integrated to any robot system. The selected concept can incorporate an internal, external, or hybrid beam system. The system can be run internally through the chassis of the tug, up through the rotational base of the robot arm and down the telescoping boom. Motor and drive mechanisms for the telescoping boom would need to be located so that they do not interfere with the beam delivery system. The beam could be run externally from the laser to the work head. The scrubber system vacuum hose can follow the robot arm externally in a similar fashion.

6.1.2 Sensor Systems. The selected sensor systems for collision avoidance, contour following, color discrimination, and global locating are presented in the following sections. Examples of product literature on the selected sensors are provided in the Appendix.

Contour Following and Collision Avoidance. Several ultrasonic and laser-gauge systems can be used. These systems will provide noncontact methods of contour following and collision avoidance. Ultrasonic systems which can be used include the following:

A. Ultrasonic Arrays DMS-1000 - This system provides measurement accuracies to within ±0.001 inches. Surface color texture and reflectivity have no effect on the accuracies of the system. The sample rate is 1800 time/second.

B. Cleveland Machine Controls Pulsonic System - This system used ultrasonic technology to produce a coherent column of sound. The pulsonic uses a discrete pressure wave with only one highly repeatable pulse. It continually compensates for speed of sound variation with a calibration bar mounted to the front of the sensor. The sensing range is 2.5 to 40 inches, with a repeatability of ±0.05% of the range. The sampling rate is 800 times/second.

C. Staveley AG-101 - This system uses a state-of-the-art ultrasonic transducer to provide distance measurement and profiling. Sample rate is 500 times/second with accuracies of ±0.002 inches or 0.1% of the range. Sensing ranges are 1 to 120 inches.

Laser gauge systems which can be used include the following:

D. Medar MDC-250 - USBI is currently using a Medar MDC-250 for this application in its robotics laboratories. This microprocessor-bases, solid-state gauging device scans with low-power infrared laser-based light across the feature to be gauged, and calculates the feature contour based on the light reflected/scattered back to the sensor's CCD detector array. Each scan is a collection of individual measurements. The sensor can be used to maintain a constant standoff and orientation to the surface of the aircraft.

E. Chesapeake Lasers LTG-2100 - This sensor provides a measurement range of 1 to 25 inches, with an accuracy of 0.1% of the range. The microprocessor is a proprietary high-speed data acquisition device providing direct coordinate data output.

Color Recognition Sensor. The color recognition system would be specifically designed to provide color recognition for a limited number of pretaught colors. The system must provide reliable answers at least at a 600 Hz rate. In general, the required color sensitivity will dictate how many different wavelengths are characterized. The detector integration time is preset by the cycle time. Thus, the only free variable is the illumination intensity, which must be bright enough to provide enough signal-to-noise ratio for reliable measurements under all process conditions.

Global Locating. Use of a vision system for global locating will be necessary to define the robot's orientation with respect to the aircraft and generate rough path trajectories. Although vision systems suffer from slow processing speeds, use of the vision system for edge tracking is the only application in which processing speed is a factor. Even in edge tracking, slower processing speed does not severely impact system performance. The vision system capable of handling the global locating requirements, as well as edge tracking and collision avoidance tasks is the Silicon Graphics 4D/210 GTX Graphics Supercomputing Workstation with the Live Video Digitizer option. While this system has not yet been proven, initial research indicates that it is feasible. This workstation provides high-resolution real-time graphics which can be integrated with the workstation software to provide visual simulation, image processing, and animation. Special graphics processors allow computational and graphics tasks to run simultaneously at full speed, providing the capability of real-time visual interaction with applications.

6.1.3 Controller and Software. The block diagram in Figure 6.1.3 shows the relationship of the controller with the system. The host computer workstation can act as the main operator interface for monitoring and controlling the controllers and any facility/support equipment processors during all on-line production operations. Complete 3D cell simulation and robot off-line programming capability can be provided with a separate CAD workstation.

The controller will communicate to the host computer and the off-line CAD workstation over an Ethernet local area network. A machine-vision system computer and a PC computer are included on the network. The PC computer can be interfaced on a separate network to all facility and process support equipment, programmable logic controllers (PLCs), and can act as a central operator station. Special cameras and sensor systems needed for globally locating the aircraft, mapping the structure, and performing collision avoidance functions would be incorporated into a machine vision system or work head or would be mounted to the arm as needed.

Controller. The robot controller would be a multiprocessor-based continuous path, multitasking unit to handle simultaneous control of the 7-axis robot. In addition, the controller would control and concurrently monitor various digital and analog work head or process equipment I/O. Programming for the robot controller can be generated off-line at the CAD workstation or on-line at a PC-compatible computer.

The work cell controller design incorporates two 68030 processors, a 68882 co-processor, and open-architecture VME-based bus and 8-MB of RAM. The operator

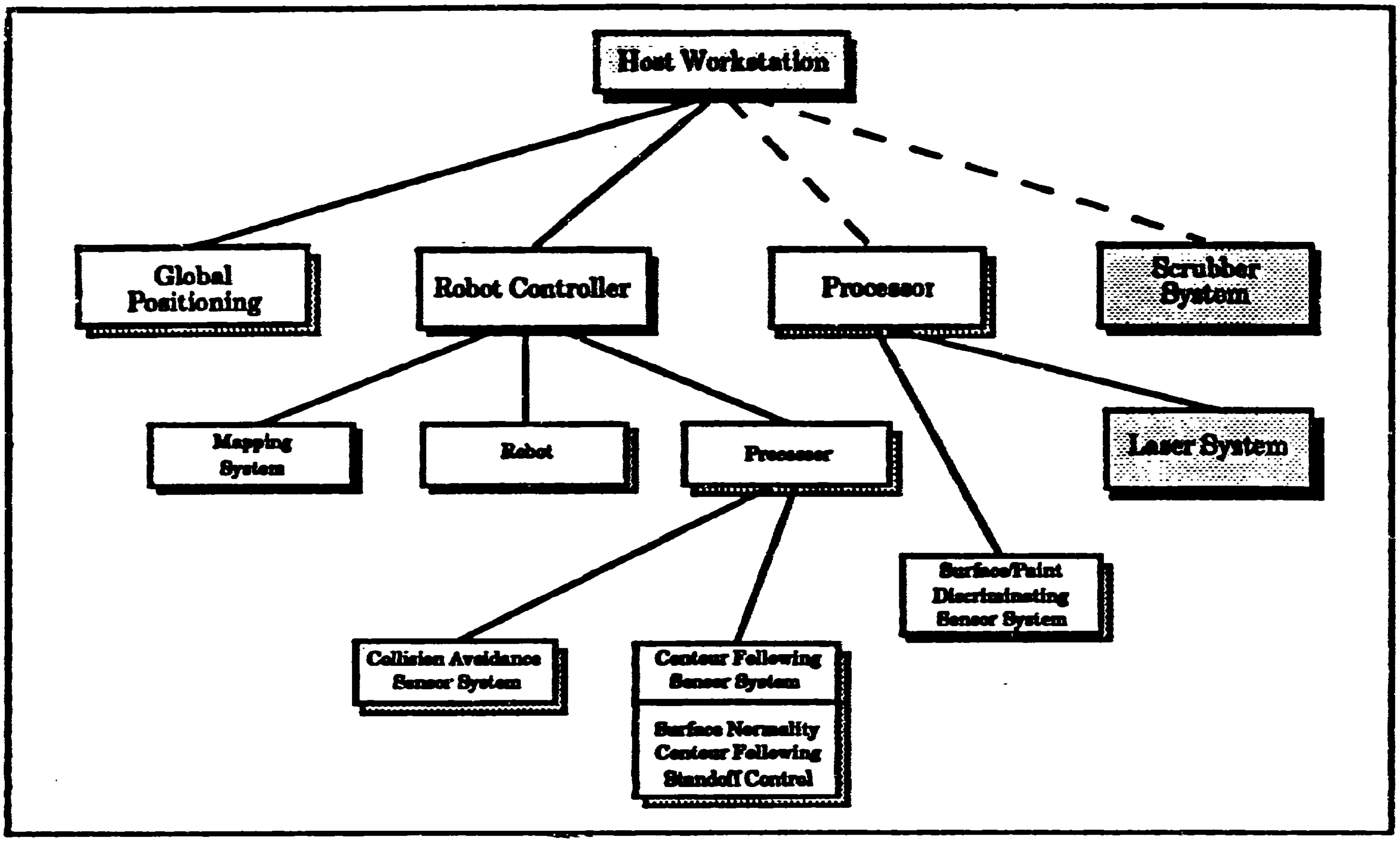


Figure 6.1.3 System Configuration

interface PC computer would be an 80386-based VME bus by a high-speed data bus. In addition to the gh-level robot programming language, software allows direct access to the in-process robot program from the host computer and a communication interface for the Ethernet local area network. The work cell controller is linked to the robot through a high-speed serial link. A teach pendant and end effector I/O is also connected to this remote robot interface.

Process Equipment Programmable Logic Controllers. The following basic requirements exist for programmable logic controllers.

A. Programmable logic controllers (PLCs) should provide monitoring and control of the various work cell support process equipment I/O and general facility requirements.

B. All facility-related equipment that supports the entire cell (such as the water reclamation system, door interlocks, ventilation, and lighting) should be routed to the single PLC.

C. PLCs should be provided for all process equipment.

D. Each PLC should utilize interchangeable digital and analog I/O modules and should be capable of high-level math, logic, and communication functions, as well as controlling its local I/O, using standard ladder logic.

E. Each PLC should be networked together via a separate data highway to a PC computer which would act as the central operator interface for on-line/off-line PLC programming, program storage, diagnostic and alarm displays, and remote access to and control over all system I/O.

F. Any required communication and data transfer between the host computer and the PLC network computer should be handled first through the PC computer over the Ethernet and then over the dedicated PLC network.

Host Computer Workstation. The following basic requirements exist for a host computer workstation.

A. The host computer should be a 3D CAD workstation with multitasking and multimode graphics capability which acts as the main operator station during all in-process operations.

B. From the host computer terminals, operators should be able to interact with all work cell robots and process equipment controllers to provide a controlled start-up and shutdown, to modify operating parameters, upload/download or store files, and to print historical reports.

C. Critical in-process data displays and error control should be provided in a variety of custom graphic displays that the operators can interact with.

D. Although a separate off-line CAD workstation is included, the host should be able to perform 3D cell simulations and robot off-line programming if the need arises.

E. The workstation should provide multiple 25 MHz RISC processors and co-processors, a VME interface, large memory system disk, a minimum of 24 MB of RAM, and both floppy and tape drives.

F. Standard software should include a UNIX operating system, C compiler, and a communication interface for the Ethernet local area network.

Off-line CAD Workstation. The following basic requirements are presented for an off-line CAD workstation.

A. Complete cell 3D CAD simulation and robot off-line programming capability should be provided via a smaller workstation.

B. The operator should have the capability to enter or retrieve a CAD model of each unique aircraft and then to retrieve or modify an already existing 3D CAD simulation of the entire cell.

C. A robot software package for developing complete robot programs should be provided.

D. Completed robot programs should be stored or uploaded/downloaded between the workstation, the host computer, and controllers over the local area network.

6.1.4 Laser System. The selected laser system is the UTIL Model SM1-6/6 kw CO_2 laser. The laser system comprises a modular gas circulation and discharge section integrated into a single system with a common optical section and control. Utility and service requirements for the system are listed in Figure 6.1.1. A complete specification is provided in the Appendix. The laser is shown in Figure 6.1.4.

6.1.5 Operational Scenario. The operation begins with positioning the aircraft into Building 2122. The robot system is positioned to the first processing location. The global locating process is then performed to orient the robot to its position relative to the aircraft. One of three processing approaches could then be used:

A. The surface area would be mapped using a mapping sensor system which inputs data points into a path program. This program is then used to guide the robot through its motions.

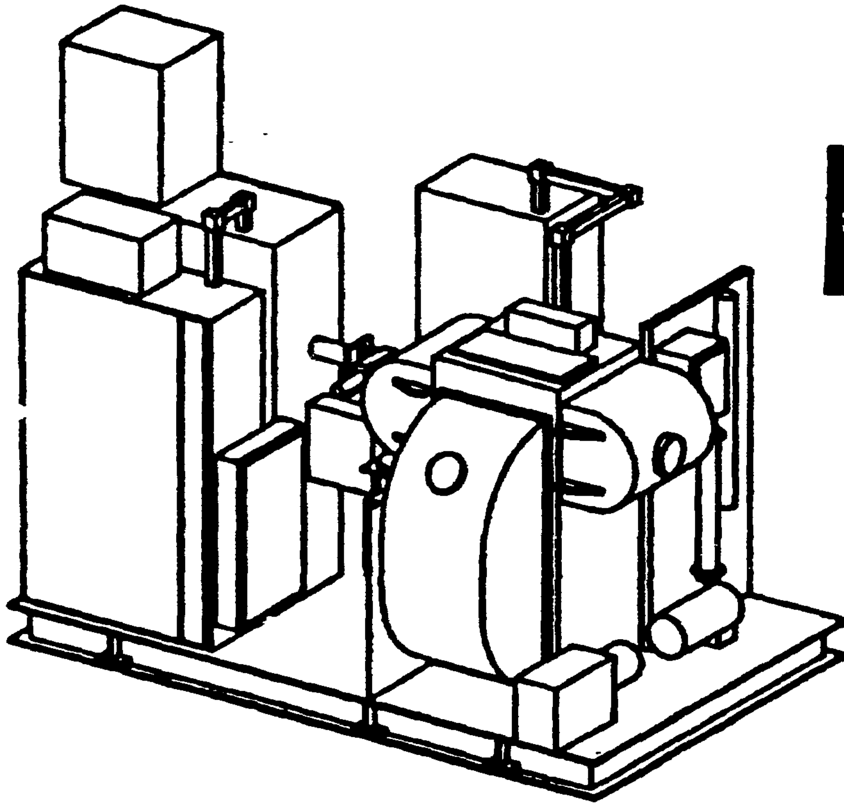


Figure 6.1.4 Model SM11-6/6kW CO_2 Laser

B. A prewritten path program would be used based on off-line CAD data of the airplane. The robot would then follow this off-line program with sensors adjusting for variances between aircraft.

C. Real-time surface following and collision avoidance techniques would be totally responsible for the robot path.

After processing is performed on this area, the robot would be moved to the second processing location. Based on the concept presented in this section, the robot would be moved six times for each of the aircraft, as shown in Figure 6.1.5.

The preferred operational concept would incorporate method B, above. This method is presented in the following sections.

Global Locating and Surface Mapping Process. Each time an aircraft enters the building for paint stripping, its approximate 3D positional location with respect to the robot must be determined so that program offsets can be generated. A gross surface mapping process would then be performed with the generated data used to modify, plan, and verify the final robot trajectories and paths for the paint removal process.

Aircraft Positioning. The aircraft would be towed into the facility by a standard aircraft tug. The aircraft can be placed on jacks, or left on its wheels. If the aircraft is on jacks, the landing gear can be retracted to provide access to the underbelly.

Process preparation. Vision targets would be attached at key specific locations on the aircraft. The off-line CAD workstation computer, machine vision system computer, and any extra structural lighting will be turned on.

Global locating procedure. From the off-line CAD workstation, the operator would call up the model of the aircraft in the facility in its optimum location for robotic processing. The machine vision system would begin running the global locating

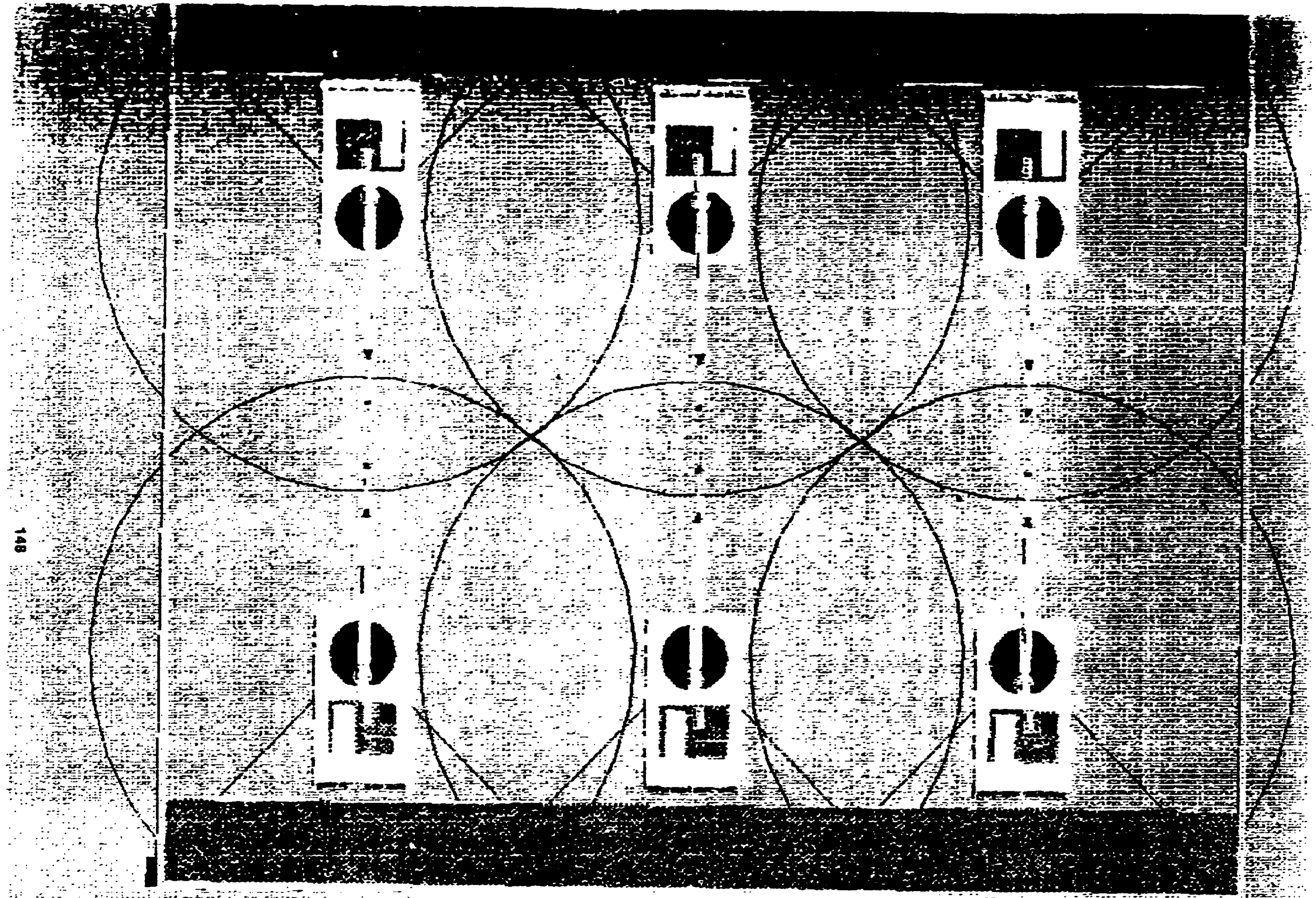


Figure 6.1.5 Robot Positioning in Building 2122

software to determine the orientation deviation of the actual plane location compared to the model. The orientation deviation offsets would then be used to first verify the aircraft is within locational tolerance for processing and then to refine the working 3D CAD model of this specific aircraft (if this information is being maintained).

Mapping-path generation (optional). If used, the surface mapping procedure would adequately define the local aircraft surface contour relative to the robot work envelope. Using the working model of the cell generated from the locating procedure, the operator would download the rough robot mapping programs to the robot. After mapping, the final robot programs will be generated at an off-line CAD workstation and then transferred to the host computer for storage. After the process is started, the operator would download robot programs as required from the host computer to the robot. If a database is being kept on all aircraft, and if the aircraft has not been in before, the CAD file associated with the aircraft would be the default for the aircraft type.

6.1.5.2 Paint Removal Process. The removal of old paint, primer, and decals would be performed, using the high power CO_2 laser system. The System will be capable of removing paint at a rate of 120 to 240 square feet per hour (based on the requirement of 2-4 square feet per minute).

Process preparation. Controls and computer equipment would be turned on by the operator. The robot will move to the start location. The system would begin monitoring the depainting process equipment. Any protective masking necessary (i.e., for protecting cargo door seals or window seals) would be done before process start-up. A different color masking can indicate to the paint/substrate discriminating sensor that no pulse should be provided by the laser system. The laser system would be readied for use.

Process performance. During the stripping process, the robot would follow the preprogrammed path for the specific aircraft, possibly updated through mapping.

Nominal standoff will be maintained by the surface-following sensor. The paint/substrate discriminating sensor would report on removal status. Collision avoidance sensors would be operating. Edge detection would keep pulses from being generated without a target. The waste collection system would collect paint debris for disposal. After processing at this position, the robot would home itself and the system would move to the next processing location.

6.1.6 Facility and Safety Considerations. Steady-state or cyclic noise produced by machinery equipment measured at the operator's position in the control room should not exceed 85 decibels. Operators are prohibited in the work cell during paint removal operations because of the Class IV designator assigned to the laser system by OSHA. The robot system and its process equipment should not create a chemical, physical, or biological hazard to operators or other employees. To eliminate potential health hazards, exhaust ventilation, protective guards, and filters are used.

Warning signs placed in the facility should conform to OSHA (and NFPA-70) requirements (see OSHA 1910.145 for definitions, colors, symbol for danger, and examples):

DANGER	red, black and while
CAUTION	yellow and black
SAFETY INSTRUCTIONS	green and white

The locations of warning signs should be chosen carefully to assure that hazards are clearly marked with the safety cover removed or attached.

6.2 Building 2122 Issues and Impacts - New Floor

Since the selected concept for the existing facility can easily be incorporated onto the new floor, no new requirements are derived. The new floor, with a smoother finish, will only enhance the performance of the robot system.

7.0 Technical Risk

For the selected concept, the technical risk evaluation is divided into the areas of robot, sensors, and controller. A system risk summary chart is shown in Table 7.0.1. Two enabling technologies are projected for this system; one is the process itself. The other is the color discrimination system proposed by InTA. All components of the system are off-the-shelf, or based on off-the-shelf items.

System Risk Summary
Table 7.0.1

SUBSYSTEM	RISK
Robot Arm	Low - Medium
Tug	Low
Beam Delivery System	Low - Medium
Controller	Low - Medium
Software	Low - Medium
Sensors:	
Contour following	Low
Color discrimination	Medium - High
Mapping	Low
Global positioning	Low - Medium
Laser	Low
Process	Medium - High

7.1 Robot and Controller

The risk associated with the robot arm is low to medium. The counterbalanced, telescoping arm technology incorporated in this conceptual design has been proven in several applications. In a situation where large-scale robotics are needed, however, the challenges must be accepted.

The risk associated with the tug is low. A standard unit will be modified to meet the requirements of the robot arm and laser system. The beam delivery system is rated as a low to medium risk because of the number of mirrors that will be required. However, the technology for beam delivery is well established for both internal and external systems.

The controller is evaluated as a low to medium risk because of the need for an in-house designed system to accommodate the specifics of the robot system. Software is always a potential problem area.

7.2 Sensors

All sensor equipment specified is readily available for procurement. The selected sensors are already performing the similar operations in other applications.

7.2.1 Contour Following. Little risk is associated with the contour-following system. These are being used extensively in other applications.

7.2.2 Color Discrimination. The color discrimination sensor system is assigned a higher risk because of the responsibility it has for not allowing the laser to damage the aircraft and because of the feedback rate requirements. If the InTA system proves to be feasible, then this risk is significantly reduced.

7.2.3 Mapping. If this function is used, it will be similar to several applications in industry. The risk associated with this process is low.

7.2.4 Global Positioning. Machine vision has been proven in industry. Use of the SGI system and video digitizer are not proven specifically; hence, the low to medium risk.

7.3 Lasers. Lasers that can be used are standard commercial products today and represent a low technical risk. (See Appendix.)

7.4 Process. The laser paint stripping process has not been proven beyond test panels in a laboratory and is rated a medium to high risk.

8.0 Program Plan

A draft Work Breakdown Structure for an ALPS system is presented in the following list. This top level WBS will need to be broken out into the lower levels prior to beginning the effort.

Most of the cost associated with "1.0 Design" is labor. The majority of material costs would be incurred in "2.0 Fabrication."

Work Breakdown Structure

1.0 Design

- 1.1 Robot System
  - 1.1.1 Robot Arm
  - 1.1.2 Tug
  - 1.1.3 Power and Service Trailer
- 1.2 Laser System
  - 1.2.1 Laser
  - 1.2.2 Workhead
  - 1.2.3 Beam Delivery System
  - 1.2.4 Scrubber System
- 1.3 Computer Hardware
  - 1.3.1 Host Computer
  - 1.3.2 Controller
  - 1.3.3 Off-line Workstation

1.4 Computer Software

1.4.1 System

1.4.2 Process

1.4.3 Off-line Programming

1.4.4 Simulation

1.5 Sensor Systems

1.5.1 Collision Avoidance

1.5.2 Contour Following

1.5.3 Color Discrimination

1.5.4 Mapping

1.5.5 Global Positioning

2.0 Fabrication

2.1 Robot System

2.1.1 Robot Arm

2.1.2 Tug

2.1.3 Power and Service Trailer

2.2 Laser System

2.2.1 Laser

2.2.2 Workhead

2.2.3 Beam Delivery System

2.2.4 Scrubber System

2.3 Computer Hardware

2.3.1 Host Computer

2.3.2 Controller

2.3.3 Off-Line Workstation

2.4 Computer Software

2.4.1 System

2.4.2 Process

2.4.3 Off-line Programming

2.4.4 Simulation

3.0 Integration

4.0 Testing

4.1 Subsystem Testing

4.1.1 Robot System

4.1.2 Laser System

4.1.3 Computer Hardware

4.1.4 Computer Software

4.1.5 Sensor Systems

4.2 System Testing

5.0 Activation

5.1 Start-up

5.2 Checkout

5.3 Documentation

5.4 Training

6.0 Management and Control

6.1 Reports

6.2 Reviews

7.0 Technical Risk

8.0 Program Plan

AUTOMATED LASER DEPAINTING OF AIRCRAFT
SURVEY OF ENABLING TECHNOLOGIES

Appendix

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January 199

Final Report for the Period May 1989 to January 1991

Approved for public release; distribution unlimited

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Table of Contents

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1. INTRODUCTION

Laser Paint Stripping (LPS) offers the opportunity to reduce the cost of de-painting aircraft as well as to eliminate an environmentally unacceptable process. The InTA approach to LPS uses a pulsed laser and spectroscopic feedback control. The feedback is provided by a special spectrometer and sensing element, called a multispectral camera (MSC). This report describes a cost shared program between A.D. Little and InTA to demonstrate the elements of the MSC. A spectrometer, sensor and frame grabber were purchased, assembled and demonstrated. The demonstration was held on 30 May 1990.

2. LASER PAINT STRIPPING SYSTEM DESCRIPTION

LPS involves a laser ablation process, a laser delivery system, a feedback control system, a positioning system and a waste removal and processing system. It is not sufficient to develop a successful laser paint removal process. The entire system must be successfully developed and integrated.

The InTA laser ablation process utilizes a pulsed CO_2 laser operating with a peak power between 50 kW and 1 MW, a pulse width between 20 microseconds and 30 microseconds (FWHM), and an energy of 5 J to 6 J per pulse. To achieve a coating removal rate of 4 sq. ft/min. requires average of 6 kW of laser power which at 6 J/pulse, requires 1000 pulses per second. To maintain a low average power density (watts/cm^2) impingement on the coating the pulsed laser beam must be moved rapidly. The method chosen to achieve this low power density is a raster pattern of 30 laser pulses across and 30 laser pulses down. This raster pattern, called a "frame," therefore has 900 laser "footprints" covering approximately 1.0 sq. ft. (see Figure 2-1). With the laser operating at 1000 pulses per second it takes the system 0.9 s to complete one pass over the pattern. If 6 J per pulse is delivered to the coating removal surface, the average power density is 6.7 W/cm^2. A standard paint coating thickness averages 3.0 mils. Each pass over the frame removes approximately 0.3 mils (300 micro-inch) of paint, therefore, ten passes are required to remove all the paint within a frame. These ten passes require 9 seconds for a peak paint removal rate of 6.7 ft^2/min. Another common method of expressing the removal rate is in square feet per mil of removed paint per hour. In these units the peak removal rates are 1200 ft^2/mil/hr.

As shown in Figure 2-1, the rastering operation then moves to the next (overlapping) frame.

To provide the feedback control, a spectrometer must determine the color of each footprint and decide if that color is to be stripped. This process must be carried out at the rate of 1000 decisions per second. To further improve the system's ability to properly categorize each footprint color, the footprint is divided onto four segments, each approximately 2.5 mm wide by 10 mm high. All four spectra from a footprint must match the allowed spectrum for the foo.print to be processed. Thus 4000 decisions per second are required with each decision requiring up to 20 comparisons to various allowed and disallowed spectra. Up to 80,000 spectra comparisons per second may be required. This computational intensive task will be carried out by array processors.

3. THE MULTI-SPECTRAL CAMERA (MSC)

The camera consists of a lens system, a flat field spectrometer and a two dimension 256 x 256 element sensor. The camera electronics includes the digitizer and the memory to store each digitized frame.

The camera is equivalent to 256 single spectrometers. This allows an entire frame row to be processed simultaneously. The frame row (path) consists of 30 footprints, each of which is examined over four segments for a total of 120 areas. If every other spectrometer is utilized and eight of the remaining spectrometers are used for normalizing ambient light then 120 spectrometers are available to process the row. This approach improves the processing throughput since the data transfer overhead is a major source of processing time. In addition array processors perform best when they process many identical calculations simultaneously.

The spectrometer selected for the demonstration was a model 100s from American Holographic (see Appendix A). The sensor was a model MC9256 from E G & G Reticon (see Appendix B). The frame grabber was a model MV-1 from MetraByte (see Appendix C).

4. DEMONSTRATION SYSTEM

The equipment for the demonstration system is shown in Figure 4.1. In the demonstration system, the color sample is positioned on the sample table so that a region of interest is imaged on the slit. No scanner is needed for the demonstration tests.

The electronics and data reduction allow for storing, analyzing and identifying various colors, and for comparison against stored sequences of spectra.

The following sections describe the Multi-Spectral Camera (MSC), the software for control and analysis, and the electronic hardware of the demonstration system.

4.1 Multi-Spectral Camera (MSC)

The components of the camera are detailed in Figure 4.2. The major elements are:

Sample Table
Light Source
Imaging Lens
Spectrometer Slit
Holographic Grating
2-Dimensional Detector Array

For the present experiments it is not necessary to scan the sample, so that color samples may be placed on a horizontal table surface and positioned by hand.

Two light sources were employed in the tests - one, a xenon strobe, and the other a continuous xenon arc lamp. The data presented in a later section was taken with the continuous source. The light is arranged to shine down on the sample at a small angle to vertical, which prevents specular reflection and at the same time maximizes light collection at the lens.

The imaging lens, a 50 mm F1.8 photographic objective, creates an image of the sample at the slit plane. Magnification is 1/8X. Only that portion of the image which lies within the slit is re-imaged on the detector. Since the slit is 5 mm x 50 um, the corresponding sample area visible to the system is a rectangle 40 mm x .04 mm.

The holographic concave diffraction grating is equivalent to a 97 mm F2.2 lens. It performs two functions; it disperses light from the slit rectangle, and images it on the detector.

One-to-one imaging is used in this arrangement for 35nm/mm dispersion at the focal plane. The grating is capable of 190nm-1065nm operation, With the limited detector size, we can choose a coverage of 330nm anywhere within this range (e.g. 375nm-705nm) across the detector.

The detector itself is a 256 x 256 silicon array with pixel-to-pixel spacing of 40um. It has a fairly linear response from 400nm-700nm, with a relative responsitivity within this range of 0.4-1.0 respectively. Spectral resolution is 1.4nm/pixel, and array saturation energy is $0.4uJ/cm^2$.

Figure 4-3 shows the transfer of information from the sample to the slit to the detector. The reflectance spectrum ($R(\lambda)$) of the sample; is used to identify the sample materials, the function of the MSC is to generate appropriate reflectance spectra for analysis and comparison to known spectra. This requires that we illuminate the sample and then, measure the spectrum of the light reflected from each visible element of the sample.

Starting with the slit size and magnification, we can say that the visible portion of the sample is a rectangle 40 x .04 mm.

At the receiving end of the system, the detector matrix is 256 x .04 10.24 mm square - and the slit is imaged on this detector with a magnification of 1X. Then each detector (40 x 40 um) sees a 40 um high portion of the slit, hence a .32 mm high portion of the sample (at 8X). But light from each 40 um high "cell" of the slit is spread across the entire width of the detector by the grating, dispersed according to its wavelength. The 5 mm slit is converted to a 5 mm high, stack of spectra, occupying 5/.04 = 125 of the 256 detector lines.

Figure 4-4 shows how the "cells" of the slit map onto the detector matrix. These are not physically separate, of course, but simply regions of the slit space, divided to show where the energy goes after dispersion. The position of the image data on the detector is arbitrary - the image can be tilted vertically, to occupy any 125 of the 256 lines; or it can be tilted horizontally to bring any wavelength group onto the detector. We have shown an image beginning at line 4, ending at line 129, and set so that light of wavelengths from 350 to 680 nm falls on the detector matrix.

The data stored in each pixel of line is proportional to the spectral reflectance ($R(\lambda)$) of the corresponding point on the target material. Therefore, for a given line, we can generate a curve of ($R(\lambda)$ vs λ from the stored light level, (R) and the corresponding column number, representing wavelength λ . A sample curve is shown in Figure 4-5. Curves from the actual samples are collected in Section 5, Data.

Figure 4-5 shows raw data from a blue region of the sample. On the same graph, we have plotted background spectral data. The difference between these two is also shown, as a corrected spectral curve. The edge-of-field peak contains no information about the sample; it indicates the end of the spectral scan.

In the demonstration system, the operator can view the dispersed pattern directly on the monitor. The presence of light at any point X, Y on the monitor, position vs. wavelength, indicates that light of wavelength X is being reflected by the target area at "slice" Y. The brightness is proportional to reflectance at that wavelength. The entire frame of information is saved and processed by an efficient algorithm to yield material identification data.

4.2 Software

MetraByte's VOS (Vision Operating System) offers a user-friendly programming alternative for MetraByte's MV1 Frame Grabber. An icon-based program, VOS, allows one to select and modify the analog front end settings for the board, and to acquire and modify frames of video data.

All functions of VOS are easily accessed using the keyboard or a mouse. Other pointing devices which are supported include tablets, trackballs, and lightpens. VOS allows you to easily perform such functions as: set/changing the MV1's parameters, add/define objects, manipulate Look-Up Table (LUT) settings, and adding text. Additionally, VOS features an extensive on-line Help. These windowed screens can be enabled or disabled with the click of a button.

Another feature of VOS is its Record/Playback function which can be activated to record all point and drag operations, store them in a user-specified file, and then be "played-back" from that file. This feature is ideal for automatically sequencing complex routines in applications ranging from repetitive testing to self-running demonstrations.

4.3 Hardware

MetraByte's MV1 Frame/Line Grabber is a 512 x 512 x 8-bit frame/line grabber for real-time digital image processing on the IBM Personal Computer XT/AT^{tm} or compatible. The board digitizes an analog video signal, stores the digitized image in one of the video memory banks, allows graphics and text imagery to be added, and then displays the image in R-G-B psuedocolor or monochrome at a rate of 30 image frames per second. If desired, the image can be stored on a hard or floppy disk.

The MV1 accepts monochrome video input signal from RS-170, RS-330, or CCIR compatible sources. Input can be of interlaced or non-interlaced format. Cameras with digital output may also be interfaced to the MV1.

The MV1 features 512 KB of dual-ported video memory and an 8-bit digitizer which achieves 512 x 512 resolution in 1/30 of a second. The MV1 supports a variety of system configurations and is equipped with the following connectors:

- o DB-15 for I/O of video, synchronization, and timing signals
- o DB-9 allows display to analog, multisync monitors
- o BNC for video sources
- o 26-pin Digital I/O Interface
- o 10-pin Timing Bus for multiple board applications

5. DATA

Eight samples were measured and recorded using the demonstration system. They are:

- #1. Blue - Red - Green
- #2. Brown - Purple - Orange
- #3. Grey with Yellow Squares
- #4. Dark Green with Yellow Squares
- #5. Aluminum with Yellow Squares
- #6. Composite Back
- #7. Composite Front
- #8. Painted Composite, Partially Stripped

Color prints of the samples are shown on the following pages. Figure 5-1 contains samples 1 (blue-red-green) and 2 (brown-purple-orange). In Figure 5-2, the upper image is the partially stripped painted composite, sample 8, showing various layers through the paint stack. The bottom image is the aluminum plate containing samples 3, 4 and 5. The composite back surface is shown in Figure 5-3 (sample 6), with a visible fiber texture. The smooth front surface of the composite (sample 7) is shown in Figure 5-4. The appearance of sample 1 is shown in a sketch of the monitor display, Figure 5-5. The corresponding line map is given in Figure 5-6, to show regions of constant color and transitions between colors.

The curves of the various samples (raw data - background = corrected spectrum) show clear and distinct differences between the colors in any one sample (e.g. between yellow and green, in sample 4). Furthermore, the transition regions introduce no ambiguities of color. Given a set of colors for a given task, we know the spectrum for each layer. At the interface between one layer and the underlying layer, the transition spectrum is a weighted sum of the two spectra. If K(n) is a weighting factor depending on line number n, and, for example,

If the pure red spectrum is $I_R(\lambda)$

while the pure blue spectrum is $I_B(\lambda)$,

then in the transection region, the spectrum is:

$K_1(n)\, I_R(\lambda) + K_2(n) I_B(\lambda)$:

This is a predictable function, and the mixture of spectra in transition regions does not compromise identification of the sample.

Samples 1 and 2 are obvious patterns, and the spectra are different enough in each region to offer no difficulty. Samples with various greys and neutral colors are more complex, and require more care in separation. Here, the number of energized spectral regions increases. Nevertheless, we were able to establish clearly different spectra for all the different samples under test. Simple inspection of the spectral curves reveals their unique spectral fingerprint.

A change in system light shielding greatly reduced background energy and scattering. Samples 1 and 2 were measured before the change; samples 3 through 8 were measured after this improved shielding was installed. Since the first two samples had clear colors and sharp boundaries, they yielded identifiable spectra despite the scattered light. After the change, background light levels dropped and transition regions became much sharper. These changes can be seen in the curves for samples 3, 4 and 5. Transition regions for these samples were only 3 to 4 lines wide, compared to the much wider transitions detailed in samples 1 and 2.

The composite front and back look very similar to the eye, except that the web texture is visible on the back. However the spectral curves shows a definite difference in the 350-420 nm region, below the visible. This illustrates the importance of selecting wavelength regions in the analysis of spectra.

Sample 8 is of special interest, because it is an actual sample of a laser stripped material. Several print layers are visible. The stripping process, taking material off to continuously increasing depth, has itself wide transition areas where material from two layers is visible in most regions. A definite yellow region appears at line 88. On the sample, this color gradually changes to grey at line 109. Here, the characteristic "grey" peak appears at 450 nm. The sample then changes gradually to a brown, with an almost uniform reflectance across the visible spectrum.

6. DISCUSSIONS

The experiment was two fold in purpose: 1. To show that a spectrum could be easily produced, captured and identified; and 2. To show that transition regions from one color to anotner can be analyzed without introducing ambiguities into the identification process. Both these demonstrations were successful.

The system hardware for illuminating the sample and dispersing light will follow, in general, the laboratory set-up, but at an appropriate scale up. The major change will be addition of a scanner mechanism to follow the raster pattern, synchronized to the ablating lasers raster. For this task, we expect to use conventional scanner hardware such as is used in InTA's other robotic and contour-scanning devices.

Clearly, the light source must contain the wavelengths at which samples exhibit their peak reflectance. A xenon arc lamp (whether strobed or continuous) generates a continuum in the visible region, as well as considerable short IR.

For any particular stack of paint layers, there may be some advantage to removing certain wavelengths - those that are reflected equally by all members of the stack. A filter can be inserted in the source for this purpose. While it is certainly possible to remove common wavelengths electronically, it should be done in the optics, if possible, where such a filtering operation can improve the scatter and background at the same time.

Quality of the MSC components is more important in the final system, where the camera must operate in the presence of extraneous light sources strobing will help on some of these problems. The detailed design of the grating system must be studied to improve dispersion, reduce line-to-line scatter, and provide the highest efficiency in the selected order.

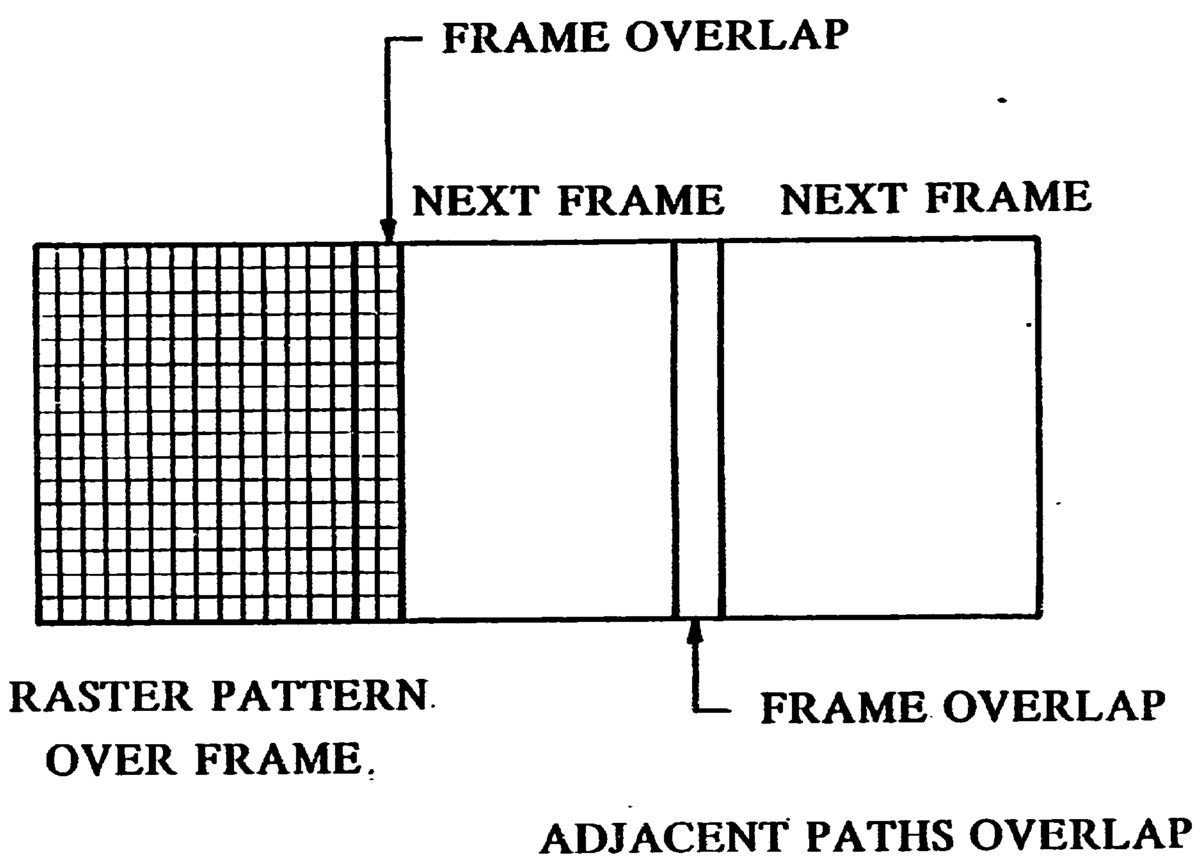
The most important optical component in the entire system is the sample itself. Its reflectance spectrum is the subject of the entire process. We must also consider its spectral scattering properties and its specular reflectance - for example, so that other light sources in the work area do not reflect from it into the lens. A thorough study of the paints' properties will save money in hardware, time in processing, and trouble with unwanted signal.

7. CONCLUSIONS AND RECOMMENDATIONS

On the basis of data collected for this program, it is clearly possible to discriminate between different paints and substrates on the basis of their spectral diffuse reflectance. The hardware to implement this process can be assembled from commercially available components. The process can be completed quickly enough to control a paint stripping laser scanner.

In a practical paint stripping system, the target area will be shielded from direct room light by the shroud containment, so the background conditions should be no worse than the laboratory system.

We believe that such a system can be built with a minimum of risk, now that the basic detection mechanism has been proven. Improvements in speed and in discrimination will continue as the software is developed. Applications to paint stripping, surface texturing and laser cleaning are already obvious. Any laser process that modifies the spectral reflectance of a surface can now be implemented and controlled with systems similar to this.



PATH COMPOSED OF FRAMES

FIGURE 2-1

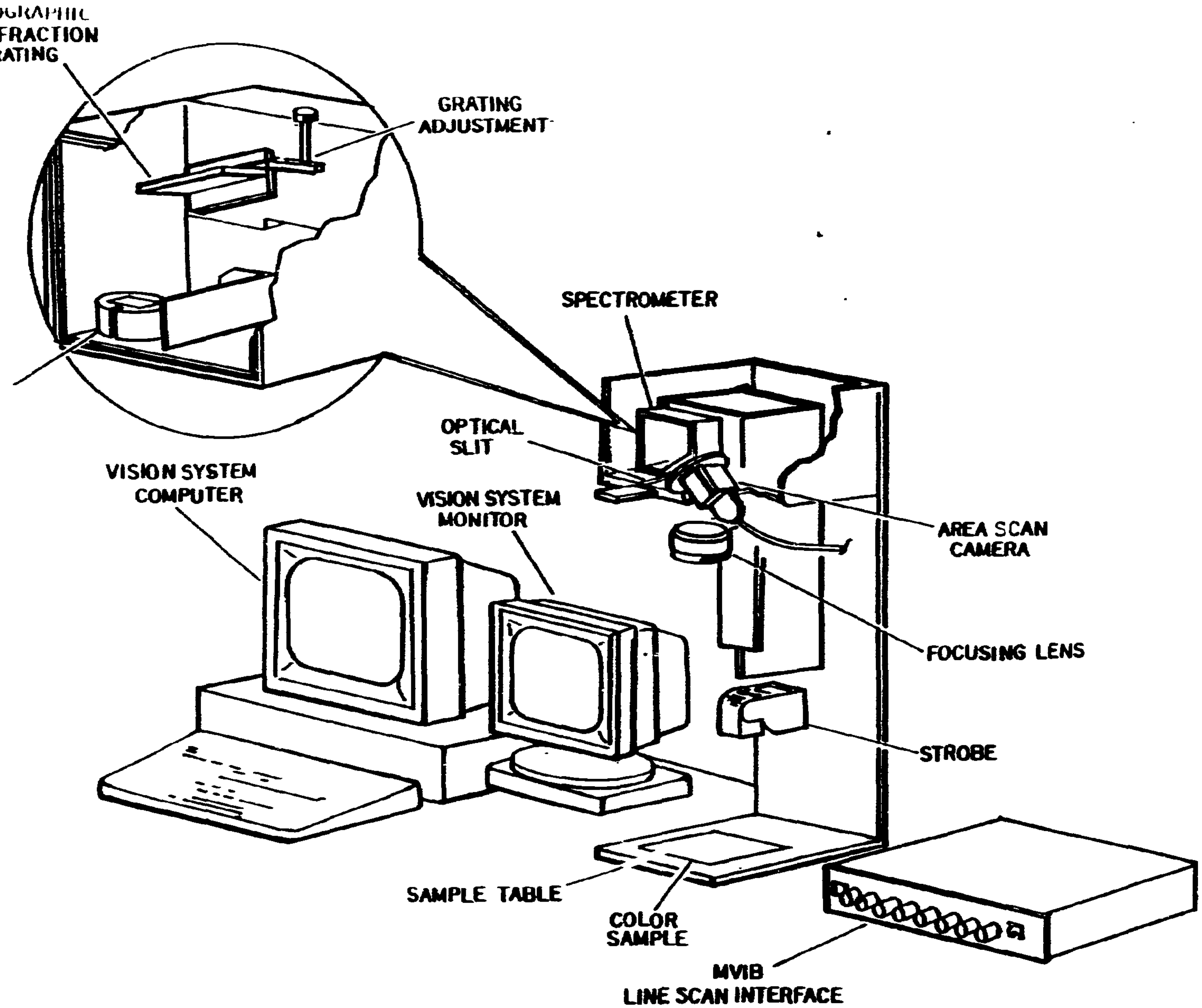
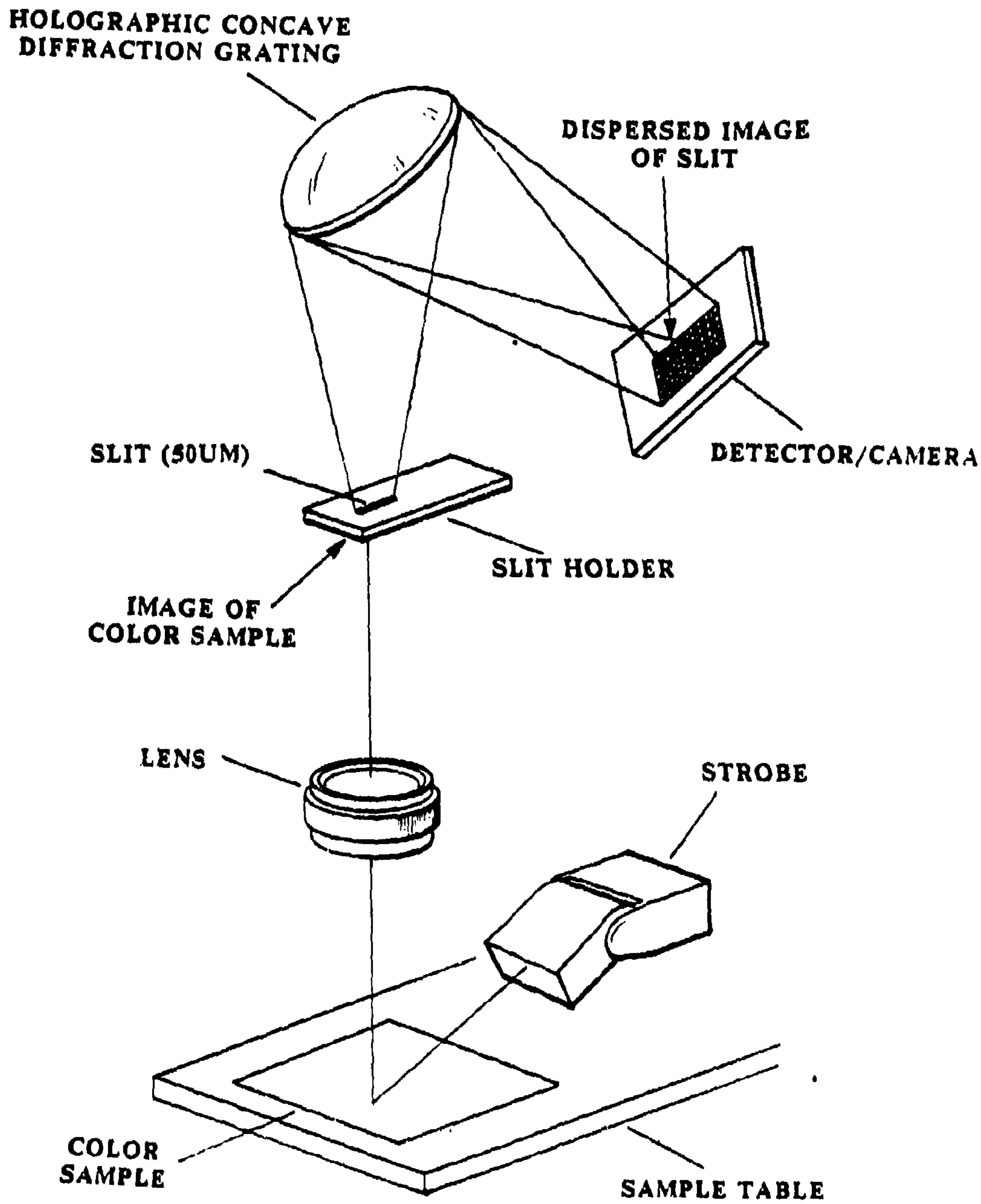
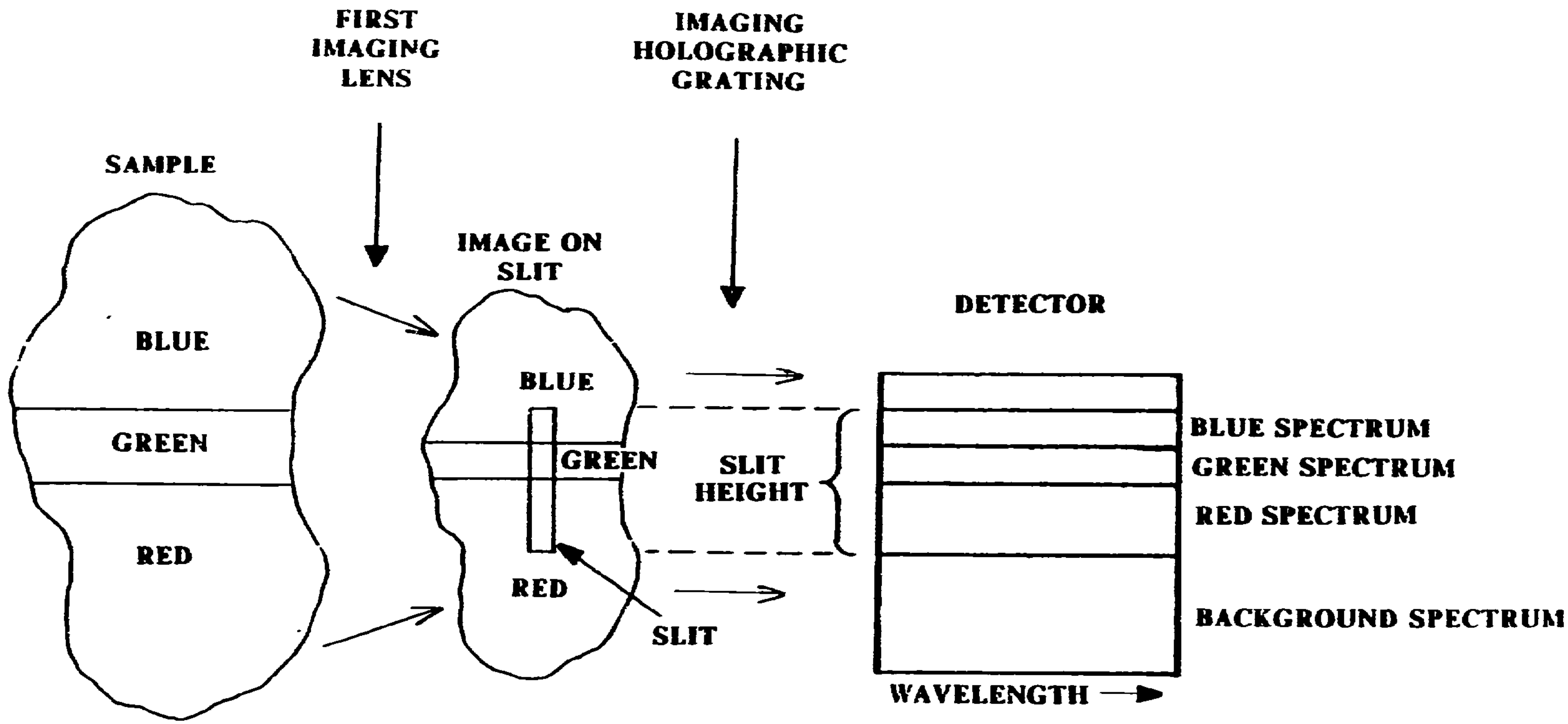


FIGURE 4-1 SPECTRAL ANALYSIS SYSTEM -DEMONSTRATION SET-UP



MULTI-SPECTRAL CAMERA (MSC)

FIGURE 4-2



TRANSFER OF INFORMATION FROM SAMPLE TO SLIT TO DETECTOR

FIGURE 4-3

MAPPING REGIONS OF THE SLIT ONTO LINES ON THE DETECTOR MATRIX

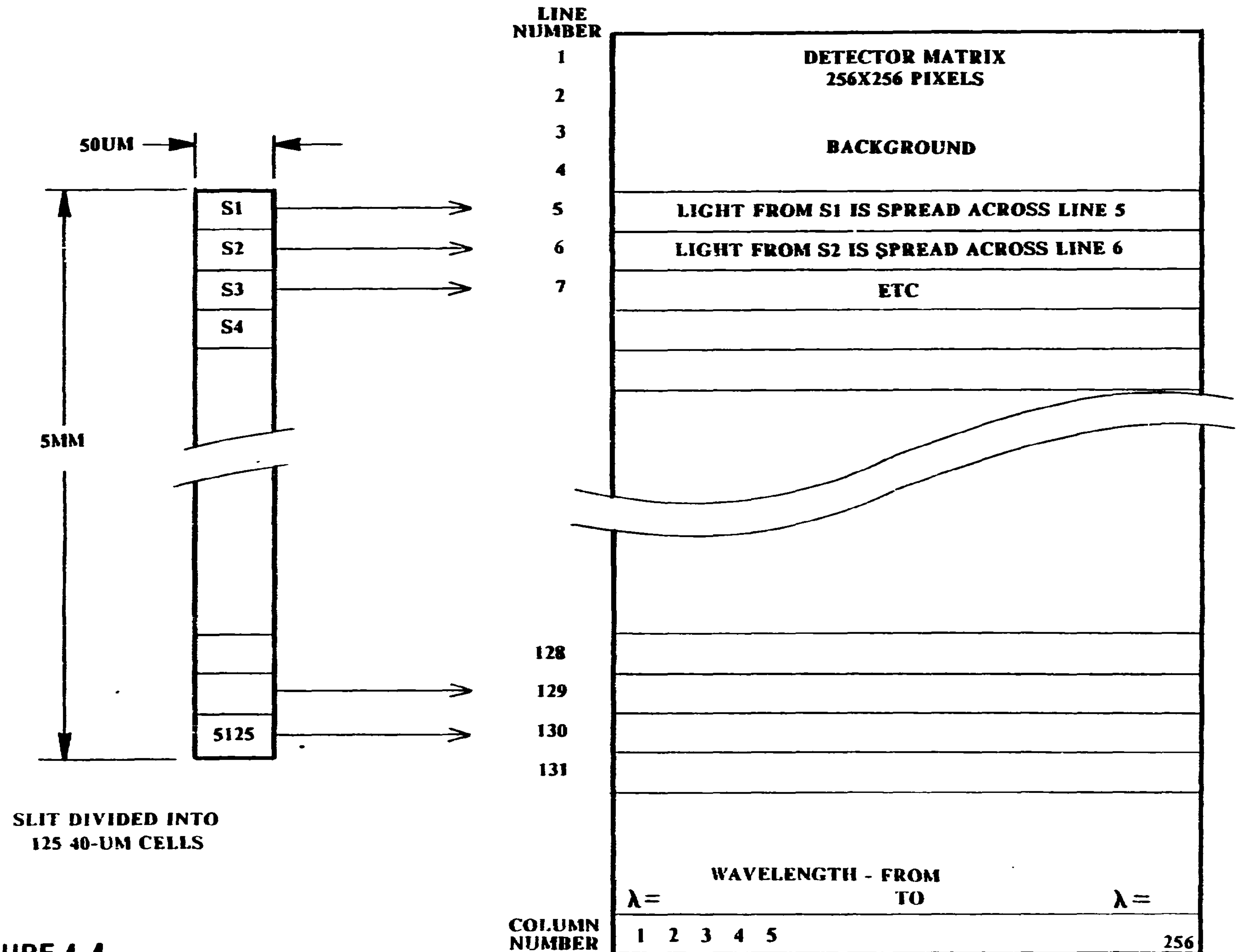


FIGURE 4-4

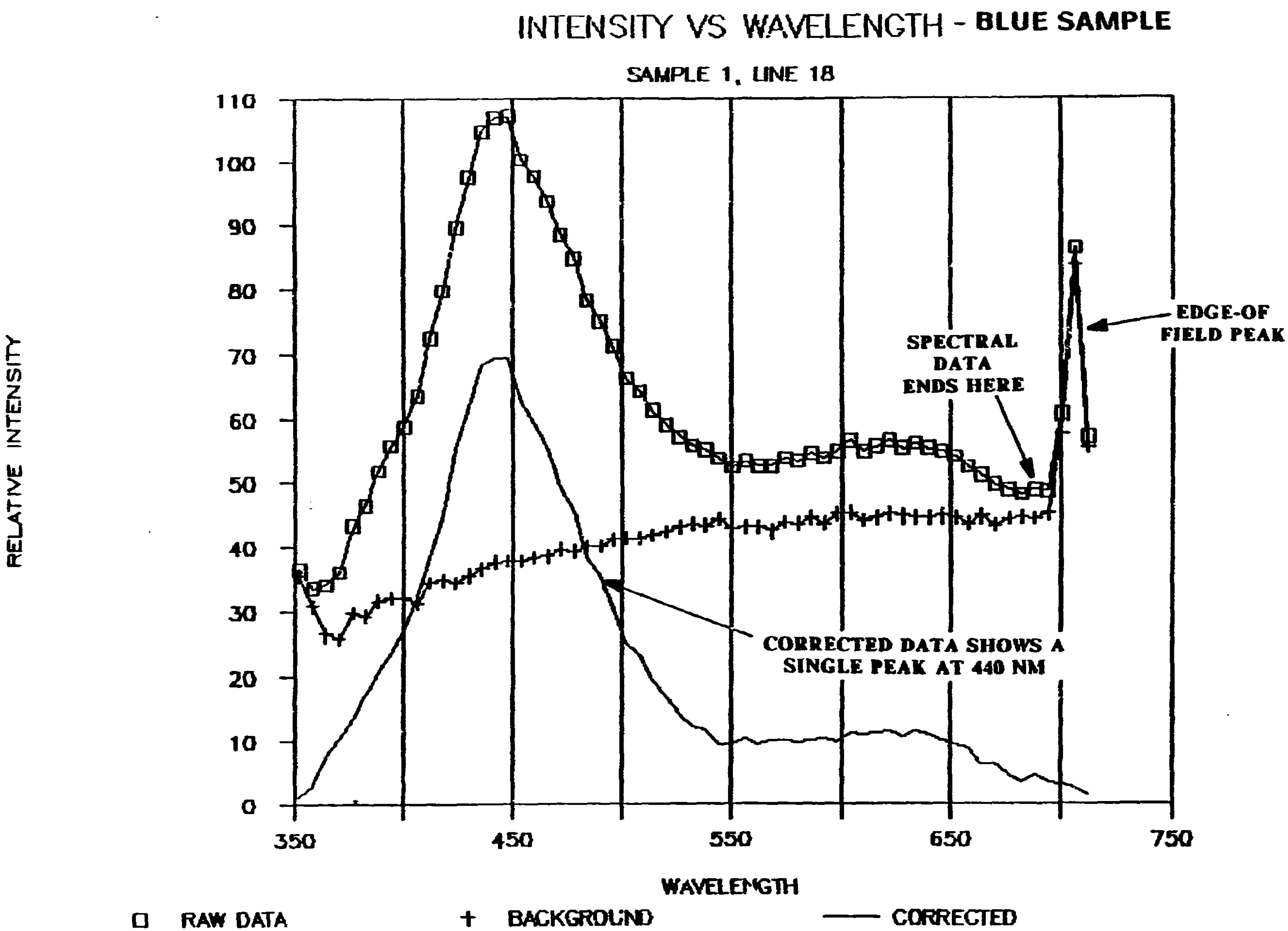

INTENSITY VS WAVELENGTH - BLUE SAMPLE
SAMPLE 1, LINE 18
RELATIVE INTENSITY
110
100
90
80
70
60
50
40
30
20
10
0
350
450
550
650
750
WAVELENGTH
SPECTRAL DATA ENDS HERE
EDGE-OF FIELD PEAK
CORRECTED DATA SHOWS A SINGLE PEAK AT 440 NM
□ RAW DATA
+ BACKGROUND
— CORRECTED

FIGURE 4-5

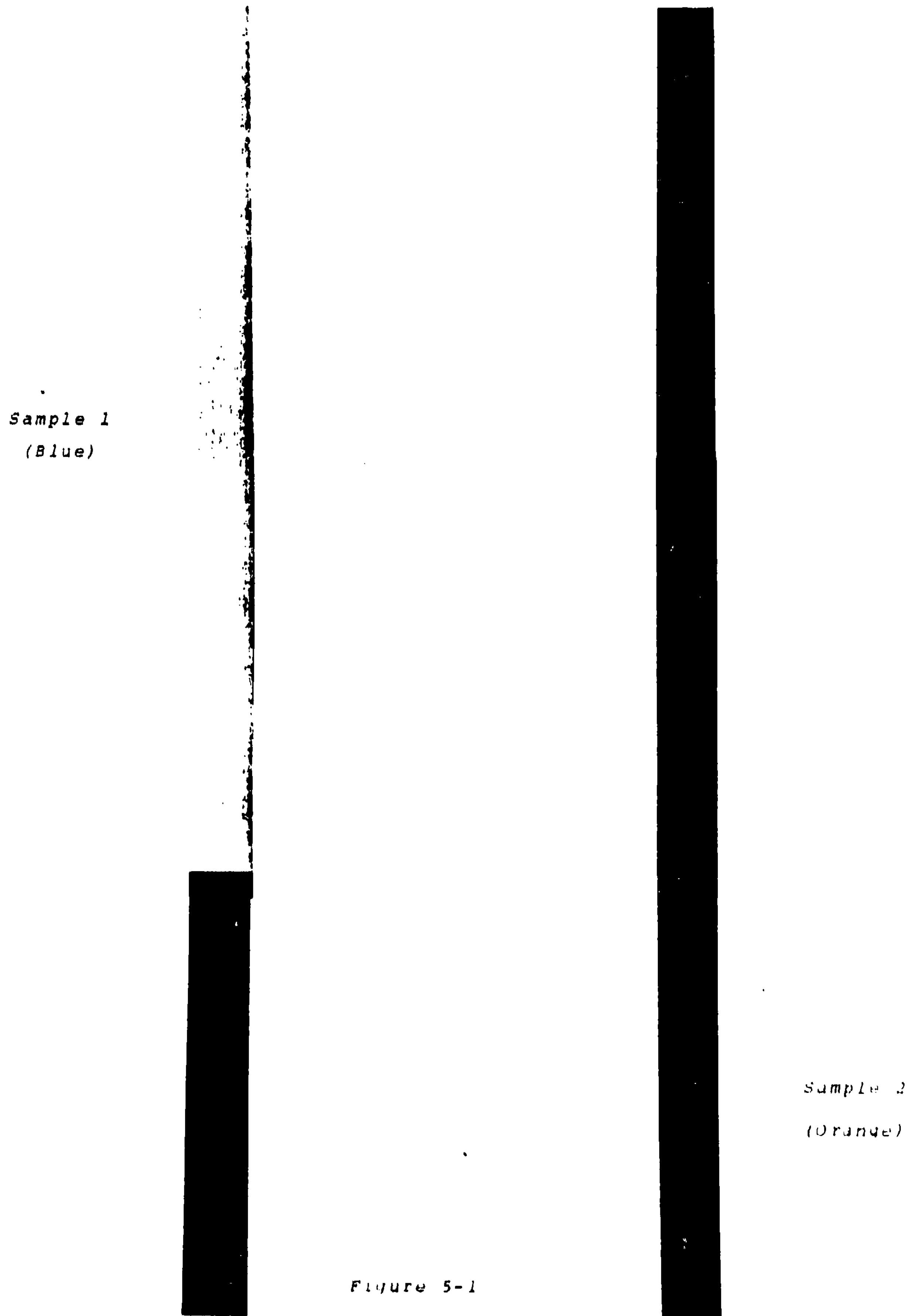
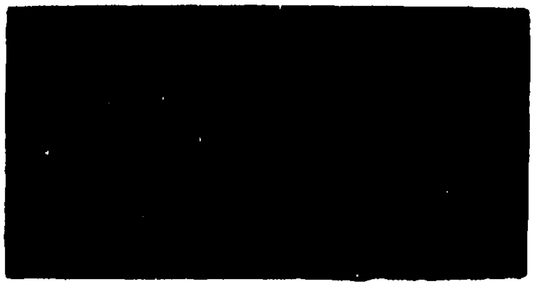


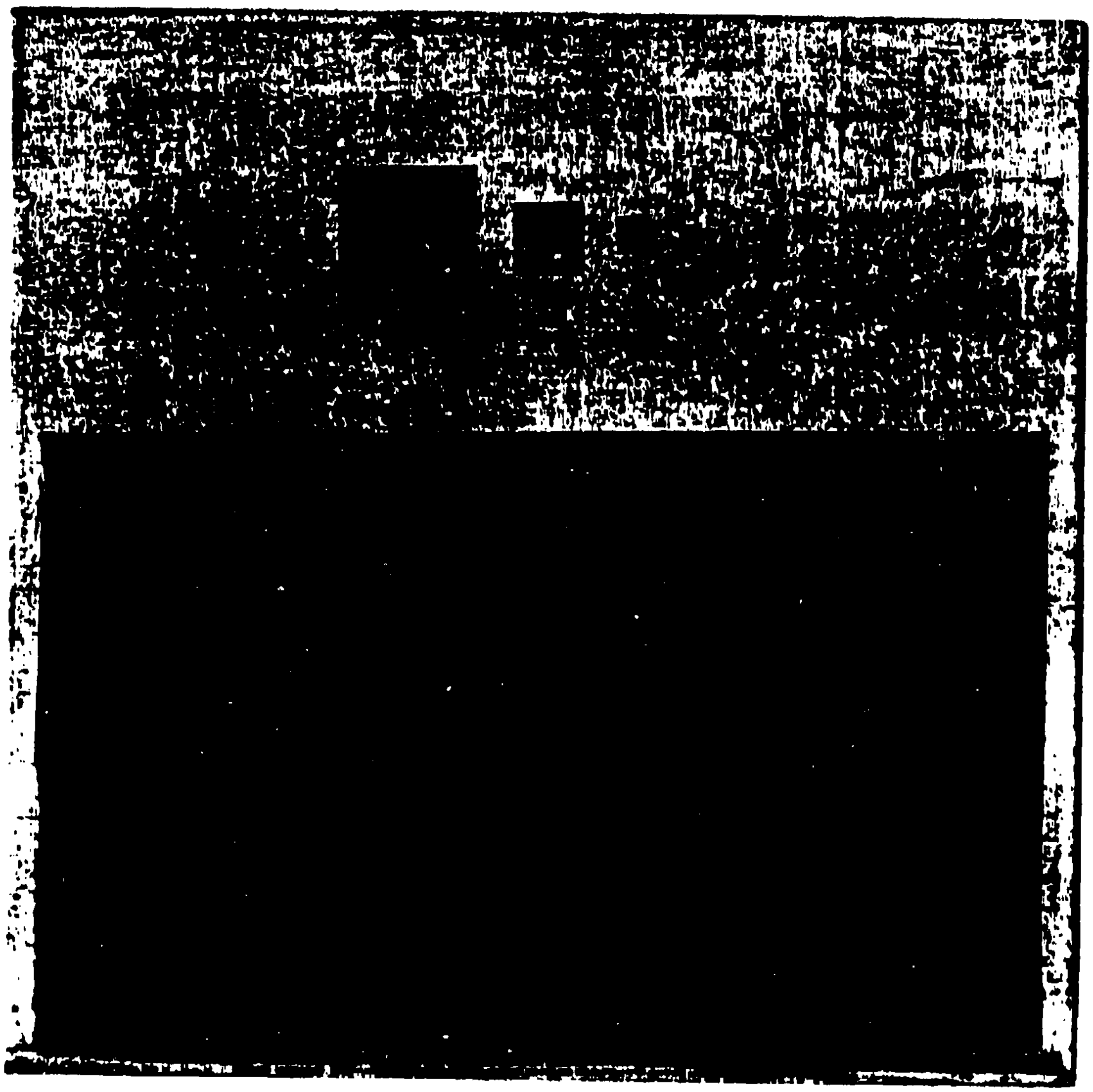
Figure 5-1

Figure 5-2



Sample 8

Sample 5



Sample 3 *Sample 4*

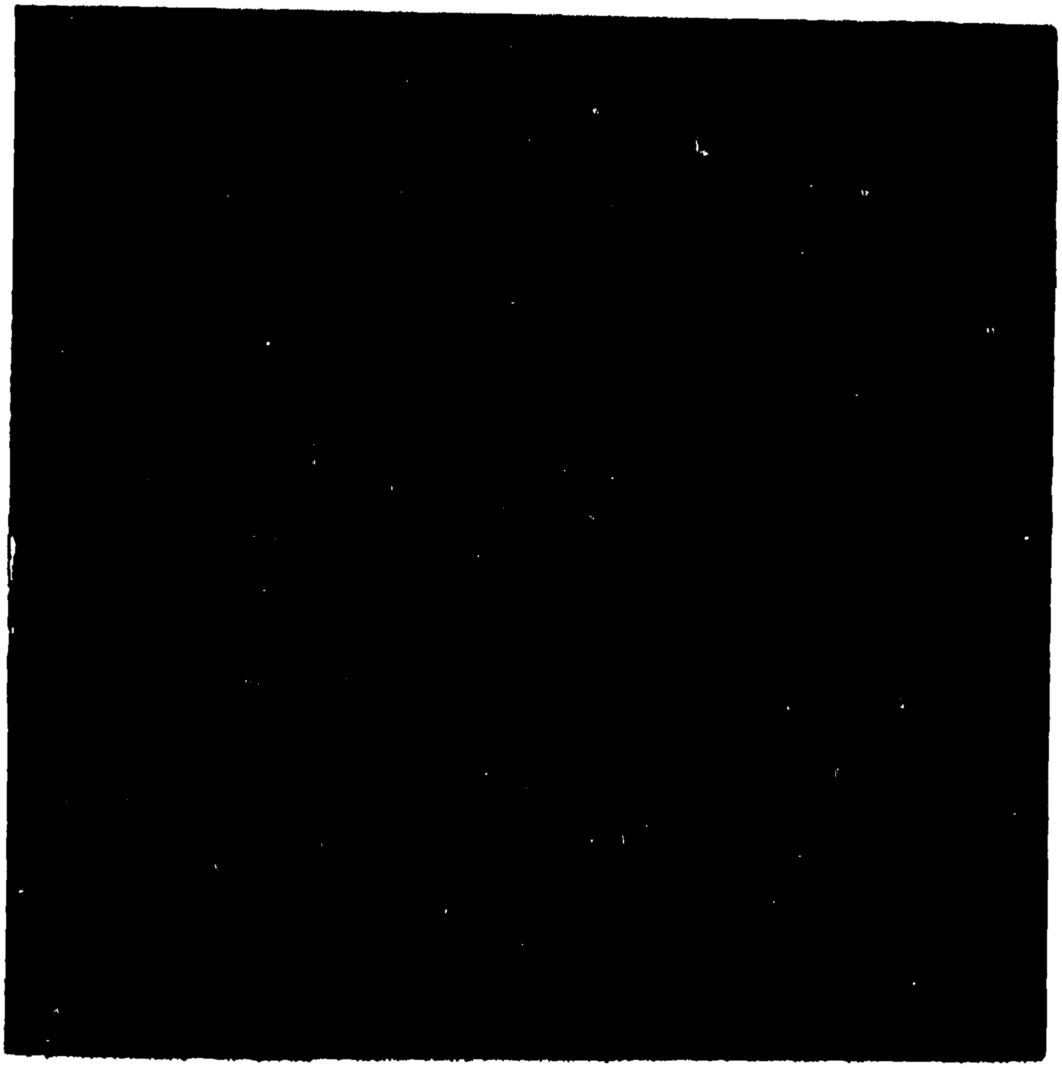


Figure 5-3

Back surface of Composite Material

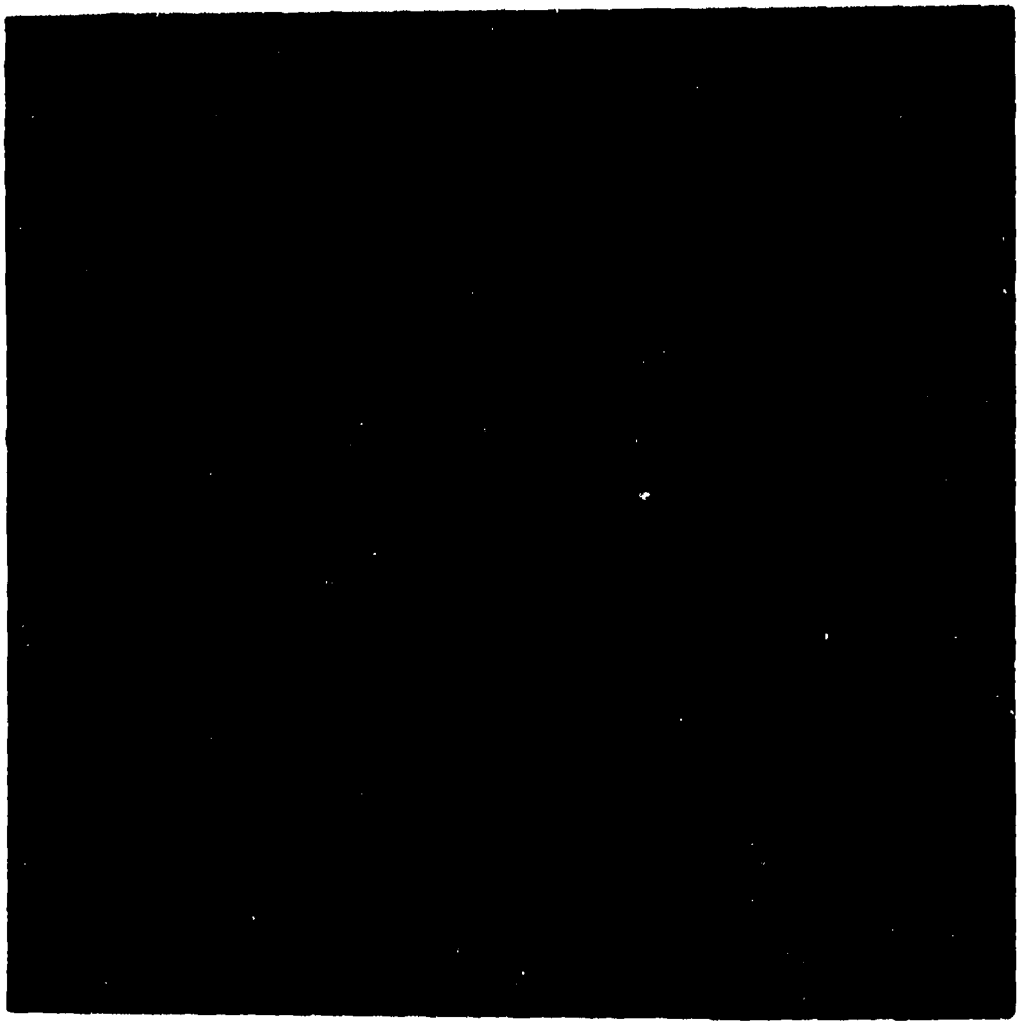


Figure 5-4

Front surface of Composite Material

MONITOR DISPLAY SAMPLE # 1

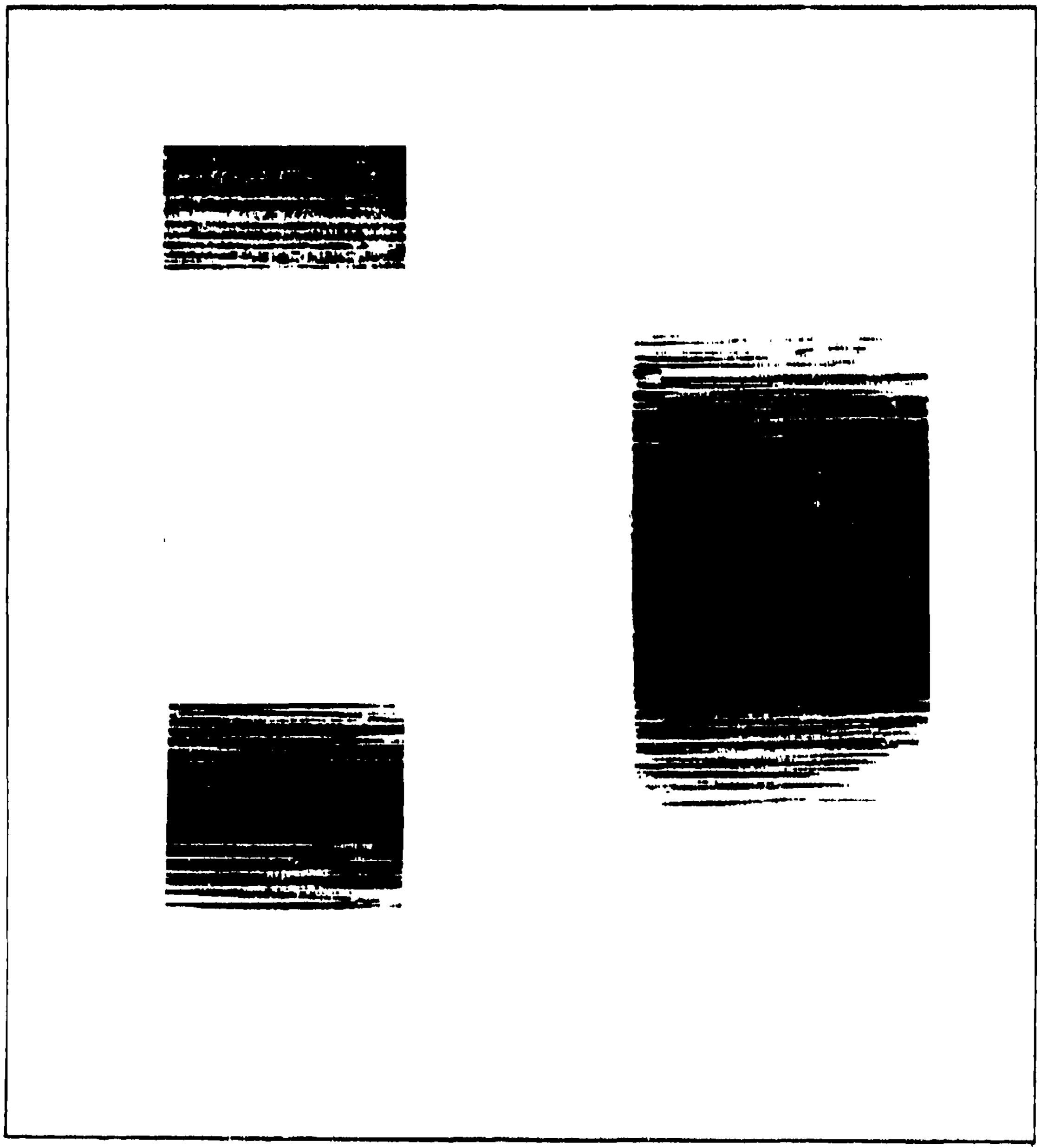
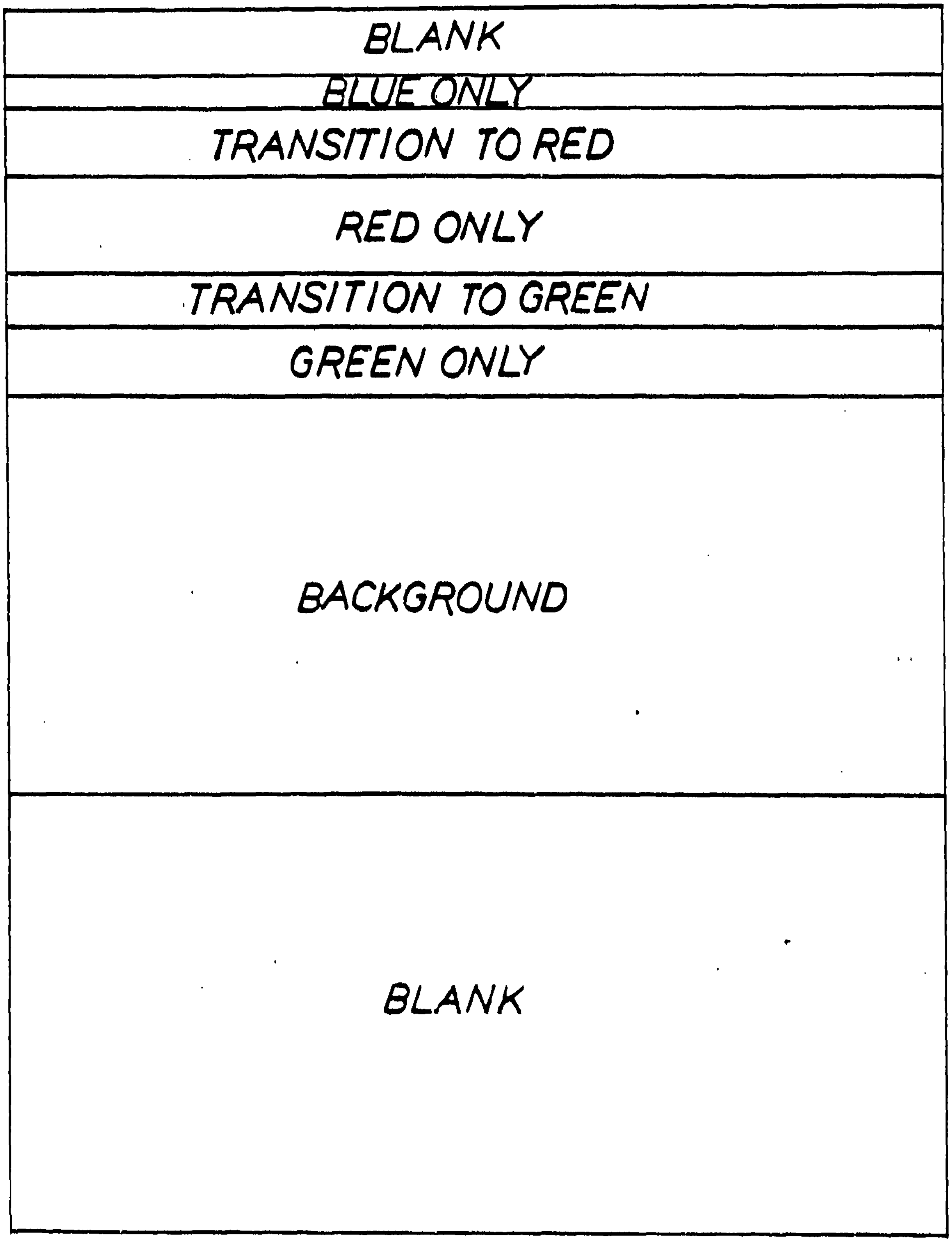


FIGURE 5-5

FIGURE 5-6

LINE MAP SAMPLE # 1



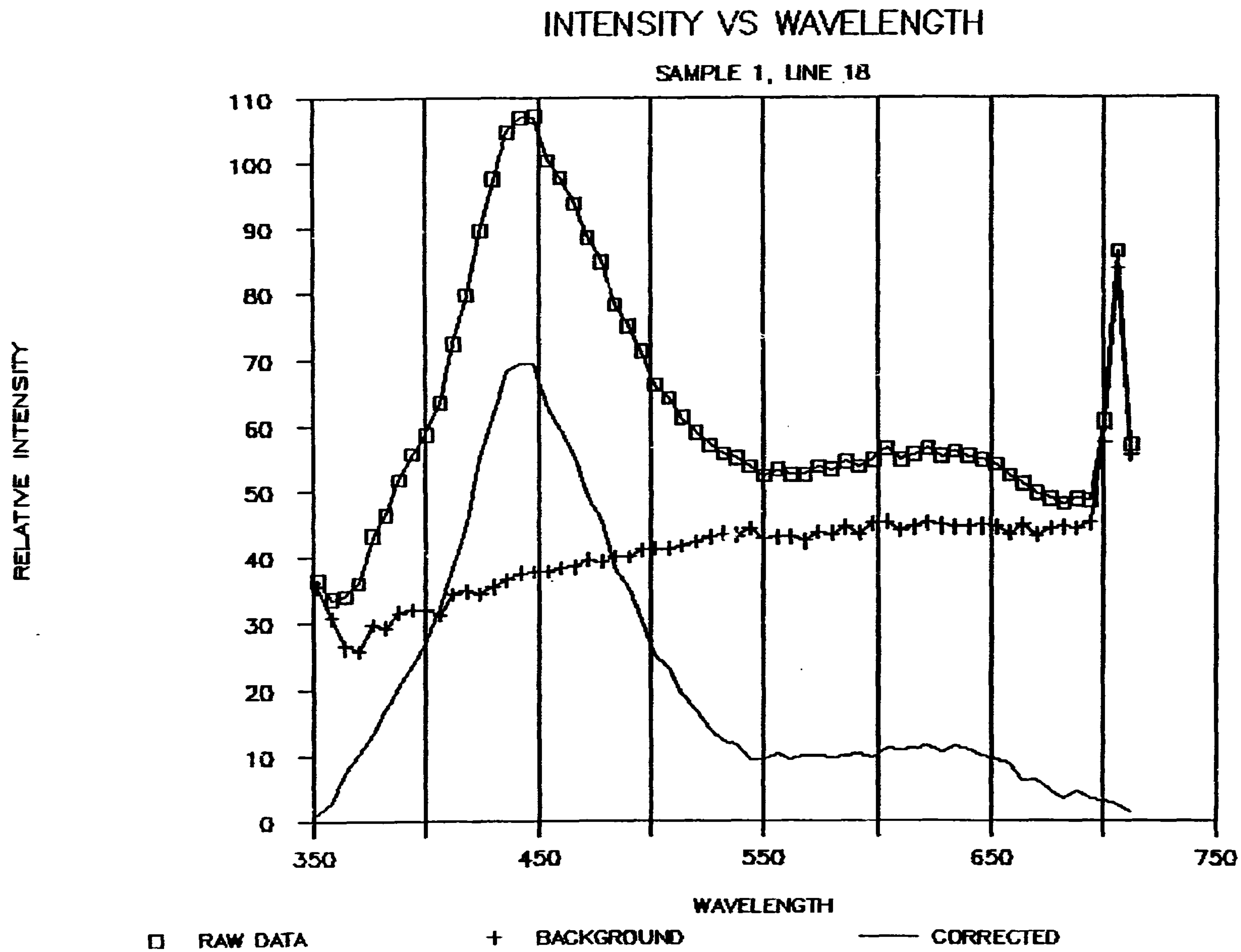


Figure 5 - 7 Blue

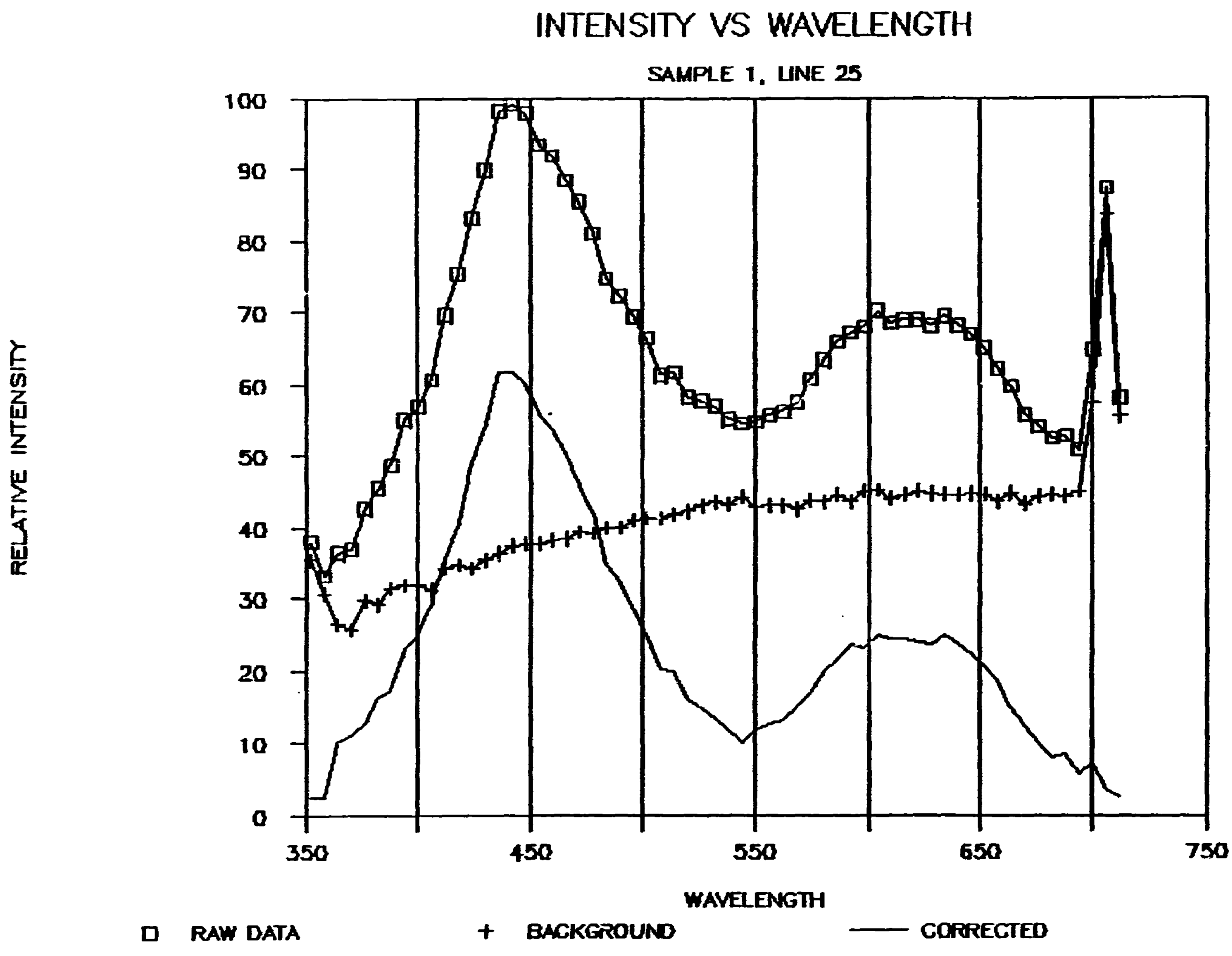


Figure 5-8
Beginning Transition from blue to red

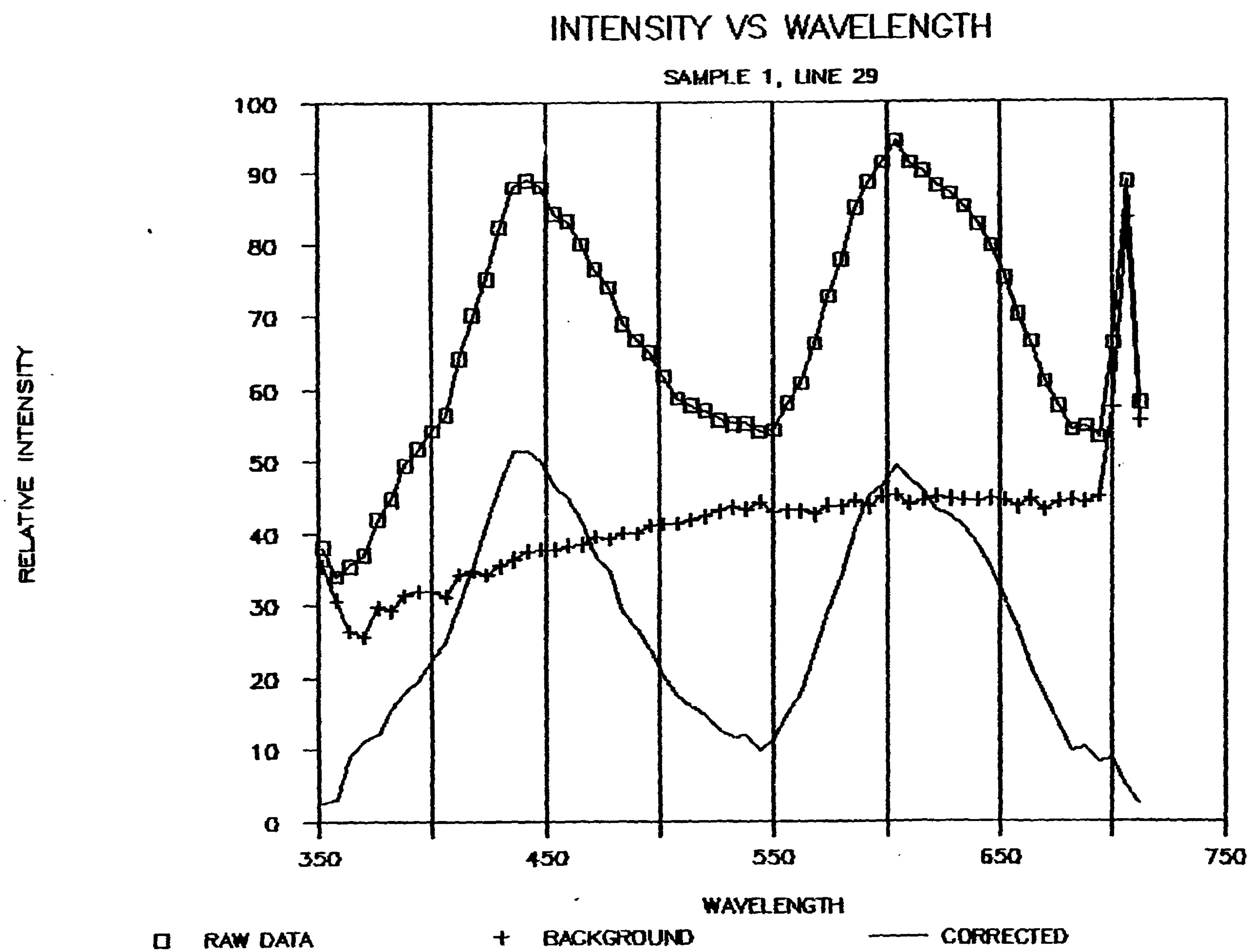


Figure 5-9
Center of Transition
Blue to Red

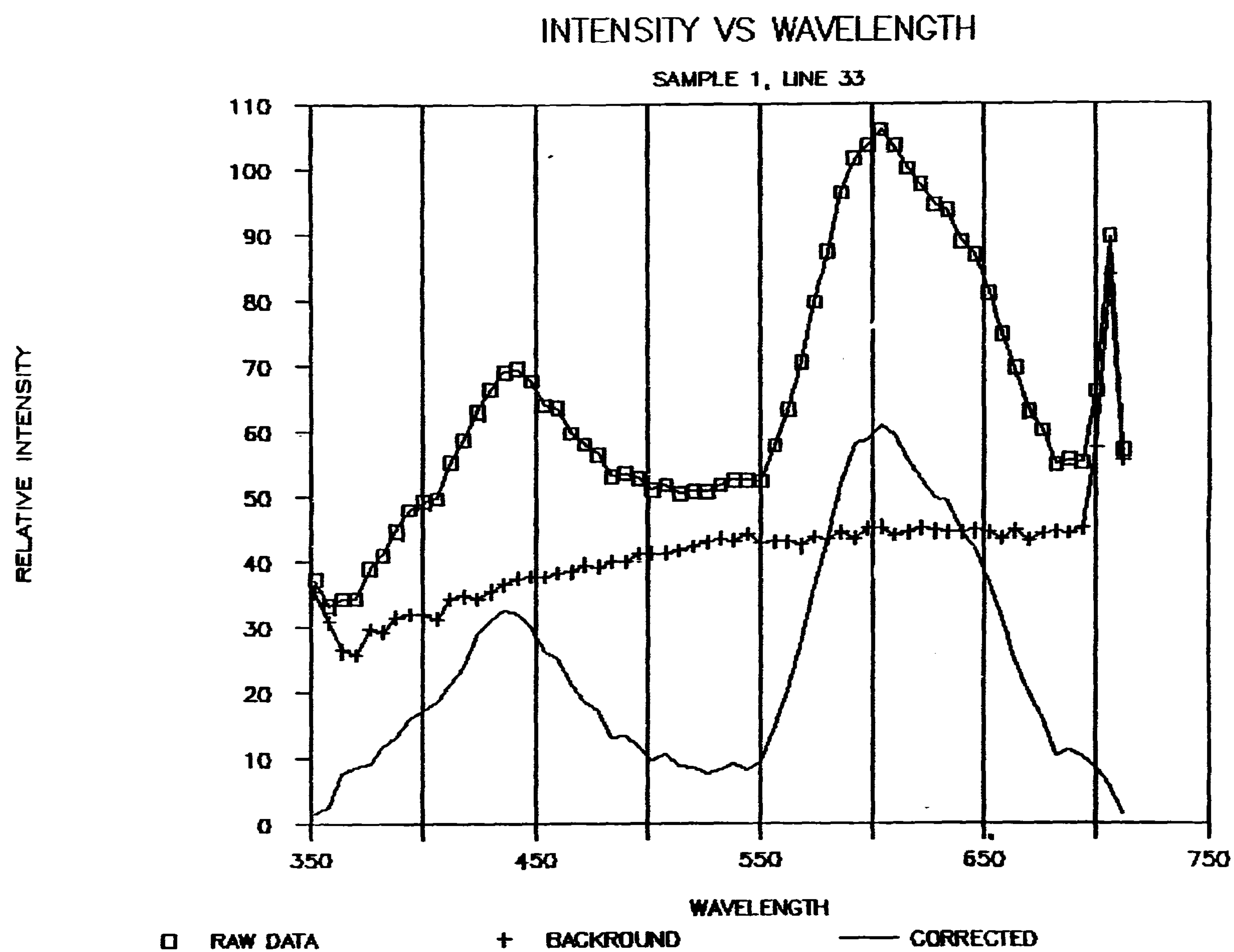


Figure 5-10
End of Transition

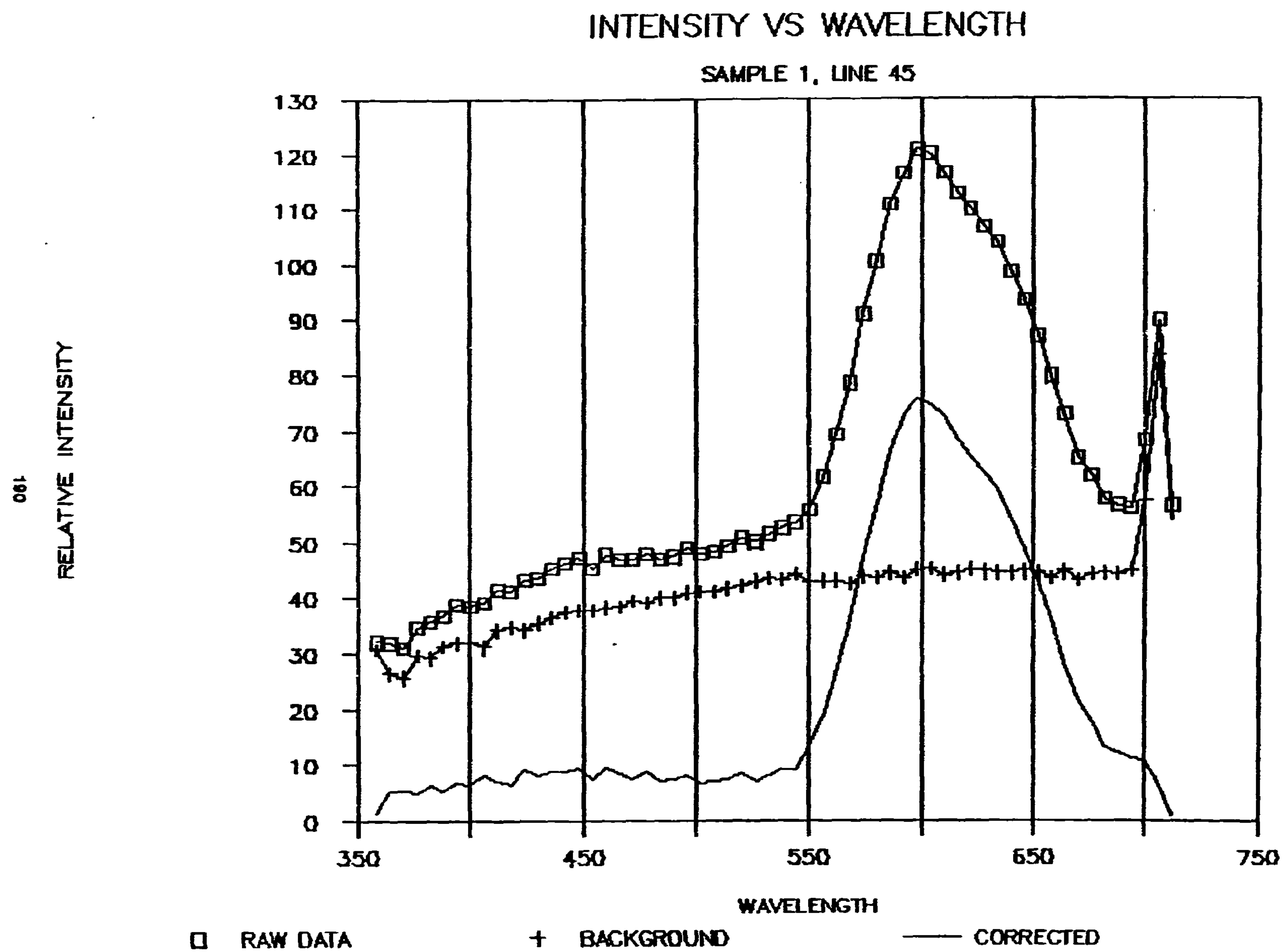

INTENSITY VS WAVELENGTH
SAMPLE 1, LINE 45
RELATIVE INTENSITY
130
120
110
100
90
80
70
60
50
40
30
20
10
0
350
450
550
650
750
WAVELENGTH
RAW DATA
BACKGROUND
CORRECTED

Figure 5-11

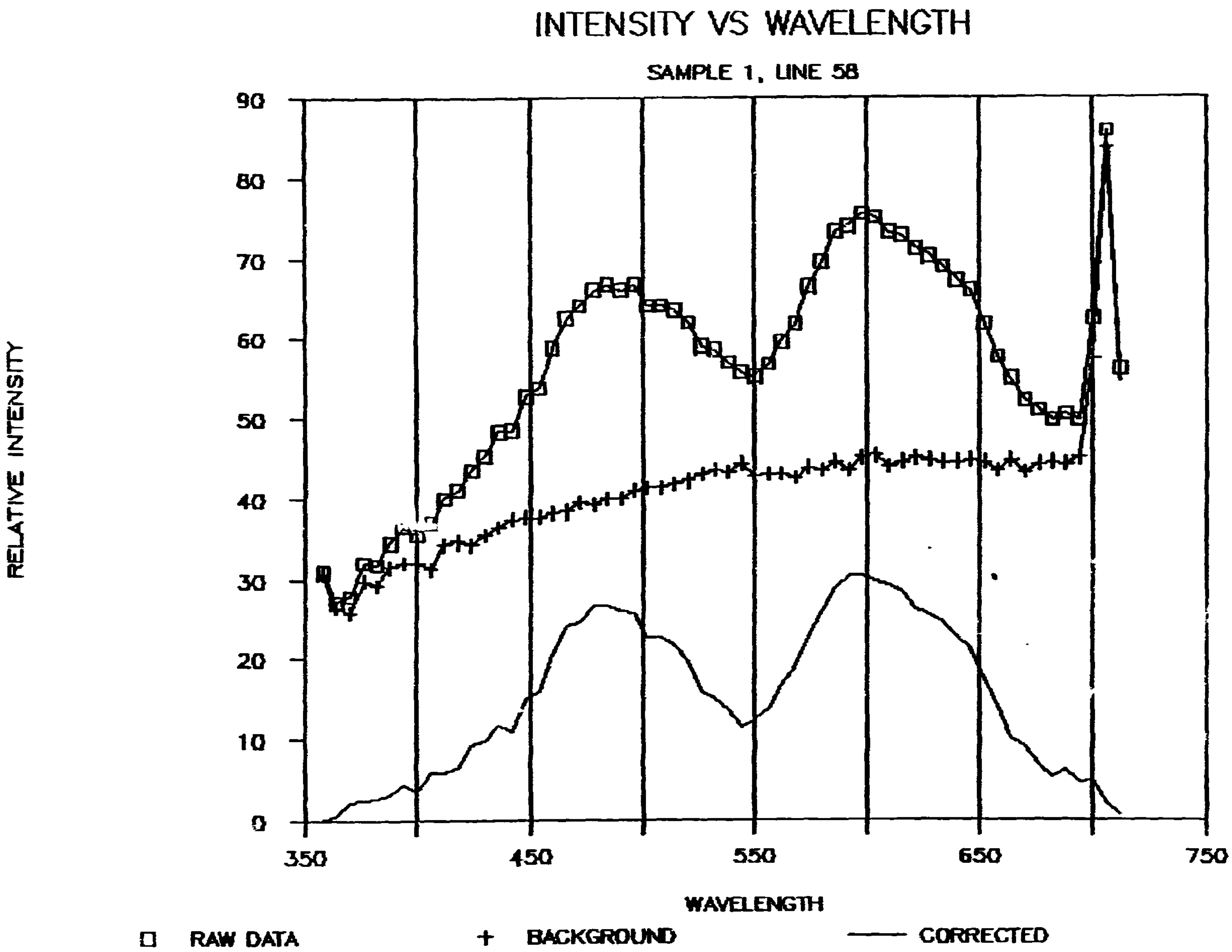


Figure 5-12

Beginning of Transition

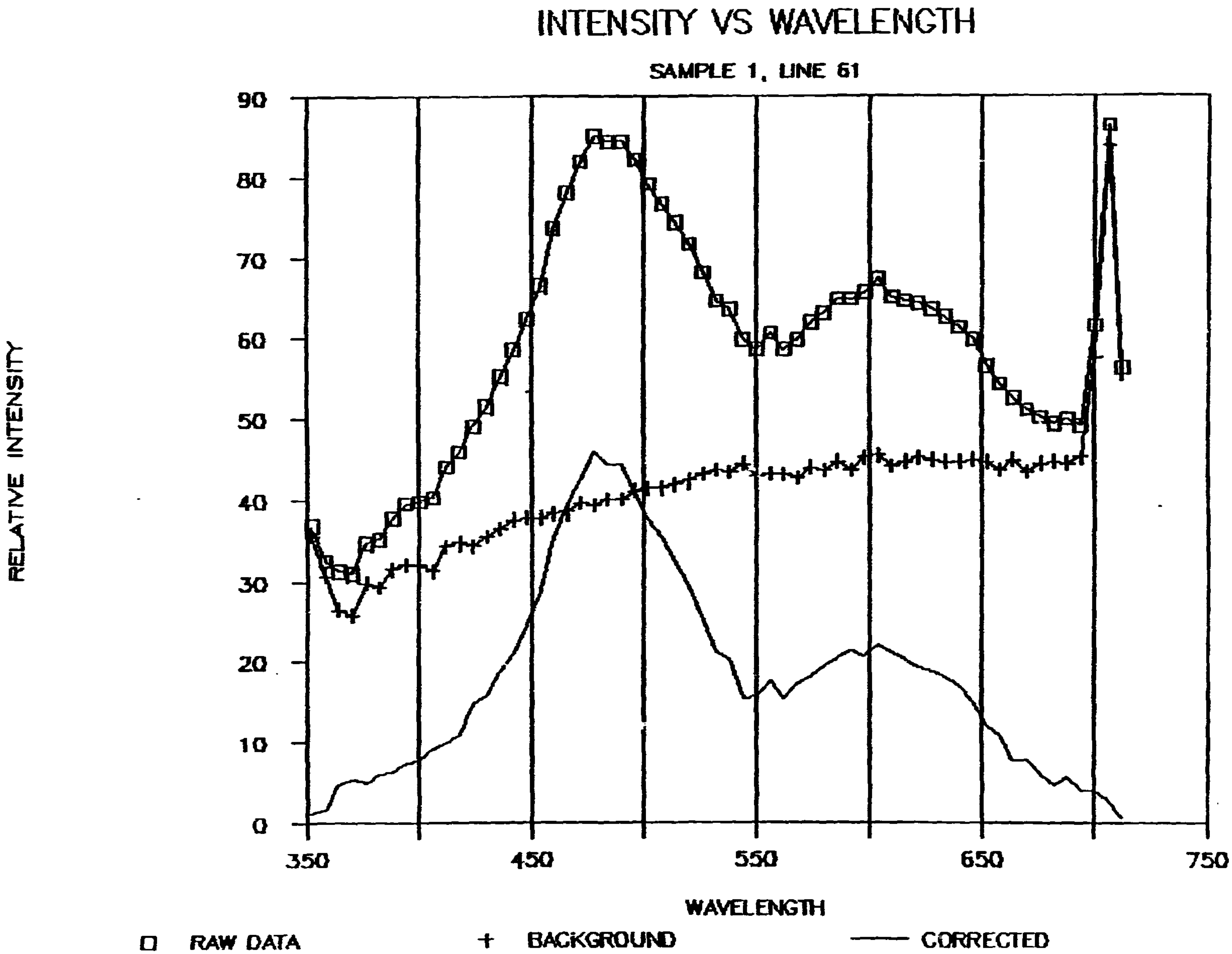


Figure 5-13

Center of Transition

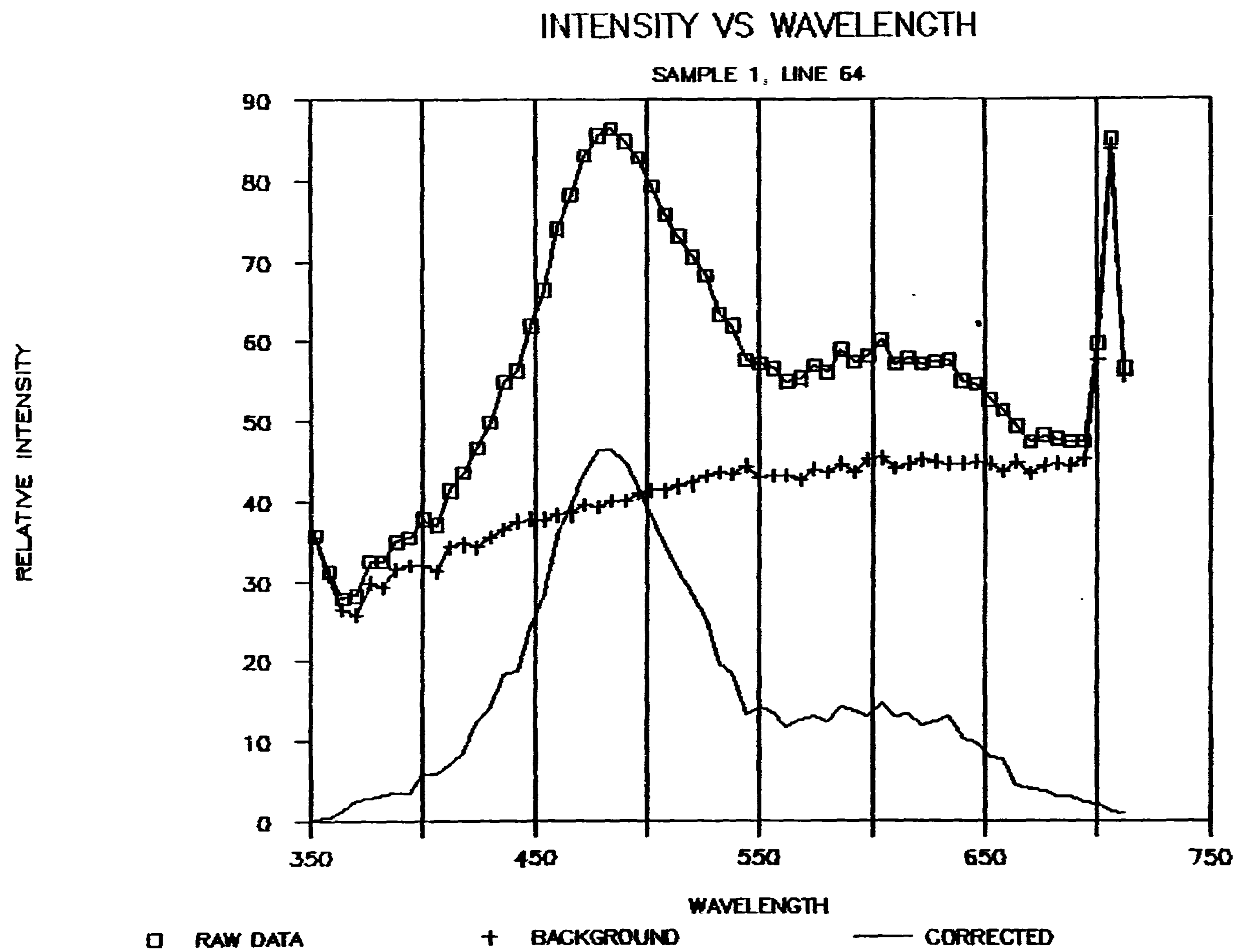


Figure 5-14

End of Transition

Red to Green

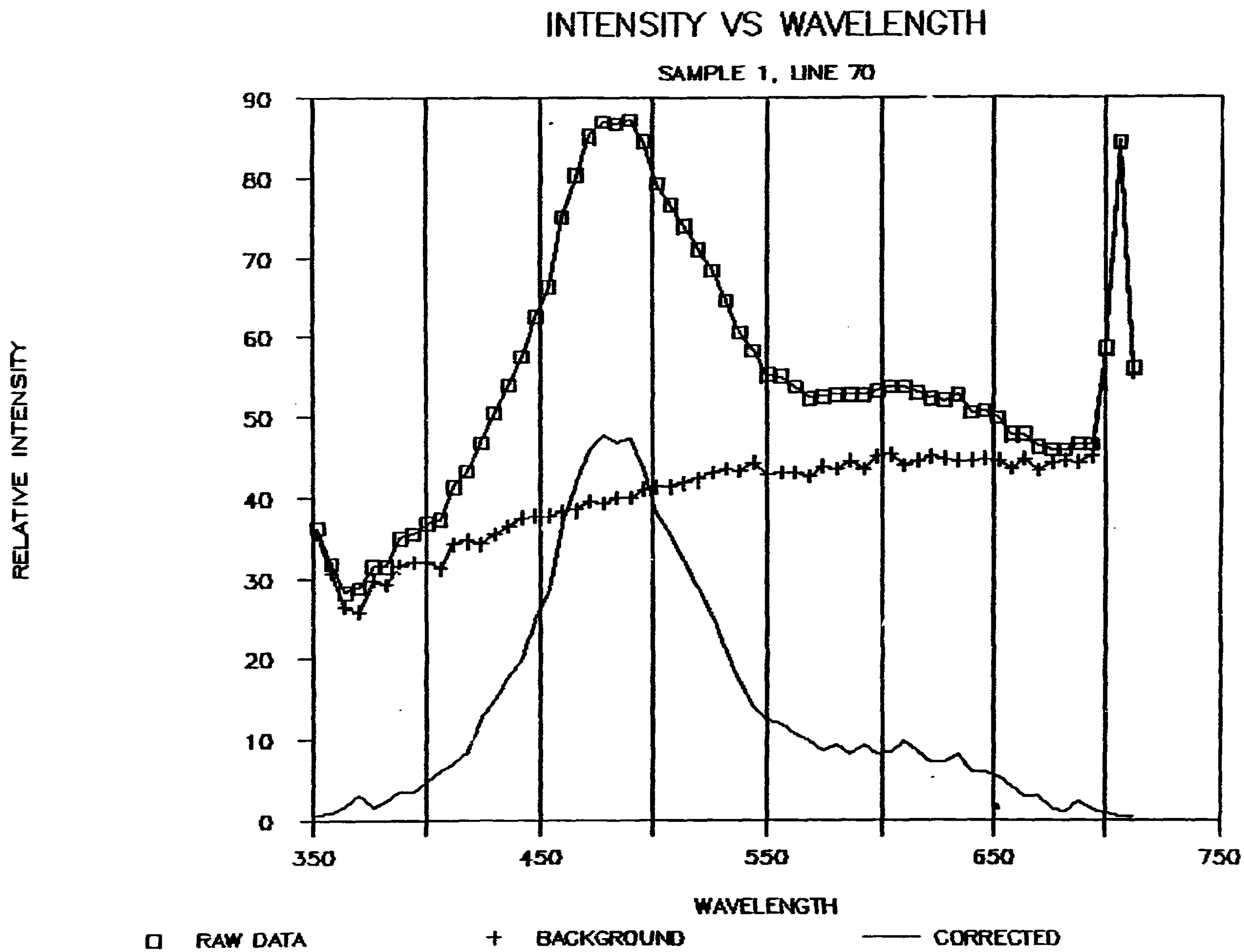

INTENSITY VS WAVELENGTH
SAMPLE 1, LINE 70
RELATIVE INTENSITY
0
10
20
30
40
50
60
70
80
90
350
450
550
650
750
WAVELENGTH
RAW DATA
BACKGROUND
CORRECTED

Figure 5-15

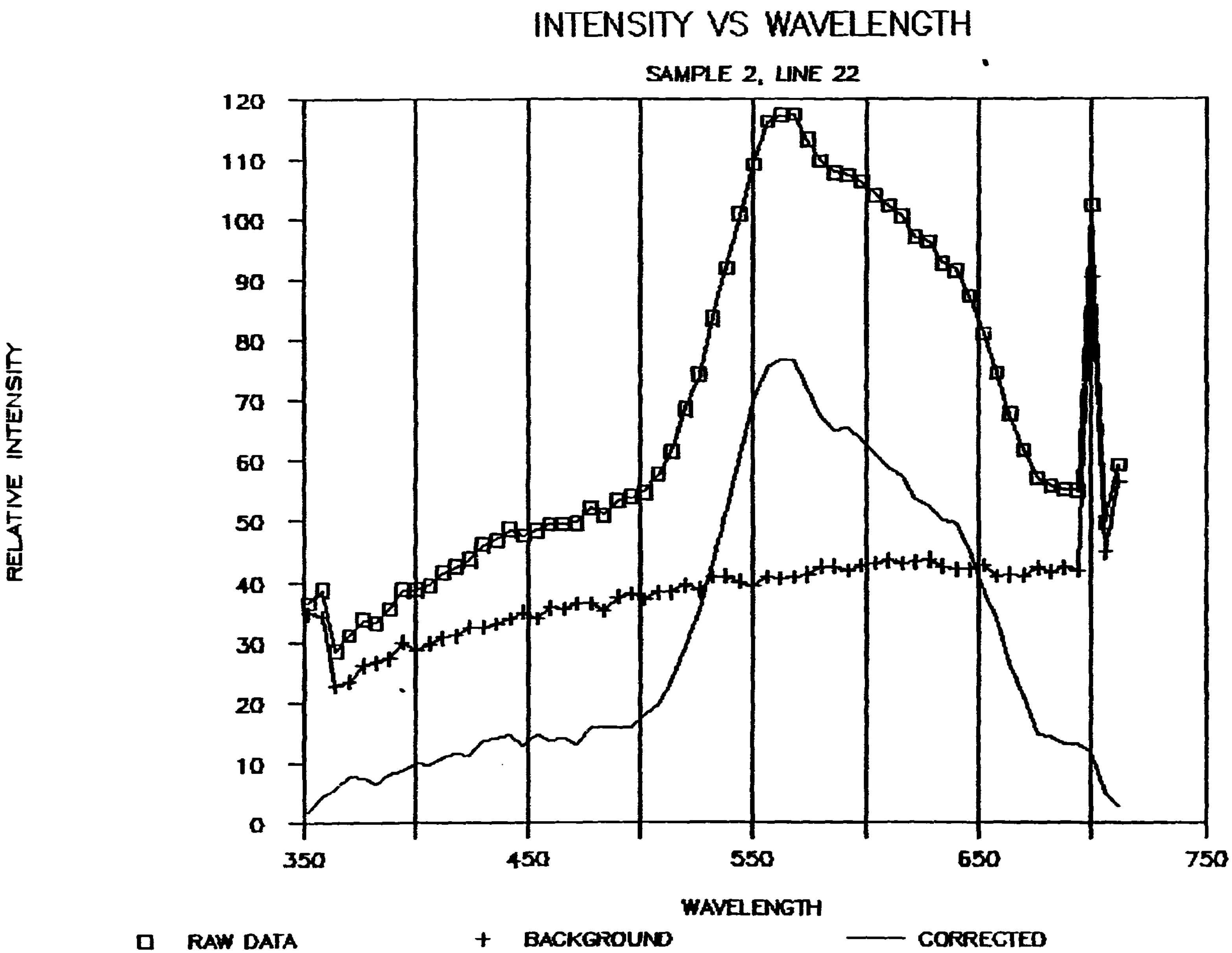


Figure 5-16

Brown

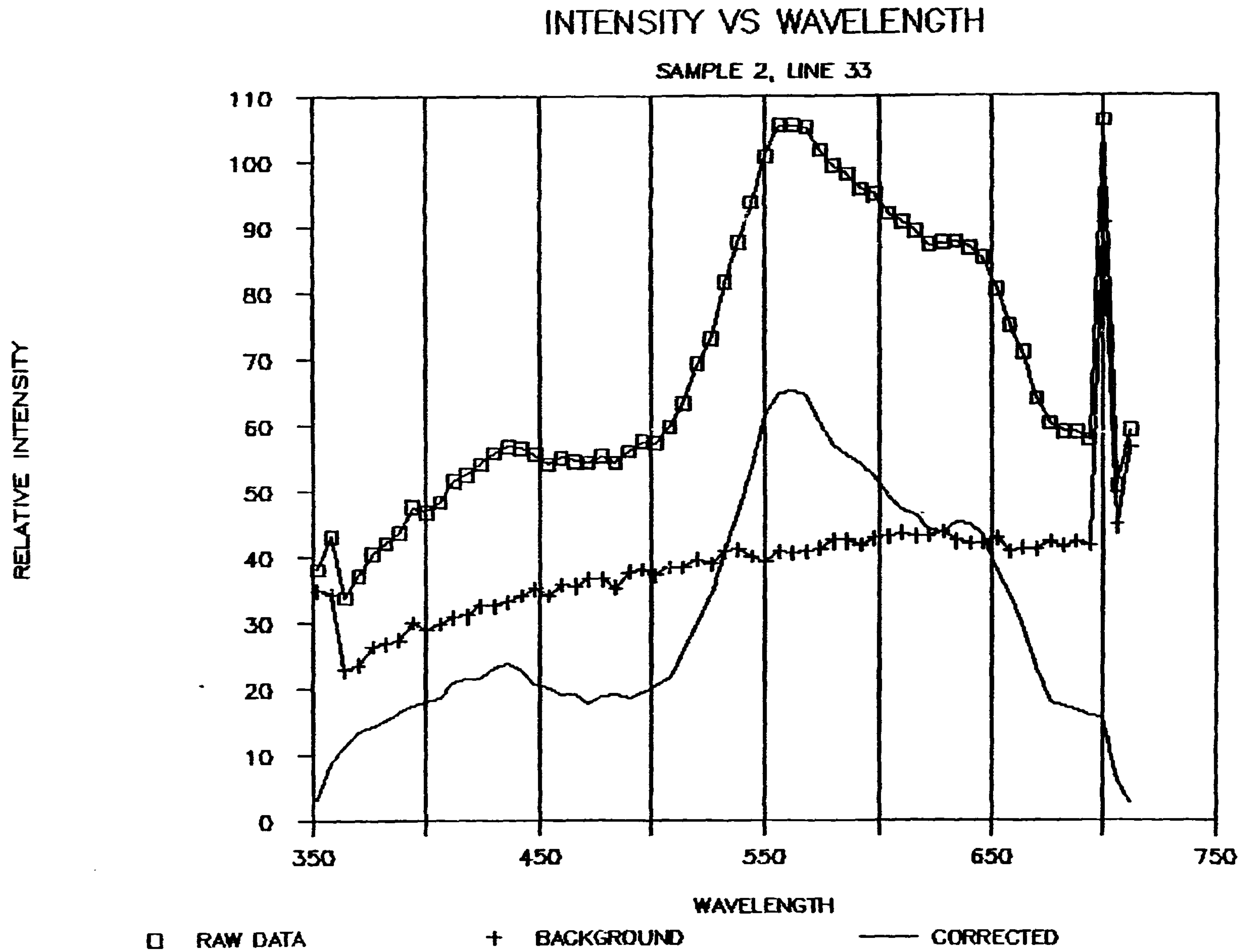

INTENSITY VS WAVELENGTH
SAMPLE 2, LINE 33
RELATIVE INTENSITY
110
100
90
80
70
60
50
40
30
20
10
0
350
450
550
650
750
WAVELENGTH
RAW DATA
BACKGROUND
CORRECTED

Figure 5-17

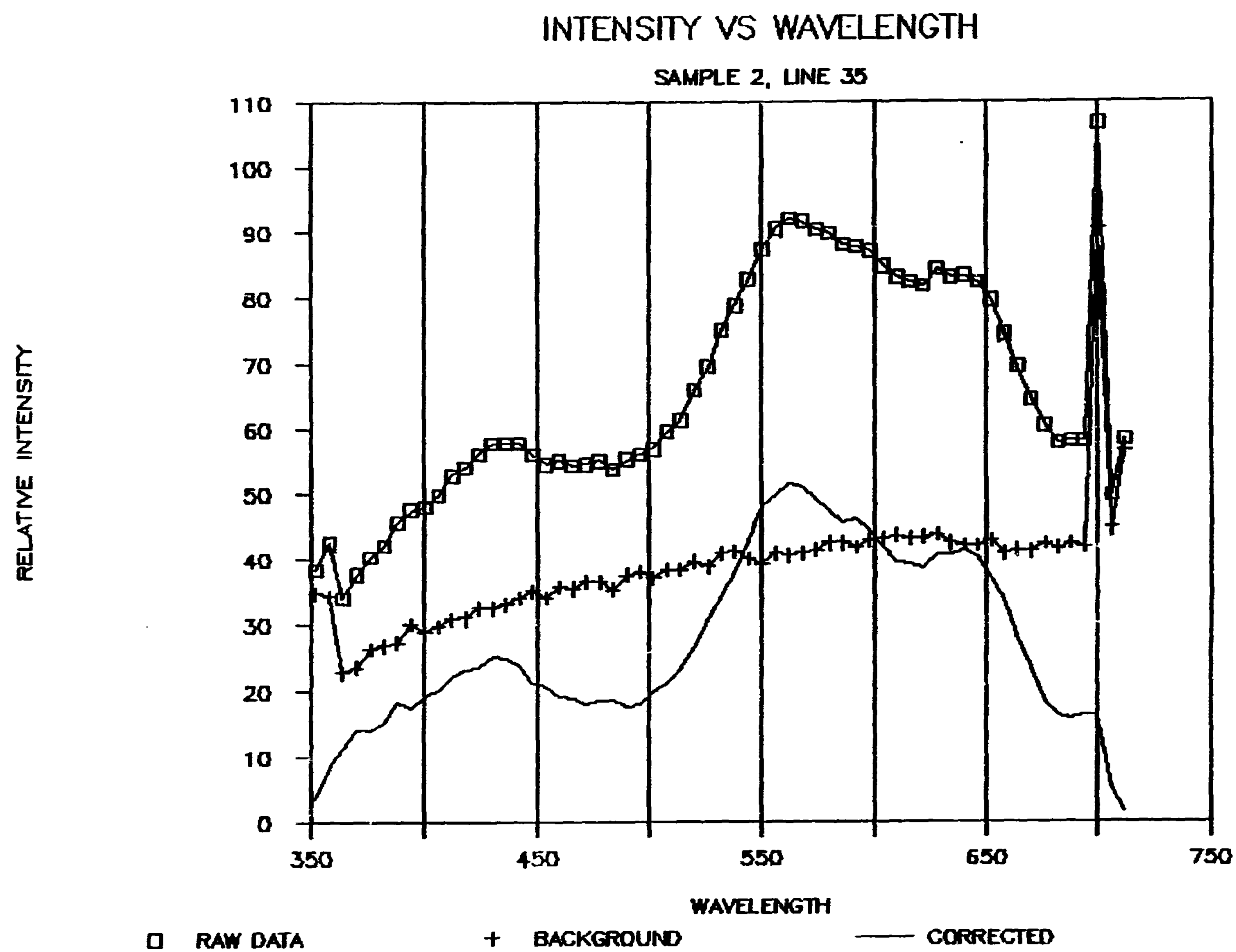


Figure 5-18

Center of Transition
Brown to Purple

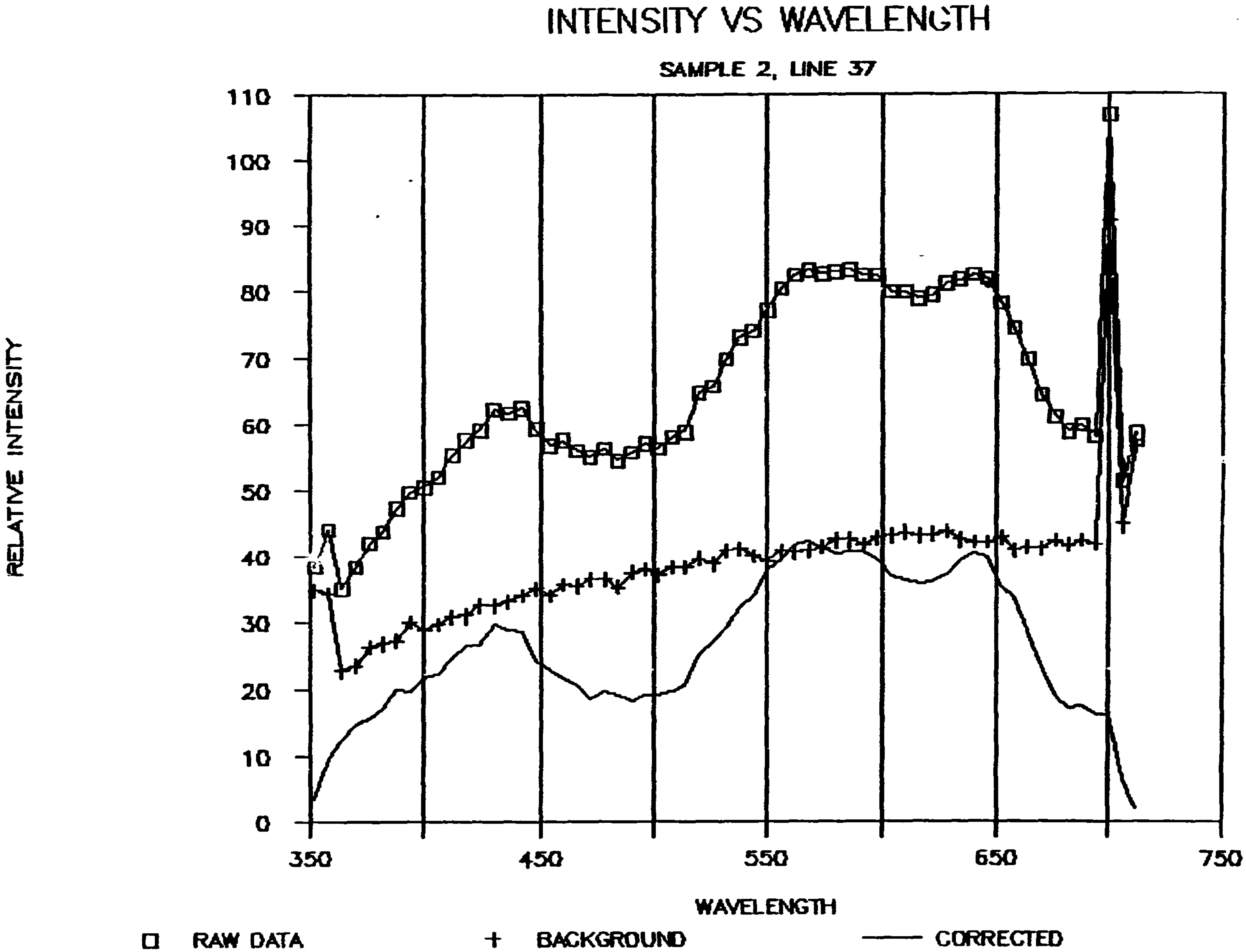


Figure 5-19

End of Transition

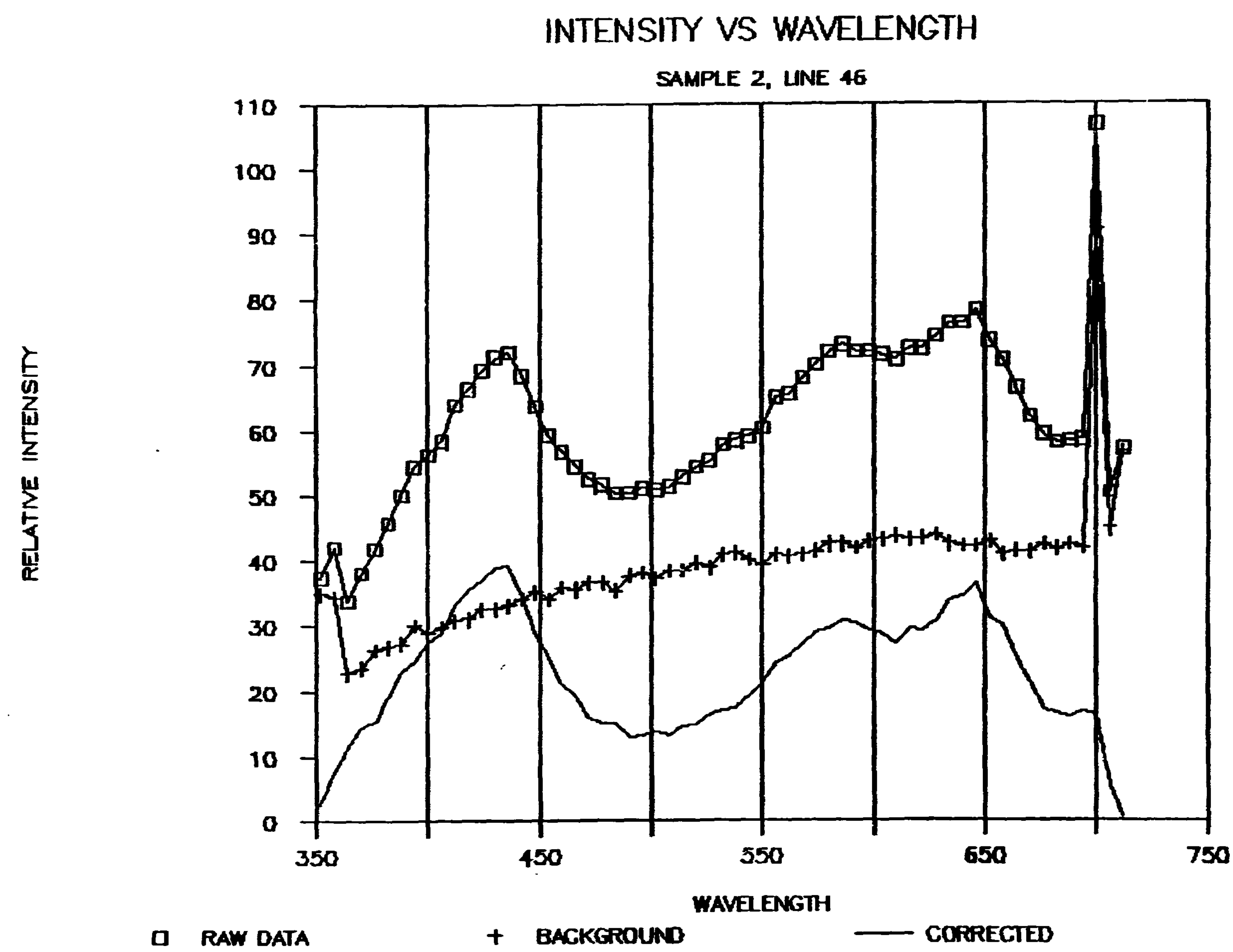


Figure 5-20

Purple

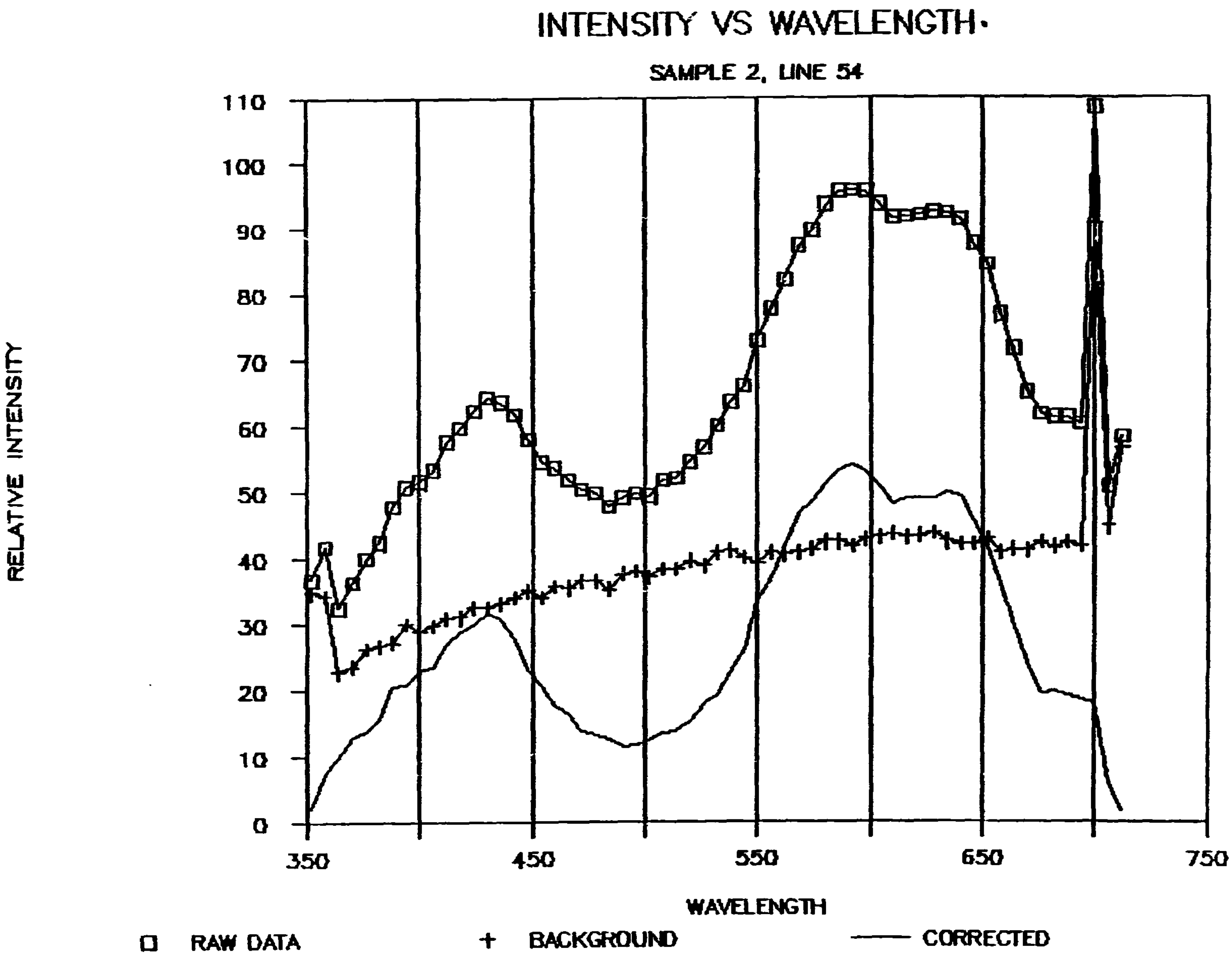


Figure 5-21

Beginning of Transition

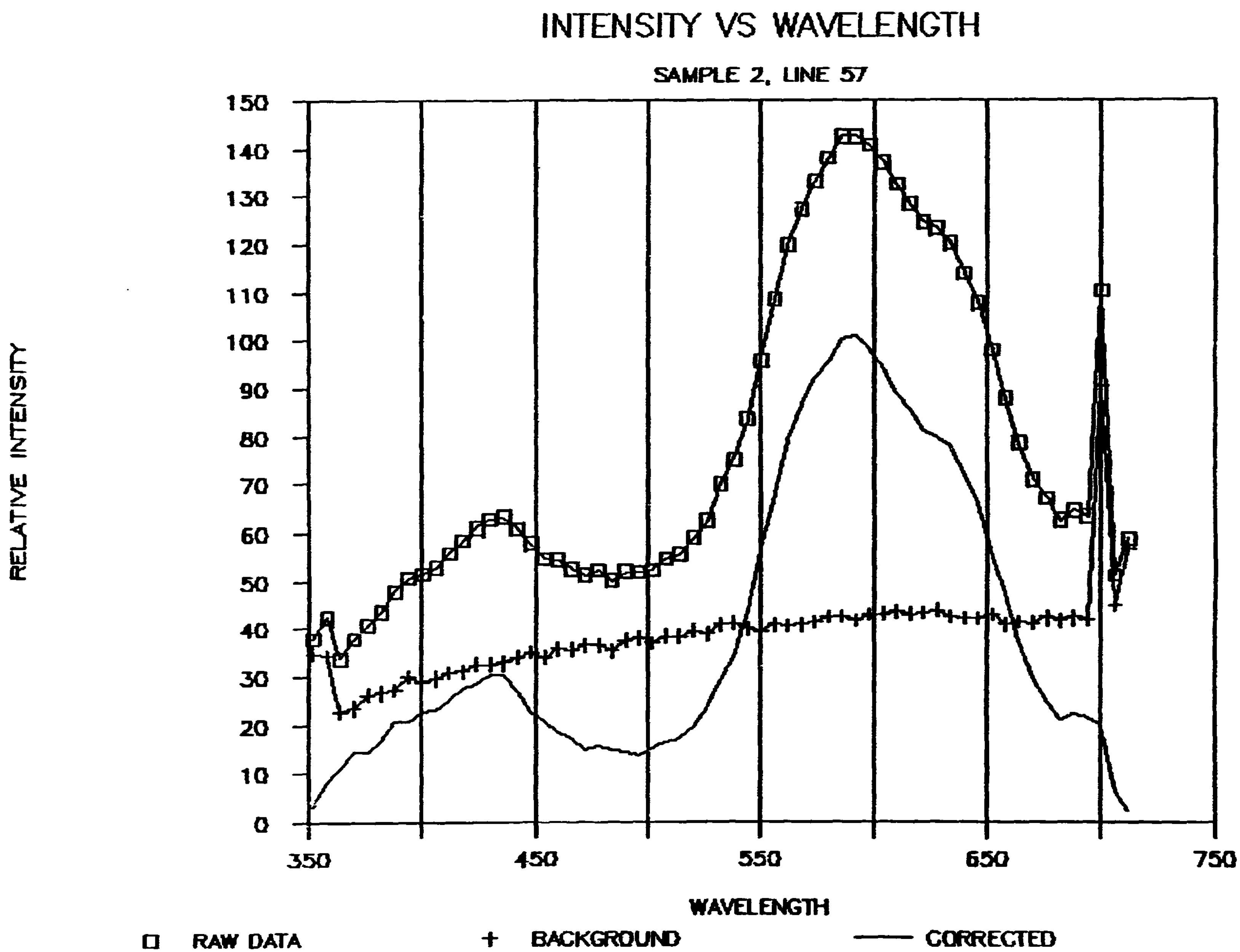


Figure 5-22

Center of Transition

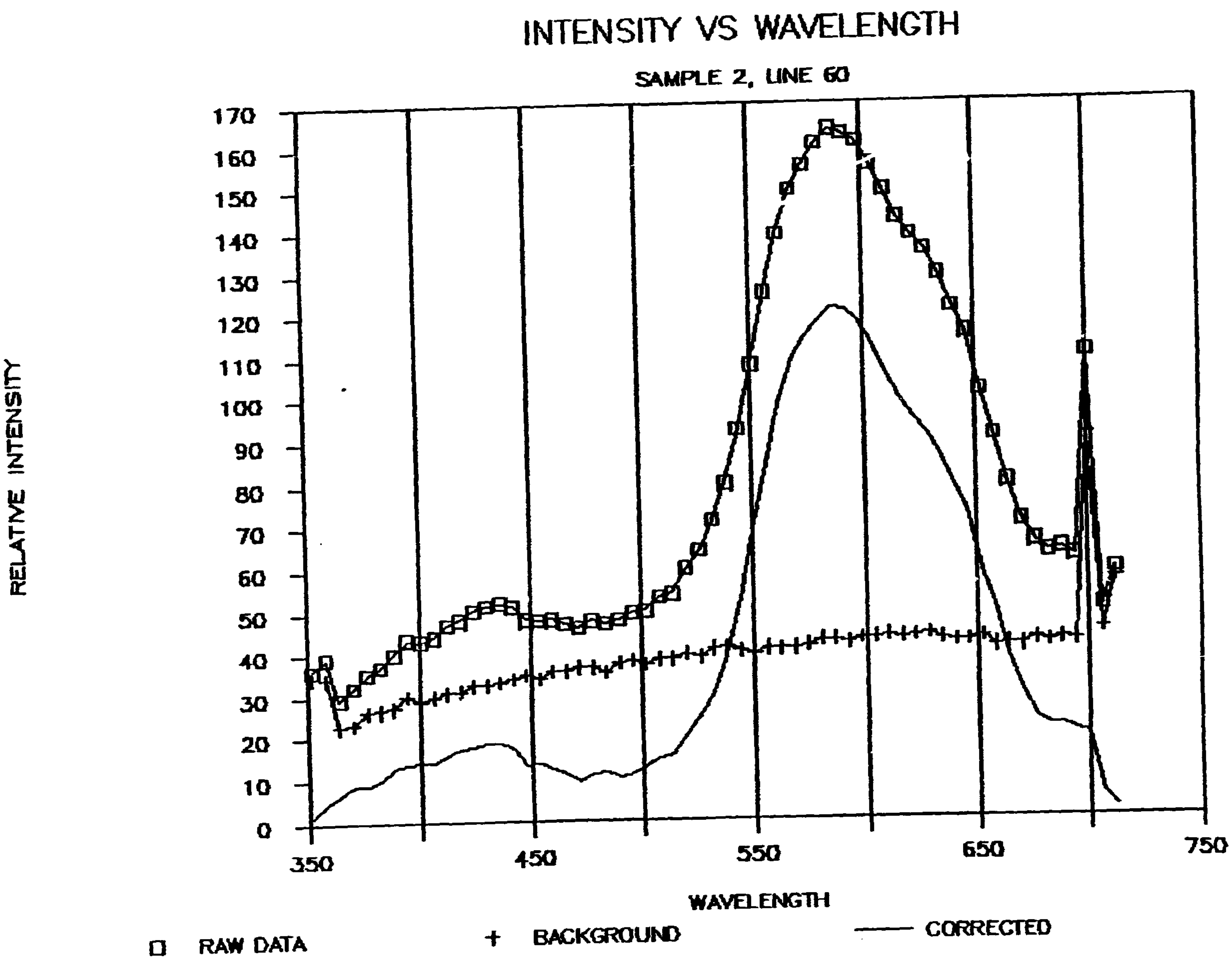


Figure 5-23

End of Transition

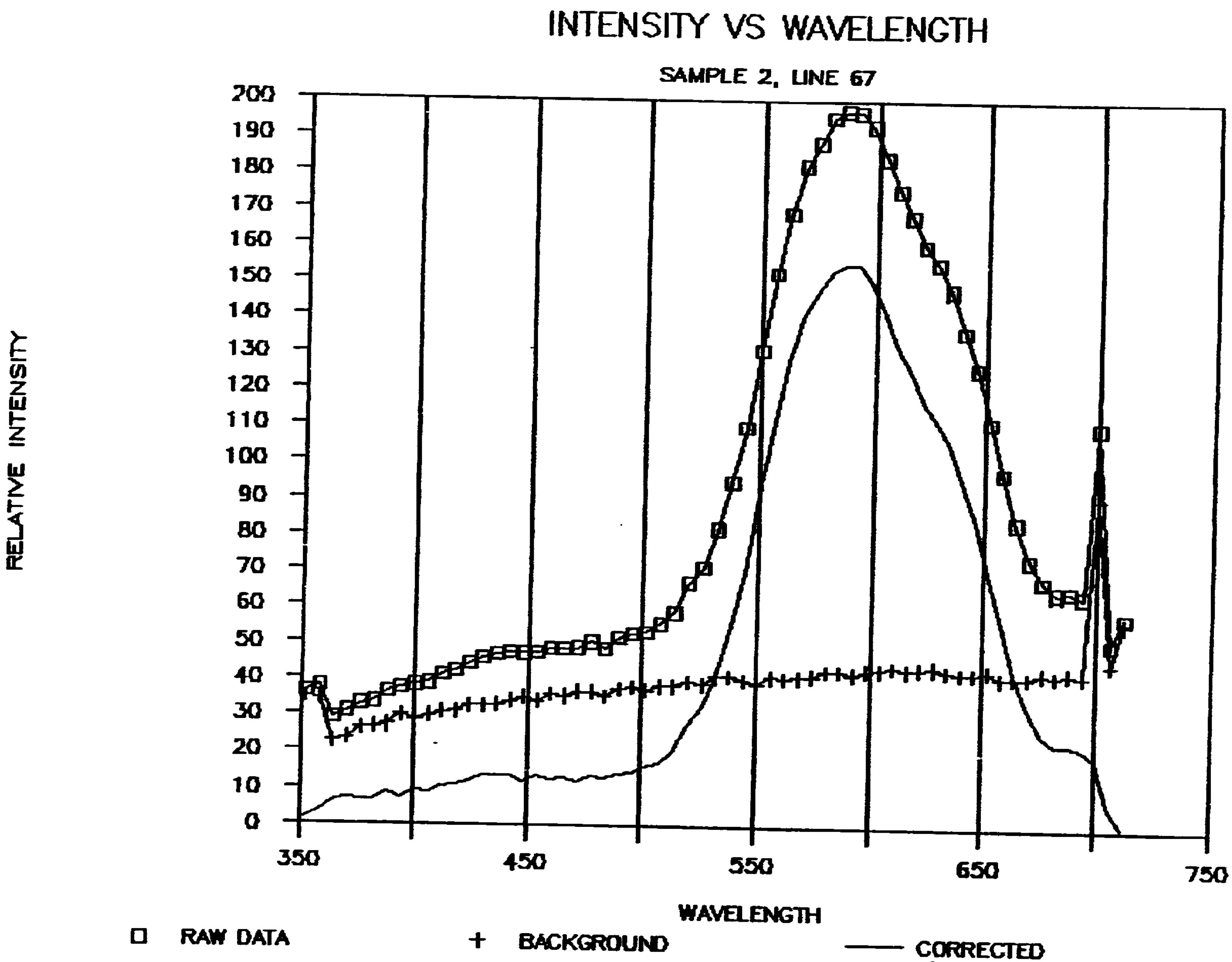


Figure 5-24

Orange

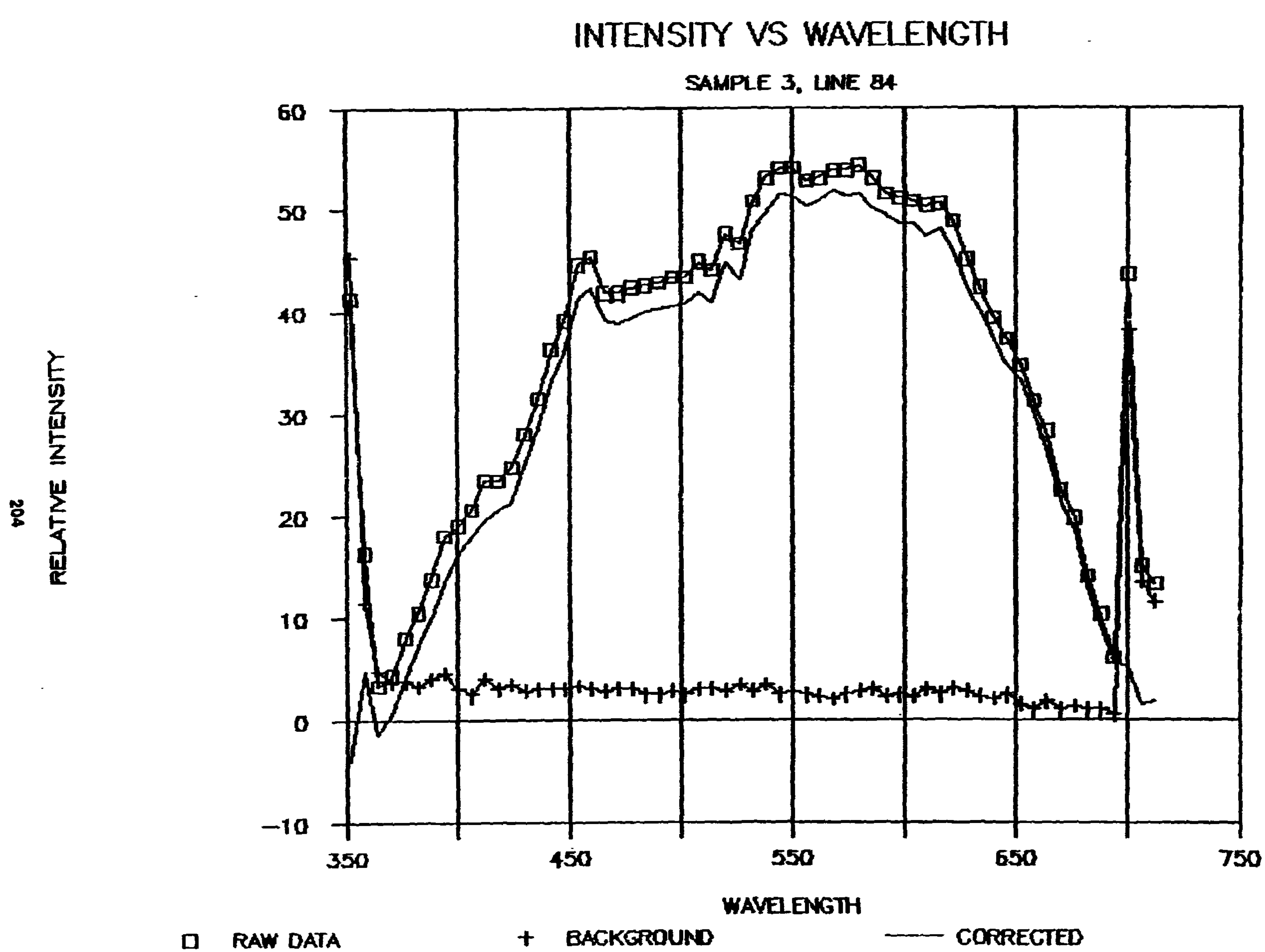


Figure 5-25

Grey

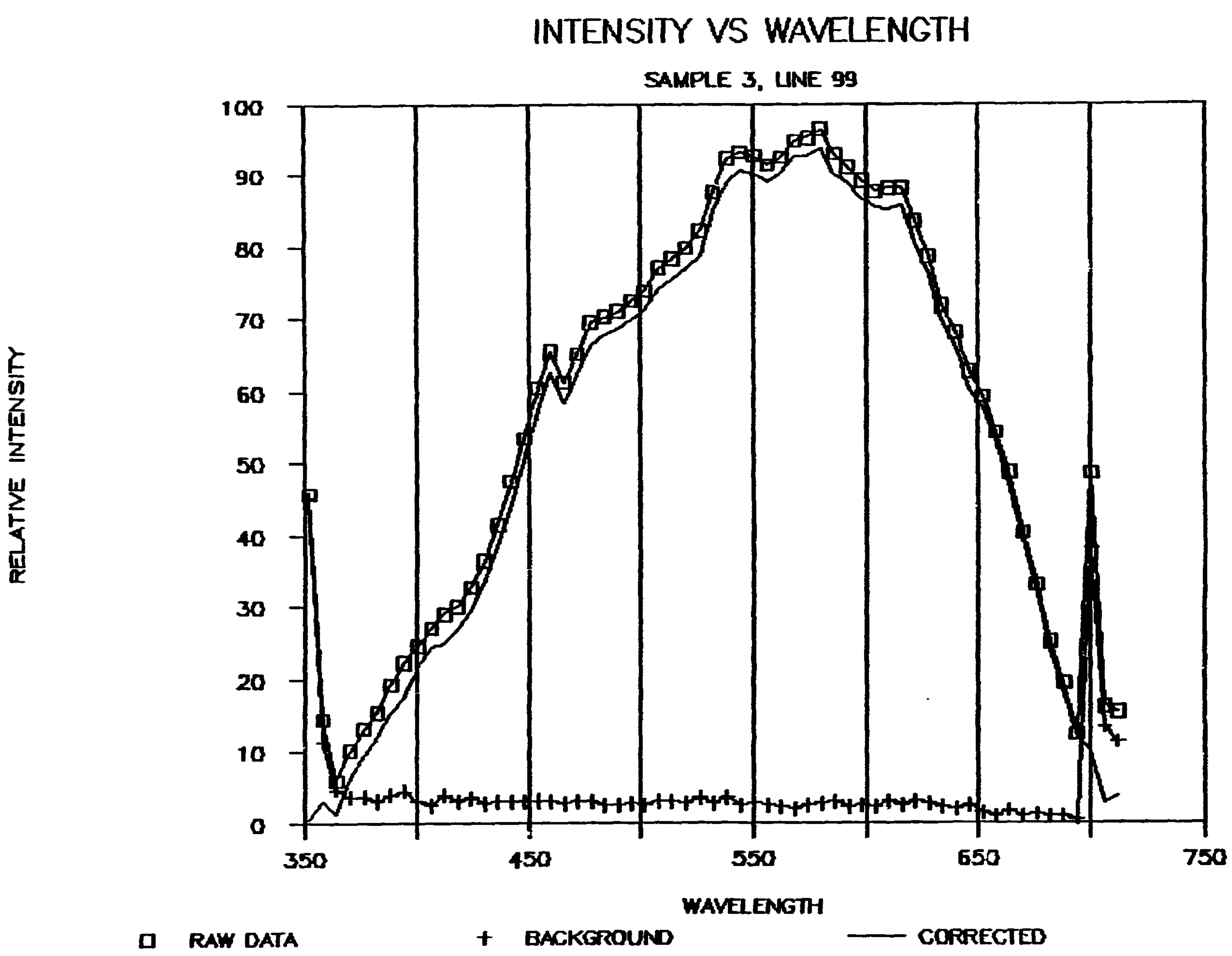


Figure 5-26

Transition

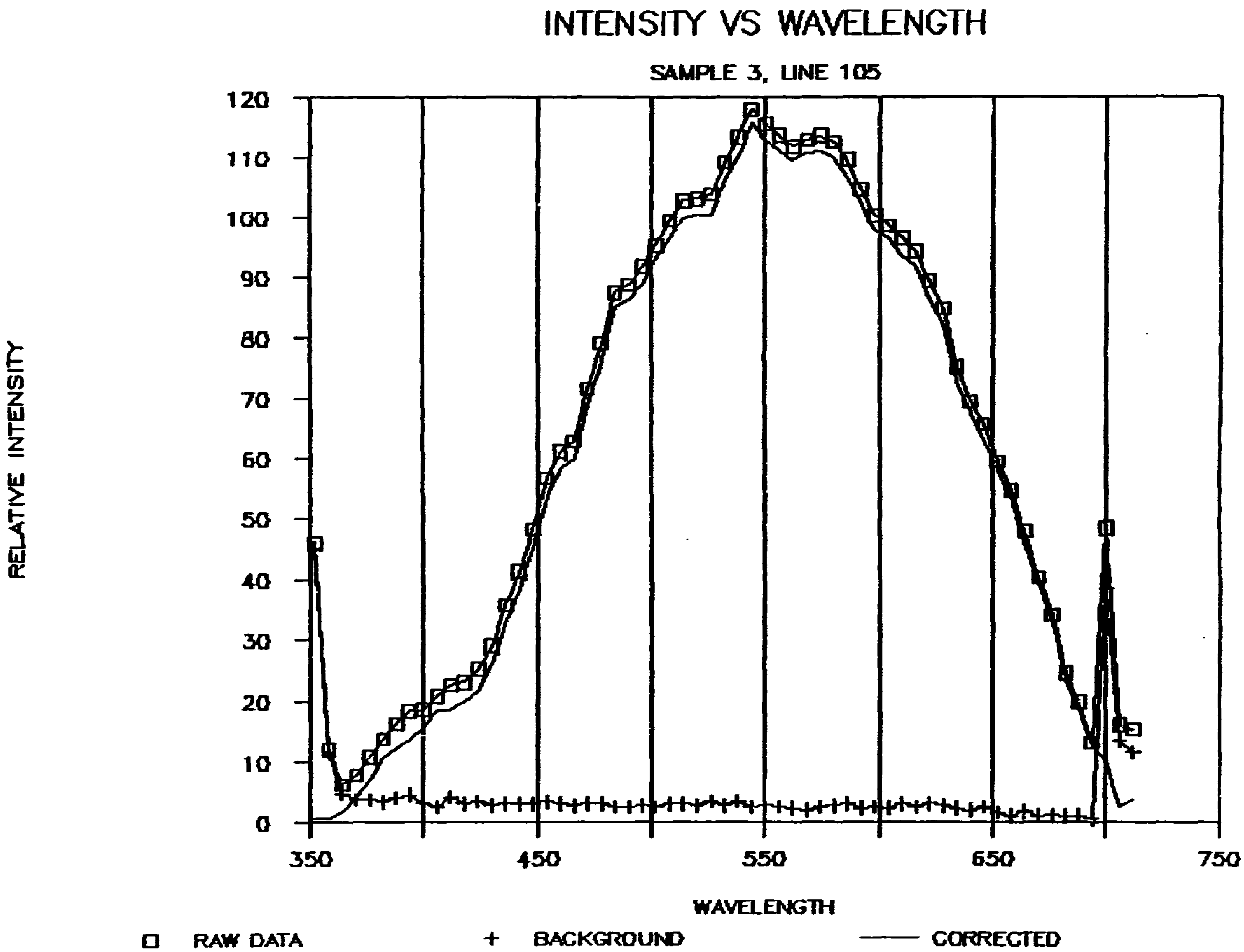


Figure 5-27

Yellow

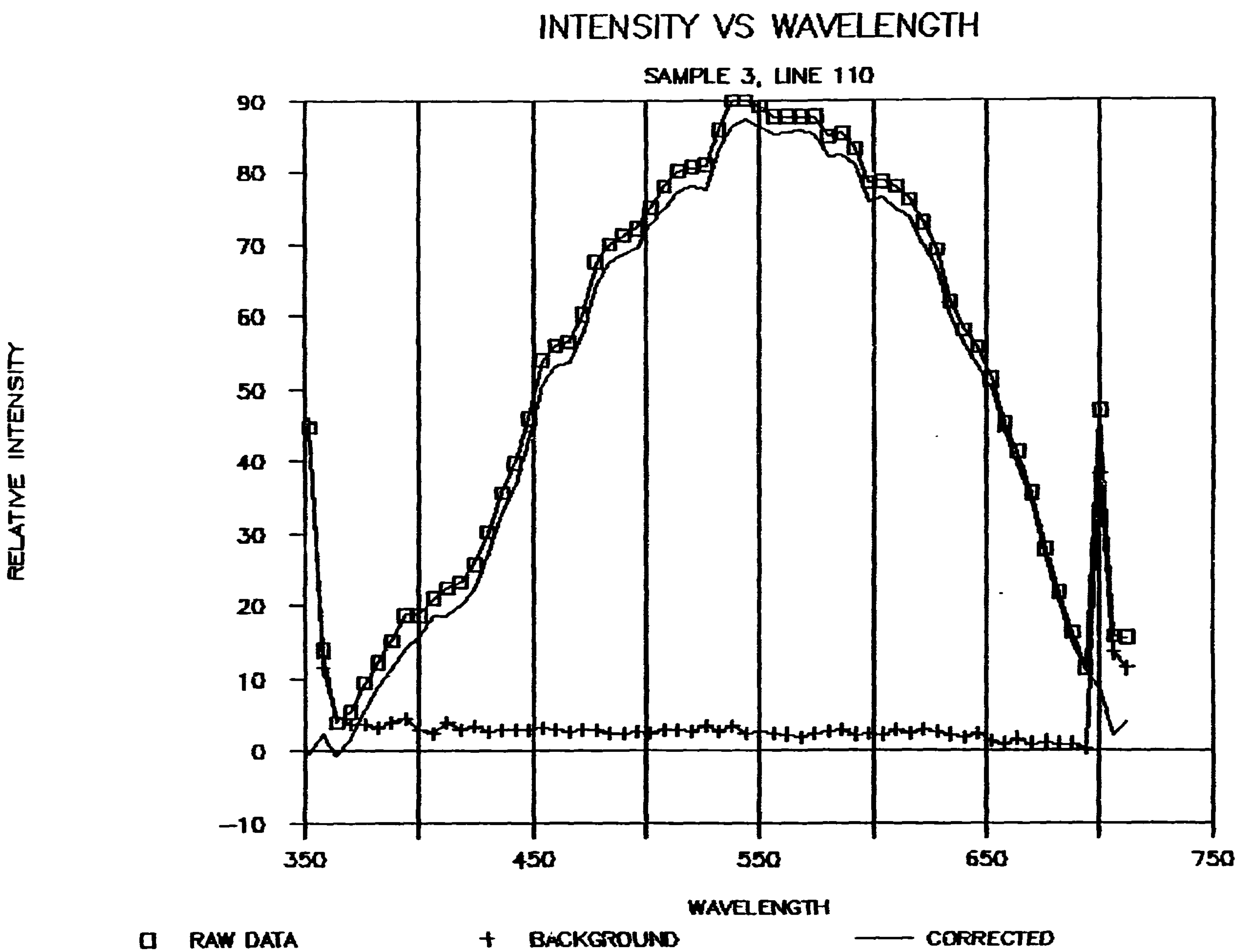


Figure 5-28

Transition

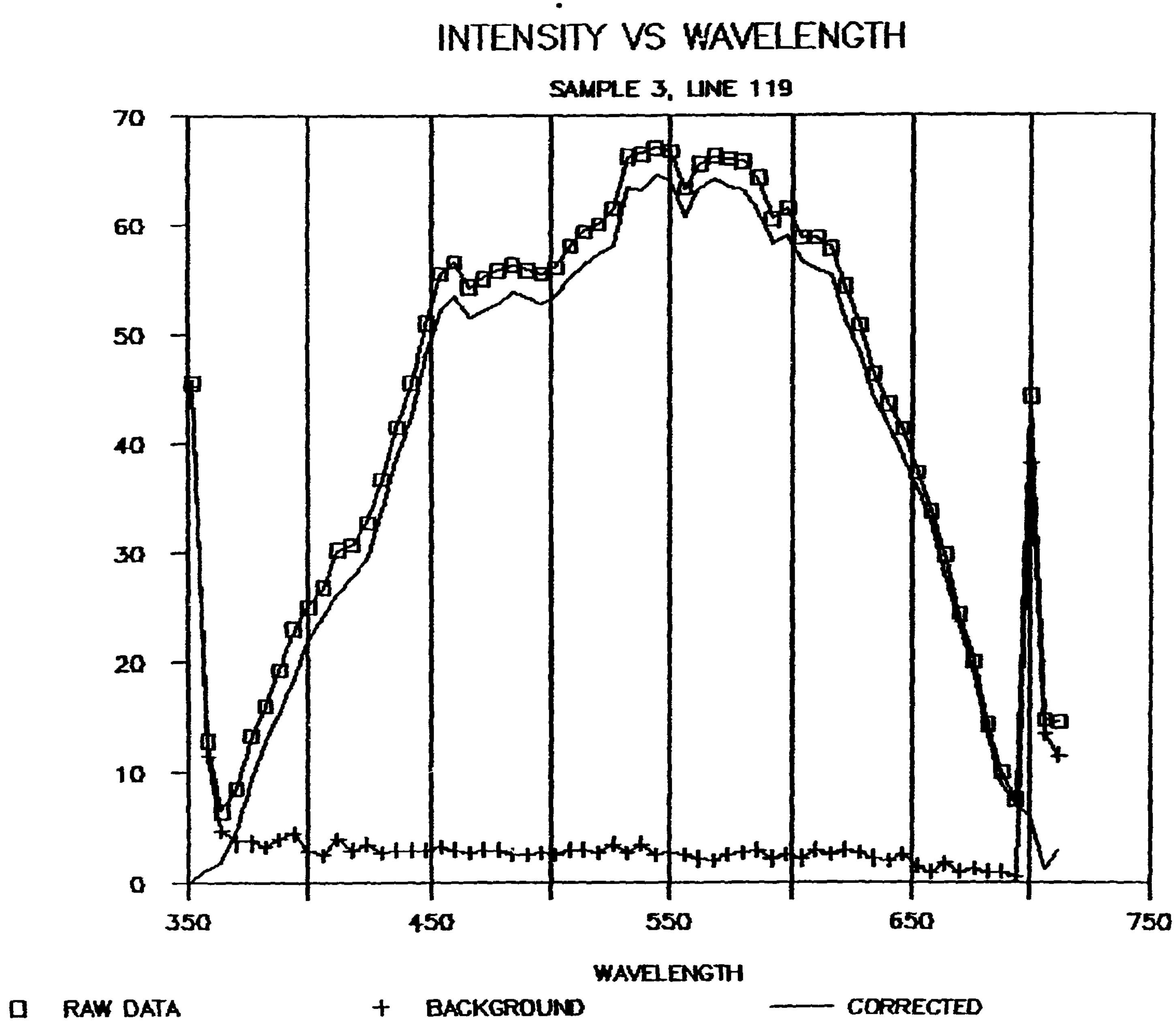


Figure 5-29

Grey

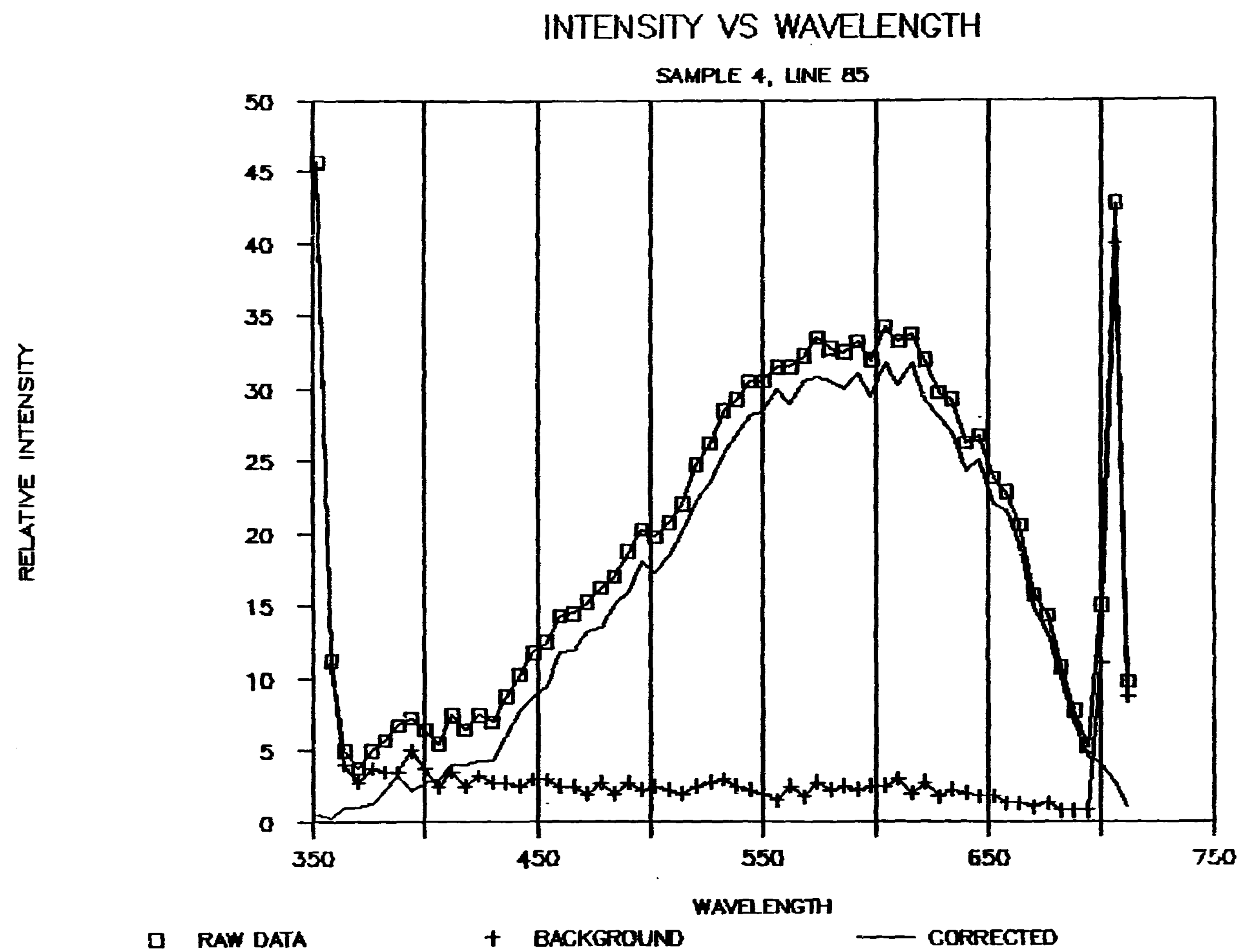


Figure 5-30

Dark Green

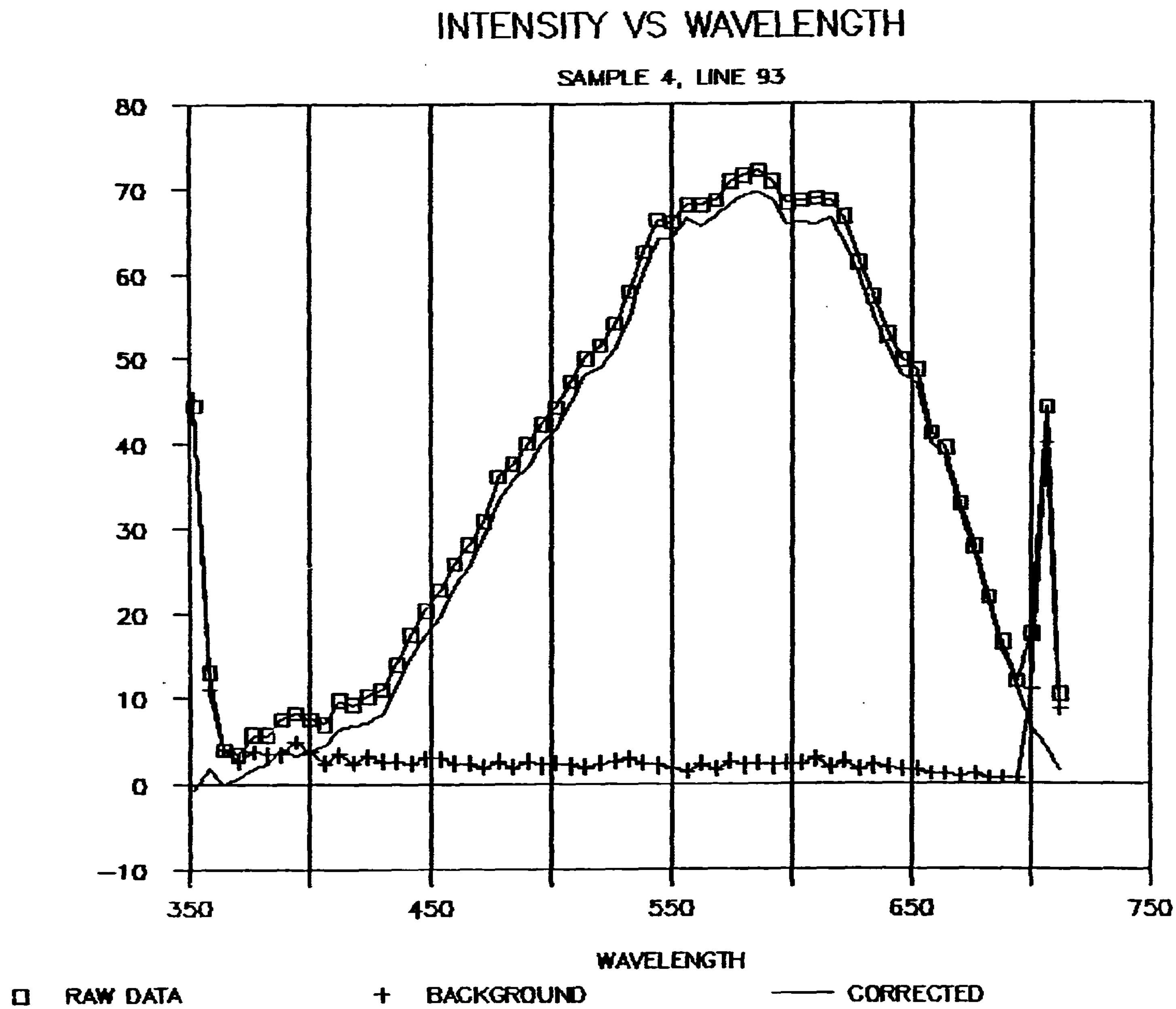


Figure 5-31

TRANSITION

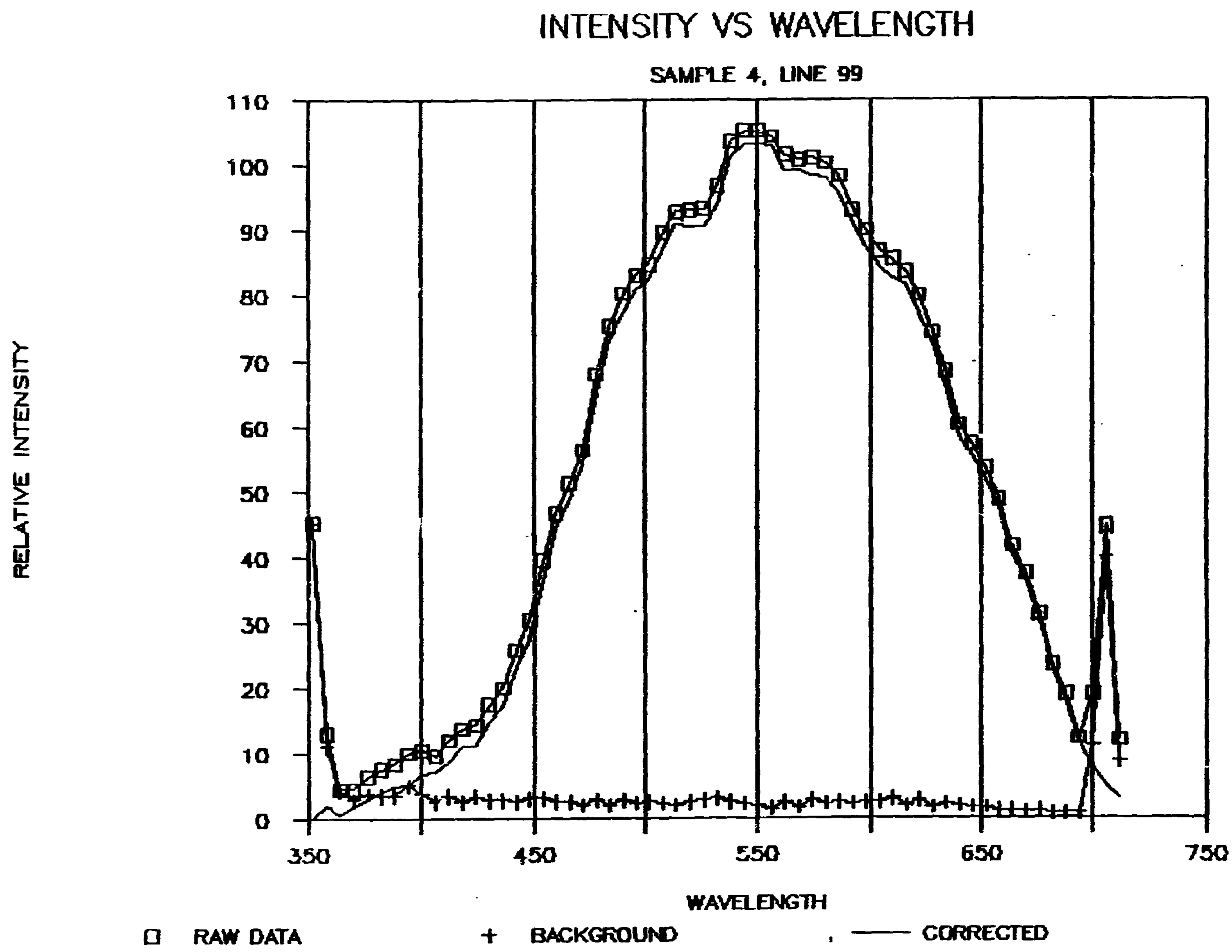


Figure 5-32

Yellow

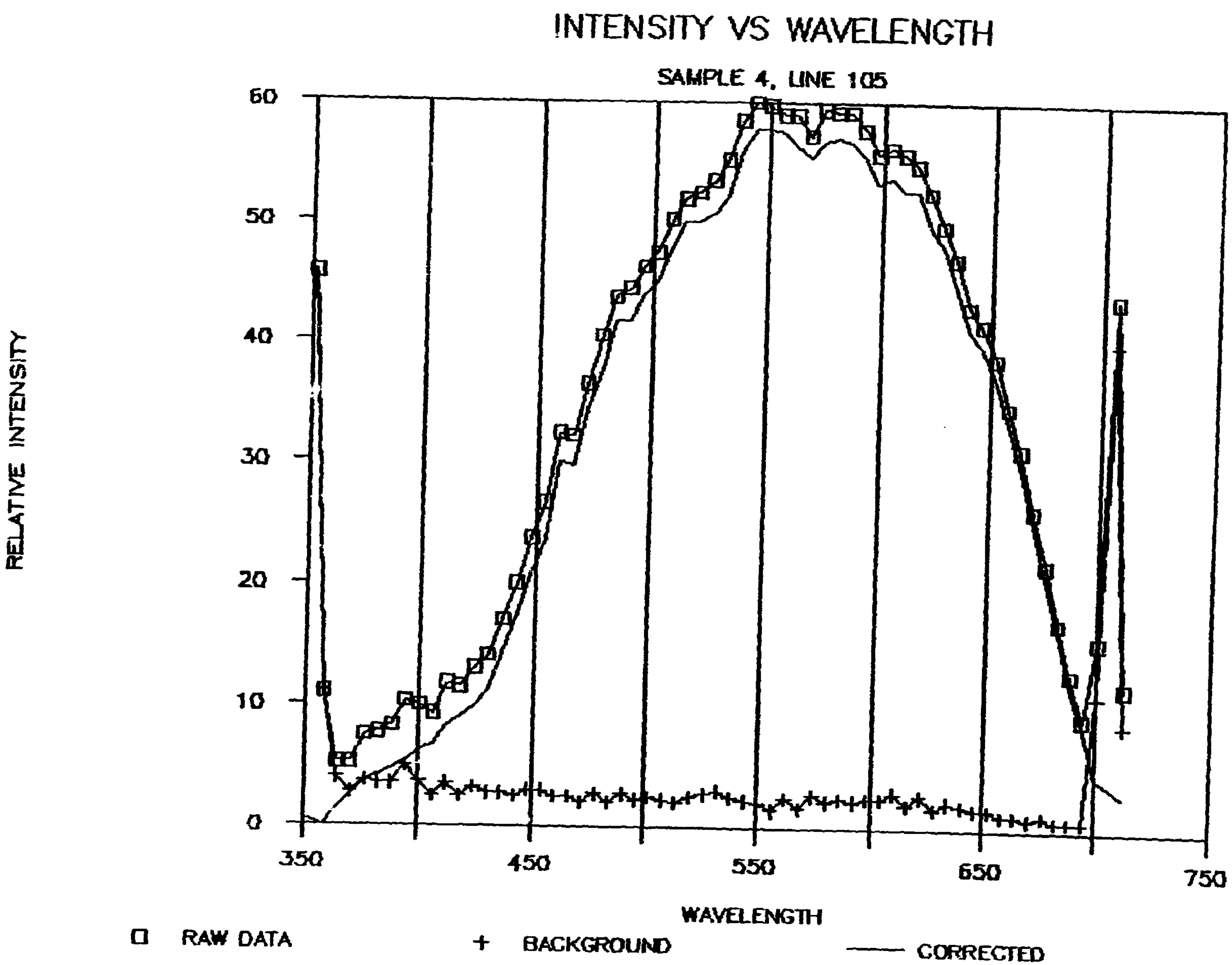


Figure 5-33

Transition

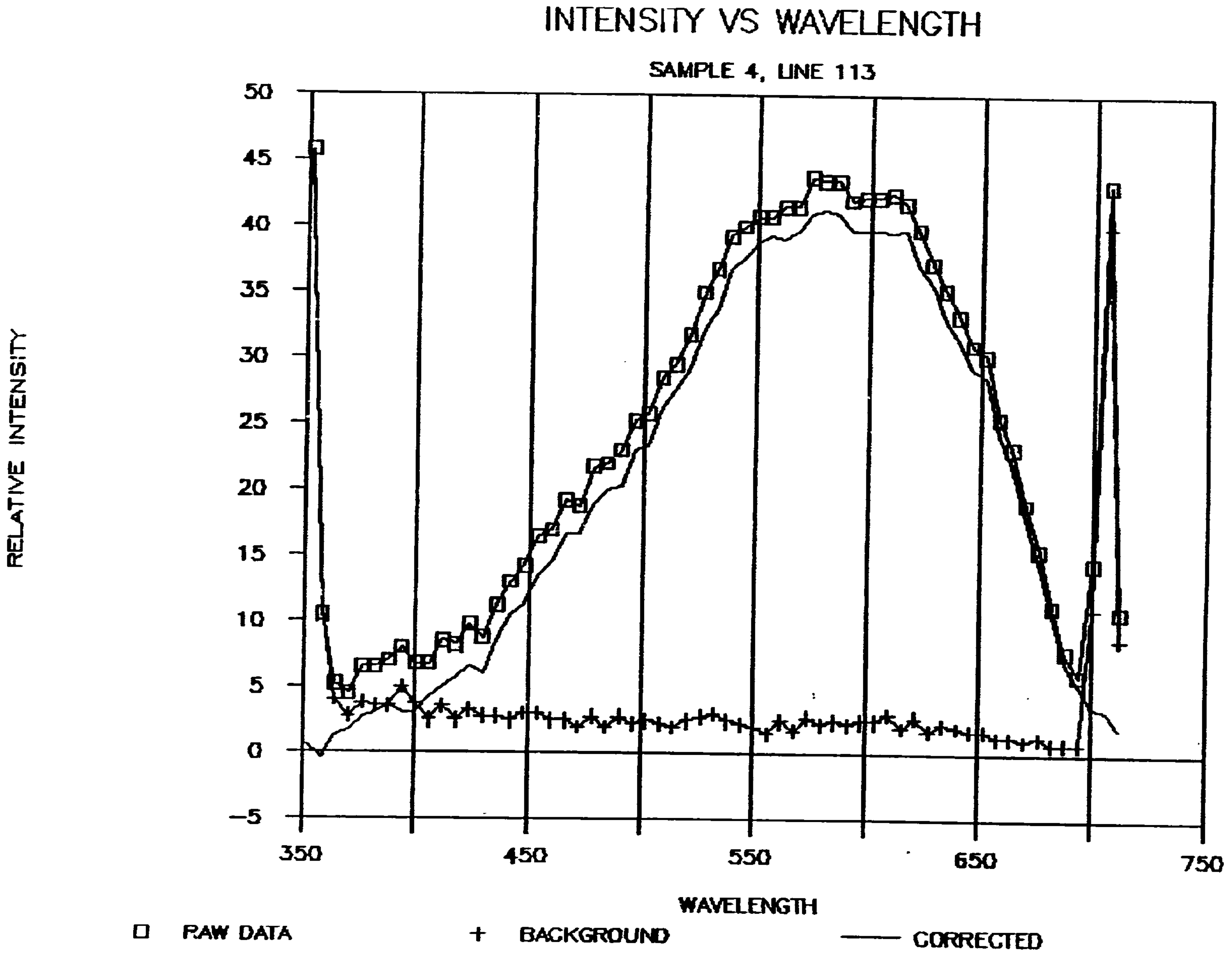


Figure 5-34

Dark Green

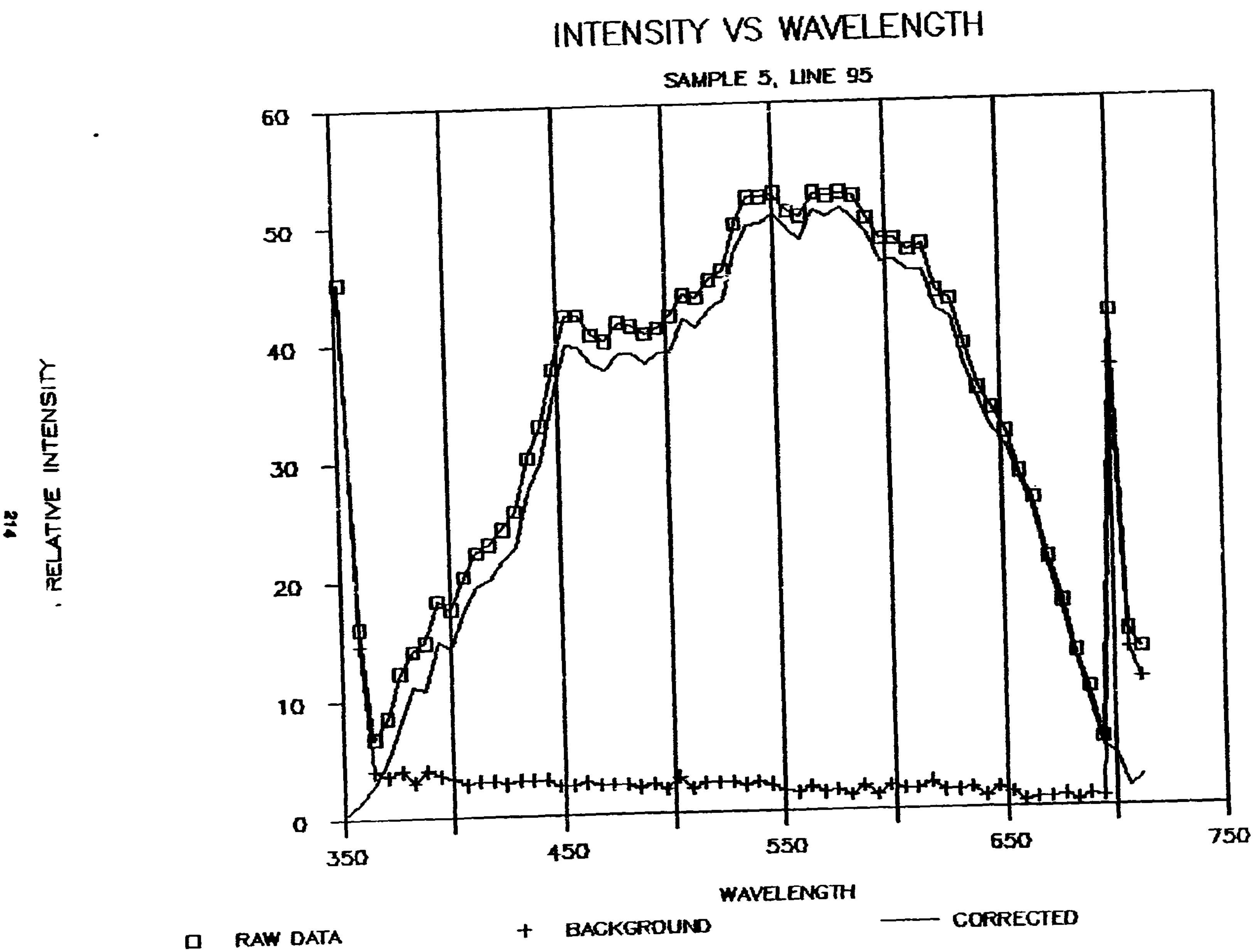


Figure 5-35

Aluminum

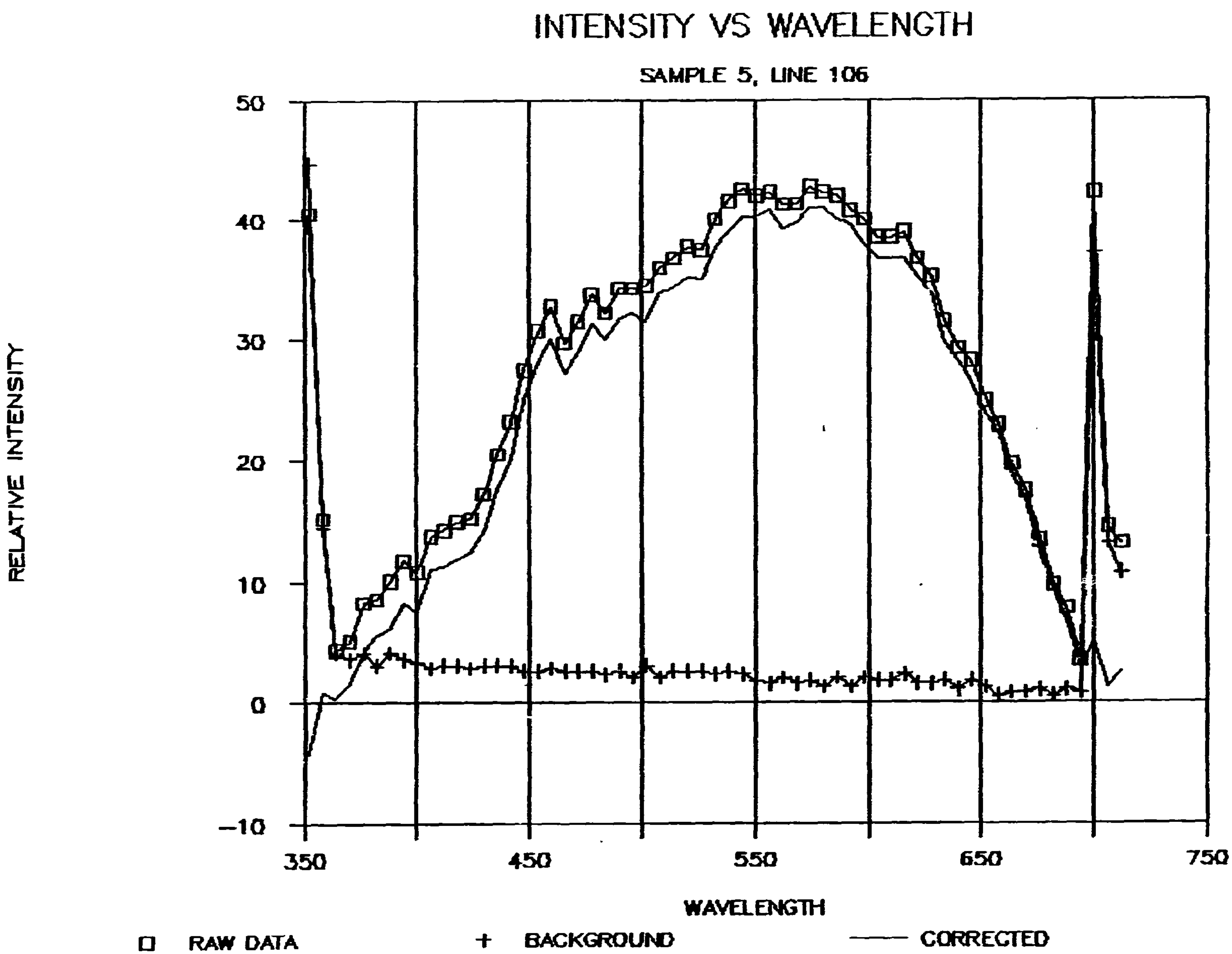


Figure 5-36

Transition

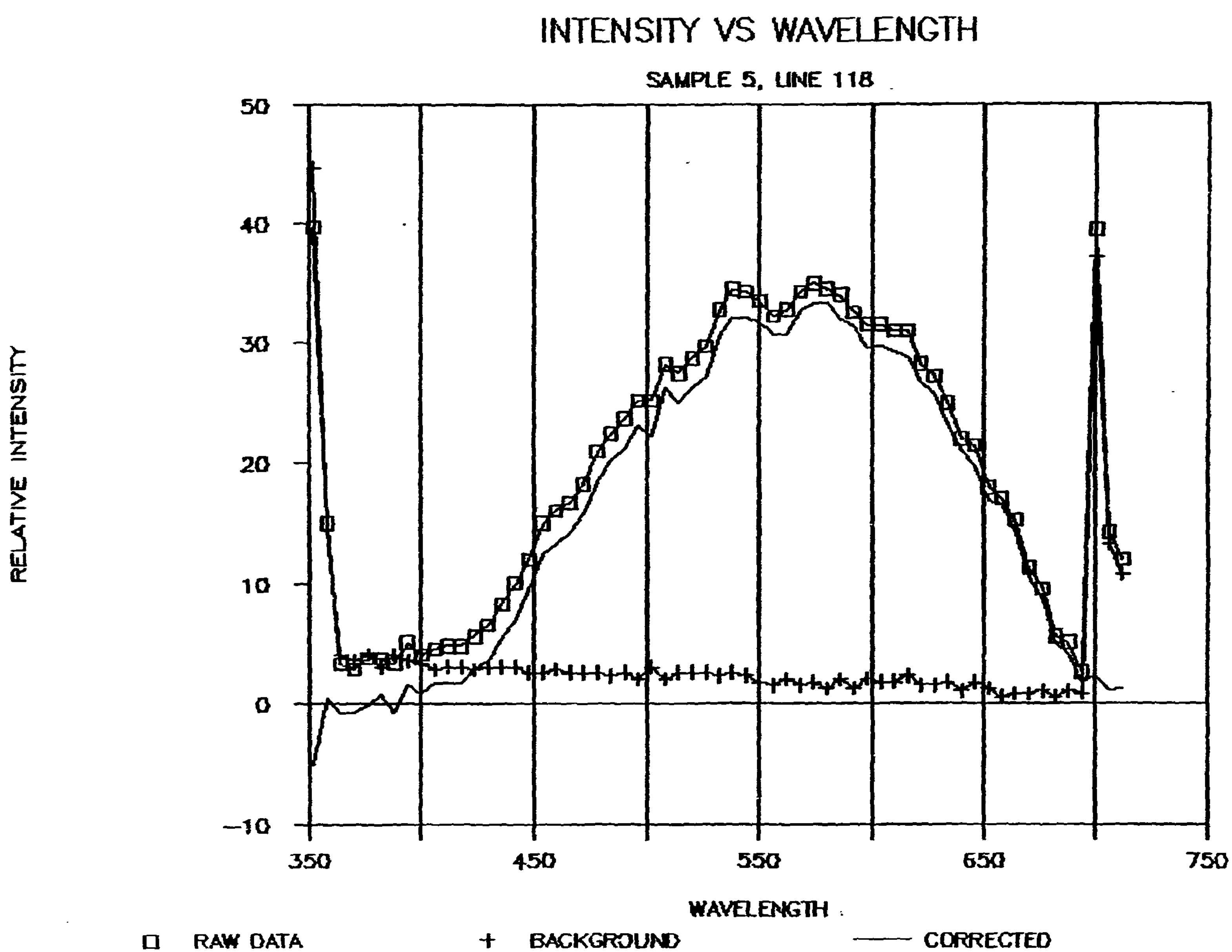


Figure 5-37

Yellow

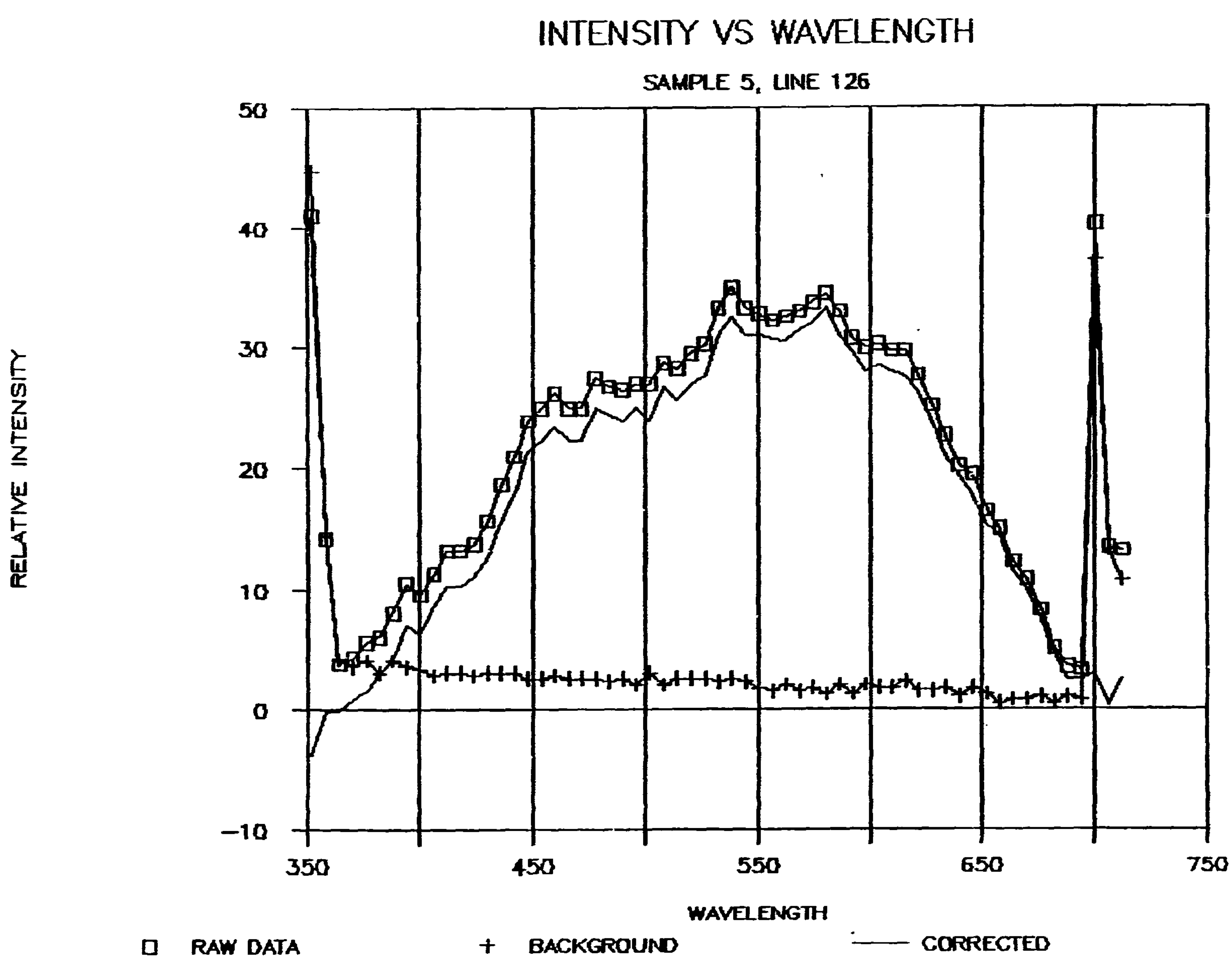

INTENSITY VS WAVELENGTH
SAMPLE 5, LINE 126
RELATIVE INTENSITY
50
40
30
20
10
0
−10
350
450
550
650
750
WAVELENGTH
RAW DATA
BACKGROUND
CORRECTED

Figure 5-38

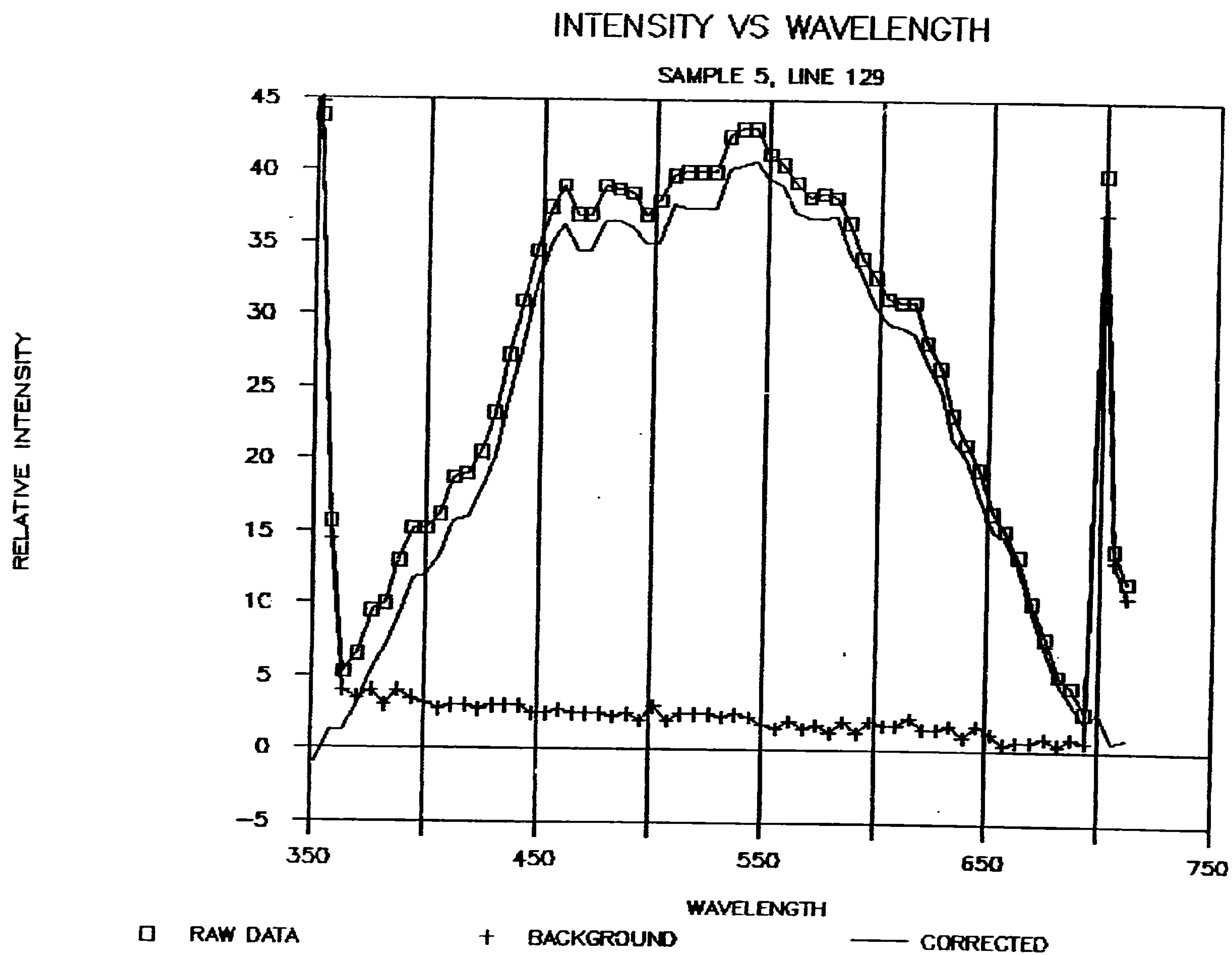


Figure 5-39

Aluminum

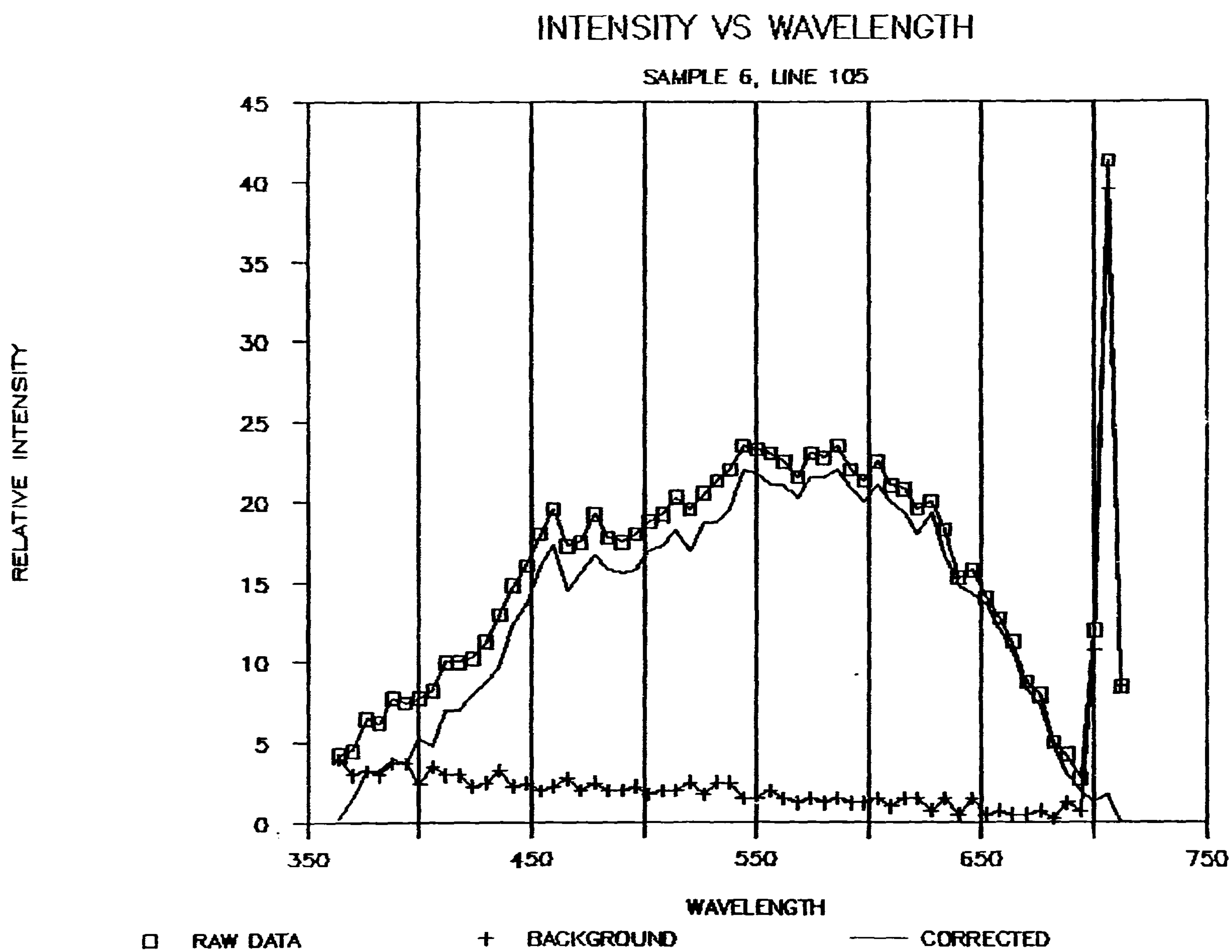


Figure 5-40

Composite Back

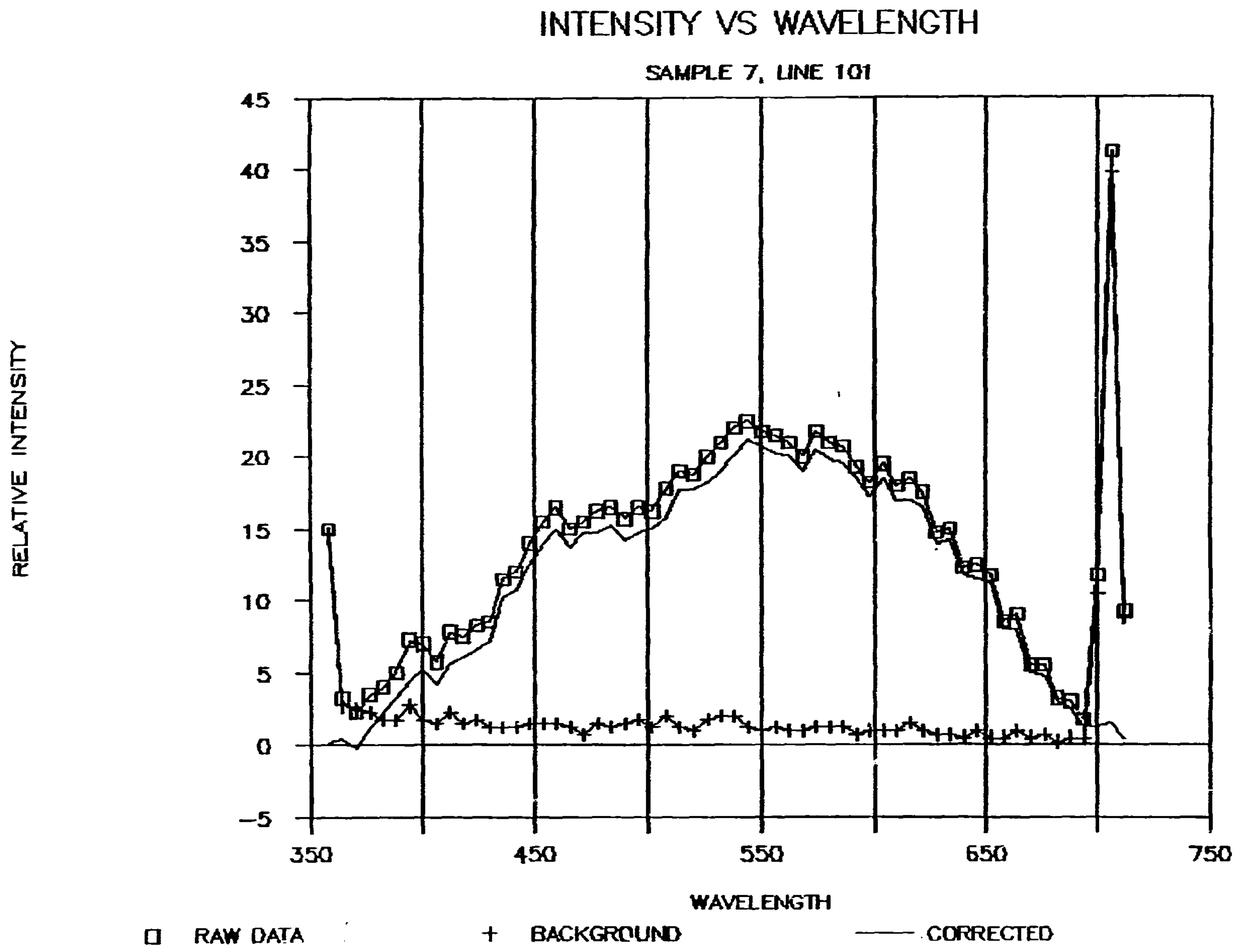


Figure 5-41

Composite Front

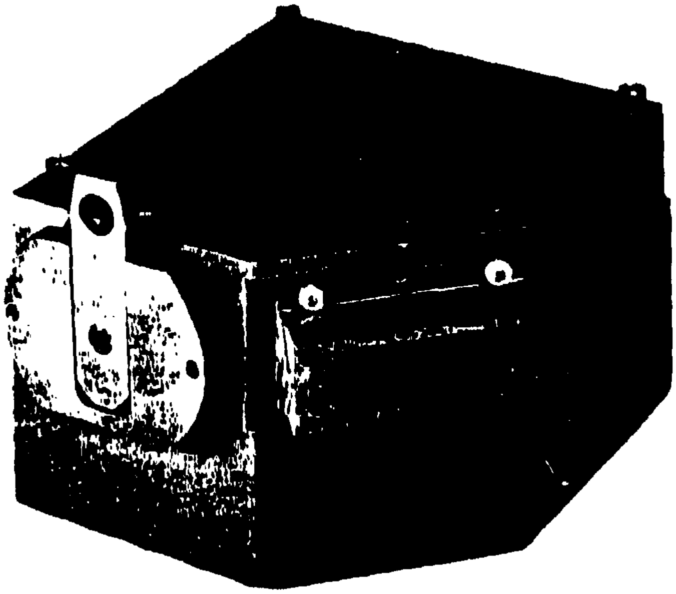
Appendix A

CHEMSPEC **SPECTROMETER** 100S

AMERICAN HOLOGRAPHIC

CHEMSPEC 100S
CONCAVE HOLOGRAPHIC DIFFRACTION GRATINGS

This high performance, compact, rugged, spectrometer/spectrograph is designed for use with a variety of multi-channel diode array detectors.



At last, a Versatile tool for the Instrument Developer

The CHEMSPEC 100S is a Research or Development instrument for the:

BIO-MEDICAL INSTRUMENT DESIGNER

INDUSTRIAL CHEMIST

ELECTRO-OPTICAL ENGINEER

UNIVERSITY RESEARCHER

AMERICAN HOLOGRAPHIC QUALITY

The CHEMSPEC 100S has the largest selection of aberration corrected Holographic Diffraction Gratings available in any commercial spectrometer. All AMERICAN HOLOGRAPHIC gratings are original master quality to insure the lowest stray light levels possible in a small instrument.

CURRENT APPLICATIONS:

ABSORPTION SPECTROSCOPY	CLINICAL CHEMISTRY
FLUORESCENCE	EMISSION SPECTROSCOPY
COLORIMETRY	HPLC DETECTION

Chemspec 100S SPECTROMETER

FEATURES

- HIGH THROUGHPUT · F/2.2
- 24 DIFFERENT HOLOGRAPHIC DIFFRACTION GRATINGS
- CONVENIENT DETECTOR MOUNTING BLOCKS FOR STANDARD DIODE ARRAYS
- CAST ALUMINUM HOUSING FOR MECHANICAL RIGIDITY
- INTERCHANGEABLE FIXED WIDTH ENTRANCE SLITS and/or FIBER OPTIC INPUT
- EXTERNAL FOCUS AND WAVELENGTH ADJUSTMENT

SELECTION OF YOUR 100S CONFIGURATION

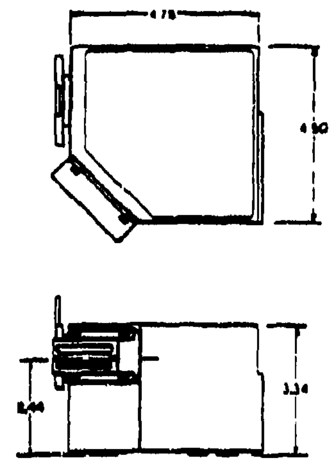
STEP 1: Select a diode array based upon the following requirements:

SPECTRAL RANGE
RESOLUTION
NUMBER OF ELEMENTS
COST

Determine the proper detector mount from Tables I and IV

STEP 2: Select the CHEMSPEC 100S Grating from Table II that produces the required spectrum over the length of the detector array

STEP 3: Choose the optical slit that matches the diode array pixel size. (Assume 1:1 ratio between slit and slit image.)



Flat Field Spectrograph Outline

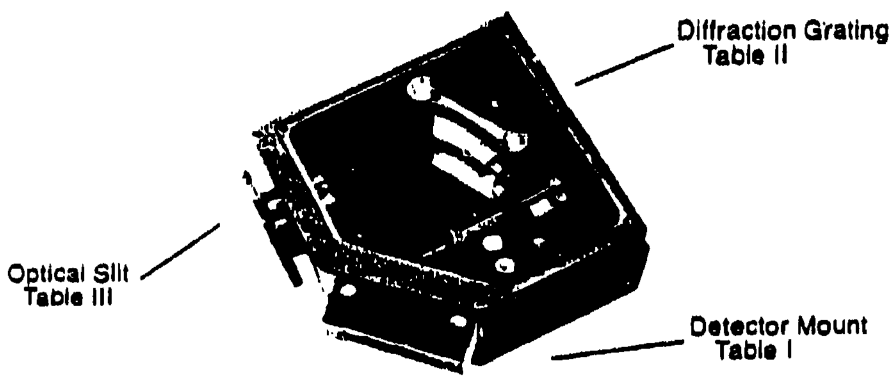


TABLE I

CHEMSPEC 100S DETECTOR MOUNT SELECTION:

Detector Mount Catalog #	Detector Package size Length	Height	Material	Typical Diode Array (See Table IV)
DM001	2.00"	628"	Delrin	35 or 38 element Hamamatsu
DM002	1.60"	41"	Delrin	25.4 mm Self Scanning Array
DM003	4.0" diameter round flange		Aluminum	Intensified Diode Arrays
DM004	2.1"	800"	Delrin	38 element United Detector
DM999	CUSTOM	(please specify)		

See TABLE IV for Diode Manufacturer Cross Reference Chart

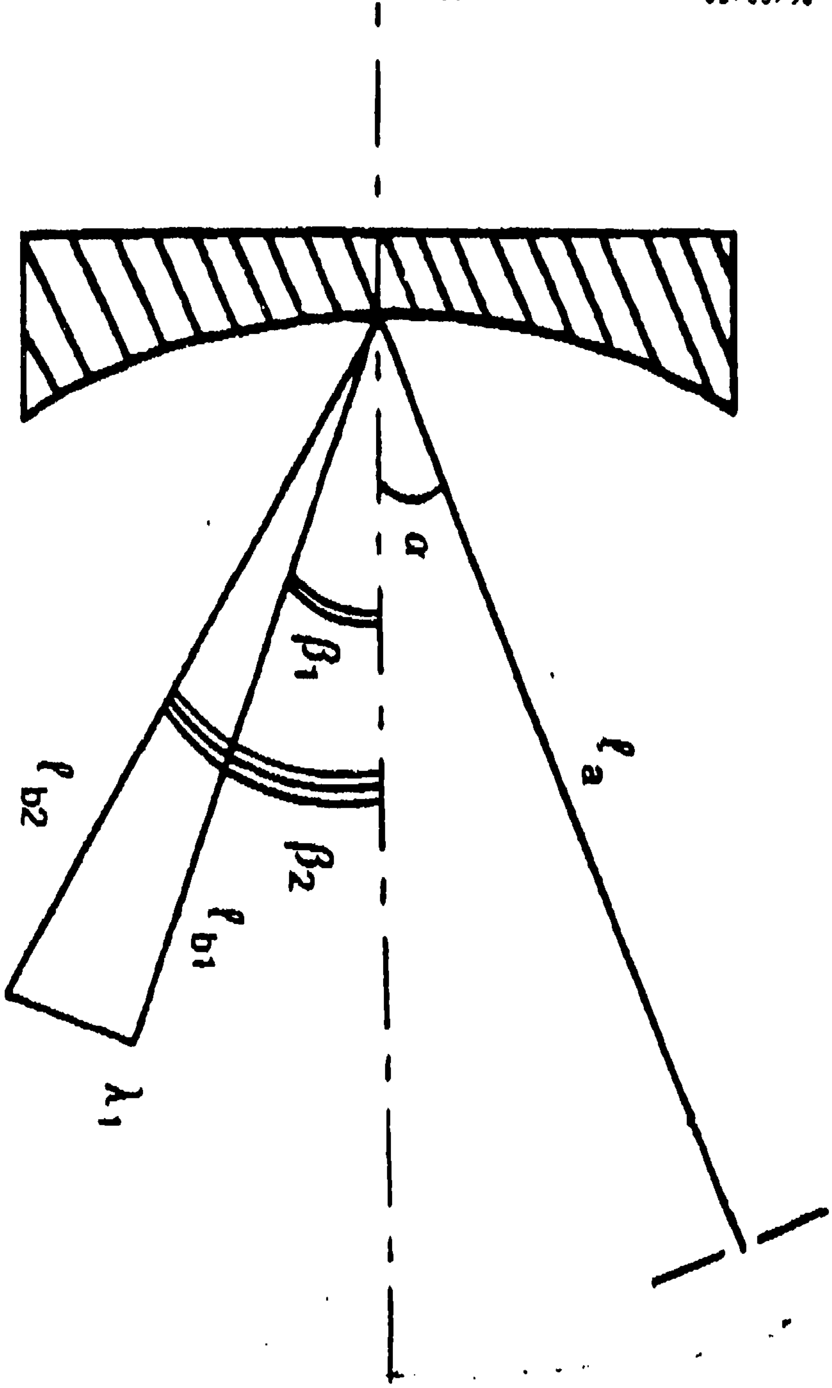
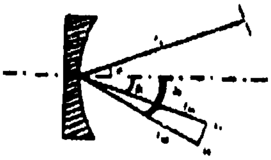

α
β1
β2
ℓa
ℓb1
ℓb2
λ1
λ2

Table 3. FLAT FIELD GRATING



For Array Detectors—Concave • Holographic • Original

Catalog #	Detector length (mm)	λ_1	λ_2	Linear Dispersion (nm/mm)	ℓ_a	σ	β_1	ℓ_{b1}	β_2	ℓ_{b2}	Groove per mm	F/#	Blank Dimensions (mm)
410.01	3.2	400	800	125	33.5	17	−11.7	34.2	−6.5	34.7	225	1.4	25 dia
430.01	18.0	380	740	20	206	7	−2.4	209.9	2.4	209.9	238	2	108 dia
440.01	25.4	200	1100	35	208	0	1.3	209.5	7.3	212.7	118	2	108 dia
440.02	25.4	200	900	27	209	0	1.7	209.4	7.7	211.4	150	2	108 dia
440.03	25.4	400	1100	27	208	0	3.4	212.0	9.5	216.6	150	2	108 dia
440.04	25.4	100	300	8	208	2	−4.8	210.9	−10.6	217.0	500	2	108 dia
440.05	25.4	200	400	8	208	2	−7.7	214.6	−13.6	219.2	500	2	108 dia
446.01	25.4	200	400	8	93.6	12.4	−25.5	97.3	−40.3	97.3	1080	2.2	37 × 37
446.02	25.4	300	500	8	96.5	9.5	−28.5	97.4	−43.2	97.4	1040	2.2	37 × 37
446.03	25.4	400	600	8	99.3	6.8	−31.2	97.6	−45.9	97.6	1000	2.2	37 × 37
446.04	25.4	500	700	8	100.1	4.3	−33.7	97.9	−48.4	97.6	1000	2.2	37 × 37
446.05	25.4	600	800	8	101.4	1.8	−36.2	98.1	−50.9	97.5	960	2.2	37 × 37
446.06	25.4	385	585	8	99.0	7.3	−30.8	97.3	−45.4	98.0	930	2.2	37 × 37
										97.2	1000	2.2	37 × 37
446.10	25.4	200	500	12	91.2	14.4	−23.4	97.2	−38.3	97.2	740	2.2	37 × 37
446.11	25.4	340	640	12	94.5	11.6	−26.3	97.3	−41.0	97.3	710	2.2	37 × 37
446.12	25.4	400	700	12	95.9	10.3	−27.6	97.4	−42.5	97.4	710	2.2	37 × 37
446.13	25.4	500	800	12	97.7	8.5	−29.5	97.6	−44.3	97.5	690	2.2	37 × 37
446.14	25.4	600	900	12	99.2	6.7	−31.3	97.7	−46.0	97.7	670	2.2	37 × 37
446.15	25.4	270	570	12	92.5	13.2	−24.8	97.4	−39.3	97.1	710	2.2	37 × 37
446.20	25.4	200	600	16	89.9	15.5	−22.3	97.2	−37.2	97.3	580	2.2	37 × 37
446.21	25.4	340	740	16	92.7	13.2	−24.6	97.2	−39.5	97.2	550	2.2	37 × 37
446.22	25.4	600	1000	16	96.9	9.5	−28.5	97.4	−43.2	97.4	520	2.2	37 × 37
446.30	25.4	200	700	20	89.2	16.2	−21.6	97.1	−36.4	97.1	460	2.2	37 × 37
446.31	25.4	300	800	20	90.8	14.8	−22.9	97.2	−37.9	97.2	450	2.2	37 × 37
446.32	25.4	340	840	20	91.2	14.4	−23.5	97.3	−38.2	97.2	440	2.2	37 × 37
446.33	25.4	400	900	20	92.0	13.6	−24.3	97.3	−39.1	97.2	440	2.2	37 × 37
446.34	25.4	500	1000	20	93.5	12.5	−25.5	97.4	−40.2	97.3	430	2.2	37 × 37
446.40	25.4	200	800	25	88.6	16.7	−21.2	97.1	−35.9	97.1	376	2.2	37 × 37
446.41	25.4	500	1100	25	92.4	13.4	−24.5	97.3	−39.3	97.3	355	2.2	37 × 37
446.42	25.4	340	940	25	90.7	15.1	−22.7	97.0	−37.0	97.2	365	2.2	37 × 37
446.50	25.4	190	1065	35	87.7	17.4	−20.4	97.1	−35.3	97.1	260	2.2	37 × 37
448.01	25.4	200	1400	48	210	9	−7.9	206.4	−1.0	208.4	100	2.3	91 dia
448.02	25.4	200	1200	40	210	9	−7.8	206.4	−0.9	208.4	120	2.3	91 dia
448.03	25.4	300	1200	36	210	9	−7.3	206.4	−0.4	208.4	133	2.3	91 dia
448.04	25.4	200	800	24	210	9	−7.3	206.4	−0.4	208.4	200	2.3	91 dia
448.05	25.4	400	600	16	210	12	−4.8	206.4	2.0	208.4	300	2.3	91 dia
448.06	25.4	200	400	8	210	12	−5.0	206.4	1.9	208.4	600	2.3	91 dia
447.01	32.6	400	900	15	152	2	6.6	161.0	17.6	169.0	378	1.8	85 dia
450.02	35.0	380	720	10	160	3	8.1	163.0	18.3	180.4	510	2	85 dia
452.01	46.0	340	690	7.6	168	28.5	−14.3	191.2	−0.6	185.2	675	2	108 dia
452.02	46.0	340	710	7.9	204	16.5	−4.7	212.3	7.8	211	593	2.3	91 dia
455.01	75.0	240	800	7	212	3	−11.1	227.99	−30.1	275.0	550	2	108 dia
460.01	127.0	380	720	3	480	8	−19.2	486.6	−29.9	559.4	500	4.4	108 dia

In addition to the high quality flat field gratings shown above, American Holographic offers a variety of spectrographs and detector packages for both research and OEM. Call our sales department today for details.

Appendix B

Section 2

Camera Specifications

2.0 MC9000 Series Camera Specifications

2.1 Mechanical

Weight	12 ounces (340 grams, excluding lens, extension tubes, etc.
Dimensions	See Figure 1

2.2 Optical

2.2.1 MC9128

Sensor	MOS
Resolution	16,384 pixels (128 x 128)
Active Area	7.68 x 7.68 mm (.30" x .30")
Pixel Spacing	60 μmeter (center-to-center)
Saturation Exposure	0.155 μjoule/cm^2 (test light source @ 2870°K, typical)

2.2.2 MC91256

Sensor	MOS
Resolution	65,536 pixels (256 x 256)
Active Area	10.24 x 10.24 mm (.40" x .40")
Pixel Spacing	40 μmeter (center-to-center)
Saturation Exposure	0.4 μjoule/cm^2 (test light source @ 2870°K, typical)

2.3 Electrical

2.3.1 Power Inputs

Voltage/Current	+12V ±50 mV @ 300 mA -12V ±100 mV @ 300 mA +5V ±100 mV @ 500 mA
Power Consumption	<5 watts

2.3.2 MC9128 Differential Video (A) and (B) Outputs

Pixel Rate	525 KHz - 8 MHz
Frame Rate	25 - 380 frames/second
Line Flyback Period	36 clock cycles (minimum)
Frame Flyback Period	36 clock cycles (minimum)
Peak Saturated Video	1V ±100 mV (into 100Ω load) 2V ±200 mV (open circuit)

NOTE: Refer to Section 4.3 for a description of the recommended differential video line receiver and the output to be expected.

Sensor Photo Response Nonuniformity	±10% of saturated output
Dynamic Range	≥100:1 (defined as the ratio of saturation voltage to p-p dark pattern, @ 50 frames per second)

NOTE: The Dynamic Range specification excludes the first and last pixel of each line and the first and last line of each frame.

Signal to Noise	≥1000:1 (defined as the ratio of saturation voltage to peak random pixel noise)

2.3.3 MC9256 Differential Video (A) and (B) Outputs

Pixel Rate	1.9 MHz - 8 MHz
Frame Rate	25 - 105 frames/second
Line Flyback Period	36 clock cycles (minimum)
Frame Flyback Period	1201 clock cycles (minimum)
Peak Saturated Video	1V ±200 mV (into 100Ω load) 2V ±400 mV (open circuit)
Sensor Photo Response Nonuniformity	±10% of saturated output
Dynamic Range	≥100:1 (defined as the ratio of saturation voltage to p-p dark

	pattern, @ 50 frames per second)

NOTE: The Dynamic Range specification excludes the first and last pixel of each line and the first and last line of each frame.

Signal to Noise	≥1000:1 (defined as the ratio of saturation voltage to peak random pixel noise)
2.3.4 Differential Digital Signal Outputs	Conform to EIA-RS422 specifications (see Section 4)
2.3.5 Differential Digital Signal Inputs	To be driven by line drivers meeting EIA-RS422 specifications (see Section 4)

2.4 Environmental

Shock	20G
Vibration	3G, sinusoidal over 5 Hz to 150 Hz
Operation Temperature Range	0 to 50° celsius (measured at camera mounting baseplate)
Storage Temperature Range	-40 to +80° celsius

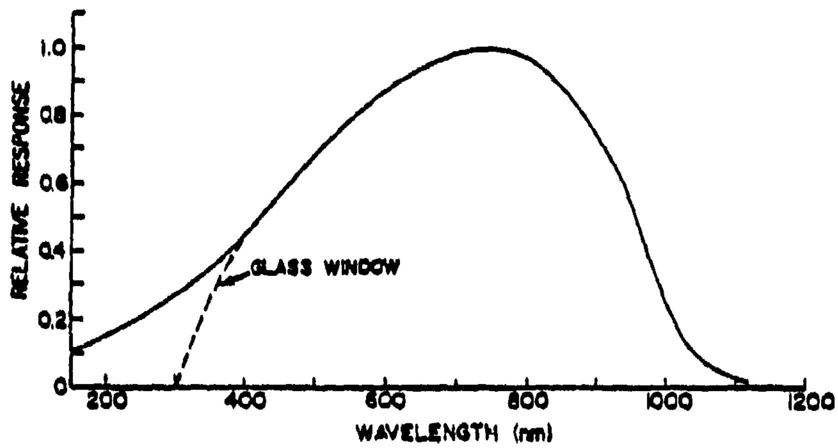


Figure 3. Spectral Response

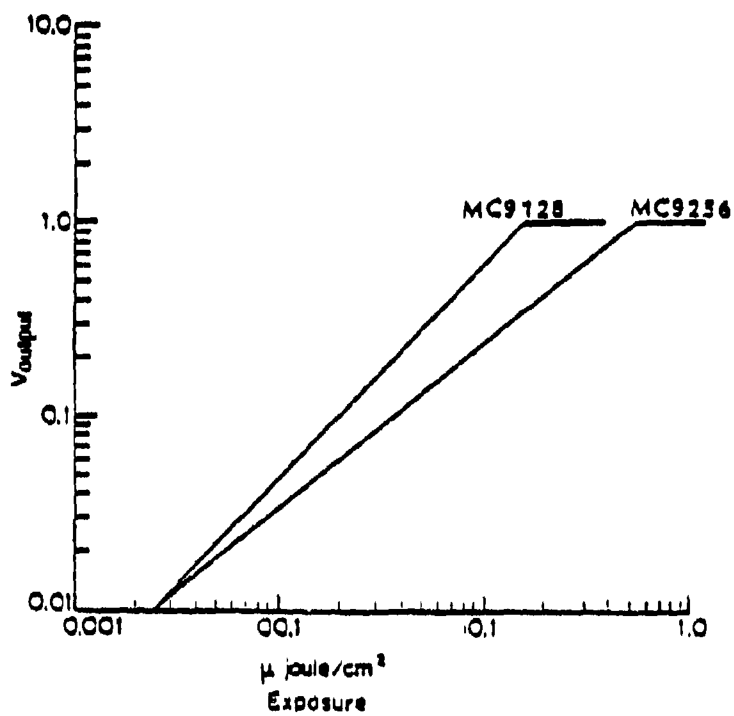


Figure 4. Saturation Exposure

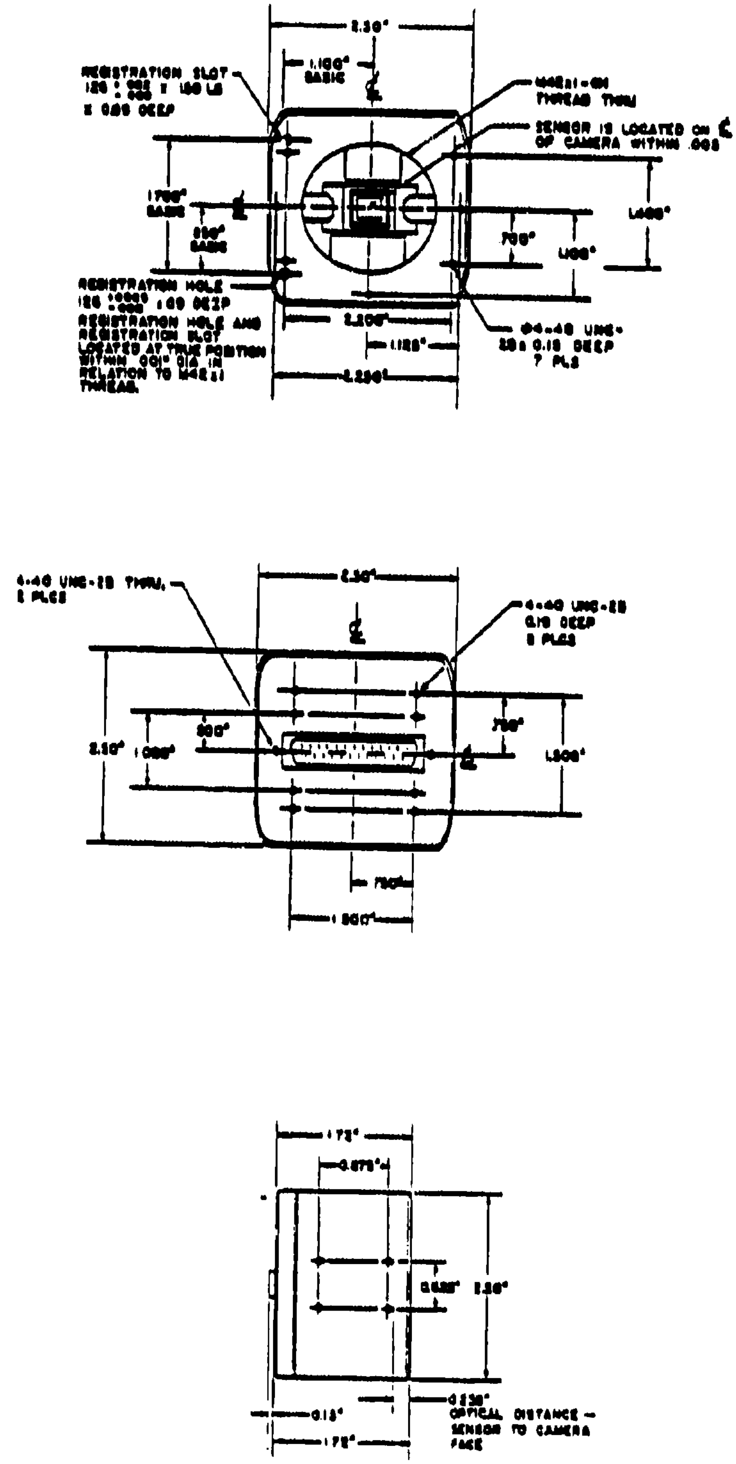


Figure 1. Camera Front, Back, and Side Views

Appendix C

1.2 MV1 SPECIFICATIONS

This section contains performance, physical, and environmental specifications for the MV1 board. Additionally, power requirements are provided. Refer to Chapter 3 for information regarding video input, video output, frame store memory, and host access specifications.

POWER REQUIREMENTS

+ 5 Vdc 2.50 A	
- 5 Vdc 185.00 mA	(**NOTE:** The PC's power supply must meet this specification.)

SIZE

13.3 " L x 4.25" H	(Occupies a full IBM PC/XT card slot.)
(33.78 cm. x 10.70 cm.)	

ENVIRONMENTAL

Storage Temperature:	-4° to +126° F (-20° to +70° C)
Operating Temperature:	+32° to +122° F (0° to +50° C)
Relative Humidity:	to 95%, non-condensing

VIDEO INPUT CHANNELS

3 input channels via DB15 connector
1 input channel via BNC connector

SYNC I/O

Horizontal and Vertical Sync I/O are TTL compatible and user-programmable as inputs or Outputs. A built-in Sync Stripper and Phase Locked Loop allow automatic synchronization to composite video signal.

EXTERNAL SAMPLE CLOCK OUTPUT/ MAIN CLOCK INPUT

User Programmable TTL External Clock input or TTL sample clock output with jumper selectable pin functions.

EXTERNAL BLANKING

User-programmable TTL external Blanking input allows area of interest capture of line to be externally controlled.

EXTERNAL INTERRUPT

User-programmable TTL negative edge interrupt allows acquisition to be externally controlled.

RS-343A VIDEO DISPLAY UNIT

Standard DB-9 connector output to VDU supplies RS-343A composite or separate sync output.

OUTPUT VIDEO DAC

Triple 8-bit high speed video DAC's produce over 16 million colors.
Can also support monochrome composite display with 256 shades of grey.

VIDEO DISPLAY STANDARDS

Board can be factory-configured for NTSC or CCIR compatible video displays.

VIDEO INPUT

NTSC, CCIR, RS-170, RS-330, and CCD Line/Frame cameras.

1.3 ORDERING INFORMATION

Table 1-1 provides the part numbers and a general description of each part associated with the MV1 Board. Detailed descriptions of the options and accessories are provided in Chapter 6.

Table 1-1. MV1 Ordering Information

MV1 Boards and Interface Boxes	
Part No.	**Description**
MV1-170	MV1 Frame/Line Grabber with RS-170 interface.
MV1-CCIR	MV1 Frame/Line Grabber with CCIR interface.
MVIB-1	Generic Interface Box.
MVIB-PS	Interface Box Power Supply.

Cameras	
Part No.	**Description**
JE2362	RS-170 CCD Camera w/ 16 mm a/i lens
CT-3800	RS-170 CCD Camera w/ 16 mm a/i lens
JE2352X	CCIR CCD Camera
CAM-PS	12 Vdc @ 300 mA wall-mount external power supply with screw terminal output connectors (for cameras)

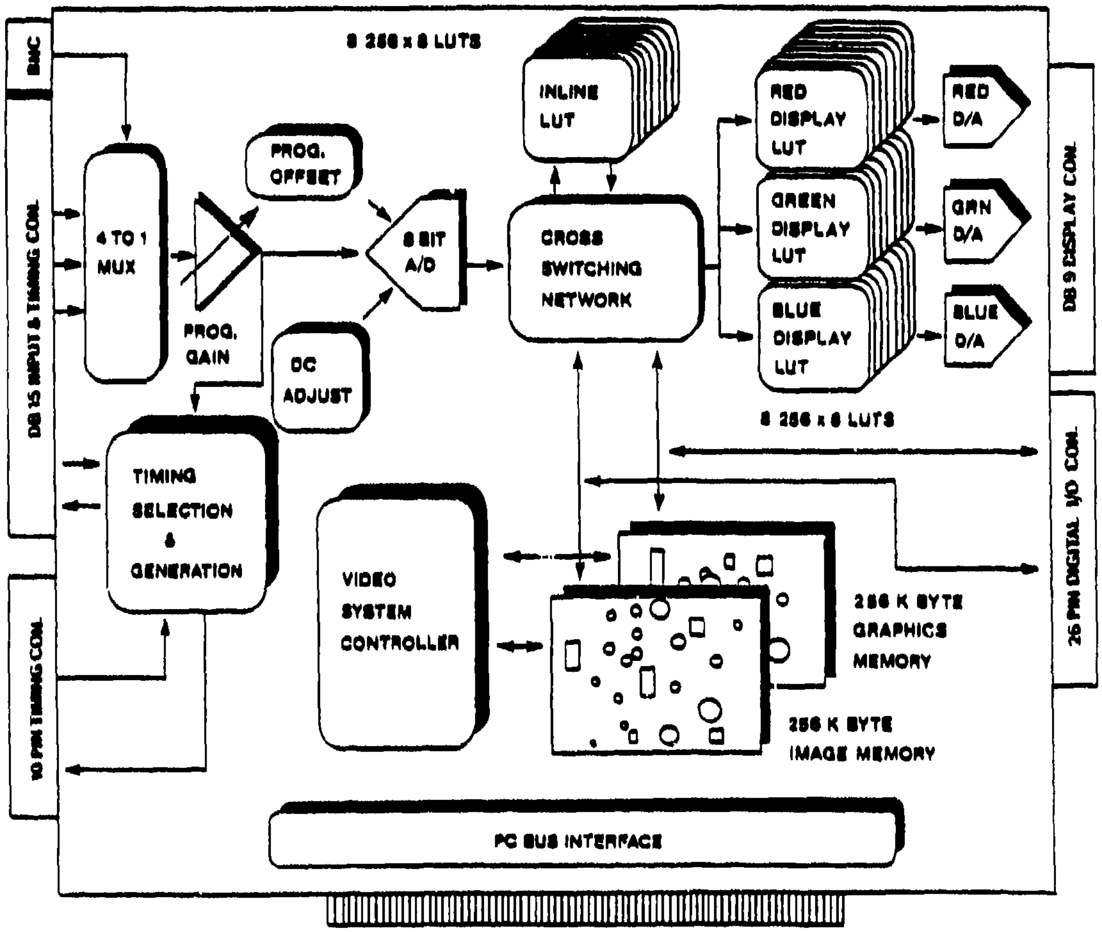


Figure 2-1. Functional Block Diagram

CHAPTER 3
OPERATING SPECIFICATIONS

3.1 GENERAL

This chapter details operating specifications for the MV1 Board. Specifications for standard video input types, video output signals, and timing specifications are given.

All specifications are typical at +25°C and rated voltage unless otherwise specified.

3.2 STANDARD VIDEO INPUT

Analog Input	4 channel interlaced, non-interlaced, or line scan. A jumper-selectable low-pass filter is available to attenuate unwanted high frequency information from NTSC and PAL signals.
MV1-170	RS-170, RS-330, NTSC; ac-coupled: programmable channel, D.C. offset, D.C. restoration, gain
MV1-CCIR	CCIR,PAL; ac-coupled; programmable channel, D.C. offset, D.C. restoration, gain
Number of Inputs	4
Synchronization	
External	From video source via on-board sync stripper or Sync I/O pins.
Internal	From on-board VSC or TV Gen. with jumper selectable TTL Sync outputs VRES or VSYNC and CSYNC or HSYNC.

Geometric Resolution	
MV1-170	480 lines by 512 pixels
MV1-CCIR	512 lines by 512 pixels
Gray Scale Resolution	8-bit gray scale resolution for all boards. Digitization speed is as follows:
Pixel Sampling Rate (Internal Sync)	MV1-170 10.08 MHz. MV1-CCIR 10.00 MHz.
Frame Grabber Speed	
MV1-170	1/30Th. of a second
MV1-CCIR	1/25Th. of a second
Line Grabber Speed	1 MHz. - 10 MHz.
Inline Look-Up Tables	Eight tables, 256 x 8-bit in RAM

Table 3-1. Input and Output Voltage and Impedance

Characteristic	Value
Reference White Level	Variable ± .5V
Reference Black Level	Variable ± .5V
Setup	Variable ± .5V
Blanking Level	Variable ± .5V
Sync Level	Variable ± .5V
Impedance	75.0 Ω

3.3 VIDEO OUTPUT

Output Signal	Interlaced, RGB, or monochrome Embedded Composite Sync in Green (Separate Composite Sync also available)
MV1-170	RS-343A, RS-170, dc-coupled
MV1-CCIR	RS-343A, CCIR, dc-coupled
D/A	3
Resolution	8-bit
RGB Output	16 million colors
Monochrome Output	256 grey levels
Display Look-Up Tables	Eight 256 x 24-bit RAM
Sync Signal Output	RS-170 and CCIR defined signals: Composite sync on green or separate
Aspect Ratio	4:3
Overlay Modes	7 user-programmable overlay modes

3.4 FRAME STORAGE MEMORY

Number 2

Size

Each 512 x 512 x 8-bit. 256 Kbytes

Total 512 Kbytes

Banks can be arranged as 512 x 512 or 1024 x 256 and any size range within these outer limits.

Access Transparent from bus; read or write any time; bit-plane mask available

3.5 RS-170 AND CCIR TIMING

*Table 3-2. Horizontal Timing**

Characteristic	MV1-170	MV1-CCIR
Horiz Frequency	15,570 Hz.	15,625 Hz.
Horiz Period	63.49 µs	64.00 µs
Horiz Active Scan	52.26 µs	52.17 µs
Horiz Blanking	11.23 µs	11.82 µs
Horiz Sync	4.900 µs	4.687 µs
Scan Clock	10 MHz.	10 MHz.
Pixel Rate	100 ns.	100 ns.
Pixel Aspect Ratio	4/3	4/3

*Normal Timings. All are programmable for non-standard acquisition and display.

Robot Companies

ABB Robotics	16250 West Glendale Drive
	New Berlin, WI 53151-2840
Jack Dreyer	(414)785-3400
AEG	PO Box 160
	Pittsburgh, PA 15230
Advanced Manufacturing Systems	6075 The Corners Parkway
	Norcross, GA 48120
	(404)448-6700
Cybermotion	5457 Aerospace Road
	Roanoke, VA 24014
Robert J. Breen	(703)982-2641
Cimcorp	899 West Highway 96
	Shoreview, MN 55126
	(612) 484-7261
Cincinnati Milacron	795 West Alexander
	PO Box 1327
	Greenwood, SC 29648
Clay-Mill Technical Systems	2855 Deziel Drive
	Windsor, Ontario N8W 5A5
Dave Thorn	(519) 944-7902
General Atomics	10955 John Hopkins Drive
	PO Box 85608
	San Diego, CA 92138-5608
GMF Robotics	Box 811
	Bloomfield Hills, MI 48303
	1-800-231-4112
GRACO Robotics	12898 Westmore Avenue
	Livonia, MI 48150
	(313)523-6300
Miller Electric	Appleton, WI 54914

NiKo Robotic Group	**21277 Bridge Street**
	Southfield, MI 48034
Dean Roberson	(313)352-4510
Thermwood	**PO Box 436**
	Dale, IN 47523
Mark Drone	(812)937-4476
SPAR Aerospace	1700 Ormont Drive
	Weston, Ontario M9L ZW7
	(416)745-9630
TOKICO	1203 Commerce Drive South
	Dearborn, MI 48120
	(313)336-5280
US Air Force	Sacramento Air Logistics Center
	McClellan Air Force Base, CA 959652
	Ogden Air Logistics Center
	Hill Air Force Base, UT 84056-5990
Yaskawa	3160 MacArthur Blvd.
	Northbrook, IL 60062
	(312)291-2340

Sensor Companies

ACE	
ADE	77 Rowe Street Newton, MA 02166 (617) 969-0600
Aerotech Charles E. Zellman	8804 Lomas Court Raleigh, NC 27615 (919) 848-1965
Agastat	
Allen-Bradley	
Alpha	
Aromat Brett Hammerschmidt	629 Central Avenue New Providence, NJ 07974 (201) 464-3550
Automatix	
Banner	
Baumer Robert Frais	122 Spring Street, C-6 Southington, CT 06489 (203) 621-2121
CCDI	
Chesapeake Laser System J. Bradford Merry	4473 Forbes Boulevard Lanham, MD 20706 (301) 459-7977
Cleveland Machine Controls, Inc. Donald Tomko	7550 Hub Parkway Cleveland, OH 44125 (216)524-8800
Computer Recognition Systems	

Contaq	15 Main Street Bristol, VT 05443 (802) 453-3332
Crystal Technology	
Custom Machine	
CyberOptics Michael Riddle	2331 University Avenue SE Minneapolis, Minnesota 55414 (612) 331-5702
Diffracto Steve Dawson	2835 Kew Drive Windsor, Ontario N8T 3B7 (519) 945-6373
Dolan Jenner	
Ealing	
Efector	
Electro Corporation	
Electromatic	
EOTec	
Flow Research	
General Scanning, Incorporated	500 Arsenal Street PO Box 307 Watertown, MA 02272 (617) 924-1010
Huntleigh Technology	
Kaman	
Keyence	17-17 Route 208 North

Fred G. Poelzing	Fair Lawn, NJ 07410 (201) 791-8811
Laser Design Incorporated	8316 Pillsbury Avenue South Minneapolis, MN 55420
C. Martin Schuster	(612) 884-9648
Lion Precision	7685 Washington Avenue South Minneapolis, MN 55435-2705
Robin Wilcox	(612) 944-1830
Magnaflux	
Massa Products	280 Lincoln Street Hingham, MA 02043-1796 (617) 749-4800
MicroSwitch	1190 W. Druid Hills Drive Suite 215 Atlanta, GA 30329 (404) 248-2565
MTS Systems Corporation	
NDC Systems	
NDT Instruments	
Ohmart	4241 Allendorf Drive Cincinnati, OH 45209 (513) 272-0131
Oldelft	
Omron	
Pepperl and Fuchs	
Perceptron	

Photo Acoustic Technology	
Photo Research	
Polaroid Ultrasonic	
Qualcorp	Shelter Rock Road Danbury, CT 06810 (800) 367-0453
Quantum Measurements Corporation	Suite 250 1270 Winchester Parkway Smyrna, GA 30080
David Robinson	(404) 433-0093
Questar	
Renishaw	
RVSI	425 Rabro Drive East Happauge, NY 11788
Paul Otto	(516) 273-9700
Scientific Technology Incorporated	
Selcom	PO Box 250 Valdese, NC 28690 (704) 874-4102
Sensotec	
Sick	7694 Golden Triangle Drive PO Box 444-240 Eden Prairie, MN 55344 (612) 941-6780
Silicon Graphics	
Simmonds Precision	

Spectron

Spectronics	9655 SW Sunshine Court #500
	Beaverton, Oregon 97005
Dennis G. Ortega	(503) 643-8030
Spindler and Hoyer	
Staveley	
Tritronics	
Turck	
Ultrasonic Arrays	18612 142nd Avenue NE
	Woodinville, WA 98072
Kerri Sheeks	(206) 481-6611
United Microwave Products Inc.	22129 S. Vermont Ave.
	Torrance, CA 90502
	(213) 320-1244
Vanzetti Systems	111 Island Street
	Stoughton, MA 02072
Richard I. Alper	(617) 828-4650
Wagner Instruments	
Weidmuller	535 Tollgate Road
	Elgin, IL 60123
Ernest J. Foldvari	(708) 742-0122
Wyco	
Zygo	Laurel Brook Road
	Middlefield, CT 06455-0448

Laser Companies

Acme-Cleveland Systems Division	1600 Enterprise Parkway Twinsburg, OH 44087-2202
ACRO Automation Systems, Inc.	2900 West Green Tree Road Milwaukee, WI 53209
Amada Laser Systems	7025 Firestone Blvd. Buena Park, CA 90621 (714)670-1439
Batelle-Columbus Division Gordon Zeidmann	505 King Avenue Columbus, OH 43201 (614)424-7405
Coherent General, Inc. Bob Reynolds	P. O. Box 1027 Tryon, NC 28782 (803)582-1872
COMAU Robotics	466 Stephenson Highway Troy, MI 48083-1195
Control Laser Corporation Al Pearson	7503-T Chancellor Drive Orlando, FL 32809
Ferranti International Michael F. Holmes	4915 West 67th Street Chicago, IL 60638-6493 (708) 564-3800
Hughes Aircraft Company	6155 El Camino Real Carlsbad, CA 92037
International Laser Machines Corp.	1806 Stout Field West Drive Indianapolis, IN 46241
International Technical Associates Dr. Paul Lovoi	2281 Calle de Luna Santa Clara, CA 95054 (408)748-9955
Laser Machining, Inc.	500 Laser Drive

	Somerset, Wisconsin 54025
Dave Plourde	(715)247-3285
Laser Mechanisms, Inc.	PO Box 2064 Southfield, MI 48037
Messer Griesheim	Steigerwald Strahltechnik BenzsrtaBe 11, Postfach 1365 D-8093 Puchheim, West Germany
LASAG Corporation	702 West Algonquin Road Arlington Heights, IL 60005
Art Spera	(312) 593-3021
Laakman Electro-Optics, Inc.	33051 Calle Aviador San Juan Capistrano, CA 92675
Laser Systemes	3 rue Denis Papin Beauchamp 95250, France
Lumonics Laser Systems Group	4504 Graham Road Greensboro, NC 27410
Jeffrey C. Jones	(919)854-9679
Plasmatronic, Inc.	2460 Alamo, S.E. Suite 101 Albuquerque, New Mexico 87106
Kim S. Crissman	(505)343-9430
PRC Corporation	North Frontage Road Landing, NJ 070850
Precision Technologies, Inc.	120 Post Road Enfield, CT 60682-5699
Heike Rukas	(203)741-2281
Spectra-Physics, Inc.	3333 North First Street San Jose, Ca 95134
US Air Force	Warner Robins Air Force Base, GA 3109[illegible]

Tug Companies

FMC

Jetway Systems

1805 West 2550 South
PO Box 9368
Ogden, UT 84409-0368

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