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DESIGN OF THE FERMILAB NEUTRINO HORN TRAIN SYSTEM REFERENCED TO RADIOACTIVE MAINTENANCE*

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Abstract

A high energy physics device known as a Horn operates at 140,000A and 8KV has unique problems relating to keeping it operationally serviced after being exposed to 300-400 GeV protons and 1-5 x 10^{13} protons/pulse. A modular system consisting of two horns, one cooled by a pulsed water spray, and the other by forced air cooling along with their associated utilities and instrumentation were designed for primary servicing using Electric Master Slave Manipulators[1] and TV[2] viewing.

INTRODUCTION

As remote systems technology moves into the field of high energy accelerators or vice versa, new names start to appear. Reactors are replaced by accelerators, critically by energy level or intensity, fuel by protons or electrons, etc. Parts of an accelerator; magnets, radio frequency (rf) systems, beam dumps, and targets come into the conversation. After reading the title of this paper, one might ask what is a neutrino horn? A horn is a device which produces an intense magnetic field (100 kilogauss) between two cylindrically symmetric coaxial current-carrying sheets, the inner and outer conductor, in order to concentrate secondary particles resulting from a primary high energy proton beam striking an aluminum target. The neutrino horn system consists actually of three horns constructed into two horn modules, a high voltage, high current transmission line, a primary target, a pair of beam dumps known as fingers and several special types of instrumentation used to monitor the proton beam.

Until the Fermi Accelerator was constructed, the energy levels were such that components were neutron activated to low levels of radioactivity and maintenance could be accomplished by controlled manual contact. The Fermi Accelerator has presently reached an energy level of 400 GeV (Billion or Giga Electron Volts), this is twice design level and has reached an intensity of 1×10^{13} protons per pulse (ppp), design intensity is 5×10^{13}ppp. Residual radioactivity has already reached 200 R/hr at one foot and therefore, levels can expect to reach 1000 R/hr when design intensity is reached. With this outlook in mind, the design of the horn system was constantly reviewed for ease of remote servicing. The system is still a long way from optimum, but we feel that our system can be serviced remotely given sufficient time.

GENERAL DESCRIPTION

The Neutrino Horn Train System is mounted on 9 mobile platforms called Bedplates. These bedplates are set in place by using a narrow gauge (30") railroad transporter car.[3,5] Each bedplate is 20-ft. long and 41" wide plus 5" on each side for a utility corridor. Therefore, the complete system is 180-ft. long x approximately 4-ft. wide and 3-ft. high. Figure 1 shows a schematic of the Horn system. The area shown as power supplies is located remotely from the remainder of the system, and therefore, does not have a radioactive service problem. Numbering of the bedplates is left to right (proton beam direction) from 1 to 9.

The major modular components are Horn 1 on bedplate 3, and Horn 2 on number 8. Primary activity is generated at the target on #2 and a special beam dump on #4 just downstream of Horn 1. Power is supplied via the polarity-reversal switch, the upstream transmission line and on through Horn 1 the downstream transmission line to Horn 2, and then returns in the opposite order. All items are in series. During operation, manual access during beam off periods is only to the upstream 2/3 of bedplate 1. In addition to the proton beam (designated NØ) as shown, a by-pass beam (designated N-7) is located on the near side which passes outside of Horn 1 tank but actually goes through the inside of Horn 2 parallel to NØ about 13½ inches to the right looking downstream. Bedplate 9 has a secondary target mounted on the N-7 line and is another area of high radioactivity.

DETAILED COMPONENT DESCRIPTION

In the introduction, a very brief description was given as to what a horn is. It was stated that there is an inner and outer conductor (Figure 2 shows the inner conductor) of Horn 1 being held in the foreground. Horn 1 is actually a double horn since there are two neck regions. The inner conductors are shaped like a horn, hence the name. The outer conductor is a straight cylinder and is sometimes referred to as the outer tank.

Horn 1 is water cooled by pulsed Low Conductivity Water (LCW) cooling system. The water is sprayed through a series of 138 fan-type spray nozzles divided into 6 separate circuits, any one of which if water flow drops below 1 gpm will result in shut down of the system. Horn current is nominally 140,000 A at approximately 7 to 8KV. The current is pulsed for 80μ sec. within a cycle of 6 sec. and the water being sprayed for 4 sec. when the current is off. Horn 1 is shown in Figure 3 mounted on the bedplate, the outer tank being approximately 18" diameter and 13-ft. long. The Horn must be insulated from ground (bedplate) so as to pass a 15KV hi-pot test. This is true even when the water system is in operation. The same test holds between the inner and outer conductor. Water is a major problem and will be covered later in the paper. The six supply water circuits have been combined into a single clamp flange, thereby requiring only one disconnect of supply and one of return for the water (see Figure 4). The drain or return is a gravity feed pipe system connected via a ceramic spool piece that may have a clamp flange removed at either end (Figure 5). Notice both of these disconnects are on the same side of the bedplate.

Making a reliable 150 to 300KA remote electrical connection resulted in designing a toggle clamp driven by an electrically operated linear actuator. The reason for the toggle is to obtain the high force necessary to keep the contact from pitting or blowing apart. The clamp had other constraints to satisfy, namely they must open 90° to enable remote removal of the horn from the bedplate. Secondly, but yet very important, they must not put any undue stress on the horn tanks which would destroy the required alignment. Tolerances for alignment of the horn are such that angular position is held to 0.010 inches in 20-ft. (bedplate length) both vertically and horizontally. Displacement tolerance is 1/16 inch. The transmission line and its yoke are mounted on adjustable springs and are set 1/16 inch below the matching contacts on the horn. The toggle clamps shown in Figure 6 are mounted in more or less a free condition with the only restraint being alignment on two pins in a slot. The transmission line yokes have a series of milled slots to reduce their stiffness, thereby keeping stress on the horn to a minimum.

The horns are mounted on four tapered pins that mate with a socket mounted on top of 15KV insulators. After placement of the horn, a rough alignment (within 1/32 inch) is then made. The sockets which also have a built-in clamp are then tightened to keep the horn from jumping during pulsing. A cross-section of the mounting arrangement is shown in Figure 7. Also shown is the horizontal and vertical adjustment provisions. The four pin arrangement allows quick and possible remote interchange of a replacement horn. Presently we only have a spare Horn 1. The four pins are such that the left side controls horizontal angular alignment with the large pin fixed on the upstream end while the downstream is restrained to move only parallel to the horn center line. This allows for expansion and tolerances between pins. The two pins on the right side are mounted using double slots to accommodate expansion and tolerances in two directions.

Figure 8 is a view looking in the same direction as the beam as it would enter Horn 2. The toggle clamps have been left off for clarity. Starting in the foreground, the transmission line and yoke is supported on springs as previously mentioned on Horn 1. The Horn 2 yoke is more complex than on 1 since with Horn 1 the yoke is basically two dimensional, while yoke 2 is three dimensional having a jog to clear the larger tank of horn 2. The milled slots are again duplicated on yoke 2 to reduce stiffness.

An overall view of Horn 2 mounted on bedplate 8 is shown in Figure 9. The outer tank is 28" diameter and 18-ft. long. Horn 2 is air cooled and much of the ducting can be seen. The air arrives from bedplate 7 via a 4" diameter aluminum pipe through a quick disconnect 12" long bellows typical of the air line connection between bedplates. The bellows allow the train to negotiate curves without disconnecting the air line. The air on bedplate 8 continues through the square aluminum tube in the foreground. The short bellows at the end of the square tube is where the air supply line is quickly disconnected if horn 2 is to be removed from the bedplate. A similar arrangement is made on the opposite side for the return air. Both supply and return lines have insulating material to isolate the horn electrically. The air system originates on bedplate 1 with a pair of fans in parallel supplying the air down the entire train length on one side and returning the air to atmosphere outside of the target tube on the other side. The fans are accessible for service during beam off periods. The only reason for the various cross-sections are space limitation as the air line passes major components such as the horns and their toggle clamp stands.

The inner conductor of Horn 2 shown in Figure 10 only has a single neck region. Basically it is a three piece bolted assembly with the neck being machined from solid stock and the large cone sections being a series of spinnings welded together. Figure 11 shows the support for the inner conductor of Horn 2. This type of spider wheel is typical of both horns and is made of G-30, a polyimide glass laminate which will retain its physical properties when exposed in excess of 2.5×10^9 rads. Material for which the beam must pass is kept to a minimum, therefore the spider or spoke design. Also it may be noted the small square hole on the right side is where the N-7 line passes through Horn 2 as previously mentioned.

The transmission line, although mainly a passive device, involved a large amount of design time. The basic cross-section of the line is like a sandwich. The inner conductor is 8" x 3/4" and is radiused and polished before wrapping with multiple layers of Kapton insulation to a thickness of 1/16". The outer conductor consists of two 12" x 3/4" plates polished on the side which comes in contact with the inner conductor insulation. The polishing prevents any peaks or sharp points from puncturing the Kapton. The two outer plates are clamped against the inner conductor. This keeps the inner and outer in intimate contact and, therefore, the inductance is kept low and constant.

It is desirable to have the transmission line one piece but the need for the system to negotiate rail curves having a radius as small as 130-ft. and angles of approximately 8 degrees would not allow one piece.

Referring back to Figure 1, the line between the polarity-reversal switch and bedplate 1 was one piece. The first 90 degree bend from the switch was a large radius while the second was a complicated time consuming joint which had to be made right at the target tube mouth and, therefore, an area of maximum radiation in the target hall. The weight of the piece required three men to work in close proximity under very difficult conditions. After revisions, the curve was eliminated, the line supported on an insulated stand and the joint almost fell together by using large bolt holes. All bolting (9 bolts) now takes place from the same direction.

The section from the second 90 degree to Horn 1 is the most complex part of the strip line. This section is approximately 30-ft. long with the first 15-ft. making a 90 degree helix angle from vertical to horizontal. The reason for the 90 degree change is first the flexibility needed to negotiate curves. Therefore, we start out vertically. Then the current must be fed symetrically to the horn but meanwhile must not block the 18" aperature of Horn 1. This required a horizontal line mounted as close to the bedplate and on center as possible. The connection from the line to the horn is made via the yoke to ears on the end flange of the horn, the two being clamped together using the previously mentioned electrically driven toggle clamps.

The transmission line between Horn 1 and 2 would seem to be simple in principle, but the length of 80 feet and the necessity of remaining flat on the bed-plate to stay outside of the horn aperatures does not make for flexibility for going around rail curves. As a method that would work but not necessarily result in the lowest radiation exposures to personnel, the line was broken into three sections, the first being 22-ft. and connected to Horn 1 with a yoke identical to the upstream end. The second is a 38-ft. section section connected by a bolted connector piece to the first and third. The third is 20-ft. and is connected to Horn 2 by the 3-dimensional yoke previously mentioned. The bolted connector is seen in Figure 12. The connector assembly is allowed to be only two conductors for a short distance at each end resulting in a reduction of the number of bolts. Also, all of the bolts may be fastened from the top surface. The connectors assemblies are centered directly between bedplates 4 and 5, and between 6 and 7.

An experimental rotary connector assembly has been undergoing tests. The rotary joint would not have to be disconnected, instead, only a single bolt would be loosened to eliminate pressure on slip ring type electrical contact faces. The joint works much like a large slip clutch. Preliminary tests resulted in uneven pressure and gauling. A revised model has been chrome plated and pressure is applied at the outside diameter.

The reasons for an experimental joint are the increasing of beam intensity and the installation on bedplate 4 of two beam dumps known as fingers. This means the radioactivity level at the connector between bedplate 4 and 5 may not allow manual removal of connector assembly. Presently, remote capability is only in the Target Service Building (TSB)[5] and two curves away, therefore, the transmission line must bend, pivot or be separated.

One of two adjacent fingers are shown in Figure 13. The finger proper is approximately 50" long with an outer aluminum 1¼" diameter tube. Within the outer tube is a 1" diameter tube filled with $A\ell_2O_3$ slugs. Between the inner and outer tube, a 1/16" water annulus is used for cooling. The finger is moved from below the 18" diameter aperature to the center of the NØ beam line. Design requirements were that a minimum amount of material be within the Horn 1 aperature, thus, the offset double triangular support. Everything is made in modular form. The finger may be removed from its support by two quarter turn clamp fasteners along with disconnecting the water supply and return lines.

Expanding on the extent of the modules concept, the entire double triangular support may be removed by loosening bolts slightly lifting and slipping off of the bolts through an over size hole at the end of a slot. This is sometimes referred to as a keyhole slot. The bolts are not removed, therefore cannot be lost or require starting of the threads when reinstalling. The position of the linear ball screw drive has a readout using a pot and a resolver mounted together on a single modular plate which includes the necessary electrical connectors. The entire light duty linear drive can be removed from the bedplate using the keyhole technique.

Figure 13 also shows a good view of the transmission line. The inner or center conductor cannot be seen, but spool pieces or spacers which help to center the inner conductor are seen at the edge of the outer conductor. They are spaced equally and have a fixed height to eliminate tightening the clamp bolt to a point that would result in damage to the Kapton film wrapped on the inner conductor.

The fingers, targets, horns, and almost all of the beam line instrumentation must be optically surveyed into position. Presently adjustments are made with manual contact, but systems have been devised to make most adjustments of height and lateral motion from one side of the bedplate. Figure 14 is a typical mount for a pair of beam line detectors known as a SWIC or Segmented Wire Ionization Chambers. The SWIC is mounted in a rotating saddle or channel and is held in by a single clamp bolt to allow quick replacement. Height, pitch and roll is accomplished by adjusting 3 nuts that are spring loaded to eliminate backlash. The individual complete module including motors and springs can be removed using the keyhole technique. An additional feature is a spring loaded hold-down-bolt with a cone or spherical washers that eliminates the need for a wrench.

Selection of materials for half-life and radiation damage or failure will become a very important part of future designs. Time must be allowed to design good serviceable modules. Standardization at a particular facility as to types of fasteners, lifting provisions, wiring, connectors, motors, etc., play a very important role in good designs. People involved in the servicing should be consulted with during the design phase, not after the fact.

OPERATION OF THE HORN SYSTEM

Preparation of the Horn Train System starts in the TSB[4,5] even when the system is new. Each active (current carrying) component is high-potted to 15KV between inner and outer conductor and between outer and ground. The Hi-pot passes if current is below 1ma. All testing in the TSB is without water spraying. Individual components are checked in the TSB and the system is rechecked after each component is added to the system in the target hall. Once Horn 2 is part of the system, inner to outer cannot be checked since the downstream end is essentially shunted to provide the return path for the current.

When the train system is in the target hall, final optical surveying takes place with all of the toggle clamps closed and transmission line connectors in position. Water lines from the hall LCW are temporarily hooked up to check for leaks in the target and finger cooling systems. This piping is independent of the horn pulsed water system. The train is then inserted in the target tube and the pulsed LCW system connected. The conductivity of the water is checked to be less than 0.5 micro mhos/cm. The maximum allowable current flow is 2ma under these conditions. When the polarity-reversing switch is set for anti-neutrino, the outer tanks operate at the high potential and good water is a must! The neutrino mode of operation has the outer tank near ground potential.

The first time the horn was used at Fermilab, there were only three bedplates and only Horn 1. The system operated successfully for approximately 8 weeks or a normal experimental period. The beam intensity had been 4 x 10^{12}ppp and when a radiation survey was made upon removal, the targets were reading 600 mr at 1-ft. and the horn 60 mr. The horn had been stored for about a month when recheck of the system began. Immediately it was evident that the hi-pot could not be passed. It seemed that enough water remained in the horn tank and had leaked by insulating water baffles. When the horn was disassembled, cleaned and dried up, it would again pass the necessary tests.

If this mode were to continue, we would soon be limited by radiation exposures to our personnel. It was found that water would run down the bottom of the inner conductor right to the water baffle and proceed to migrate to the other side of the baffle. We presently have eliminated the baffle as such, and allow the area to drain freely while having a double face seal.

Since we have no test facility at present, we will only know if we have been successful after completion of run now in process.

After Horn 2 and the remainder of the system were incorporated, we had two spectacular failures, namely large arc downs. The first was a complete melt down of the transmission line where it joins the yoke going to Horn 2. The actual cause has not been determined since two other identical joints operating at a higher potential have continued to function. Yoke 2 had been bumped slightly by another train prior to leaving the TSB and may have been the cause which allowed the initial arc gap to occur and thereby, leading to the failure. The second failure had a bolt insulator blow up after radiation damage, coupled with high humidity water problems. Changing to a polyimide (Vespel) gave both higher radiation tolerance and less water absorption properties to the insulator. The new insulators are working satisfactorily.

During the present run, we were running just in the neutrino mode. This operation was successful, but when the switch to anti-neutrinos was made, the finger was required and it was driven up into the NØ line. It was observed that its temperature was increasing by 4^0C per pulse and decreasing by 1^0C and it was hoped that it would be stabilized by the 6GPM of water flowing through the annulus. Our hopes failed to materialize and the finger temperature reached 580^0C and we had developed a water leak. Which came first, the leak or no water, we don't know, but the results were that the aluminum reached its melting point and sagged between supports and at both ends. The tube looked as though it had melted and/or exploded allowing the Al_2O_3 slugs to drop on to the transmission line. Fortunately, no shorting took place. We have replaced the aluminum tube with titanium and are presently trying to run without water cooling.

Each time we run for 6 to 8 weeks, we make modifications to better the remote maintenance and install some type of new experimental equipment, usually instrumentation, so that the many parameters of the system can be observed and recorded.

To date, the two horn systems has pulsed over 400,000 times. Even though we have had failures as already noted, there have been no failures of either of the Horns during operation.

Accelerators have the advantage of lower levels with a minimum of contamination. If a very high level module like the target is near an area that requires service, the target module may be removed from the work area remotely using an electric master slave manipulator. After removal, manual service may be started on other areas nearby. The other side of the coin is removing the component and replacing it with a spare. In the case of Horn 1 with the problems of water and not passing the hi-pot, the horn was removed and a new one put in its place, and the original sent to another service area where it was disassembled, using mechanical manipulator (CRL Model E and F). This resulted in considerable reduction in the man dose. The water piping which is stainless and, therefore, has a longer half-life was removed first. The remainder which is the aluminum tanks and center conductors after a week of cooldown was half the level of the total assembly. The levels are still low enough (40 mr) that critical assembly can be done by direct contact.

Since machine time is very valuable, new thinking must be applied to equipment to be serviced remotely. If money were no object, then long service periods could be scheduled or spare modules for everything be built. Even the best designed equipment will require 8 to 10 times longer to service remotely. The combination of manipulator and direct contact might result in at best 4 to 5 times as long as direct maintenance.

CONCLUSION

The use of the modular concept starting with the transporters and bedplates[5] has proven to be a feasible system. The Horn train load having each of its major components in modular form has not only made remote maintenance possible, but has made direct contact work possible due to quickness that a specific task may be accomplished.

ACKNOWLEDGEMENT

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FIGURE TITLES
for
FERMILAB HORN TRAIN MAINTENANCE

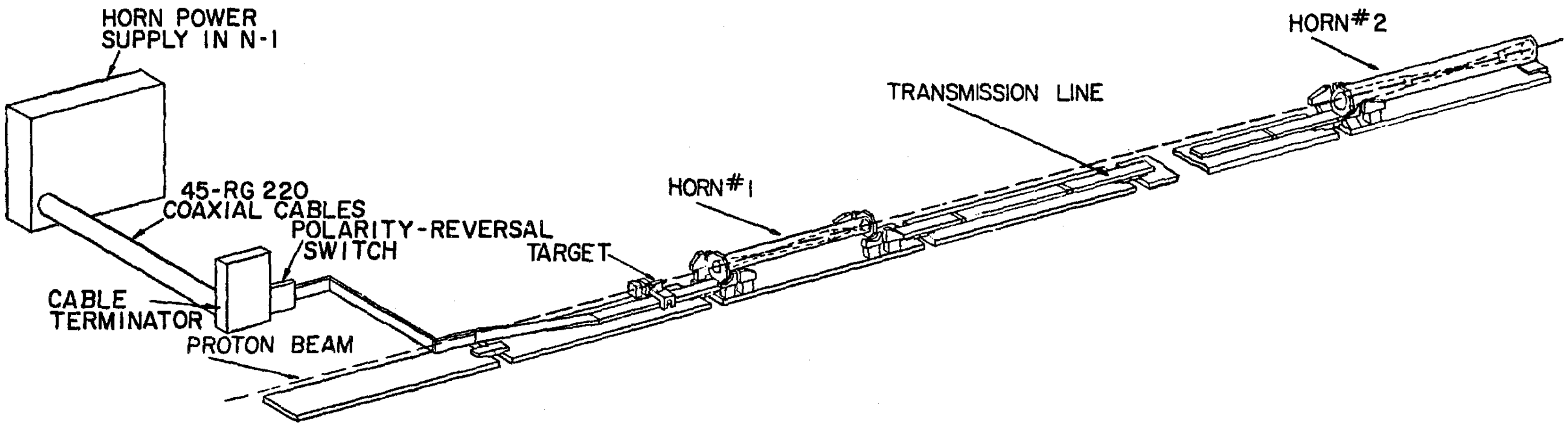
HORN POWER SUPPLY IN N-1
45-RG 220 COAXIAL CABLES
POLARITY-REVERSAL SWITCH
CABLE TERMINATOR
PROTON BEAM
TARGET
HORN #1
TRANSMISSION LINE
HORN #2

FIGURE 1

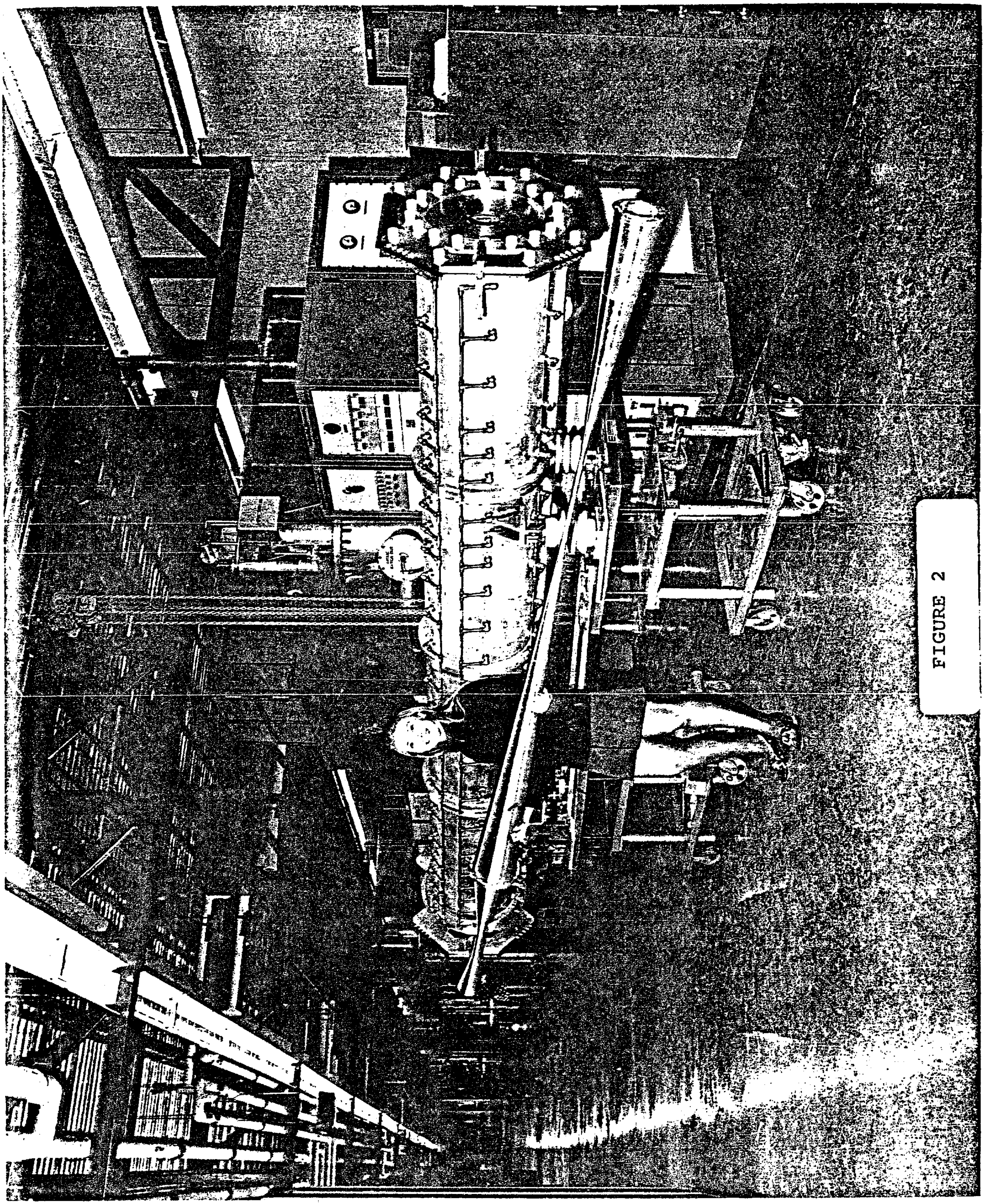

FIGURE 2

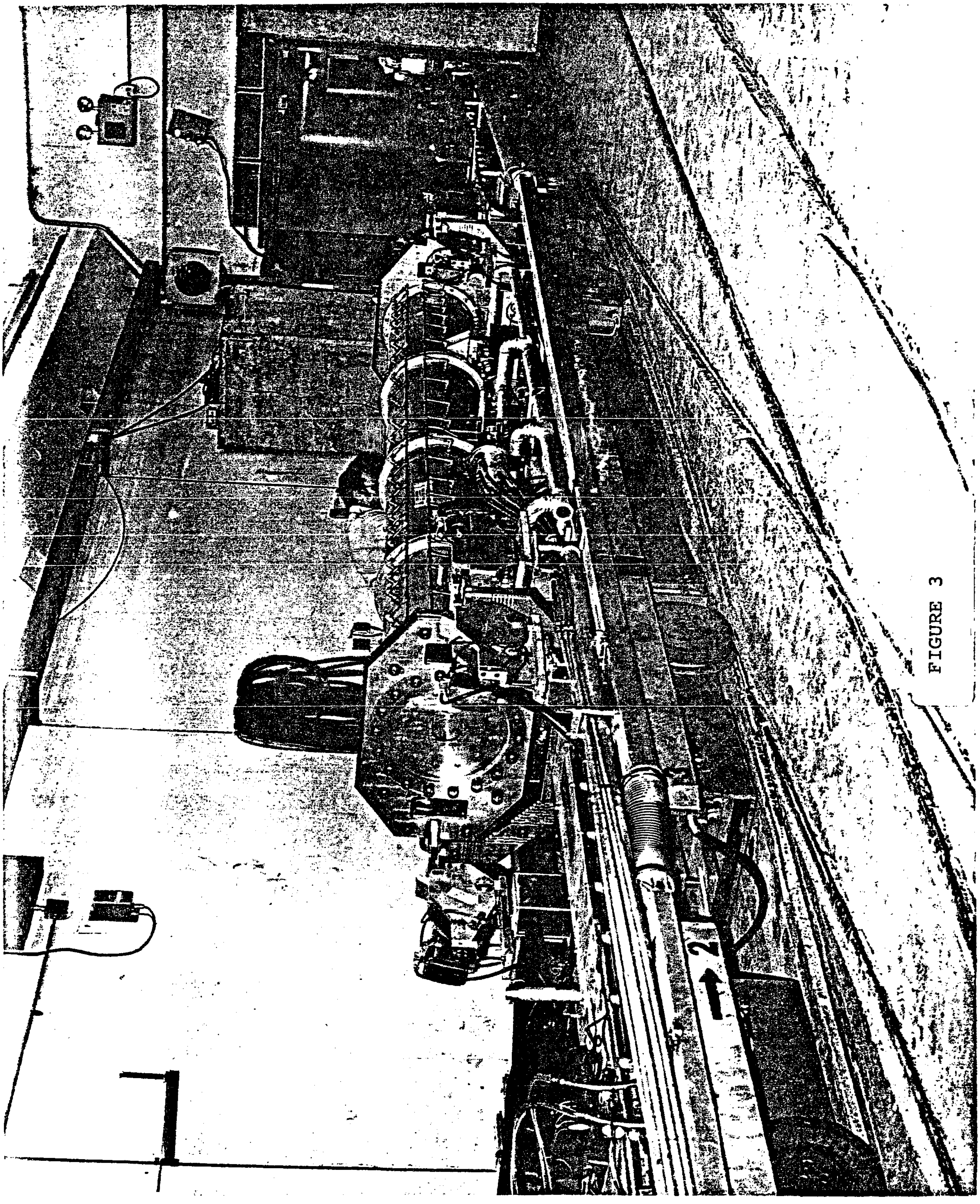

FIGURE 3

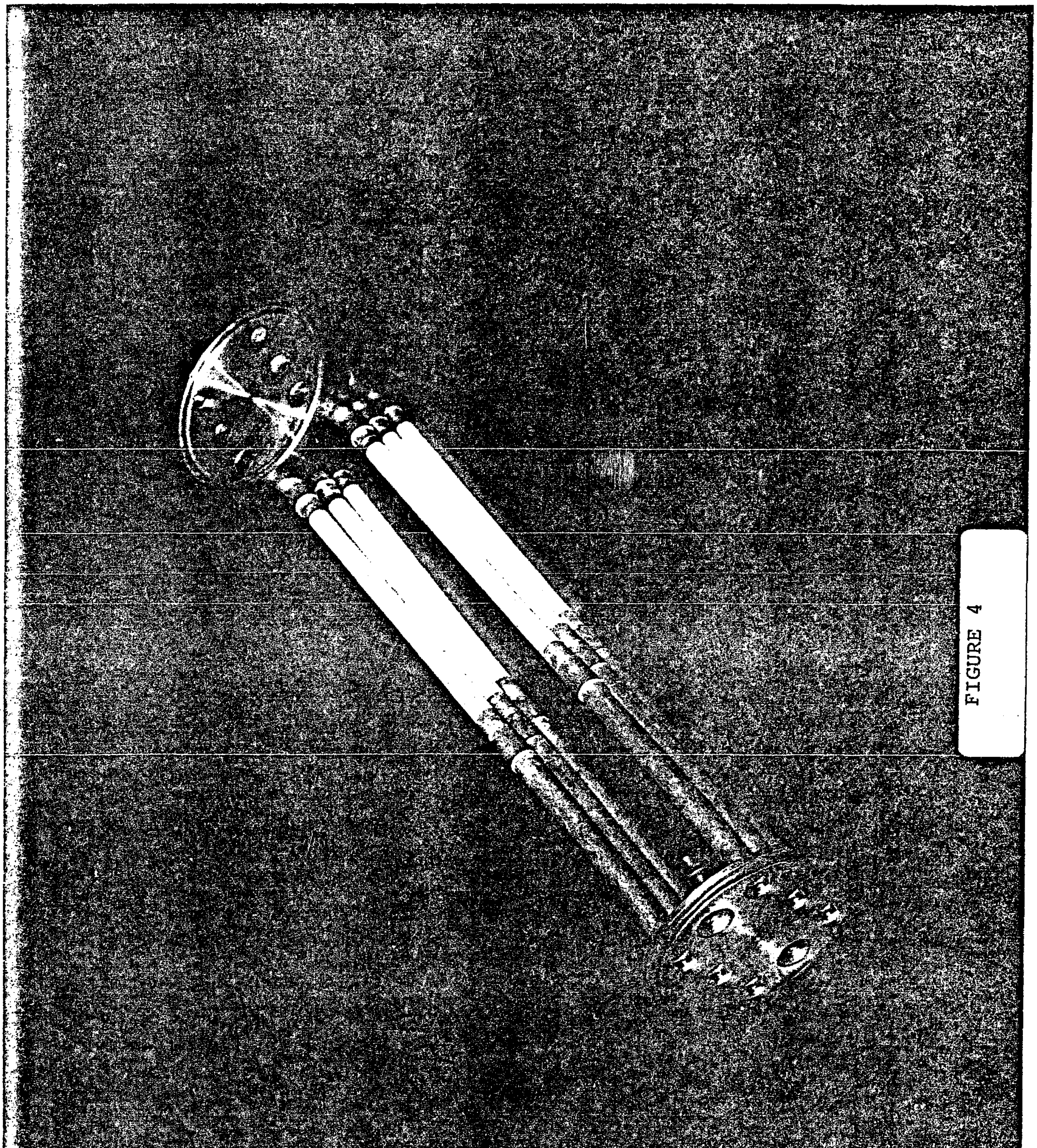

FIGURE 4

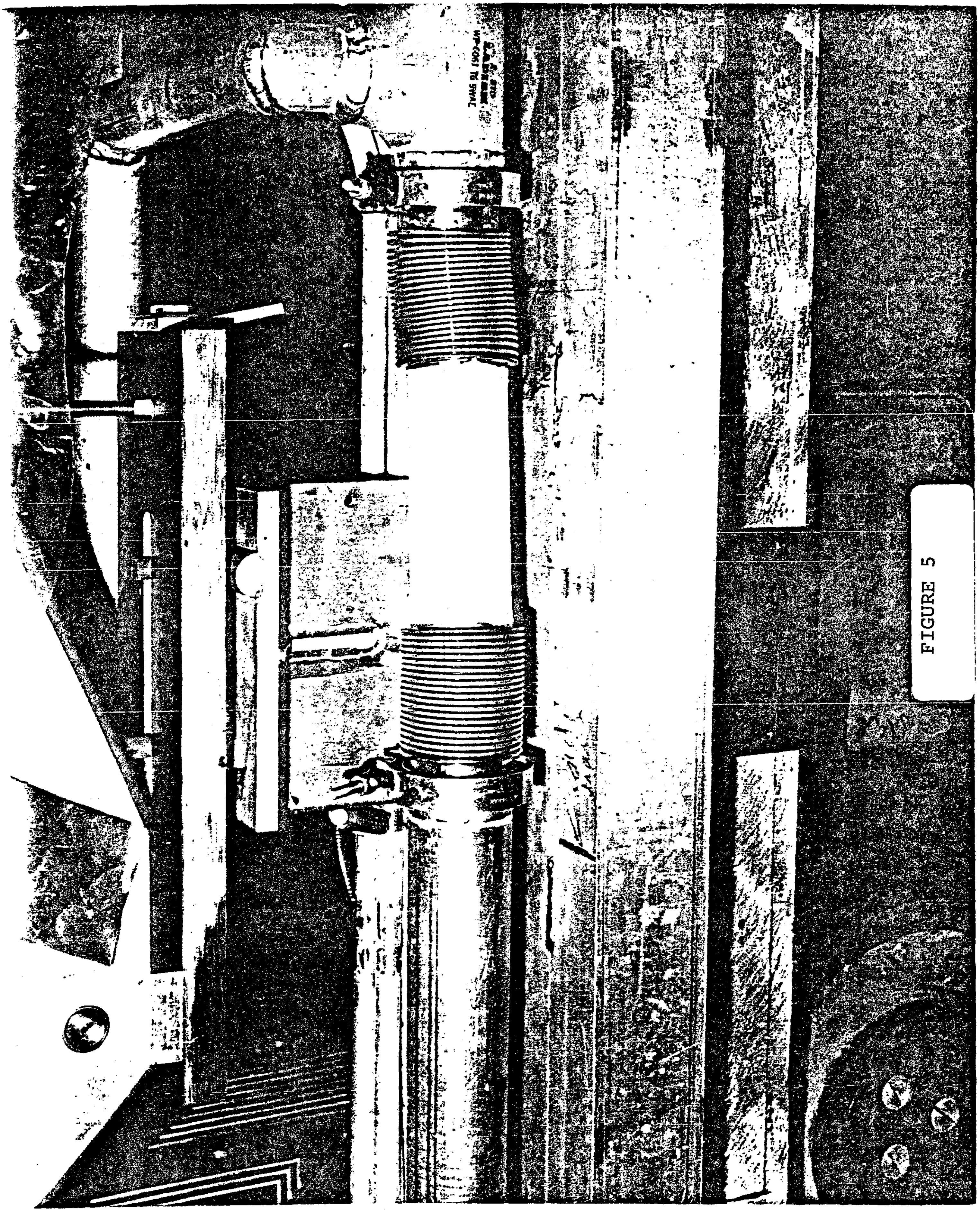

FIGURE 5

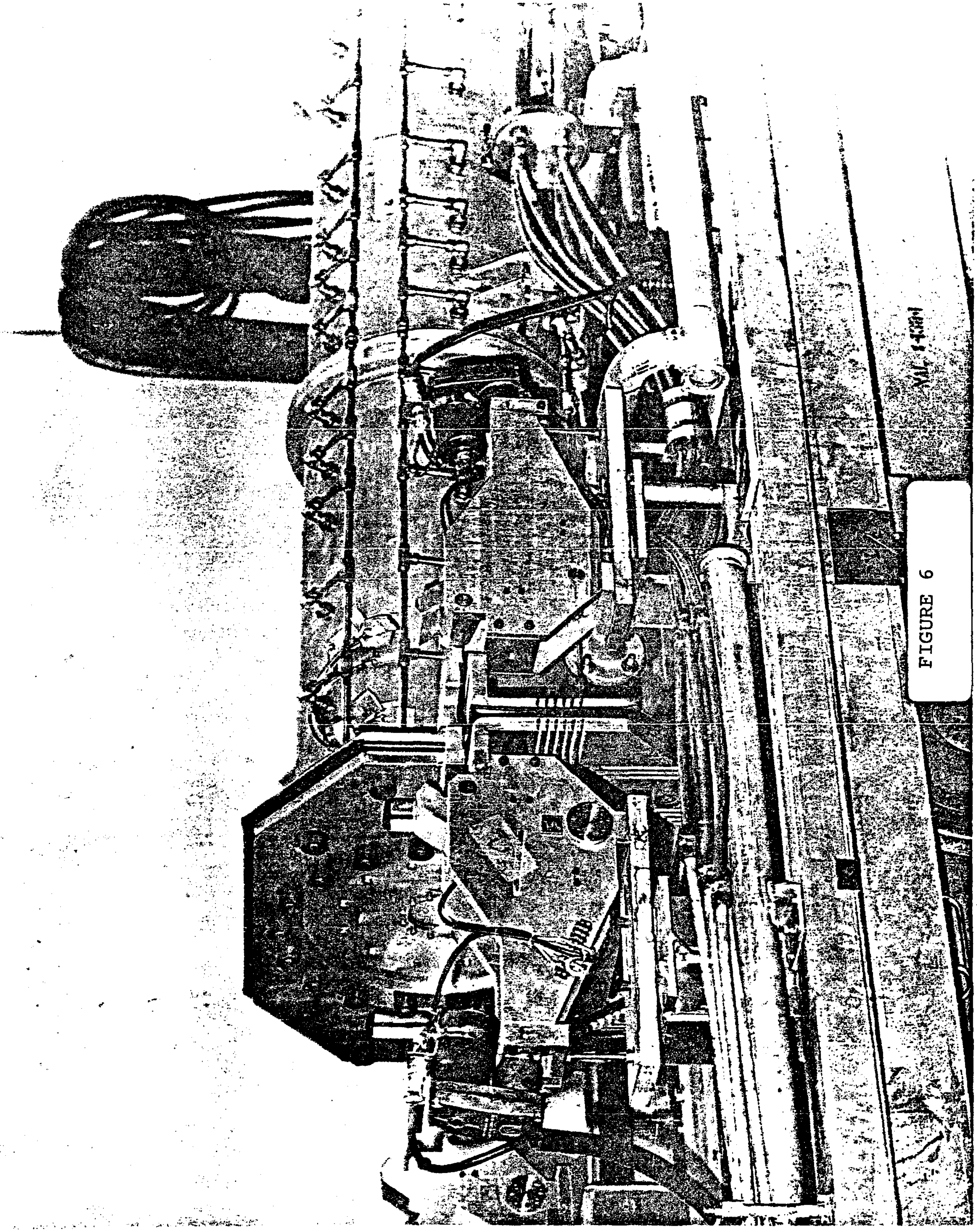

FIGURE 6

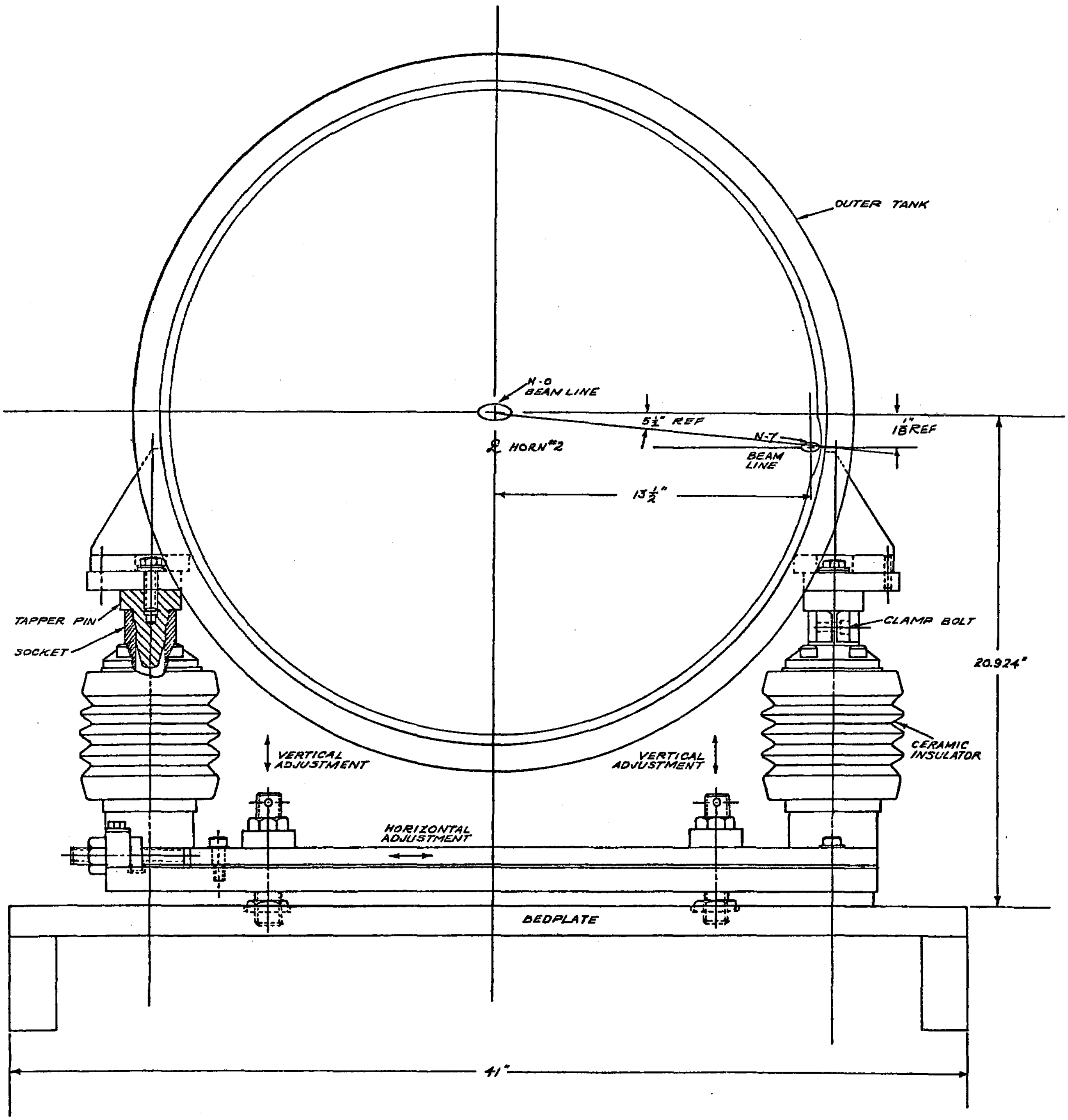
OUTER TANK
N-0
BEAM LINE
5½" REF
1⅛" REF
N-7
BEAM LINE
℄ HORN #2
13½"
TAPPER PIN
SOCKET
CLAMP BOLT
20.924"
CERAMIC INSULATOR
VERTICAL ADJUSTMENT
VERTICAL ADJUSTMENT
HORIZONTAL ADJUSTMENT
BEDPLATE
41"

FIGURE 7

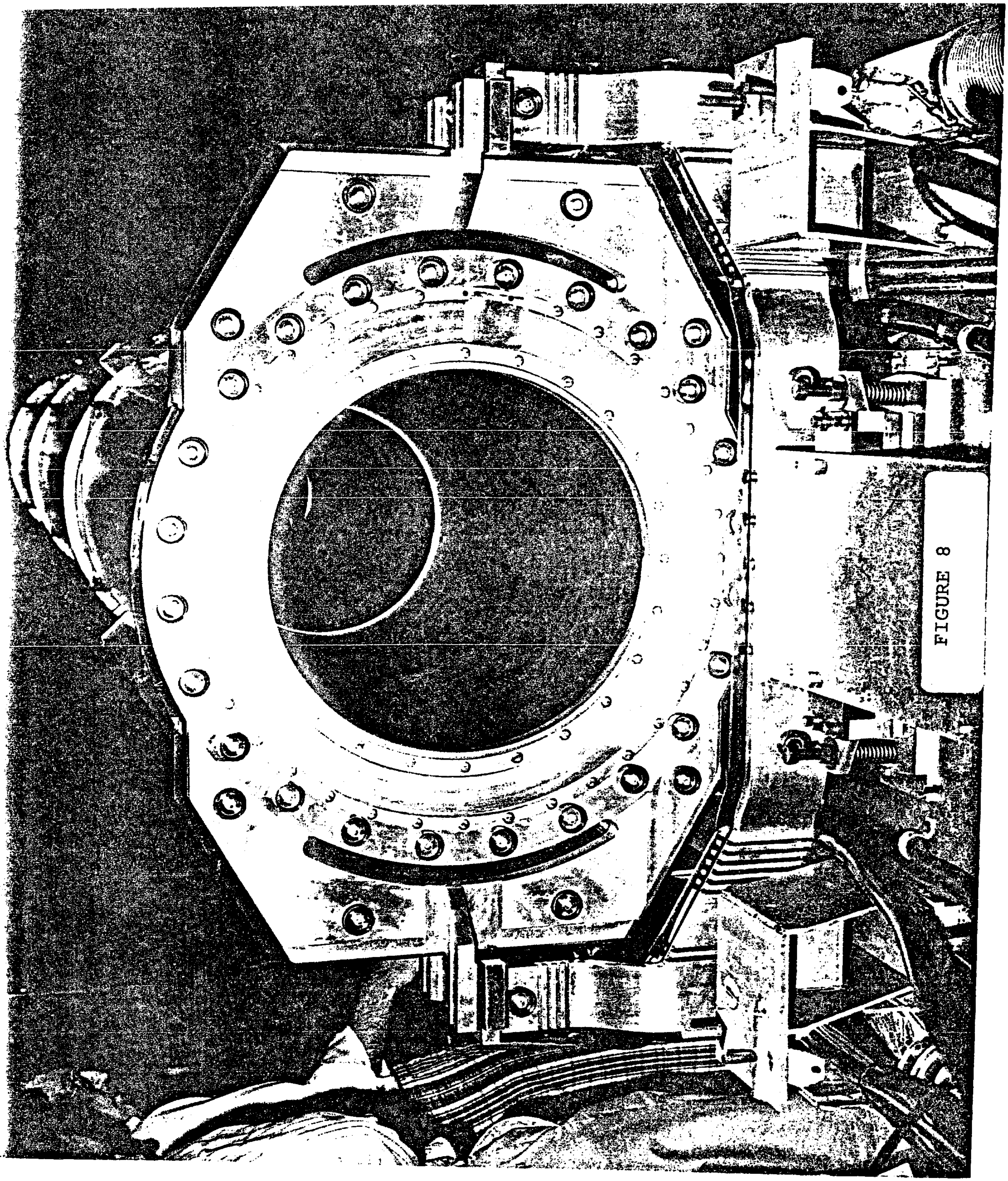

FIGURE 8

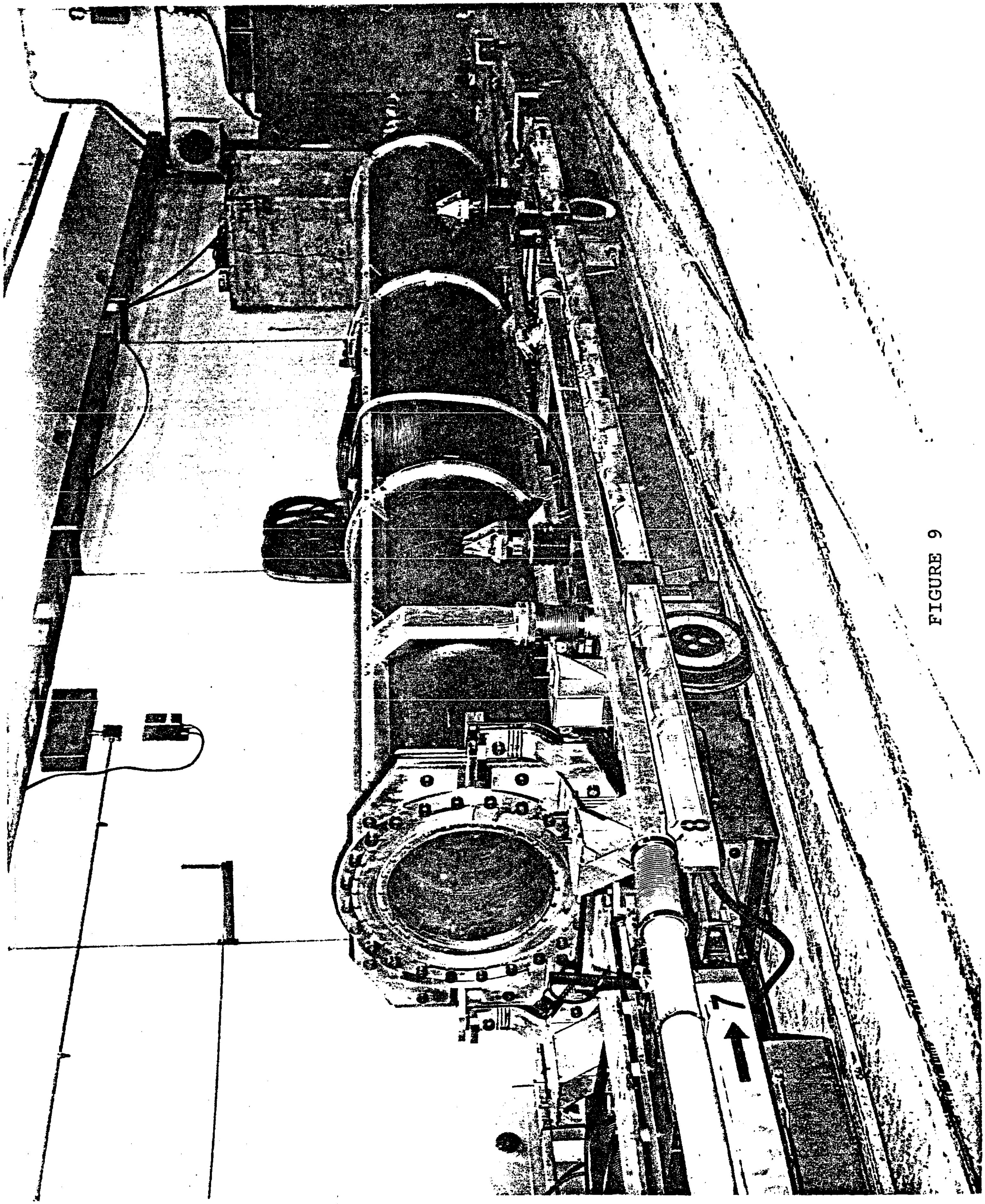

FIGURE 9

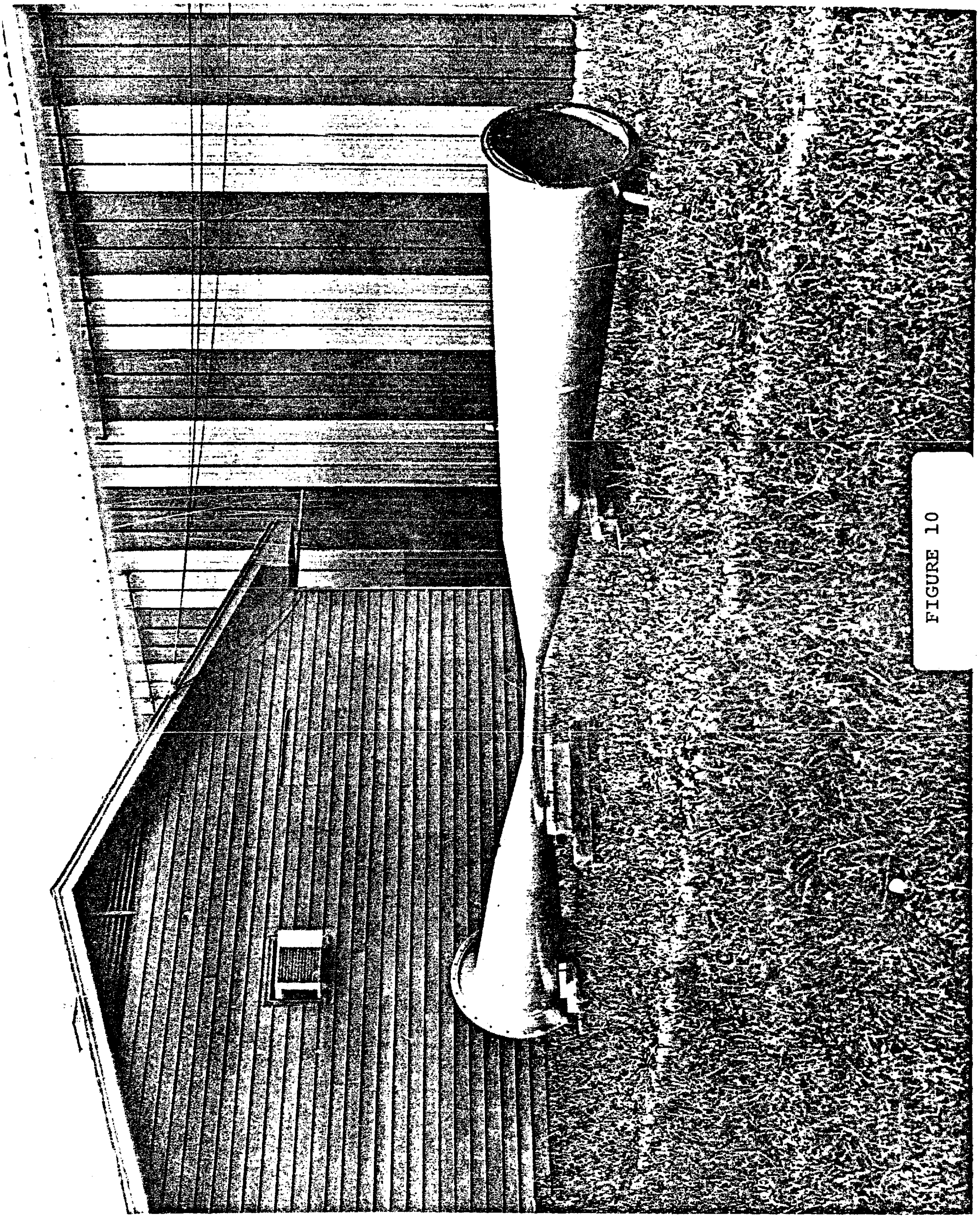

FIGURE 10

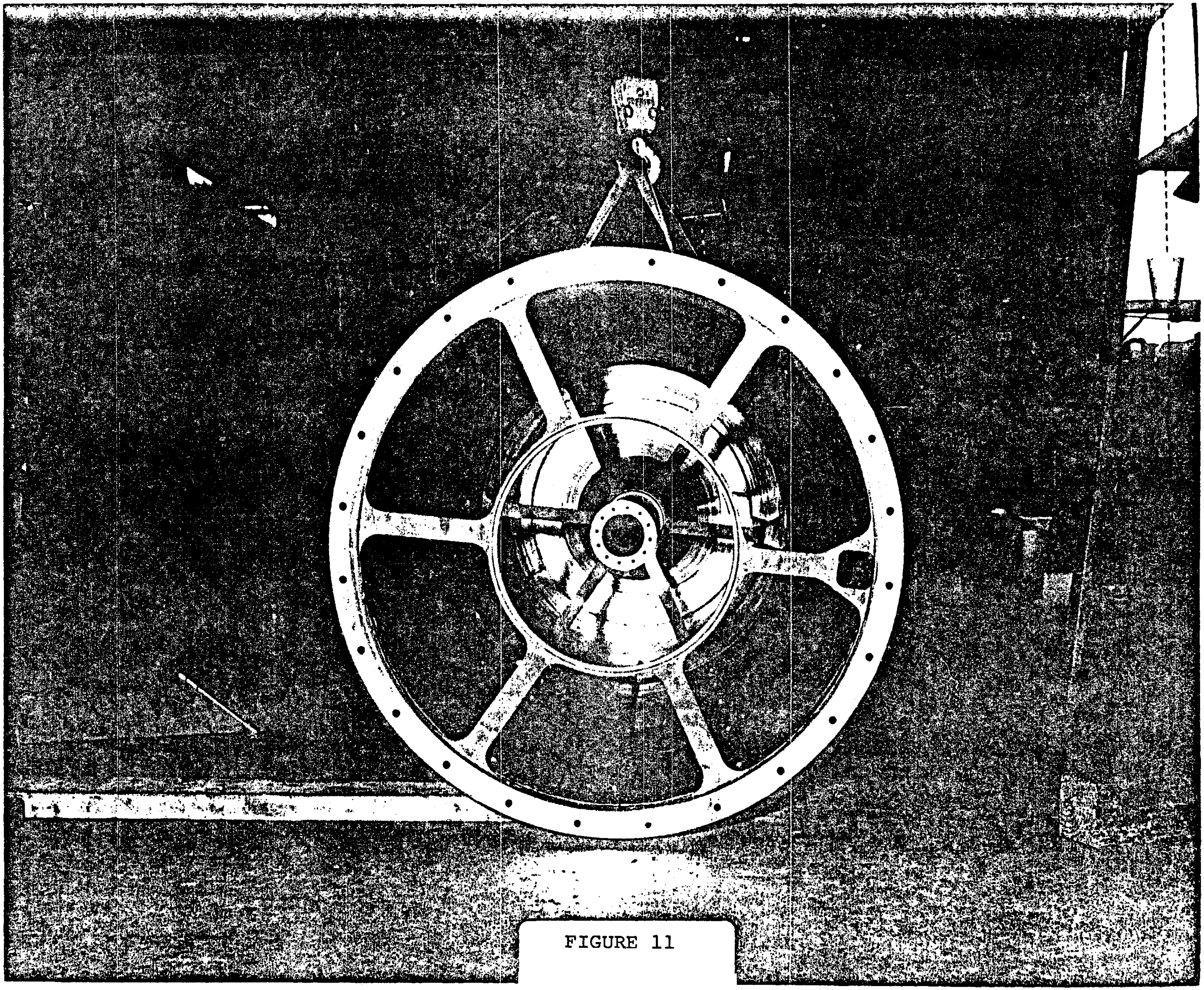

FIGURE 11

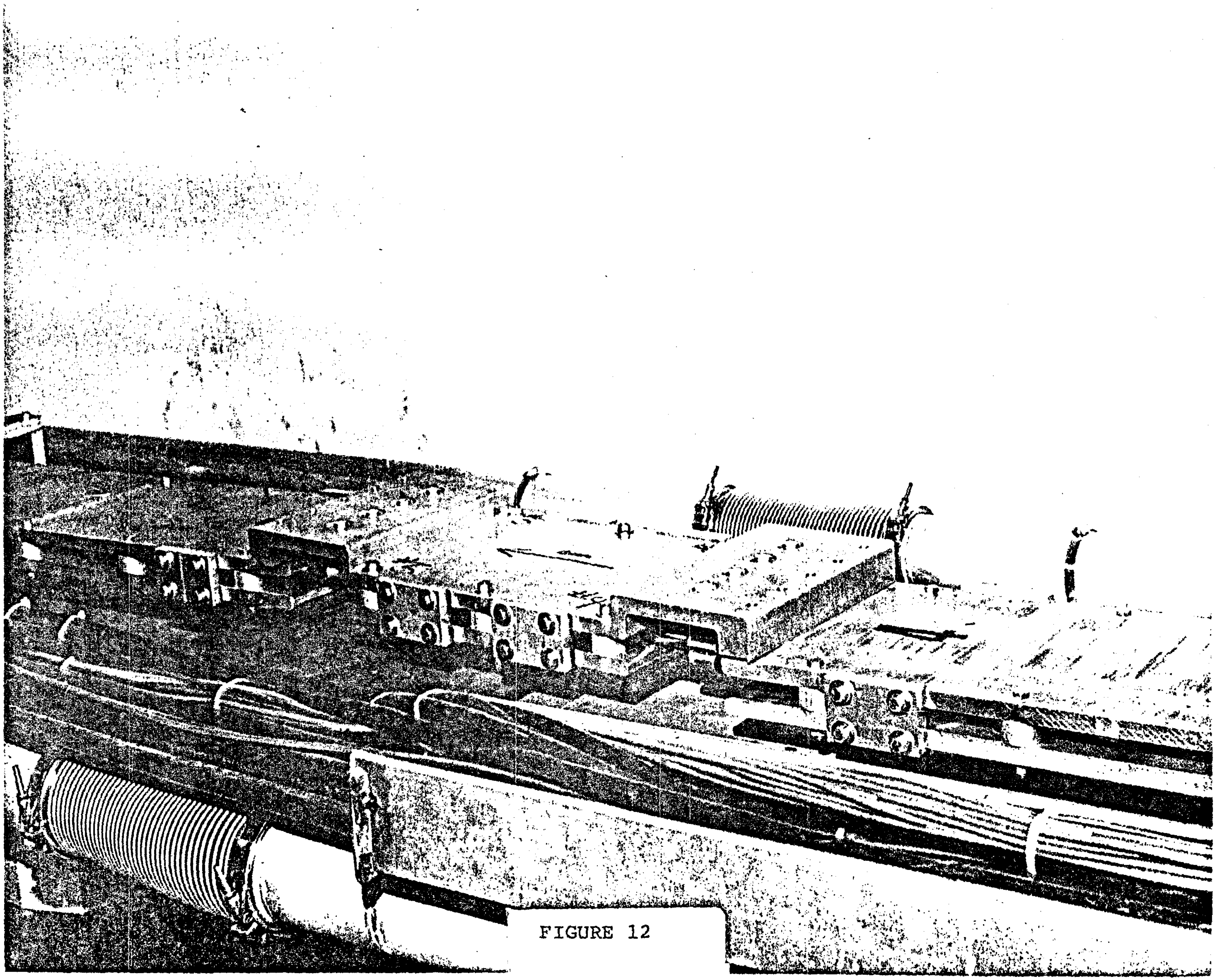

FIGURE 12

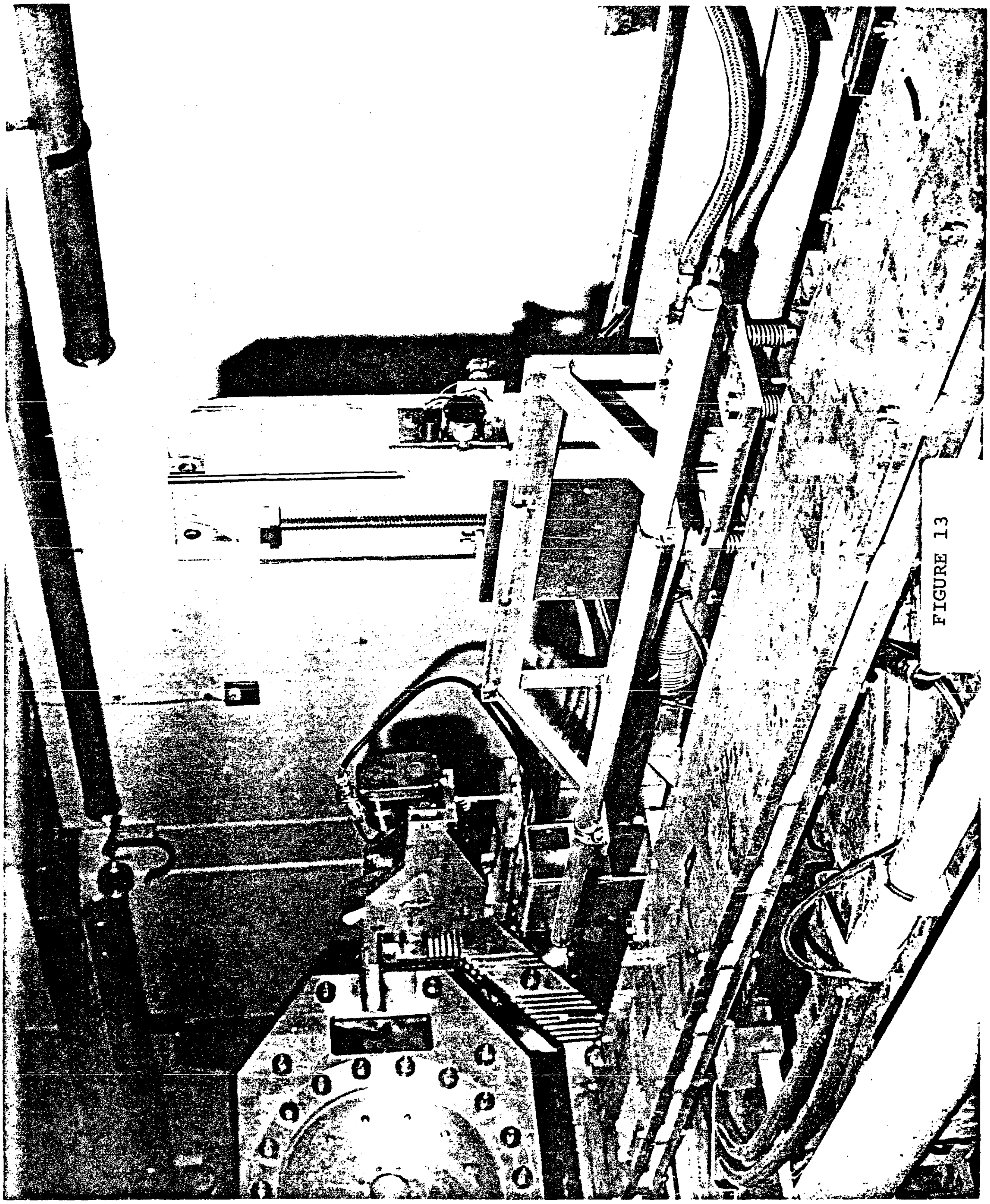

FIGURE 13

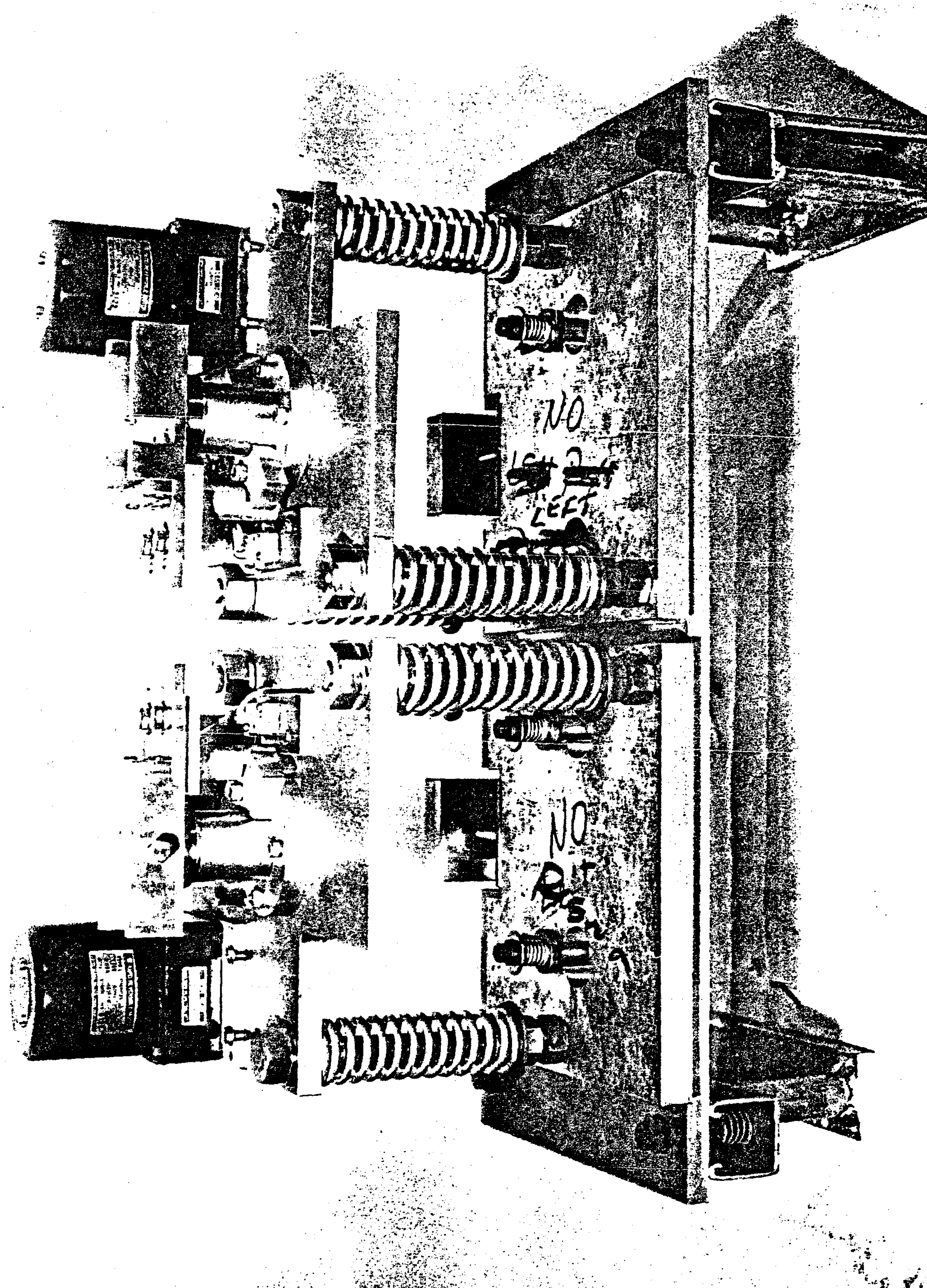

FIGURE 14