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REMOTE TELEROBOTIC REPLACEMENT FOR MASTER-SLAVE MANIPULATOR

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ABSTRACT

A remotely replaceable telerobotic manipulator (TRM) has been developed and deployed at the Defense Waste Processing Facility (DWPF) in support of its radioactive operation. The TRM replaces a Master-Slave Manipulator (MSM). The TRM is in use for both routine and recovery operations for the radioactive waste vitrification melter, the primary production device within the DWPF. The arm was designed for deployment and operation using an existing MSM penetration. This replacement of an existing MSM with a high power robotic device demonstrates the capability to perform similar replacement in other operating facilities.

The MSM's were originally deployed in the DWPF to perform routine light capacity tasks. During the testing phase of the DWPF, prior to its radioactive startup in 5/96, the need to remove glass deposits that can form at the melter discharge during filling of glass containment canisters was identified. The combination of high radiation and contamination in the DWPF melter cell during radioactive operation eliminated personnel entry as a recovery option. Therefore remote cleaning methods had to be devised. The MSM's had neither the reach nor the strength required for this task. It became apparent that a robust manipulator arm would be required for recovery from these potential melter discharge pluggage events.

The existing wall penetrations, used for the MSM's, could not be altered for seismic and radiological reasons. The new manipulator was required to be of considerable reach, due to existing physical layout, and strength, due to the glass removal requirement. Additionally, the device would have to compatible with high radiation and remote crane installation. The physical size of the manipulator and the weight of components must be consistent with the existing facilities. It was recognized early-on that a manipulator of sufficient strength to recover from a pluggage event would require robotic functions to constrain undesirable motions and to assist the operator in repetitive tasks.

A robotic arm was developed and deployed in a two part configuration. A through-wall support that contained all services and supported the balance of the device was installed from the personnel corridor through an existing MSM penetration (250 mm diameter). The arm portion was remotely deployed via the facility remote cranes and

coupled to the support. The electric manipulator is capable of 5.5 meters reach from the cell wall and 57 kilograms capacity at the end effector. The control of the device is by force ball (3D joystick) and transformations are provided for world and tool coordinates. A variety of changeable end effectors were also developed. Figure 1 shows the deployed robotic arm before radioactive startup.

The DWPF is now in radioactive operation. The telerobotic manipulator has been used successfully in routine operations and non routine melter discharge cleaning operations. During its first six months of operation, the TRM has experienced two failures. The first was a mechanical alignment/binding problem in the shoulder joint which was caused by the shifting of a bearing support and the second was premature failure of a DC servo-motor which impacted the motor control circuitry. These problems have been successfully resolved.

I. INTRODUCTION

The Defense Waste Processing Facility (DWPF) began routine radioactive operation during 1996 for the immobilization of Savannah River Site (SRS) high-level radioactive liquid waste. In the DWPF, a vitrification process solidifies high-level radioactive materials into a leach-resistant borosilicate glass. The waste glass is produced in an electrically heated melter. The glass is subsequently poured into stainless steel canisters where it cools and solidifies. The canisters are temporarily stored on-site awaiting eventual transport to an offsite Federal repository.

A very large remote hot cell, or "canyon", encloses the entire DWPF process. This area is serviced by an array of M.S. Manipulators, cranes, and other specialized mechanical devices. Operations within the remote area are observed through thick shielding windows and an array of remote, radiation hardened, video cameras.

An elaborate chemical process is used to remotely prepare the radioactive waste for conversion into the final glass matrix. A final mixture of concentrated waste and finely powdered glass frit is metered into the melter. Molten glass exits the melter into canisters. The control, monitoring, and maintenance of the melter are crucial to the continued operation of the DWPF.

II. BACKGROUND

M.S. Manipulators (MSM) are used throughout the DWPF for light duty tasks, both routine and maintenance. The MSM's are particularly useful where feel or dexterity is required. The basic design of the MSM remains unchanged over the past 40+ years. The DWPF was equipped with the largest type that was available at the time of its construction, the Type E extended reach type from Central Research Lab (CRL).

However, the MSM's have been particularly limiting in the region of the DWPF melter where additional strength and reach are required. The melter required routine operations, including glass sampling and canister plug insertion on a high frequency. The configuration of the melt cell resulted in the MSM operating near the full extent of its reach a majority of the time. This is fatiguing to the operator and has stressed the MSM's beyond their design capabilities.

During DWPF nonradioactive testing the capabilities and limitations of the MSM units had been identified and additional maintenance tasks were identified that were beyond the MSM's capabilities. Of particular concern was the recovery from potential pluggage of the melter vertical pour spout (discharge) resulting from accumulated glass and crystalline deposits. The ability to clean deposits from this area would allow continued glass production and potentially extend the life of a very expensive melter.

The MSM's were clearly incapable of the desired recovery tasks, due to capacity, reach, and the inability to view the affected area. The MSM's were also unable to withstand the impact, torsional and thermal requirements associated with deposit removal.

A device similar to the MSM devices in terms of deployment and operation, but with significantly greater reach, strength and versatility, was needed to augment the DWPF operation. The ability to deploy and maintain this new style manipulator within the constraints of an existing facility was an inflexible requirement. The DWPF could not allow modifications to potentially contaminated, thick, shield walls. Additionally, any required changes to existing service penetrations (i.e. electrical feedthroughs) would have a strong negative impact on any proposed changes. An accelerated program was initiated to develop a new Manipulator that would meet these criteria.

III. TASK DETAILS

The remote manipulator was designed to specifically address a single application in the DWPF melter cell. However, it was recognized from the onset that a manipulator designed to the requirements defined below would be applicable to many similar replacement applications in this or other facilities, at this site and others. (The DWPF has approximately 40 MSM's installed of the same size and capabilities.)

The DWPF structural design placed a major constraint on the desired replacement manipulator. The shielding walls have penetrations available only for the MSM's that are located nominally 3 meters (9.8 feet) above the operating platform. Also, there are few available penetrations for services. Modification of an existing penetration or boring a new penetration was unacceptable because of the difficulty in modifying potentially contaminated concrete and because modification of the shielding wall would require a re-qualification of the seismic integrity of the entire structure. No other convenient location within the radioactive cell had appropriately placed, or available, support options. The specification therefore required that the remote manipulator use an existing MSM through-wall penetration as the only mechanical support. These 0.25 meter (10 in) diameter openings penetrate the 1.4 meter (4.5 feet) thick shield wall. All services were required to share that MSM opening. This included electrical, instrumentation, pneumatic, and hydraulic service lines.

Deployment of the replacement device was allowed to utilize the existing handling equipment used to deploy the MSM's and use the crane access methods available in the radioactive cell. This allows a one piece design to be inserted and removed from the personnel side, or a two part design to be brought in from opposite sides and coupled together. No preference was expressed for either approach, only that the manipulator meet the overall requirements.

The portion to be inserted and retrieved from the personnel side was limited in weight to 590 kg (1300 lb), and in size to no larger than a MSM by the existing MSM handling system, contamination control procedures, and decontamination equipment. This included limitations imposed by using equipment designed for transporting MSMs from cell window areas to the MSM decontamination and maintenance bay. The crane access to the radioactive side is not as limiting to size or weight, since this equipment is designed to handle very large process equipment. (All of the major components in the DWPF cells, including the largest component, the glass melter, are designed for remote installation and removal utilizing only a crane. A remote entry point for clean components is provided at one end of the building, and remote decontamination facilities are located in special cells for the maintenance and removal of components.) However, any portion of a remote manipulator brought in from the radioactive side would have to both couple to and be supported by the portion inserted from the personnel side, thus limiting the weight of this portion. The mechanical, electrical, and service coupling of a two part device would have to accomplished remotely if it occurred on the radioactive side of the wall.

The most demanding reach requirement was for the manipulator to position an end effector approximately 1 meter below the melter pour spout. The pour spout is located 5.3 meter (17.5 feet) from the shield wall and is slightly below and offset from the available MSM penetration. (The required reach distances are well beyond the capabilities of a MSM.) The manipulator was to have a payload capacity of 57 kg (125 lb) in all joint configurations.

A suite of required End Effectors (EEs) were defined to support both routine and recovery tasks. These EEs included grippers, plug insertion tools, glass removal tools, and viewing devices. The EEs were to be remotely coupled to the manipulator by a "tool changer" device, typical of normal robotic operations.

The telerobotic control required software transformations of manipulator motion in multiple coordinate frames. This allows an operator to move the EE in predictable straight line motions, which typically require the simultaneous motion of several joints. The congested nature of a remote operation cell require the conversion of coordinates in this manner, to allow a reasonable degree of cell movement without collisions or random motions. A preferable alternative would have been the software mapping of the cell and its contents to prevent any collisions with device in the cell, regardless of the operators actions. Such systems are available but were considered too expensive for this installation. The control system design included the ability to add this feature at a later time.

The DWPF process is a high radiation system, even though it processes relatively old waste materials, due to the high concentration of the waste materials. Any device supplied for the DWPF melt cell had to survive an expected radiation dosage of 1 x 10(8) rads, with this dosage accumulating in as little as a two year period. The TRM also had to be capable of withstanding decontamination processes including wash-down with caustic, nitric acid, oxalic acid or pressurized water.

IV. MANIPULATOR

The Telerobotic Manipulator (TRM) was supplied by PaR Systems, Inc., located in Shoreview, MN, in response to the requirements described above. The TRM is an all electric device of a two part design. It is a telerobotic device that is controlled by a coordinate transforming computer and operated with a "space ball" joystick. A remote tool changing device was supplied along with several remotely coupled tools for specialized functions.

A through-wall portion is inserted from the personnel side of the shielding wall using the MSM support devices. The through-wall portion is secured in place and is coupled to the electrical, pneumatic, etc. services. The support electronics are located immediately adjacent to the wall penetration. Figure 2 shows the deployment scenario of a manipulator, the shield walls, and melter location.

After the through-wall support is in place, the active portion (or "arm") is brought in with one of the remote cranes. The arm is positioned on the through-wall support using only crane functions. Once in position, the two halves are locked together mechanically from the personnel corridor using a threaded draw bar. After mechanical locking, the electrical, pneumatic, etc. services are connected between the halves by extending a second draw bar to mate a pair of connector plates. The installed arm is now ready for operation.

Arm removal is the reverse of the above. The arm may then be maintained hands-on in a Contact Decontamination and Maintenance Cell (CDMC) or stored on its stand in a laydown area. A second through wall support is kept in a MSM penetration at the CDMC for support and operation during maintenance. If necessary, the through-wall support may be pulled into the clean area and bagged, to contain any contamination. It is taken to the existing MSM hot maintenance glovebox facility. All exterior surfaces of the TRM are 304 stainless steel to resist decontamination solutions. Short life end effectors have some exposed aluminum components. Figure 3 shows the deployment sections of the TRM.

The final design TRM has the following specifications and capabilities:

Through-wall penetration 1.4 meters (4.5 feet) thick
0.25 meter (10 in) diameter

Maximum reach from inside wall 5.8 meters (19 feet)

Maximum payload at wrist 57 kg (125 lb)

Radiation tolerance (Cumulative) 1 x 10(8) rads

Degrees of freedom 6 DOF

Weight of through-wall portion 567 kg (1250 lb)

Weight of radioactive side portion 860 kg (1900 lb)

The TRM is controlled in either robotic, telerobotic, or joint modes, as required by operations. It is anticipated that most control will be in the telerobotic mode. The operator interface is via a control computer keyboard/screen, a "spaceball" (3-D Joystick), and keypad "teach " pendant. The control system is highly modular to enable the systems to be easily moved to other MSM penetrations for future tasks and/or maintenance. A portable service cart houses all major power, air, and computer control components. Cabling between the TRM Support, the service cart, and operator controls is terminated with removable connectors. The operator controls are located remote from the service cart to be positioned close to the viewing window.

The robotic mode allows repetitive operations to be programmed once and then repeated via a single operator command. This would be a "typical" robot mode of operation. It was anticipated that a variety of routine operating, cleaning or arm placement tasks would benefit from this method of operation. Figure 4 shows the radioactive wall side of TRM robotic arm before installation.

The telerobotic mode greatly reduces the control burden on the operator. The individual joints of a robot do not lend themselves to individual control in a logical manner in most configurations. For a robot to move its gripper in a straight line, a number of separate joints must move simultaneously. Telerobotic control mathematically transforms the coordinates of the robot into an operator desired configuration, to allow a single command to perform a complex motion. For example, in telerobotic "Tool Point" mode the operator can instruct the robot that the, otherwise arbitrary, direction the gripper is currently pointed is the Z axis, with corresponding X and Y axes. Then a single joystick command can move the robot's arm along any axis in this transformed coordinate system. This type of control significantly decreases the skill level requirements and computational burden on the operator while also decreasing the likelihood of a mishap.

A video camera is positioned on the TRM's wrist near the tool changer for general viewing purposes. It is enclosed in a sealed housing that can be removed and replaced by the adjoining MSM..

Manipulator Tool Details

Several specialized End Effectors (EE) are addressed separately below along with the remote tool changer device common to all of them.

The ability to change tools remotely provides for the capability to perform a variety of separate tasks, which require significantly different tools (i.e. grippers, cutters, chippers, cameras, etc.). All services that are required, or were anticipated in the future, are coupled through the tool changer. The system includes a tool "receiver" permanently mounted on the TRM wrist and tooling plates for attaching each tool. The halves are remotely coupled to provide mechanical support and a pathway for all services. The halves are latched together with a fail safe device controlled by the robotic controller. The services to each tool pass through the tool changer on an as-needed basis. Contacts at the interface representing identification bits tell the control computer which end effector is in place.

The pneumatic gripper EE is a general purpose device designed for some routine maintenance tasks. It has a capacity of 57 kg (125 LB) and is programmable to provided a maximum gripping force of 136 kg (300 LB). This EE is used for the TRM's routine functions, including placing a temporary plug in a glass canister immediately after it is filled, actuating a glass sampler and maintaining a glass pour stream viewing window. The gripper also grasps a pneumatic needle gun and an air hammer used to remove solidified glass deposits from the melter discharge. The air is supplied to these tools via a quick-connect fitting on the side of the gripper assembly. This air supply has also been used with a nozzle to blow debris from around the melter discharge area.

The pour spout cleaning device is a specialized EE designed to facilitate a single task. The vertical melter pour spout (discharge) has a tendency to accumulate glass deposits. The pour spout cleaner is inserted into the bore of the spout from below and its high speed (0-1300 rpm) rotary action dislodges the glass using a variety of cleaning "bits". These bits are easily changed using the MSM. This tool also includes a video camera and lights for viewing the rotary shaft and end effector in action. This high resolution video camera is also used for up-close inspection of suspect anomalies, especially the interior of the melter pour spout. The camera has remote controlled lens functions.

Experience using the cleaning tool for removing glass deposits from the pour spout has resulted in the procurement of a second cleaning tool designed to produce a significantly higher torque to new designs of cleaning tool bits at reduced speeds. Additional tooling plates procured with the original system facilitate adding such tools as experience is gained during production.

The EEs were originally located on a tool rack attached to an existing table immediately in front of the operator shielding window. The working or gripping end of the EEs faced the operator and the TRM reached back toward the window to robotically couple or decouple an EE. However, it was discovered that the table could shift enough in service so that robotic coupling/decoupling was impossible due to misalignment. The EE's are now transported by crane to the table as required where they are telerobotically aligned and coupled to the TRM.

V. FIELD EXPERIENCE

The TRM has proven to be very useful in evaluating and recovering from melter discharge glass pluggage events. Its reach and capacity have allowed work to be done in-cell which otherwise would have required equipment to be removed to a maintenance cell. The facility operators have become comfortable in operating the TRM in both telerobotic and robotic modes. However, fine, light work at the shield window which requires a high degree of finesse and touch feedback continues to be done with the MSM.

During its first six months of operation, the TRM experienced two failures. These were a mechanical alignment/binding problem in the shoulder joint and the premature failure of a DC servo-motor which damaged the motor control circuitry. These failures have been considered to be a normal part of the run-in of this first-of-a-kind prototype manipulator system.

Shoulder Joint Failure

An eccentric bushing used to align a worm gear bearing shifted during operation to cause binding and wear on the shoulder drive ring gear. Recovery from this failure included re-alignment of the worm gear/eccentric and pinning the assembly to prevent future shifting. The ring gear was rotated by 180 degrees to move the affected area to an unused portion of the shoulder travel.

Servo Motor Failure

One of the axis drive motors failed prematurely (mechanism unknown) and in-turn caused its control circuitry to fail. Electrical noise associated with this motor failure also resulted in erratic motion control errors on the other axes. Recovery from this failure included replacement of the motor and associated drive circuitry. Filters were also added to the power supply circuitry to prevent future interference by electrical noise.

VI. ACKNOWLEDGMENTS

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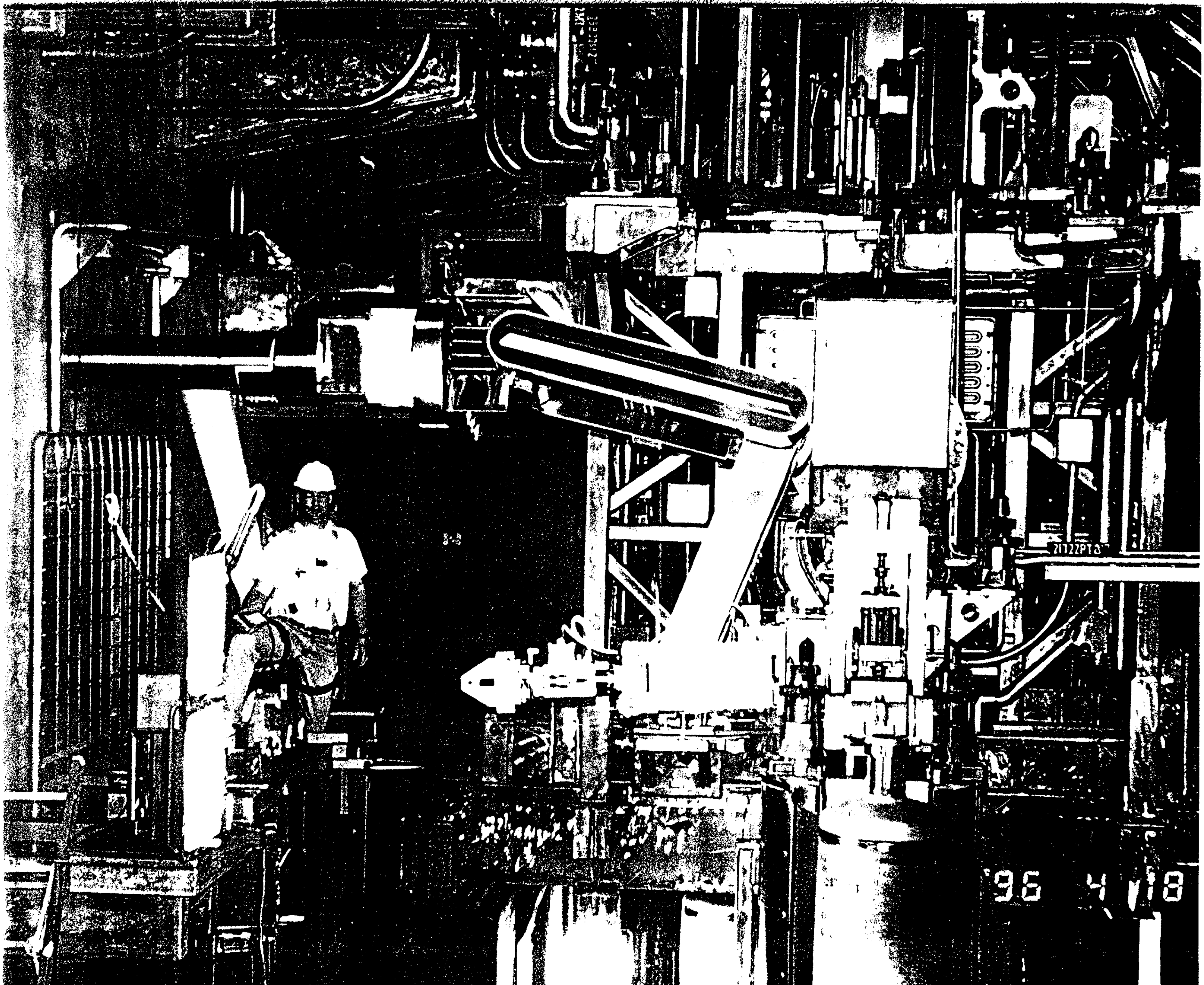

FIGURE 1

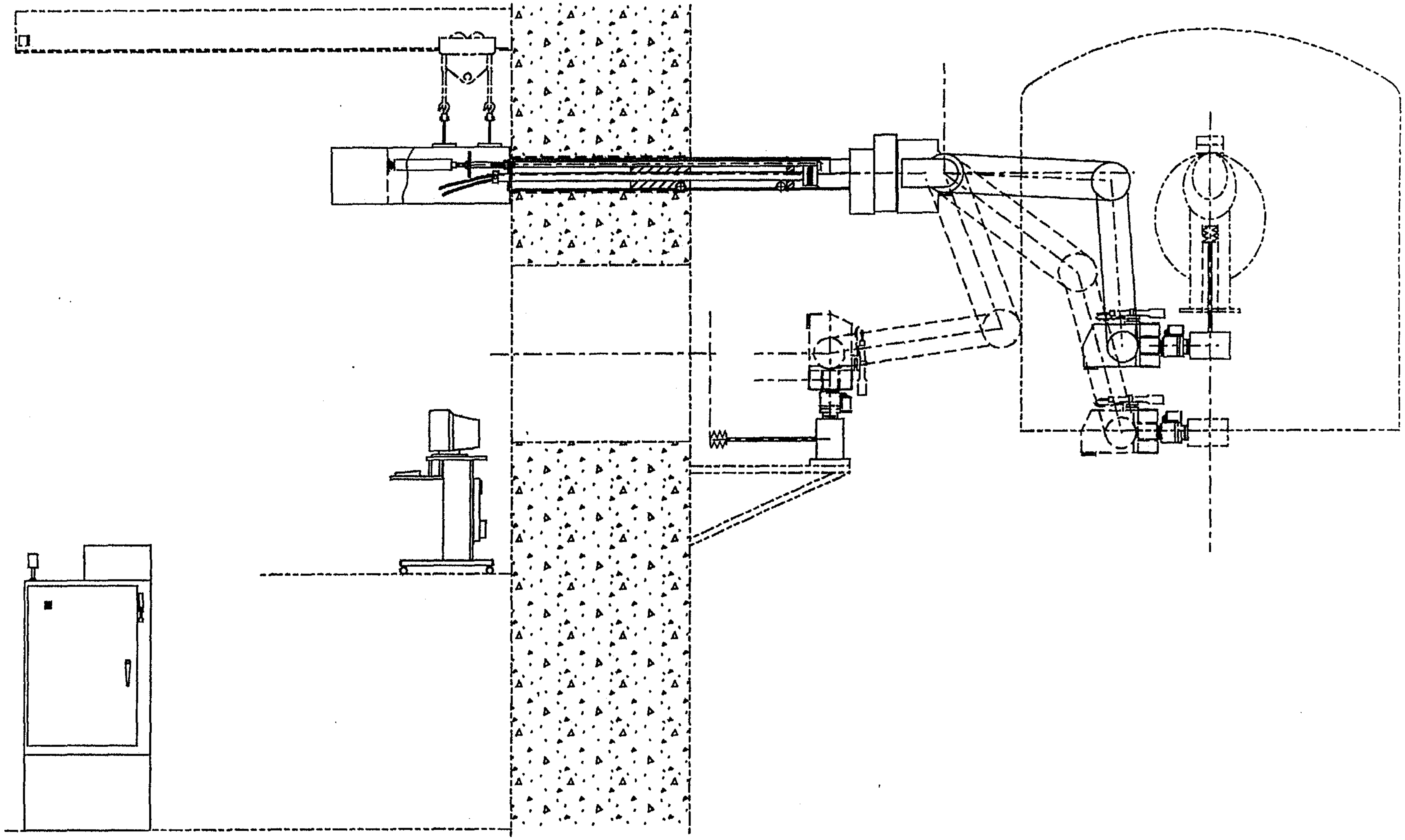

FIGURE 2

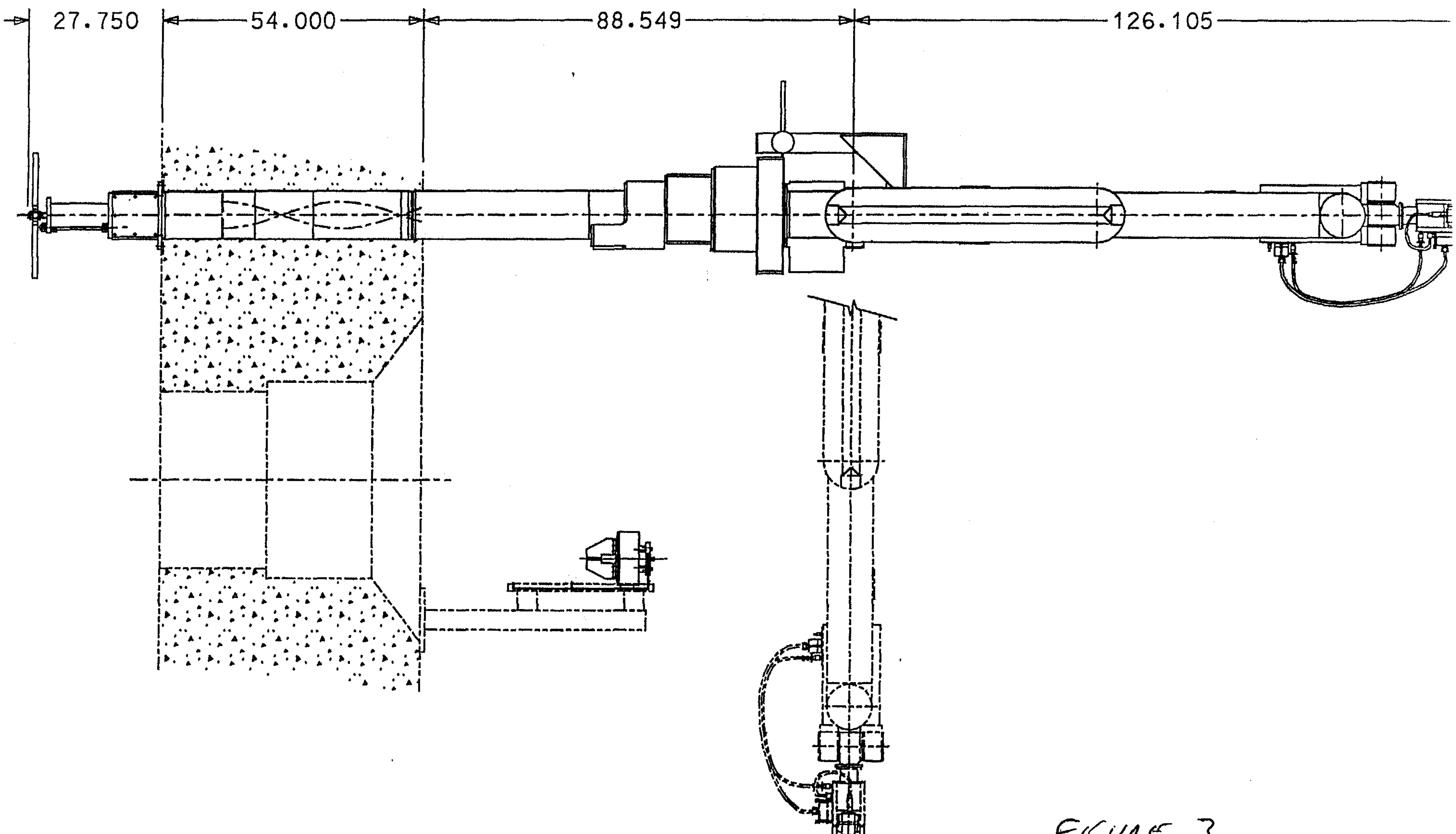

FIGURE 3

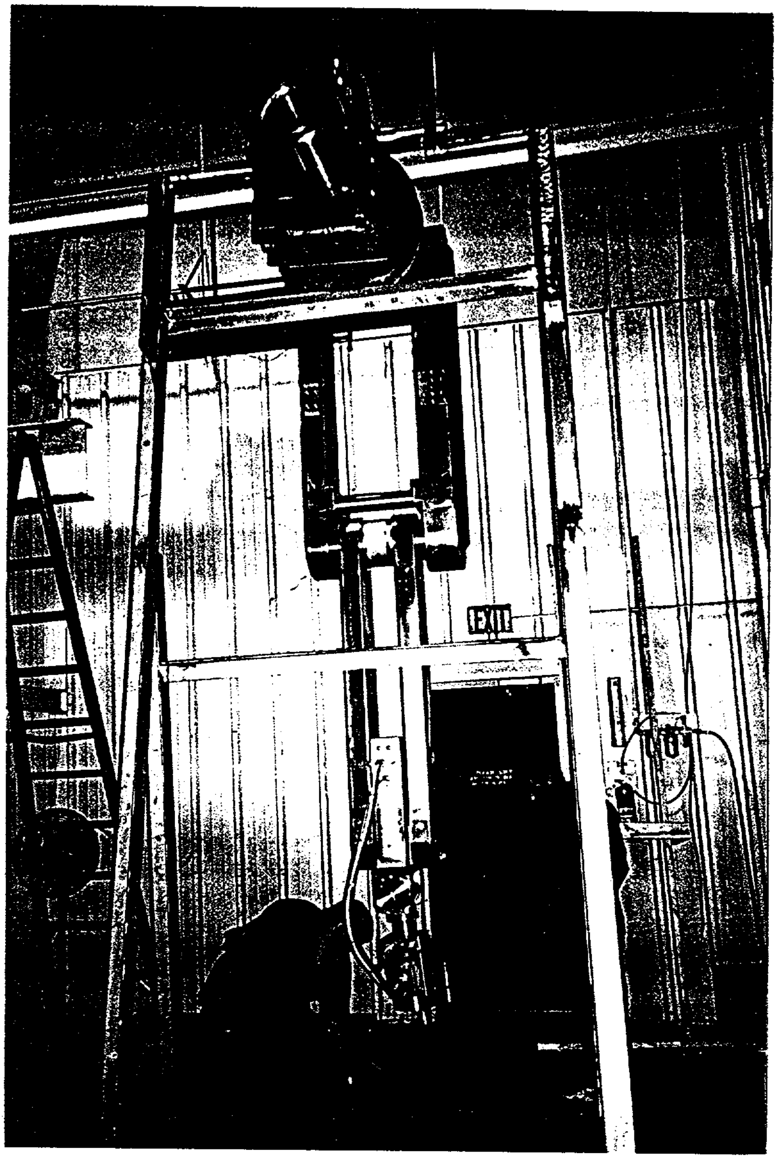

FIGURE 4