FACILITY FORM 602

N65-35253 (ACCESSION NUMBER)

59 (PAGES)

CR 59047 (NASA CR OR TMX OR AD NUMBER)

1 (THRU)

(CODE)

07 (CATEGORY)

"High Power CW Radar Transmitter" *

By Walter S. Baumgartner +

* Jet Propulsion Laboratory, California Institute of Technology, Pasedena, California.

+ This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institue of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

GPO PRICE $ _____

CSFTI PRICE(S) $ _____

Hard copy (HC) 3.00

Microfiche (MF) .50

ff 653 July 65

High Power CW Radar Transmitter

By Walter S. Baumgartner

ABSTRACT

35253

This paper is principally concerned with a description of an operational high power CW radar transmitter, but to properly orient this transmitter in the NASA-JPL space program some preliminary discussion of the space telecommunications problem, the existing Deep Space Net, and in particular the continuing program of advanced system development will be presented. The system in which the transmitter functions is described and its use as a planetary radar and as a proving ground for equipment is discussed. The design parameters for such a transmitter are delineated and the history of its development is traced. Particular attention is given to problems encountered and their solutions. There is a detailed description of the hardware involved with several diagrams and photographs. The present plans for increasing the radiated power still further and upgrading the transmitter system in general are presented.

Author

TEXT

The Jet Propulsion Laboratory of the California Institute of Technology is assigned by the National Aeronautics and Space Administration responsibility for the unmanned lunar and planetary space program. In support of this program a Deep Space Instrumentation Facility is operated with tracking and data aquisition stations located at approximately 120° spacings around the earth to provide continuous radio and radar contact with space vehicles. The present locations of these stations are Woomera and Canberra, Australia; Johanessberg, South Africa; Goldstone, California, USA, and a new installation scheduled for Madrid, Spain. Figure 1 is an aerial view of the Echo Station at Goldstone, California and is representative of the stations of the net. The 85 foot

HaDec antenna operates with a 10 KW S-band transmitter and a low noise receiver. The purpose of these stations is to provide tracking of spacecraft including two angles, doppler and range, issue commands to spacecraft and receive telemetry and television signals.

To develop improved systems and sub-systems for this net and to obtain important data on the planets of our solar system a special advanced development station is operated at the Venus Site, Goldstone, California. Figure 2 is an aerial view of this site. Two antennas are available. The 30 foot AZ-El antenna in the foreground is presently used at X-band and higher frequencies and the 85 foot AZ-El antenna is used with the high power transmitter for lunar and planetary work. Next to this antenna are the buildings housing the hydraulics for the servo motors, the 1.5 megawatt heat exchanger and pumps, and the transmitter power supply and controls. The main control building is in the foreground 1500 feet away from the antenna to avoid radiation hazard. Figure 3 is a view of the interior of this control building showing a portion of the high power radar installation. There are also limited office and laboratory facilities at this base and a permanent crew of people provides three shift, 24 hour, 7 day operation. Engineering development work is accomplished at Pasadena, California and at any time several engineers from that facility will usually be at the Venus Site. Firm power at 60 cps is furnished by a line from a commercial power system. As the pictures show this area is in the Mojave desert and all water is supplied via tank truck. Ambient temperatures can range from $+16^{\circ}F$ in winter to $+130^{\circ}F$ in summer. High winds are common. The site offers the advantages of adequate land, good isolation from other installations and low radio noise.

As mentioned previously this site serves the dual functions of field testing of advanced systems and accumulation of astronomical data. The first

function is met by continuous operation (10 to 20 hours per day 7 days a week) and the building of considerable flexibility into the equipment permitting changes as required. The planetary radar work has resulted in refinement of the astronomical unit and correction in ephemeris information which has contributed to the success of space vehicle missions.

The major components of the high power CW planetary radar are shown in block diagram form in Figure 4. It is apparent that the system is a mono-static radar using the same antenna for transmit and receive. In planetary work the round trip signal time is from 4 minutes to over one hour so the change from a transmit to receive configuration may be accomplished by wave-guide switches without the switching time becomming an appreciable part of a cycle. In addition to the operation of the waveguide switches, the receiver local oscillator is off during transmission and the transmitter drive is off during reception.

Starting at the top center of the diagram the antenna is an 85' AZ-El steerable parabola which, at the operating frequency of 2388 mc, provides 54 db gain and a beam width of .35°. The antenna and its Cassegrain feed appear in Figure 5. The small object at the apex of the quadripod is a 6' tunneled antenna used in a bi-static configuration on some lunar experiments.

The servo system of the antenna is driven by error signals developed from an ephemeris tape prepared in advance by the Jet Propulsion Laboratory for the planets of interest and time of operation. The punched paper tape is converted by digital equipment to azimuth and elevation signals which drive the hydraulic servo motors. A later development is using an on site computer to drive the antenna without going through the step of preparing tapes. The servo control and boresight TV console are shown in Figure 6.

The receiver used in this system is a low noise triple conversion

superhetrodyne with five channels capable of handling various types of modulation. The first amplifier, a traveling-wave liquid-helium-cooled maser, is located in the Cassegrain feed cone on the antenna and is shown in Figure 7. It provides a system noise temperature at zenith on cold sky of $29^{\circ}K$. With this noise temperature the receiver has been operated open loop to -190 dbm and is capable of maintaining phase lock in a 5 cycle per second loop to -176 dbm. In addition to the maser, the receiver first converter, RF switches and polarizer, and a signal generator are located in the cone. The signal is converted to 30 megacycles and conducted to the control building via coaxial cable. Figure 8 is a view of the portion of the receiver in the control room. Figure 9 shows the type of modular construction used in the receiver, the exciter and other radar components. Each of the gold plated modules shown comprises some complete circuit element such as a phase detector, mixer, amplifier etc. All have 50 ohm input and output and are shielded and filtered to maintain leakage levels below 1 microvolt around the box and on the power leads. The gold plating provides improved cover seals.

All reference frequencies for the receiver as well as all other station frequencies and time bases are derived by synthesis techniques from a master rubidium oscillator with a one minute stability of 5 parts in 10^{12} and a one year stability of 5 parts in 10^{11}.

Master station control is supplied by the special purpose computer shown in Figure 10. This digital device currently controls transmit-receive cycles, range gates, ranging codes and it is expected to take over such functions as automatic checkout and monitoring.

The Programed Local Oscillator of Figure 11, referred to previously, provides a local oscillator injection signal derived from an ephemeris tape

and so keeps the receiver tuned to the correct doppler frequency during open loop operation. It is not necessary during locked loop tracking operations.

The receiver output signal is integrated, processed, and the power spectrum plotted in the equipment shown in Figure 12. The transmitter exciter and power amplifier which will be described in detail later, complete the system.

Since this is an advanced development system we are continuously interested in improving the capabilities and range. Figure 13 shows graphically the increased capability of the Jet Propulsion Laboratory planetary radar since it was first operational in mid 1960 using a 10 KW transmitter, a receiver with a noise temperature of 1570°K and an 85' antenna. The installation of a ruby maser in early 1961 reduced the system noise temperature to 64°K, the transmitter power was raised to 13 KW, and improvements were made in the transmitting and receiving antenna feeds effecting a total improvement of 19.1 db. In late 1962 the change to a Cassegrain antenna feed system and installation of a double cavity maser improved the system capability by another 2.9 db. In early 1963 an improved two cavity maser reduced the system noise temperature to 37°K providing a .3 db improvement. At the same time the 100 KW transmitter was used for the first time increasing the capability by 8.9 db. The 1.9 db increase in 1964 resulted from an improved antenna surface and the installation of a traveling wave maser with a system noise temperature of 29°K. The projected improvement in 1965 and 1966 will result from use of the 210 foot antenna, now under construction at Goldstone, California, (8 db on transmit and 8 db on receive) and an increase in transmitter power to 400 KW (4.2 db).

The possibilities of increasing system capability are seen to consist of larger antennas, lower noise receivers, higher powered transmitters and perhaps

improved detection and signal processing techniques. The latter have been investigated intensively and present systems are near optimum for the state of the art. The 210' diameter steerable antenna mentioned previously represents about the practical limit of construction. A maser with a noise temperature of 29°K does not leave room for much improvement in this area. This leaves increased transmitter power as an attractive possibility.

High power alone is not enough in a CW radar transmitter. If this were the case it might be more easily obtained by use of a crossed field oscillator such as a magnetron instead of the exciter-linear accelerator power amplifier which is used. The requirements of such a transmitter are listed in Figure 14. Low incidental phase modulation or jitter and medium term phase stability requirements are imposed by the phase sensitive system with which the transmitter is used. Incidental phase modulation may occur in the exciter oscillator or multipliers, or in the klystron amplifier. Changes in beam voltage on the klystron result in phase changes. In the type VA858 tubes used in this transmitter the "pushing factor" is about 1° per 20V. and is a function of the electrical length of the klystron drift path. The objective on this system is a total phase jitter of less than 3° root mean square which imposes a severe requirement on power supply filtering. Direct current is used on the tube heater to avoid modulation.

Amplitude stability of .1 db over one planetary transmit-receive cycle is desired. This again, in the klystron, is a function of power supply regulation. The exciter is designed for amplitude stability but any instability there is largely eliminated from the system by operating the klystron in a saturated condition.

Frequency stability is controlled entirely by the oscillator and as the basic signal is synthesized from the rubidium standard it is held to 5 parts

in 10^{11} long term.

Bandwidth has never presented a problem in this type of operation. The exciter chain can be designed for any required bandwidth and the klystron exhibits a 3 db bandwidth of from 10 mc to 30 mc at 2388 mc depending on the tuning. The maximum requirement to date has been 3 mc. The klystron could easily provide a bandwidth of 60 mc. with a reduction in gain from 60 db to approximately 46 db.

Allowable harmonic radiation is limited by interference to other services. Originally the transmitter was designed to include a harmonic filter but subsequent measurements showed the second, third and fourth harmonic to be down 42 db, 47 db and 72 db respectively which met all requirements without the use of the filter.

Noise in the klystron is approximately 10 milliwatts in a 10 mc bandwidth with nominal beam voltage of 34 kilovolts. This is 65 db below the transmitted power of 100 KW in a useful bandwidth of 3 mc and causes no problem on the transmitted signal. However, this noise persists during receive cycles when the drive is removed from the klystron and poses a problem of isolation from the receiver. A low noise transmitter is therefore desirable.

In many modes of operation the ability to phase modulate the transmitter with digital signals up to 1 mc and to $\pm 90^{\circ}$ is a requirement. On-off keying of the drive is also used and both of these functions are provided in the exciter chain to be covered later. Saturated operation is the usual mode but specialized requirements for linear operation exist. For this reason some provision for linear operation is desirable. The Goldstone transmitter is capable of linear operation to 70 KW average power with not over 10% nonlinearity.

It can be seen from the above restrictions that the problem of providing high power output with acceptable characteristics is formidable. The Goldstone transmitter, which is the subject of this article, has been operational for 18 months at 100 KW continuous wave output and has been operated as high as 150 KW. In addition it meets all the parameters listed in Figure 12 and operates 12 to 20 hours per day 7 days a week with less than 3% unscheduled downtime. This represents a considerable improvement from the first operation in early 1963 when the mean time between failures was 17 minutes! System, component, and circuit redesign was required.

As shown in Figure 15 the transmitter consists basically of a power supply which converts the line voltage of 12600 V 3 phase 60 cycles per second to direct current at up to 55 kilovolts and 30 amperes with a power limitation of 1 megawatt, for the klystron amplifier beam. The frequency synthesizer and the exciter provide an input signal to the 100 KW amplifier which provides approximately 60 db power gain. The transmitter control furnishes monitoring and control of all functions while 38 protective devices prevent damage to equipment by removing voltage in event of a malfunction. The liquid to air 1.5 megawatt heat exchanger is used to cool the amplifier, the power supply and various auxiliaries to the transmitter.

The signal starts in the exciter which is shown in block diagram form in Figure 16. The output of the rubidium maser, which is the basic station frequency standard, is synthesized to provide 31.84 mc. The coaxial relay is used to assure adequate isolation of the driving signal during receive periods. It is followed by the solid state keyer which can handle on-off keying from DC to 1 mc. The X5 varactor multiplier is followed by a phase modulator. The only type of modulating signal encountered in normal modes

of operation is digital square waves so a special case is presented to this modulator. The ability to handle complex waves is not required but a high order of stability is necessary. The modulating signal operates two VHF solid state switches to vectorily sum a reference and a phase shifted signal to produce a phase modulation up to $\pm 90^{\circ}$ at the transmitter output. The modulating signal is therefore relieved of any rigid amplitude stability requirements. Using symmetrical modulating waveforms this system produces up to 60 db of carrier suppression at $\pm 90^{\circ}$ shift.

The signal is then amplified to 300 mw and sent through a 1500 foot cable to the transmitter compartment on the 85 foot antenna. The loss in this cable is 11.5 db, over half of which occurs in the antenna wrapup and terminal cables where the use of low loss foam type cable is not practical. A second VHF amplifier in the antenna compensates for the cable losses to drive the X15 solid state multiplier. The 0-60 db attenuator and triode cavity amplifier provide a drive signal to the klystron from essentially 0 to 3 watts. The directional coupler and power meter indicate drive level on the antenna and in two remote locations.

Since the klystron gain is 60 db in the usual tuning condition only 100 mw of drive is required. It is possible to obtain up to 2 watts from a varactor multiplier at this frequency and plans call for replacing the present X15 multiplier with a unit capable of this output therefore making the triode amplifier unnecessary. This will eliminate a major maintenance problem.

Figure 17 shows the bandpass of the exciter to be 6 mc at the 3 db points. This exceeds all system requirements by a factor of 2.

The control room portion of the exciter is shown in Figure 18. The left cabinet is the 100 KW amplifier remote control with the rubidium

standard and instrumentation in the center. The sliding plate at the right mounts the exciter proper. Figure 19 shows the antenna mounted exciter modules with the box cover removed. The elaborate double shielding is required to avoid danger of oscillation in the high gain klystron. It also provides weatherproofing. Note that all cooling is by conduction to the box sides.

The klystron power amplifier is the heart of the high powered CW transmitter and is the item which required the most development work. Figure 20 shows the amplifier with the top weather cover removed, mounted in the cage behind the antenna. Since the cage moves with the antenna in azimuth and elevation the amplifier must operate in any attitude. The 50 gallons per minute of cooling water required is handled in azimuth movement by a rotary joint and in elevation by flexible hoses. A total of 4 cables containing 4 coax and 46 pairs are conducted from the ground to the transmitter via a wrapup for azimuth movement and flexible cables for elevation. Figure 21 is a block diagram of the power amplifier. The signal from the exciter (Figure 14) passes through two series connected crystal diode switches and through a ferrite isolator to reduce mismatch to the first cavity of the power klystron. This part of the circuit is in 50 ohm coaxial cable. The function of the crystal switches is to remove the drive in the event of a waveguide arc as indicated by a signal from the arc detector, or a rapid increase in back power. These switches provide 60 db of isolation with an operating time of 5 microseconds for protection of the klystron. The 100 KW output is in WR430 waveguide to the waveguide switch which selects either the antenna or the RF water load. This load will handle the full output continuously and is used for test and adjustment of the transmitter as well as the basic standard for calibrating the power meters. The input and output water temperatures and the flow rate are monitored and power is computed by calorimetric methods.

The beam power supply input is normally 32 KV at 8.5 amperes with the positive grounded and the negative high voltage to the cathode. At 100 KW out this indicates an efficiency of 37% which is affected a few percent by the tuning of the cavities. The filament supply of approximately 10V at 10 amperes is connected to the cathode and therefore operates at 32 KV above ground. The focusing magnet coils are water cooled and are in series across a single power supply which, at best focusing adjustment, delivers approximately 500 volts at 9 amperes. The Vacion gauge gives a continuous indication of the vacuum in the tube and is particularily useful in indicating return to a safe operating condition after an outgassing in the tube. In addition the Vacion assists in pumping down the tube. Foreward and back power couplers indicate power on local and remote meters and in addition the back power coupler provides tube protection as previously mentioned.

The four cavities of this klystron are tuned by reversible gear motors and tuning may be accomplished either locally or remotely. After a tube is placed in service there is little occasion to change the tuning and it is felt that the motor tuning could be replaced with manual controls on future tubes. Further, future tube designs may well be fixed tuned with considerable simplification and no compromise in performance.

Figure 22 is a view of the power amplifier on the ground with the weather tight covers removed. The gauges to the right indicate water flow, pressure and temperature. The klystron and its magnet are in the right compartment with the two water hoses attached to the inlet and outlet fittings. The waveguide output is at the left. Because of the high powers involved only oxygen free copper guide is used to hold losses to a minimum and even this guide requires water cooling.

The main control station for the transmitter which provides switching functions, instrumentation, remote tuning, focusing control and fault indication is shown in Figure 23. This is located in the transmitter building near the antenna and control may be maintained from here or from the remote panel in the main control building 1500 feet away.

The type VA858 klystron used was developed specially for use in this transmitter and to our knowledge is the highest powered CW tube at this frequency in existance. It is 36 inches long by 10 3/4 inches in diameter and weighs 135 pounds. The magnet weight is 425 pounds. It is a four cavity klystron and provides 46 to 60 db gain depending on the broadness of the tuning. Figure 24 is a view of the tube. Two klystrons were built on the original development and these tubes have been used for 18 months on planetary work. Three additional tubes have since been procured but as yet have not been placed in service. The klystrons are satisfactory considering that they are the first tubes at this CW power level and as such are highly developmental. However, they remain the limiting factor on power output and reliability of the transmitter, and do not average over 900 hours of service. A total of seven failures have occured between the two tubes and after each failure the tubes have been rebuilt. Rebuilding costs average about half the cost of a new tube. One failure occured due to a few plugged water passages in the collector and a filter with smaller openings than the collector has been installed to avoid this problem. One output window cracked from heat during a high power test at 178 KW which is, of course, 78 KW above rating. A nitrogen forced cooling system is under consideration to remove this limitation. A third failure of this tube was caused by the manufacturer failing to properly clean foreign material from the tube before sealing. The second tube suffered three failures caused by a malfunction of external equipments. This

tube has two additional failures resulting from a cracked collector and a leak in a ceramic-metal seal.

The problem of collector errosion from the high intensity beam is a major limitation on life. The 3/8" thick copper collector walls can be erroded away to a point where water leaks occur. Future designs will use a collector with a silver coated interior and shielded magnet coils to provide better beam dispersion in an effort to reduce this problem. Most damage results from high beam energy per unit area due to poor defocussing.

The third major component of the transmitter is the beam power supply. This supply will deliver up to 55,000 volts and up to 30 amperes of direct current with a power limitation of one megawatt. It is obviously overpowered for the 350 KW input requirement of the 100 KW transmitter and was designed with a view to future power increase. The supply is shown in block diagram in Figure 25. Power at 12,600V 3Ø 60 cps is supplied to two separate substations from a commercial line which is underground the last mile because of the strong RF fields present. The 2400V substation supplies the main motor generator only, while all auxiliaries are supplied from the 480V substation. A 75 KW 400 cps 3Ø motor generator operated from this line supplies all auxiliary 400 cps requirements. The output of the main motor generator at 400 cps is stepped up in voltage in the transformer, rectified, and delivered to the load through a filter, crowbar and series limiter diode at voltages adjustable from 3000V to 55,000V.

Referring to Figure 26, the motor generator consists of a 1750 HP 60 cps 1800 RPM synchronous motor direct connected to an 1100 KVA 400 cps 3Ø alternator. At the right is the 150 HP induction type cranking motor used to bring the unit up to speed through a magnetic clutch. Output voltage of the DC supply is controlled manually or automatically by adjustment of the

field of this alternator which is supplied from a rotary exciter. This exciter also supplies the field of the synchronous motor and this is used to maintain an essentially unity power factor for the total load by over exciting the motor field. Control of the motor generator is accomplished in the cabinet shown in Figure 27, which provides switching functions, over and under voltage and current protection, automatic and manual voltage regulation, synchronization, power factor control and monitoring.

The use of a frequency changer such as the motor generator might seem to be unnecessary but actually provides technical and ecnomic advantages which make it well worth while. It will be incorporated into future designs. It isolates the power line from a crowbar of the DC supply and so greatly simplifies the line protection problem. It also isolates the supply from short duration line voltage fluctuations and transients due to the large inertia of its rotating components. The change from 60 to 400 cps reduces all transformer sizes and costs and by changing the ripple frequency from 360 to 2400 cps reduces filter size and cost. No failures other than normal start up problems have occured in this equipment and it is considered satisfactory.

The vacuum switches following the alternator are used to remove the residual field output of the alternator when it is desired to reduce the DC output to zero such as in case of a crowbar firing resulting from a fault. The vacuum relays were used instead of conventional air or oil switches because of their fast opening time of 50 milliseconds. The transformer-rectifier assembly is located in a concrete vault for safety. Figure 28 is a view of one corner of the transformer and two of the twelve rectifier tubes used in the 3 phase full wave bridge. The small size of the vault precludes a more inclusive photograph. The lead lined Xray safety door to the rectifier is open. The water hoses cooling the tubes are in the foreground

and the object at the left of the door is the safety grounding rod. The transformer contains the high voltage winding and filament windings for the rectifier tubes. It is oil immersed and water cooled. These tubes were a major source of trouble during the early months of operation and their life in some cases was only minutes. Under full voltage operation the peak inverse voltage across the tubes is 57,750 volts and even at 32 KV DC out the PIV is 33,600 volts. This was within the published ratings of the tubes, but both internal arcs, which destroyed the tubes, and external arcs, which crowbared the system off the air, were common. An intensive program of redesign was undertaken and the present tubes have operated one year without arcs or failures. Even so the use of silicon rectifies stacks is considered superior to thermonic diodes from the stand-point of reliability, reduced voltage drop, increased efficiency, reduced cooling requirements and elimination of filament supplies. An oil immersed water cooled silicon stack has therefore been manufactured and is shown in Figure 29 removed from its tank. This unit will be installed during the next availability of the system and future designs will use this type of rectifier.

The output of the rectifier is conducted out of the vault to an enclosure containing the filter, crowbar, crowbar logic circuits and an automatic shorting bar. The filter, consisting of a 1 henry choke and a .42 mfd output capacitor, is shown in Figure 30. The output ripple under full load is less than .05%. An interesting phenomena occured when the system was first placed in service. The high voltage cable is a double shielded coaxial type with 47 mmf. per foot capacity. The capacity of the cable from the rectifier to the choke resonated the circuit at 2400 cps resulting in very high ripple. The addition of a .06 mfd input capacitor shifted the resonance and cured the trouble.

Also in the compartment with the filter is the crowbar protective device. This consists of a hemisphere gap shown in Figure 31. The high voltage out of the filter appears across this gap with the lower hemisphere at ground potential. The gap opening is controlled by a servo which increases the gap with increasing DC voltage. Located in the lower half is a spark plug which is fired to initiate a discharge across the gap when high klystron body current, a step function of beam current or a rectifier tube arc is sensed. This discharges the stored energy of the filter across the crowbar, rather than across the fault, preventing equipment damage. The operating time of the crowbar is 5 microseconds. At the time the gap is fired, the contactors to the alternator field are dropped and 40 milliseconds later the vacuum relays between the alternator and transformer open removing the alternator residual field voltage and dropping the system to zero volts.

An additional klystron protective device is the series limiter diode shown in Figure 32. This is a 175 KW plate dissipation triode connected as a diode in series with the high voltage lead from the crowbar to the klystron. The filament voltage is controlled to provide emmission limiting of the pass current to 150% of normal, thus preventing high peak discharge currents in event of a klystron arc. While this device is effective, it has several drawbacks. It does not protect against the stored energy in the 17,600 mmf. capacity of the cable to the antenna which at 32 KV amounts to 8.7 joules. The voltage drop across the diode at 9 amperes is approximately 10,000 V resulting in a 90 KW power loss. In addition the filament of this tube consumes up to 21,600 watts. If contemplated higher power operation is attempted the supply does not have sufficient voltage output to afford this

10 KV loss. For these reasons the diode limiter will be replaced by a ten ohm surge resistor at the klystron. This will limit the energy in the tube arc to 2.3 joules which is 30% of the unlimited value and is adequate protection.

There is extensive equipment protection provided throughout the system and these devices have countless times prevented damage to the klystron or other components. Indeed, it has been suggested that it is statistically remarkable that the transmitter has operated at all with this multiplicity of cutoffs. In addition to the waveguide arc and back power sensors which remove the drive, and the high body current, beam pulse detector and rectifier tube arc detector which fire the crowbar as described previously, there are 38 additional sensors which remove primary power from the transformer. These are low water flow, over current and under current, over voltage and under voltage, temperature, cooling air and high voltage compartment interlocks. In the early months of operation extreme problems were encountered with the actuation of the logic circuits of these devices by extraneous electrical signals. As an example the operation of the klystron tuning motor switches on the magnet power supply variac drive motor triggered one or more protective devices. There was even an indication that the pulse from the room light switch could cause a false operation. This has been eliminated by an extensive program of shielding and filtering leads and bypassing of spark producing devices.

Because of high ambient temperature and frequent sand conditions on the desert, air cooling is generally not satisfactory. The only air cooling used is a small blower on the klystron cathode seal. The klystron, motor generator clutch, transformer, rectifier, magnet coil, series limiter and its filament supply are all cooled by distilled and deionized water from the main heat exchanger shown in Figure 33. This unit has a capability of 1.5 megawatts in

ambient air of -32°C to +57°C with a water output temperature not to exceed 62°C. The pressure at the heat exchanger is 165 psi and on the antenna 140 psi at a flow rate up to 300 gpm. There are three radiators cooled by 3 ten-foot fans. Temperature is automatically controlled by vane type air shutters. When a shutter is $\frac{1}{4}$ open the associated fan shuts off and starts again when the shutter opens beyond the $\frac{1}{4}$ point. The four circulating pumps are manually controlled. A 30 KW heater is used to prevent freezing under extreme conditions and covers can be installed on the radiators for shut down. In the picture the covers are installed on the left radiator. A still and deionizer are being installed to prepare make up water on the site. The heat exchanger is satisfactory and no problems exist with it.

Certain accessory equipment, which is not required for operation of the system but which is useful for testing and maintenance, is used. A DC water load, Figure 34, is used for testing of the power supply. It is mounted high on a wall for safety and is remotely controlled. Heat is dissipated by using the cooling water as a conductor. The unit is satisfactory at the 350 KW level but problems with insulator failure and internal arcing have been experienced at 1 megawatt. A new load is under design at JPL to handle the full power.

In order to monitor the transmitted spectrum in the control room a spectrum analyzer of the swept frequency type is used. The input to this unit is centered on 30 mc. Figure 35 is a block diagram of the antenna mounted weather proof box which hetrodynes 2388 mc to 30 mc for this purpose. The 31.44 mc synthesized from the rubidium standard is sent to the antenna and multiplied X75 in solid state multipliers to 2358 mc. This is mixed with 2388 mc obtained from a short probe in the antenna and the resulting 30 mc is returned to the control room for display on the spectrum analyzer

When super high power was first considered a major concern of the Jet Propulsion Laboratory was personnel safety and this continues to receive daily consideration of the engineers and operating crews. The value of the extensive precautions observed has been proved by the lack of accidents at the site to date. There are three potential hazards; RF radiation, X rays and high voltage.

The allowable standards for radiation have been established at 1 milliwatt/CM^2 continuously and 10 milliwatts/CM^2 for short periods not to exceed 1 hour out of 24. These are the most conservative standards known and compare with 10 milliwatts/CM^2 continuously commonly used. To insure that these limits are not exceeded there are 10 hand carried radiation monitors with direct reading scales on the site. All areas have been surveyed and safe areas are documented. All personnel entering the radiation area are issued one of these monitors. The transmitter and antenna area is surrounded by a fence with flashing orange lights when the high voltage is on and flashing red lights when transmitter drive is on. When any of these lights are on only approved transmitter personnel are admitted inside the fence. This regulation is enforced by a guard on the gate. There is an automatic cutoff which shuts down the transmitter if the antenna is lowered below 7^o which prevents the beam striking buildings or personnel areas. A safety key switch on the antenna permits personnel working there to remove the key preventing application of high voltage to the transmitter. In addition there are key switches on the control panels in the transmitter building and the control room. All of these keys must be in place to operate the transmitter. The only duplicate keys are kept at the Jet Propulsion Laboratory under lock. Red "panic buttons" located in the klystron amplifier box, outside the box and on both control panels will shut the transmitter off. In addition an

announcement is made over the public address system before the transmitter is energized.

The only unsafe areas are in the main beam of the antenna. Levels around the klystron and behind the parabolic reflector do not exceed 4 milliwatts/CM^2 and in most areas are below this. No operating area shows a field which will give an indication on the monitors with a threshold of .1 milliwatt/CM^2.

Soft X rays are generated by the klystron and hard X rays by the rectifier tubes. The latter will be eliminated with the installation of the silicon rectifier. The safe level of X ray exposure has been established at 2.5 milliroentgen/hour not to exceed 100 mr/week. The level at the klystron cathode is 9 mr/hour and with the covers in place 2 mr/hour. At a distance of 2 feet with the covers on there is no measurable X ray radiation. The rectifier tubes are enclosed in a lead lined cabinet and outside this there is no measurable radiation. The cabinet doors are interlocked with the high voltage so no measurement has been made with the doors open. An X ray meter is on site for survey or personnel use and all possible danger areas have been surveyed. Personnel working for extended periods in any possible danger area are required to wear film badges. In addition the fence and key switch system described under RF radiation also protects against X rays.

The principal high voltage danger is from the beam supply which can be as high as 55,000V, but danger also exists in the 60 cps and 400 cps circuits. All compartments and cabinets containing high voltage have door interlocks which will shut down the system if any door is opened. Shorting chains or "dead man sticks" are located at all highvoltage points and these are required to be in place before any work is done on this equipment. All control panels are dead front with no exposed voltage points. Warning signs are prominately

displayed. In addition to the "panic buttons" described previously there are cord mounted buttons in the transformer-rectifier vault and in the crowbar compartment. The key switch system and personnel control fence are a major part of the high voltage safety plan.

The most valuable safety device is a careful man and the site personnel have received considerable safety indoctrination. JPL engineers are always on the alert to correct any unsafe condition or practice. While nothing can be completely fool proof the transmitter is considered to represent a high order of safety engineering.

The experience gained with the 100 KW transmitter has placed the Jet Propulsion Laboratory in a position to proceed to even higher power. Development work is in progress on a klystron to utilize the full 1 megawatt capability of the power supply and deliver upwards of 350 KW CW to the antenna. The problems will be many but we feel sure such a system will be operable in the foreseeable future.

High Power CW Radar Transmitter

List of Illustrations

Fig.	1	Aerial View of Echo Station
	2	Aerial View of Venus Station
	3	Planetary Radar Control Room
	4	Planetary Radar Block Diagram
	5	85 foot AZ-El Antenna
	6	Antenna Servo Console
	7	Cassagrain Feed Cone Installations
	8	Receiver Mod. IV
	9	Receiver Mod IV Interior
	10	Master Controller Mod. III
	11	Programmed Local Oscillator
	12	Data Processing Equipment
	13	Radar System Improvement Chart
	14	Transmitter Requirement
	15	Transmitter Block Diagram
	16	Exciter Block Diagram
	17	Exciter Frequency Response
	18	Exciter (Control Room)
	19	Exciter (Antenna)
	20	100 KW Amplifier in Antenna
	21	100 KW Amplifier Block Diagram
	22	100 KW Amplifier (Open)
	23	Transmitter Control Console
	24	100 KW Klystron

List of Illustrations cont'd.

Fig. 25 Power Supply Block Diagram

26 Main Motor Generator

27 Motor Generator Control Console

28 Transformer and Rectifier

29 Silicon Rectifier

30 Filter

31 Crowbar

32 Series Limiter Diode

33 Heat Exchanger

34 DC Water Load

35 Spectrum Analyzer Block Diagram



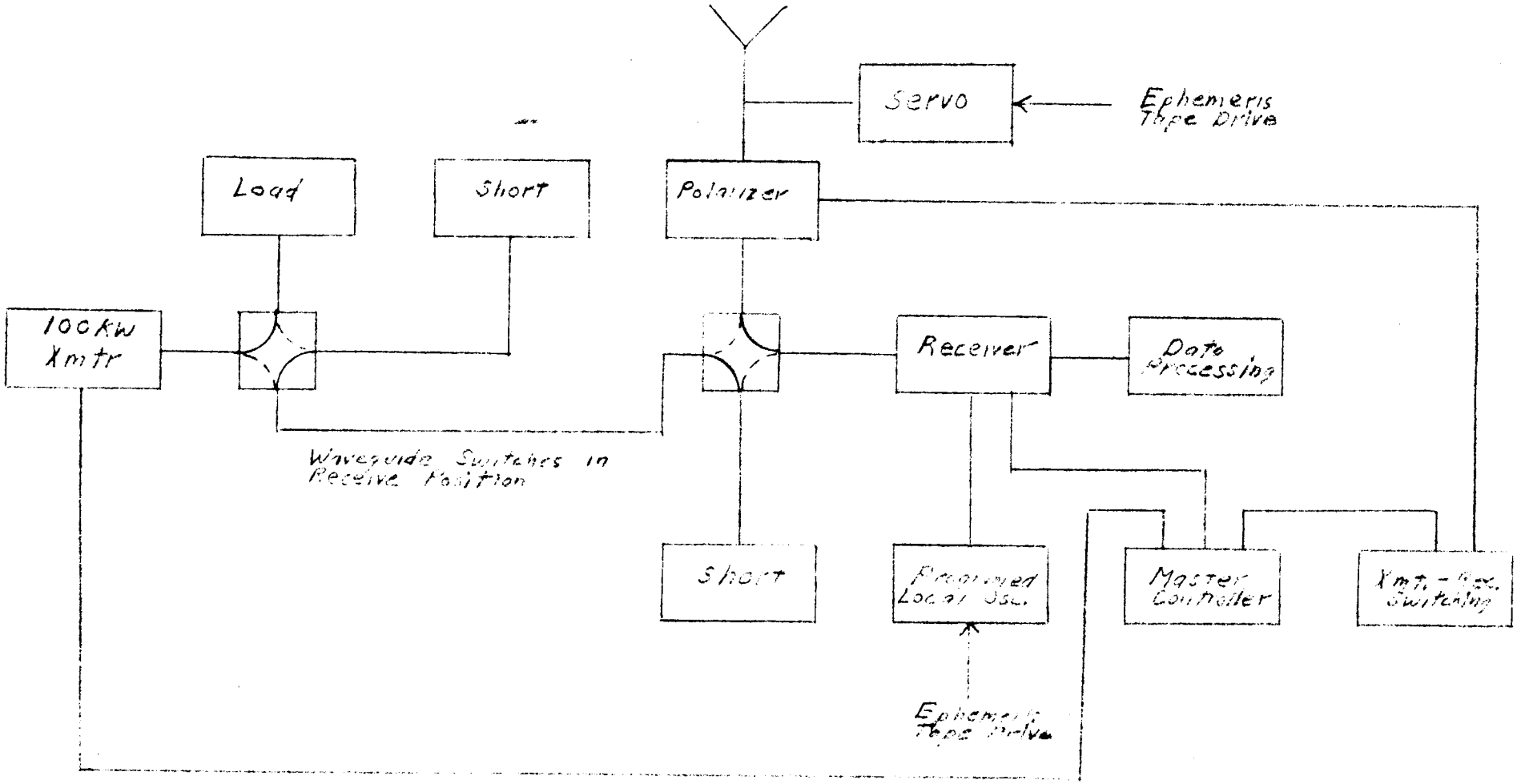
Fig. 1



Fig. 2

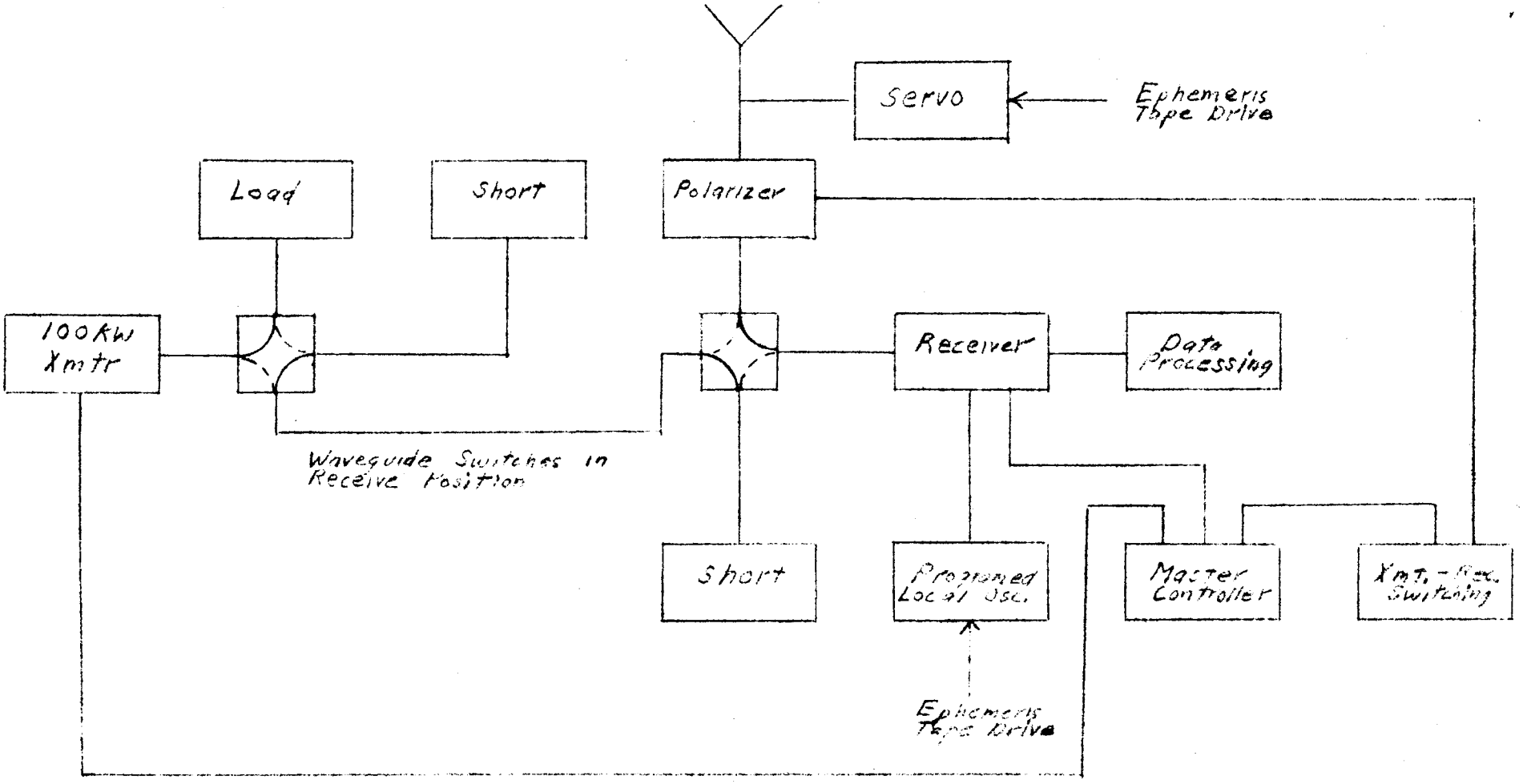


Fig. 3



Planetary Radar System

Fig. 4



Planetary Radar System

Fig. 4

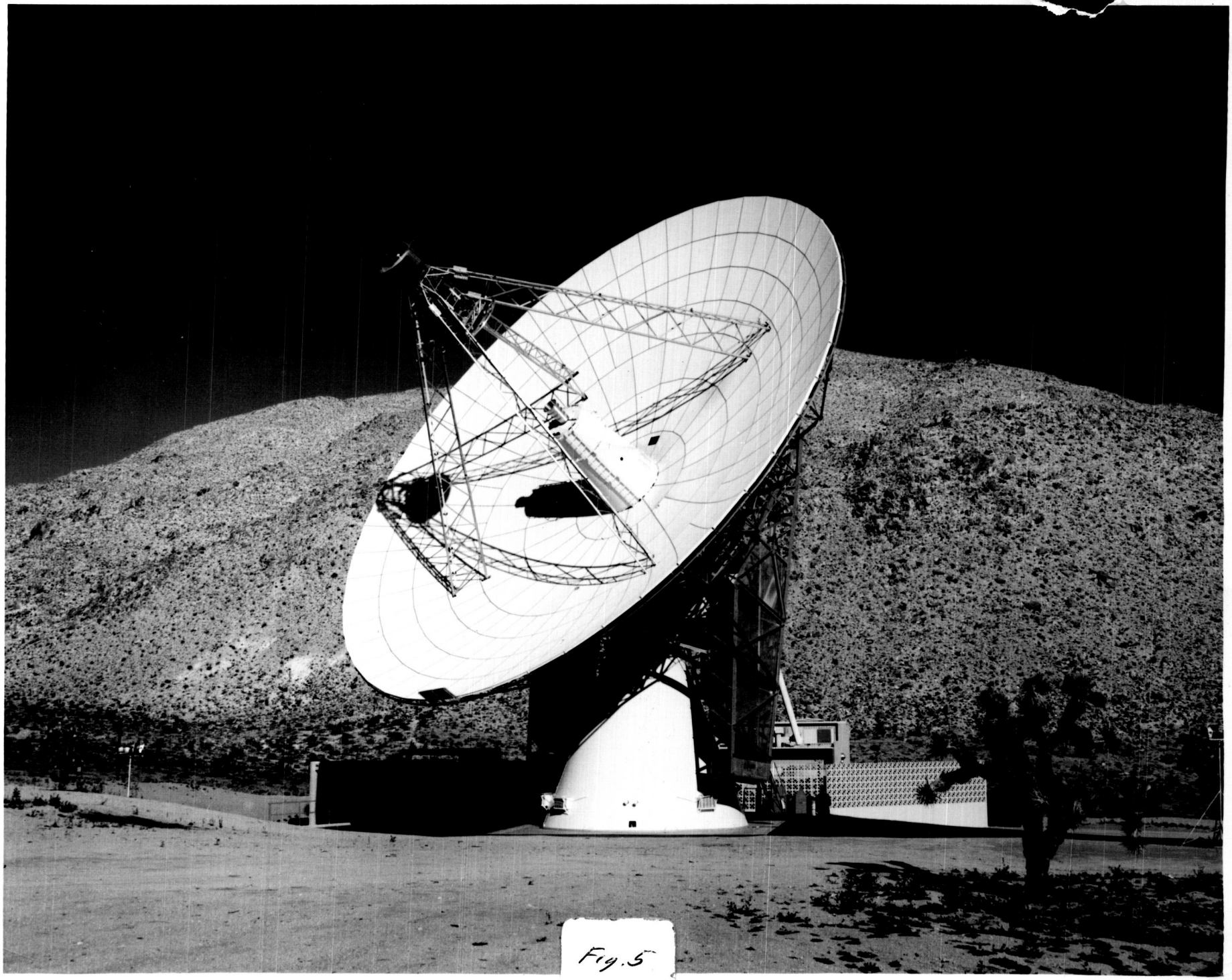


Fig. 5

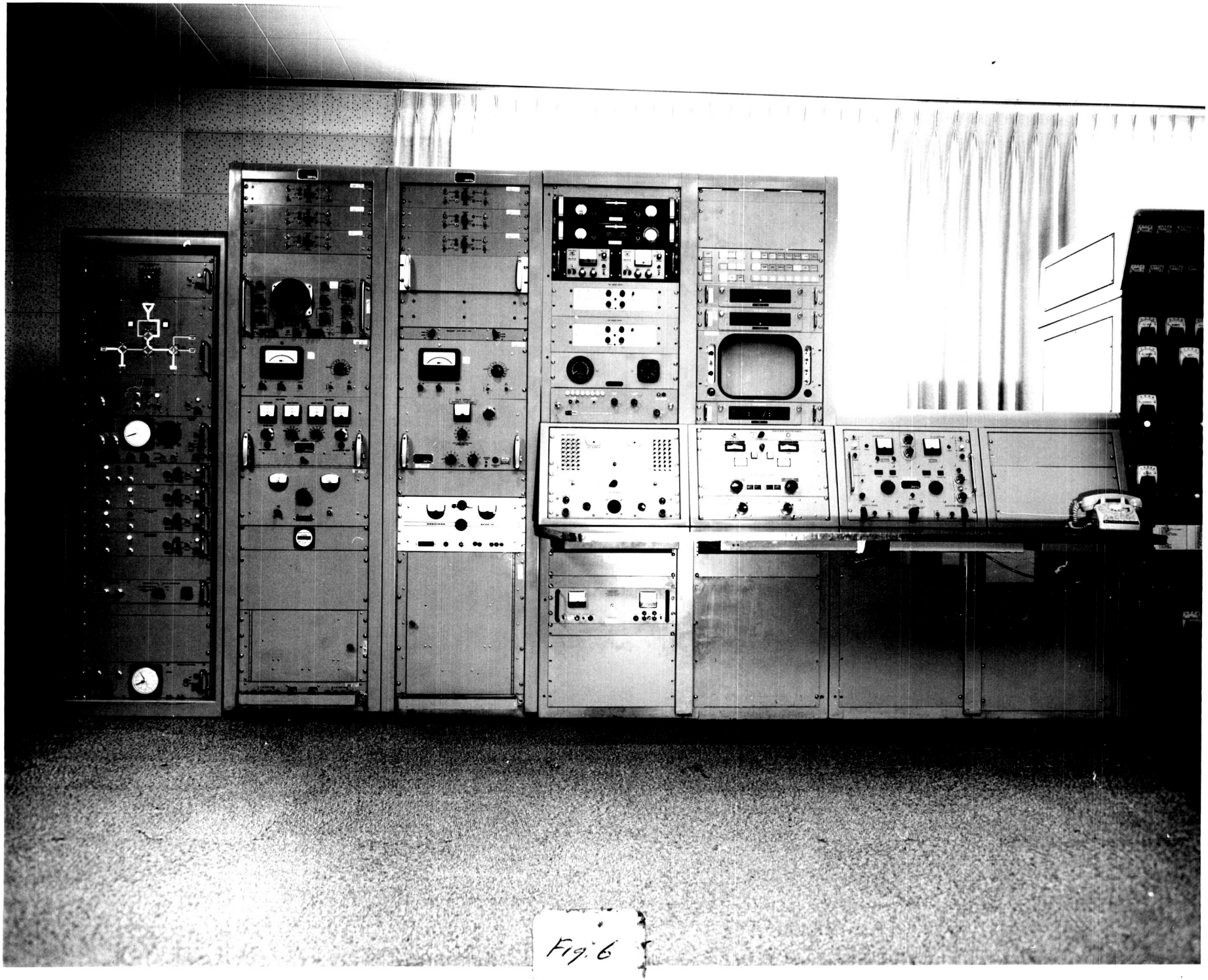


Fig. 6

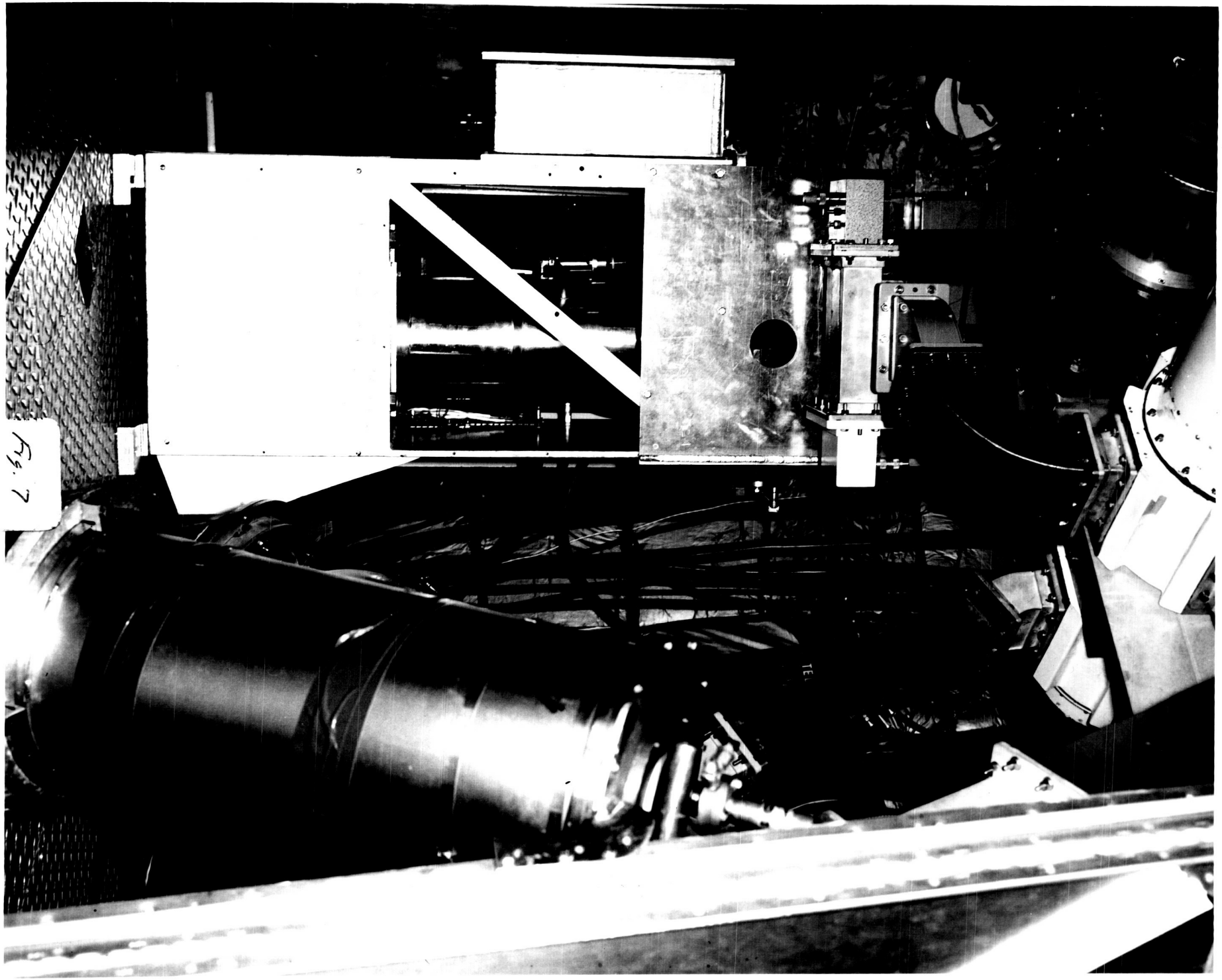


Fig. 7

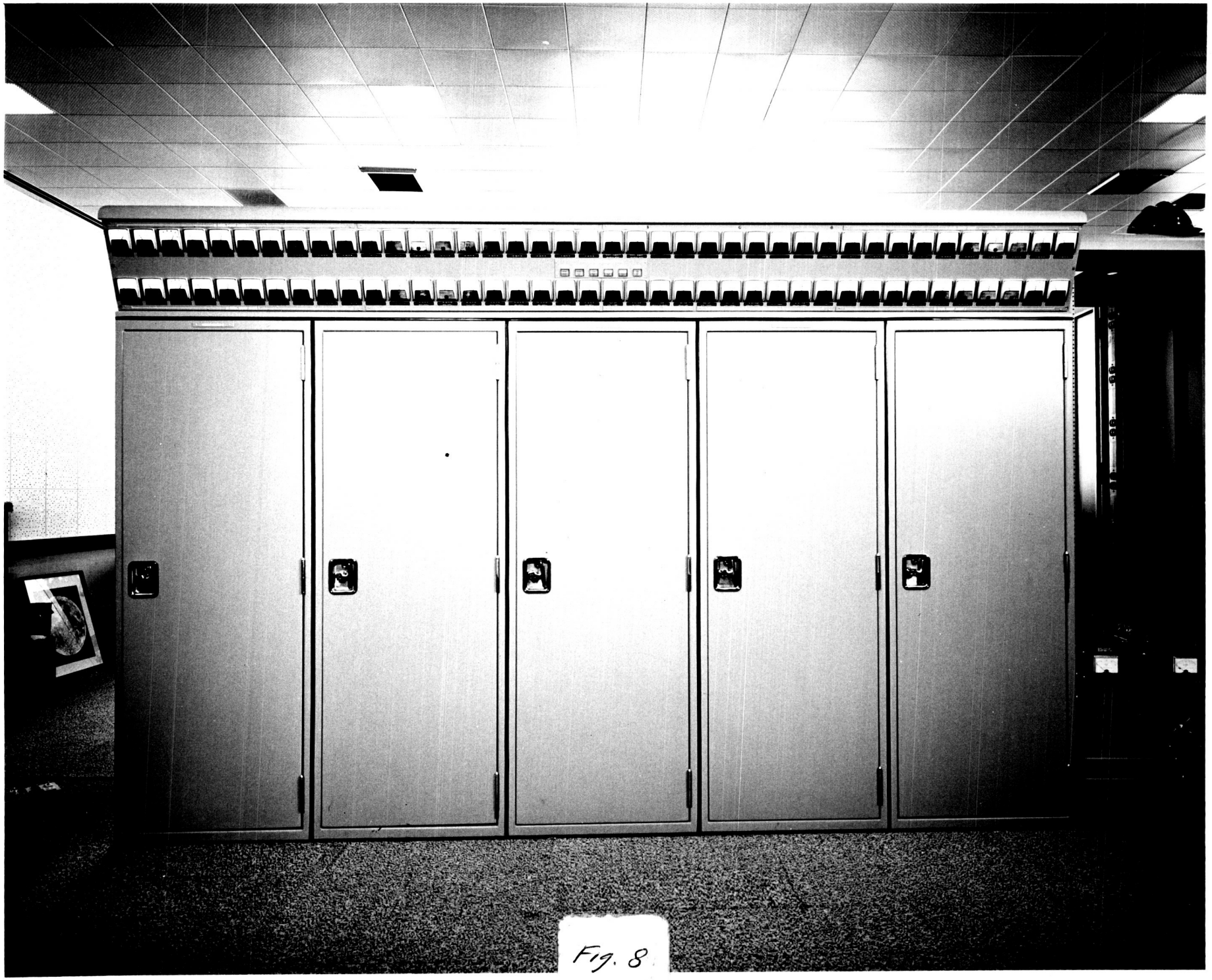


Fig. 8

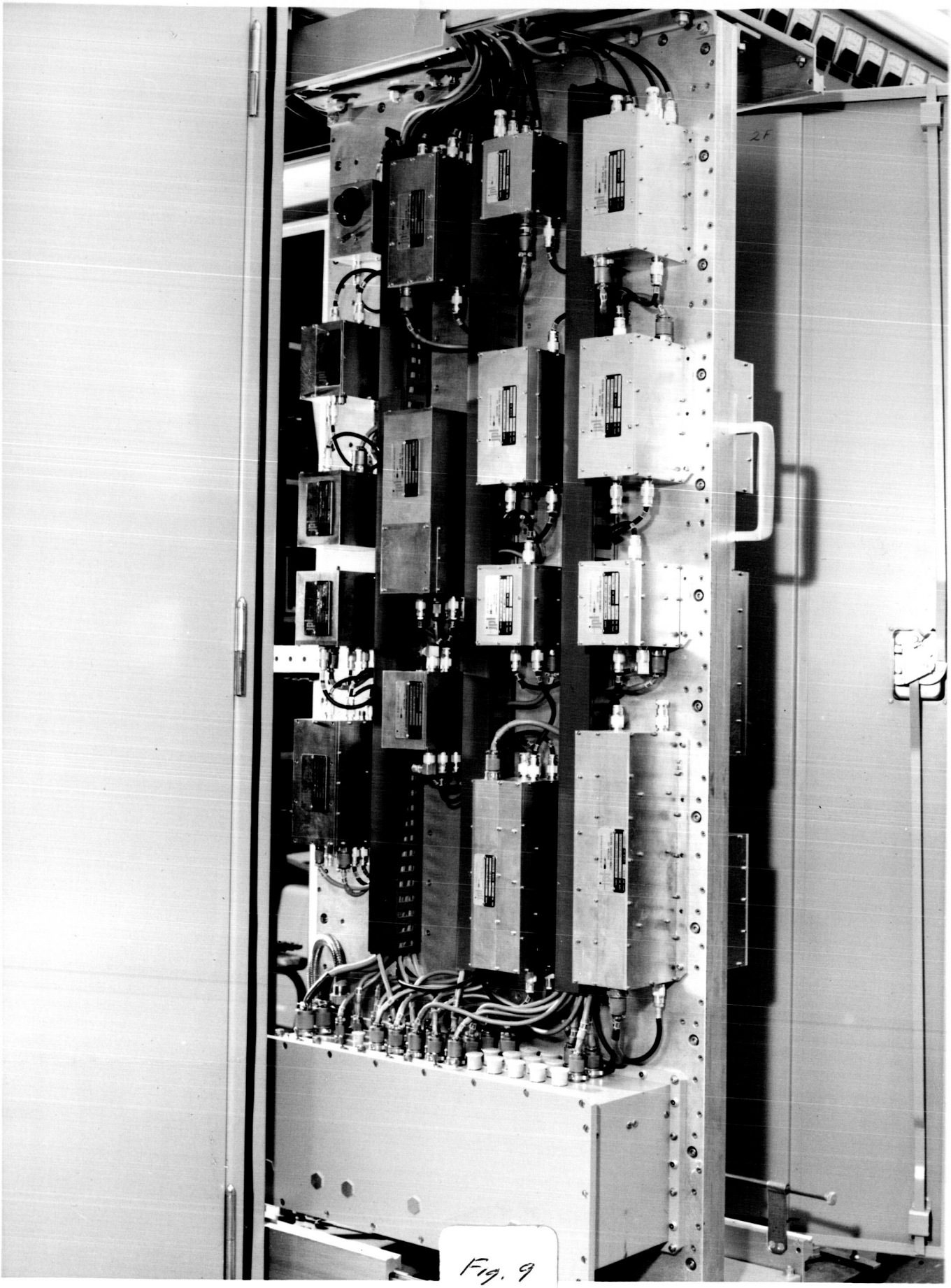


Fig. 9

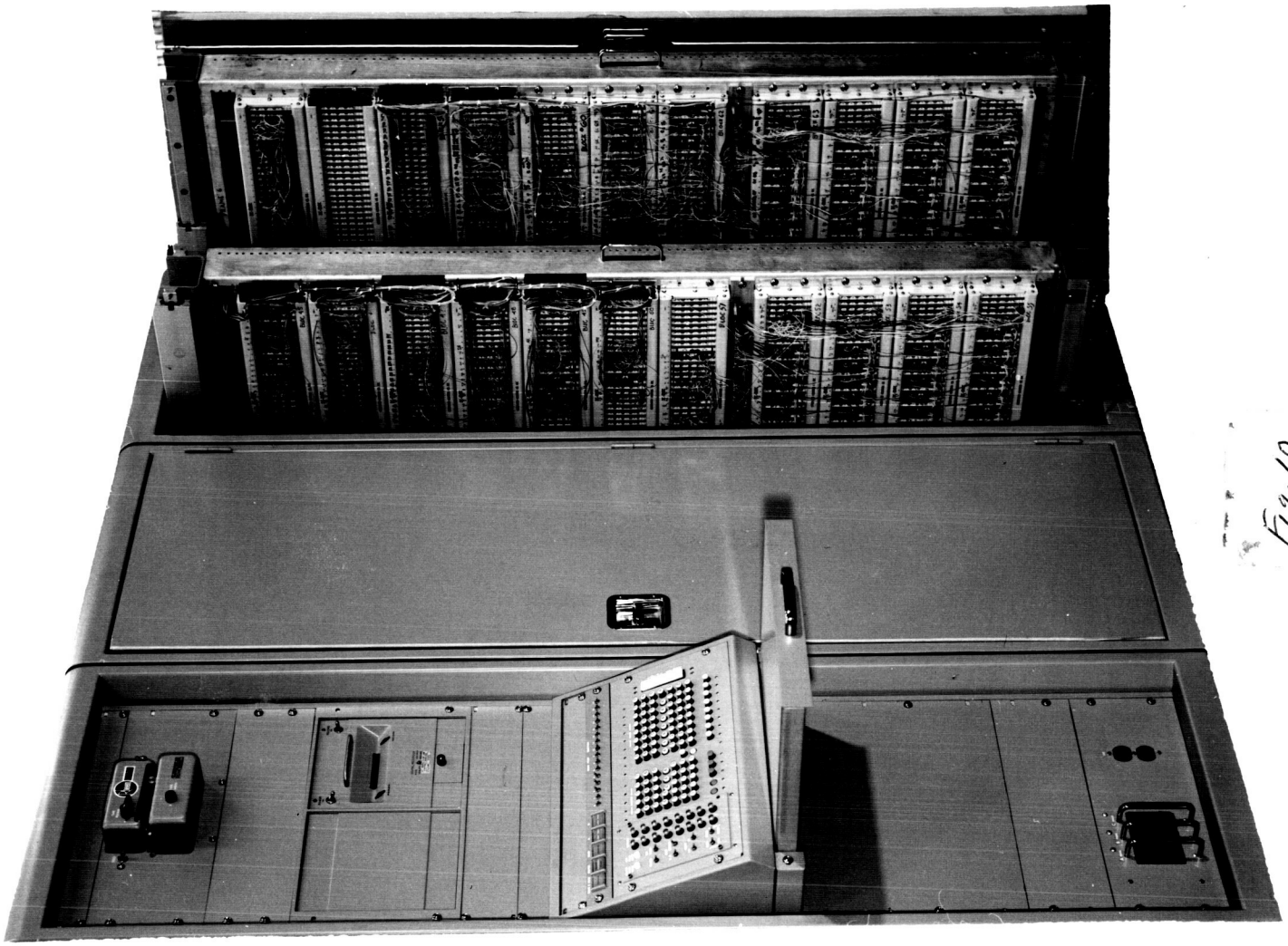


Fig. 10

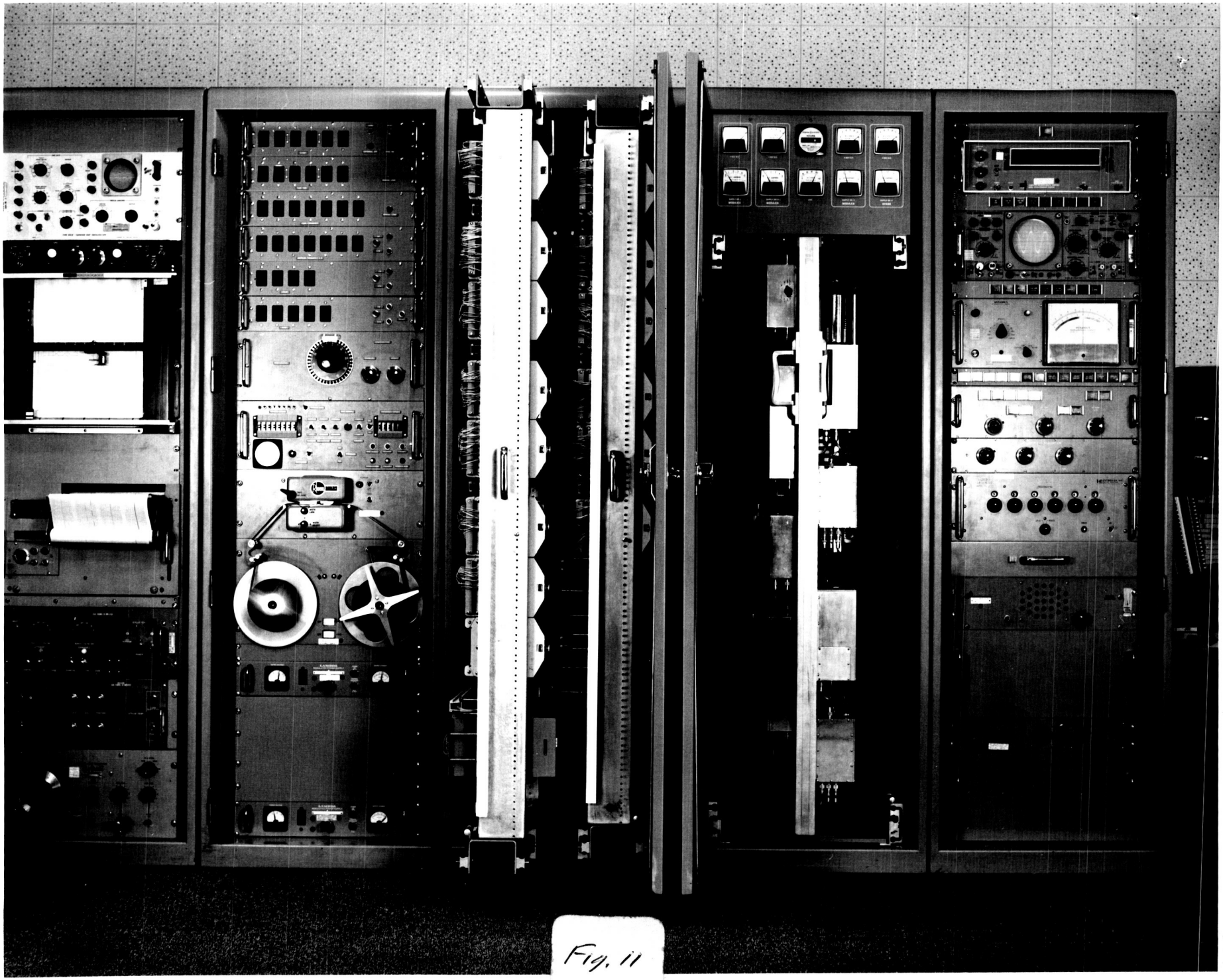


Fig. 11

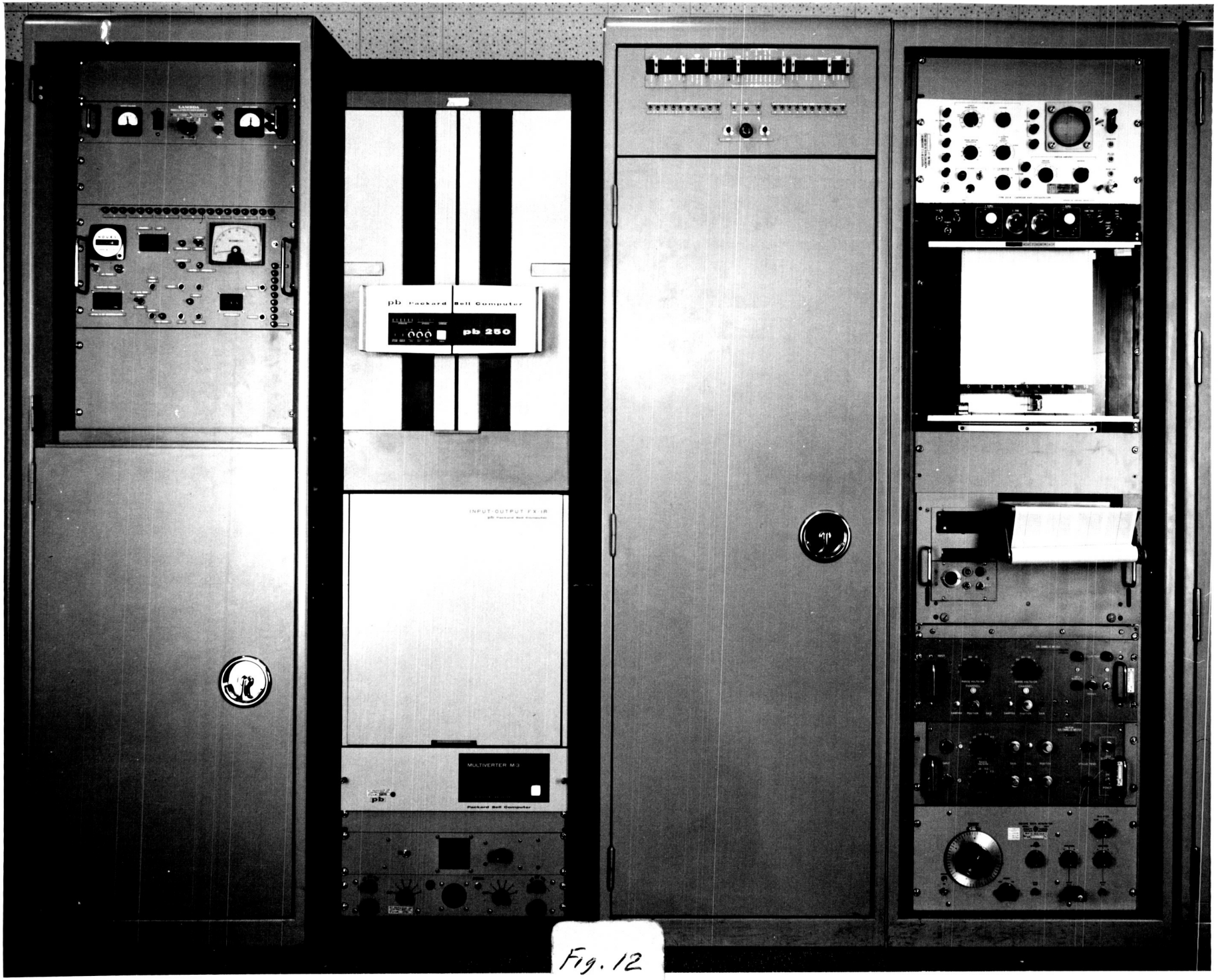

pb Packard Bell Computer
pb 250
INPUT-OUTPUT FX IR
MULTIVERTER M3
Packard Bell Computer

Fig. 12

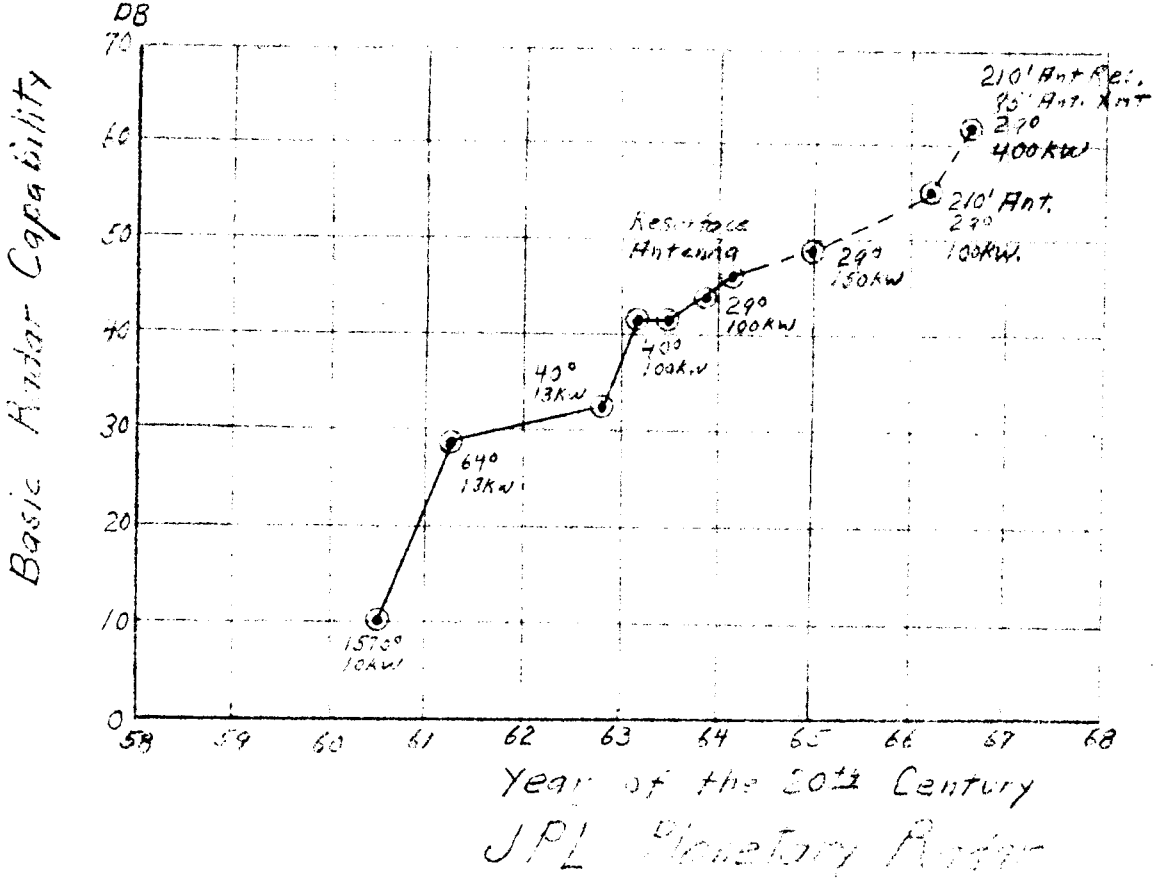
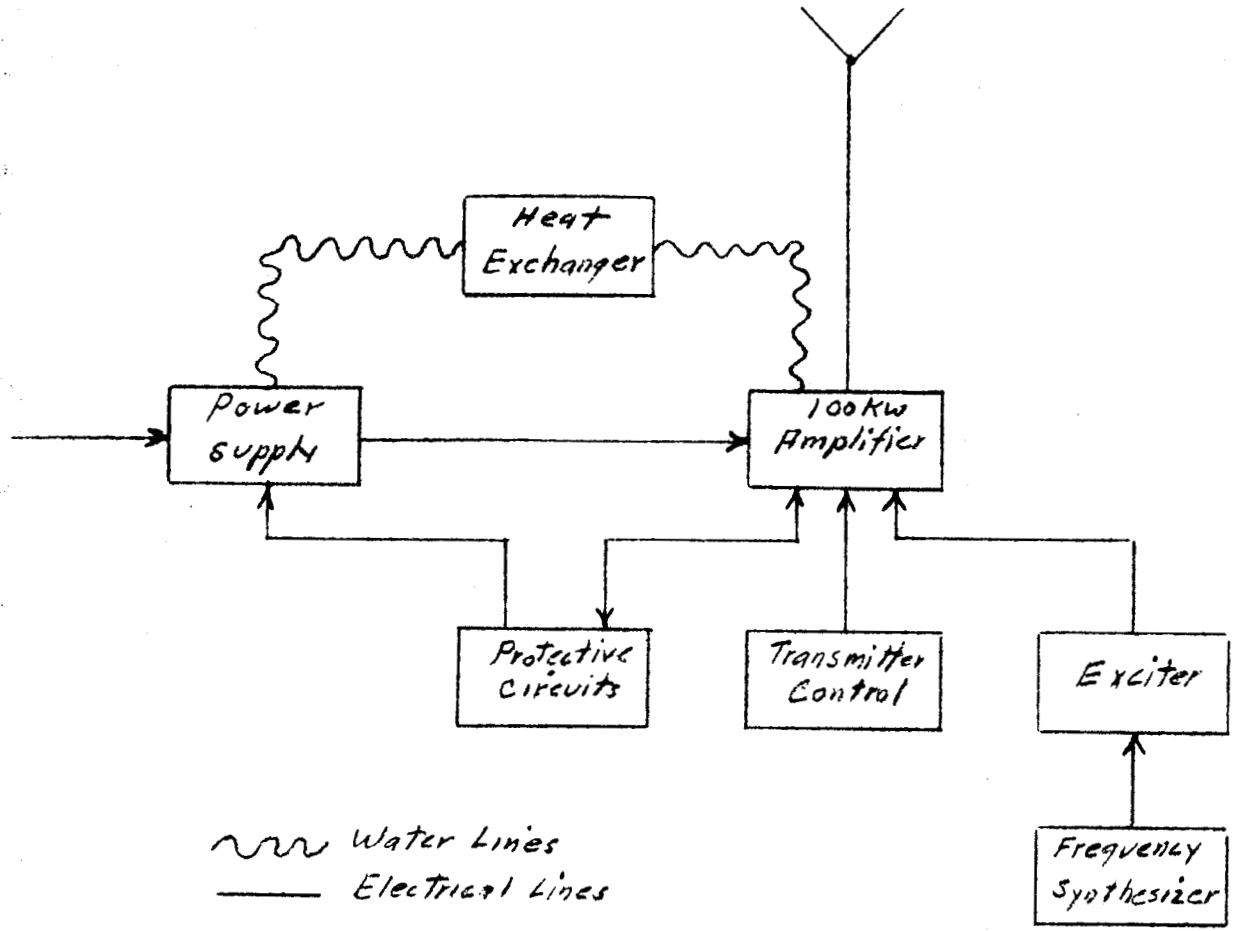

DB
70
60
50
40
30
20
10
0
58
59
60
61
62
63
64
65
66
67
68
Basic Radar Capability
Year of the 20th Century
210' Ant Rec.
85' Ant. Xmt
290
400KW
210' Ant.
290
100KW.
Resonance
Antenna
290
150KW
290
100KW
400
100KW
430
13KW
640
13KW
1570
10KW
Basic Radar Capability is Proportional
To: (Xmtd. Power Density)(Rec. Capture Area)
(System Noise Temp.)(Frequency)
JPL Planetary Radar

Fig. 13

Transmitter Requirements

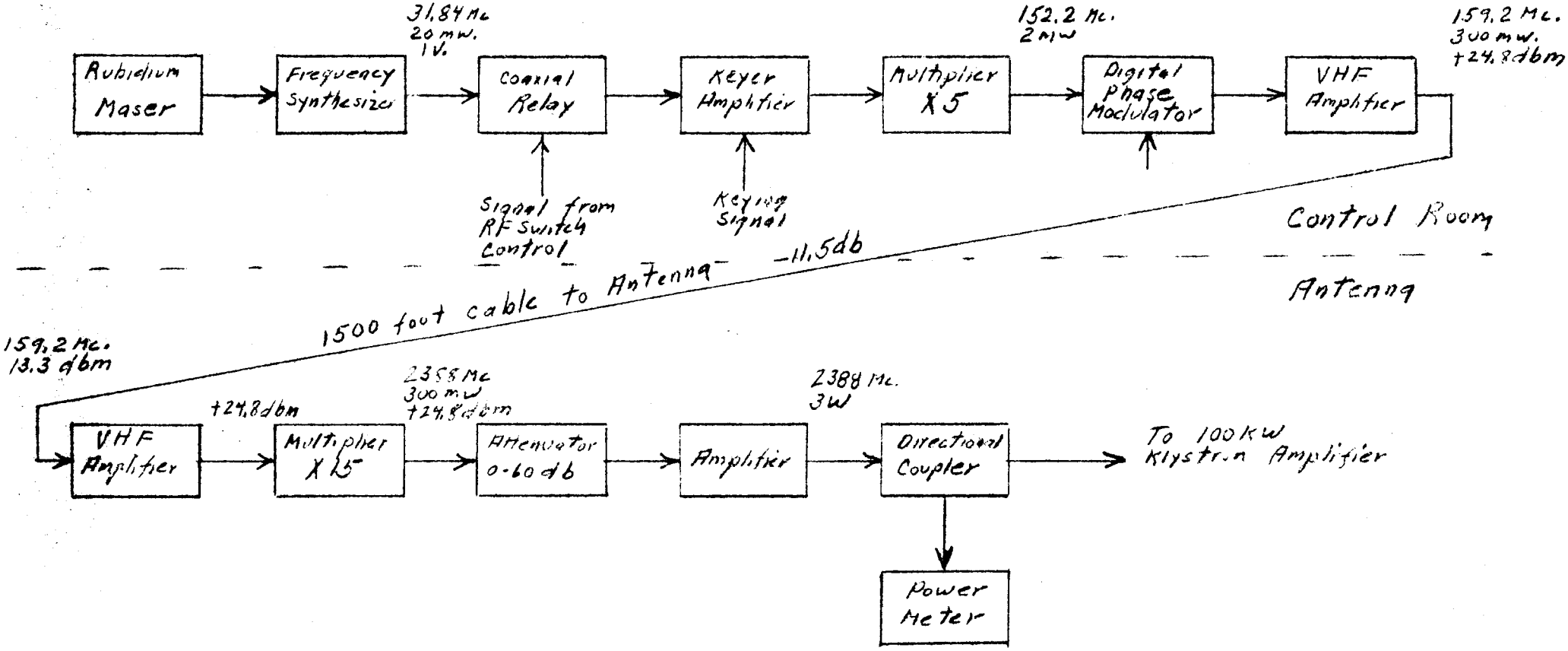
1. High Power
2. Low Incidental Phase Modulation
3. Phase Stability
4. Amplitude Stability
5. Frequency Stability
6. Bandwidth
7. Low Harmonics
8. Low Noise
9. Phase Modulation
10. Keying
11. Linear Capability

Fig. 14



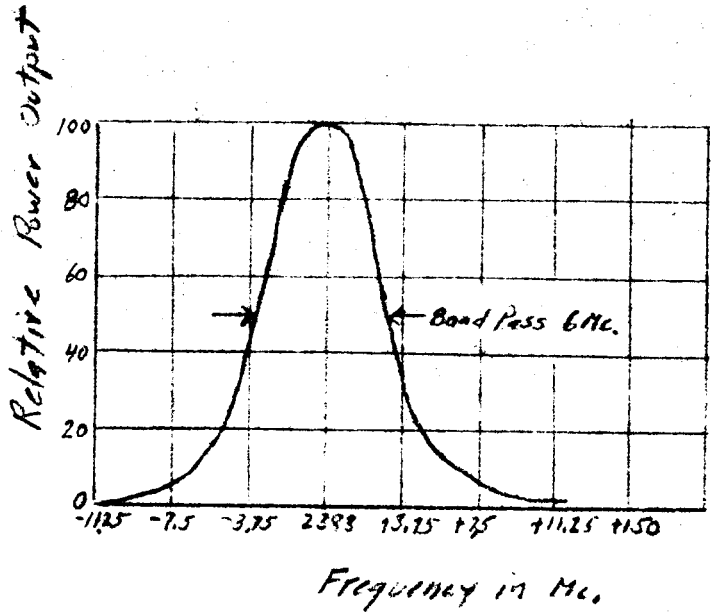
Basic Transmitter Block Diagram

Fig. 15



Planetary Radar Exciter

Fig. 16



Mod. IV Exciter Frequency Response

Fig. 17

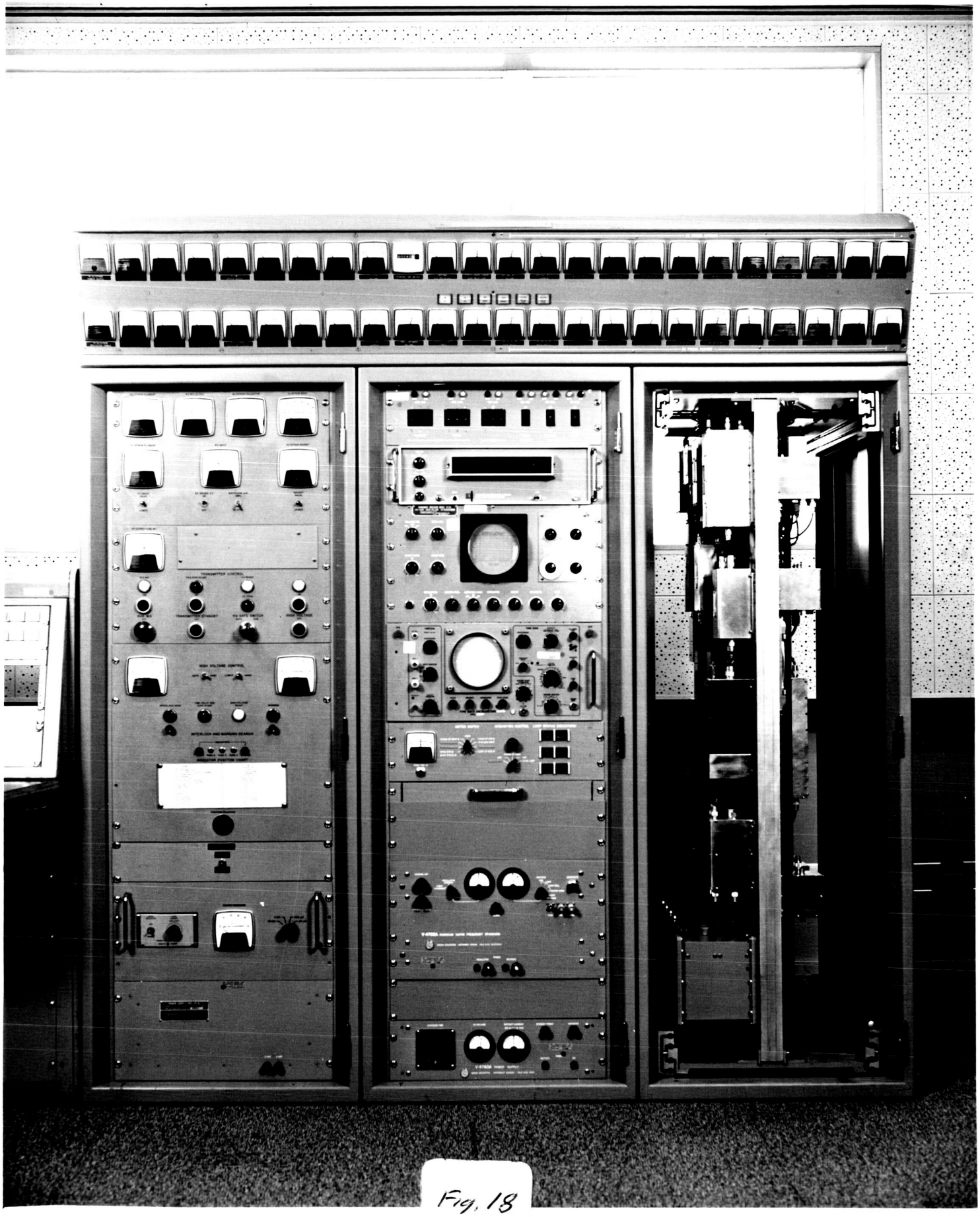


Fig. 18

Fig. 17

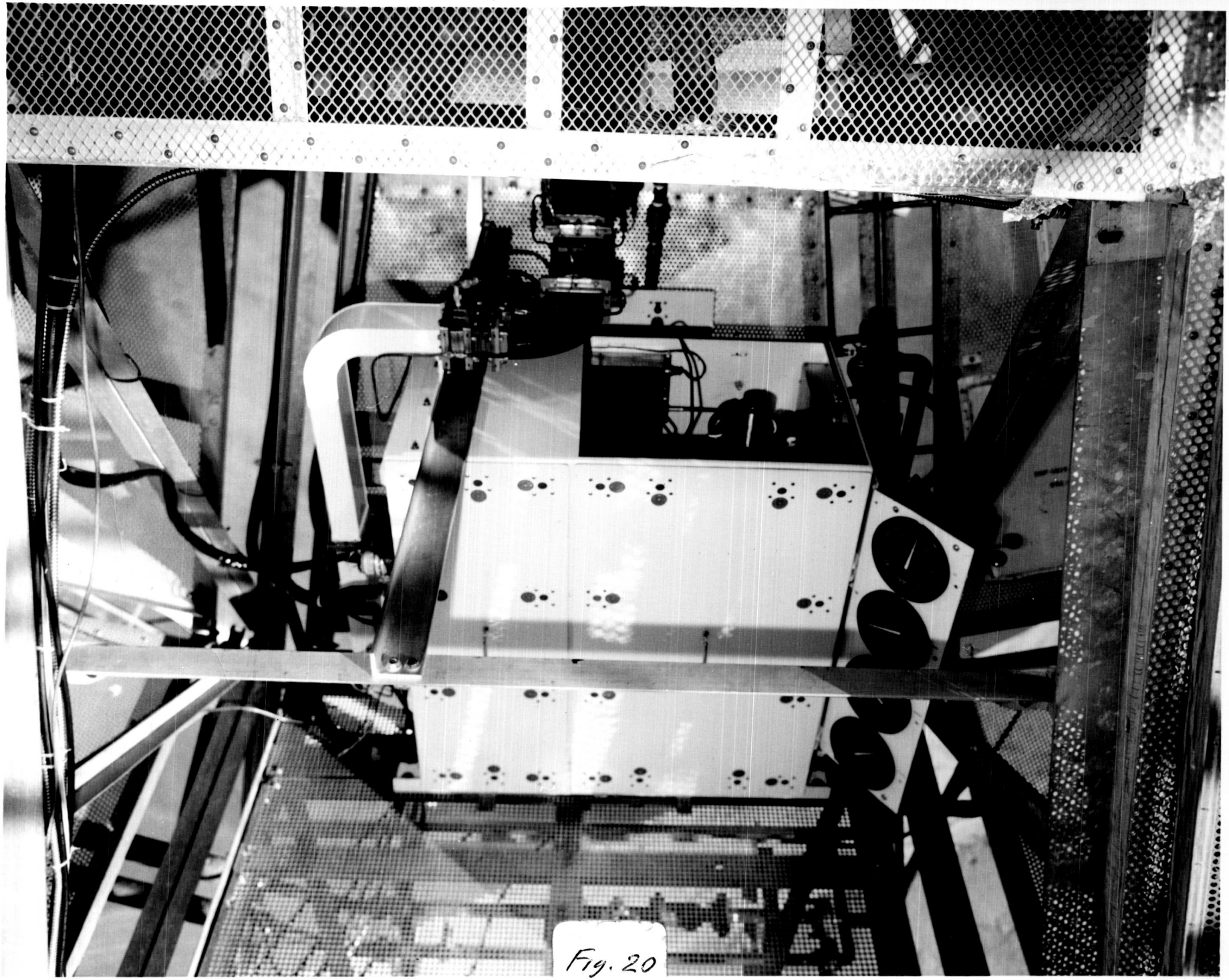
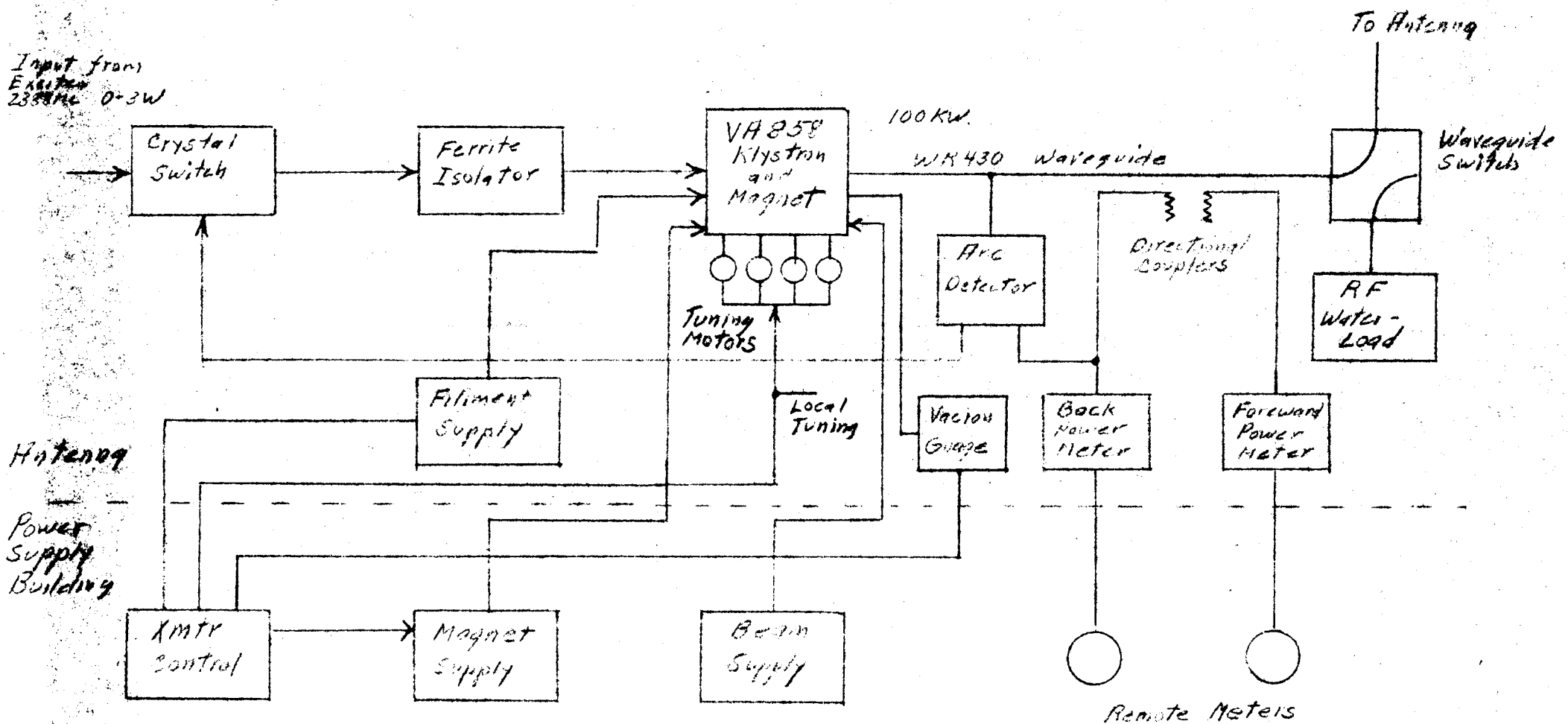


Fig. 20



Klystron Power Amplifier Diagram

Fig. 21

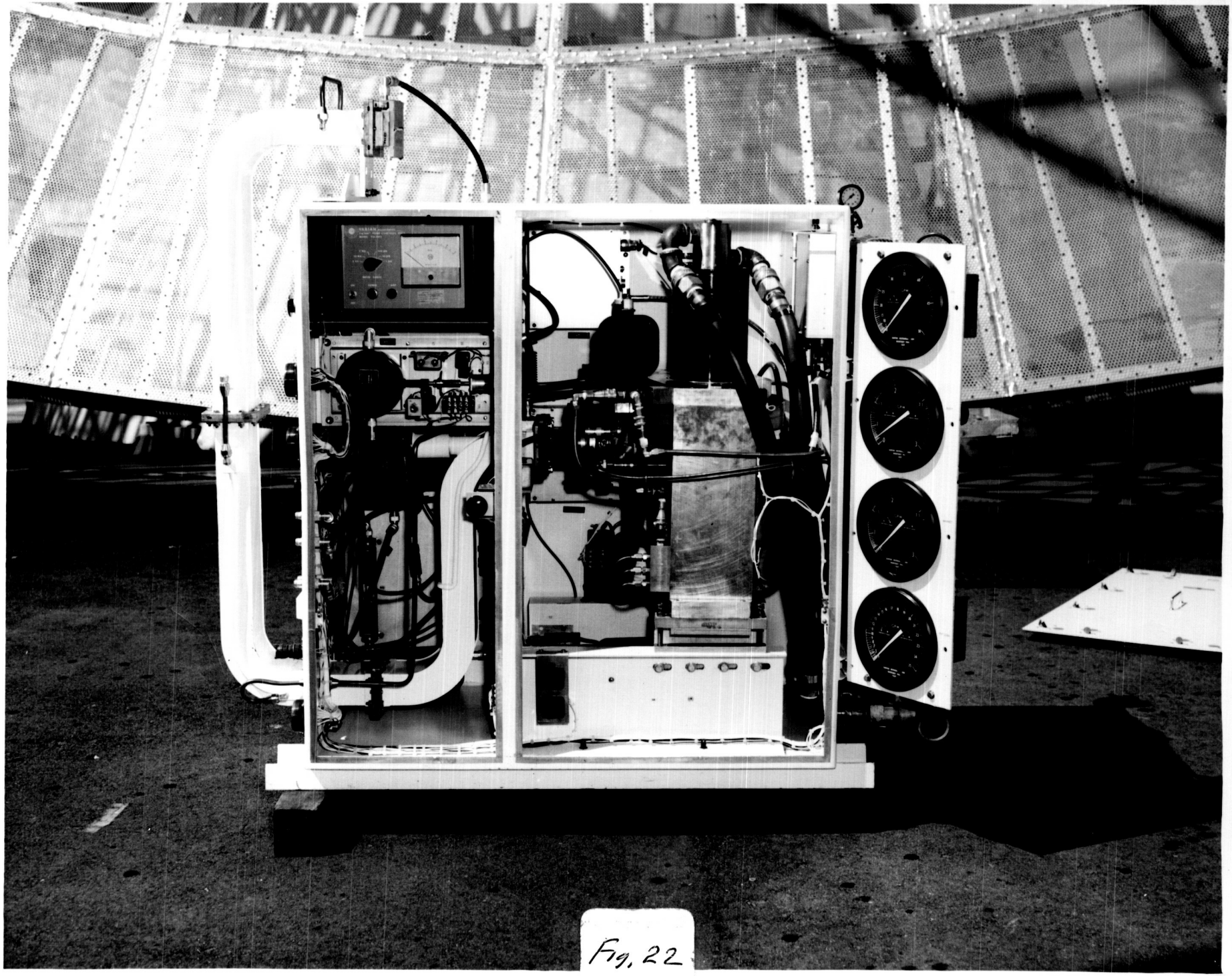


Fig. 22

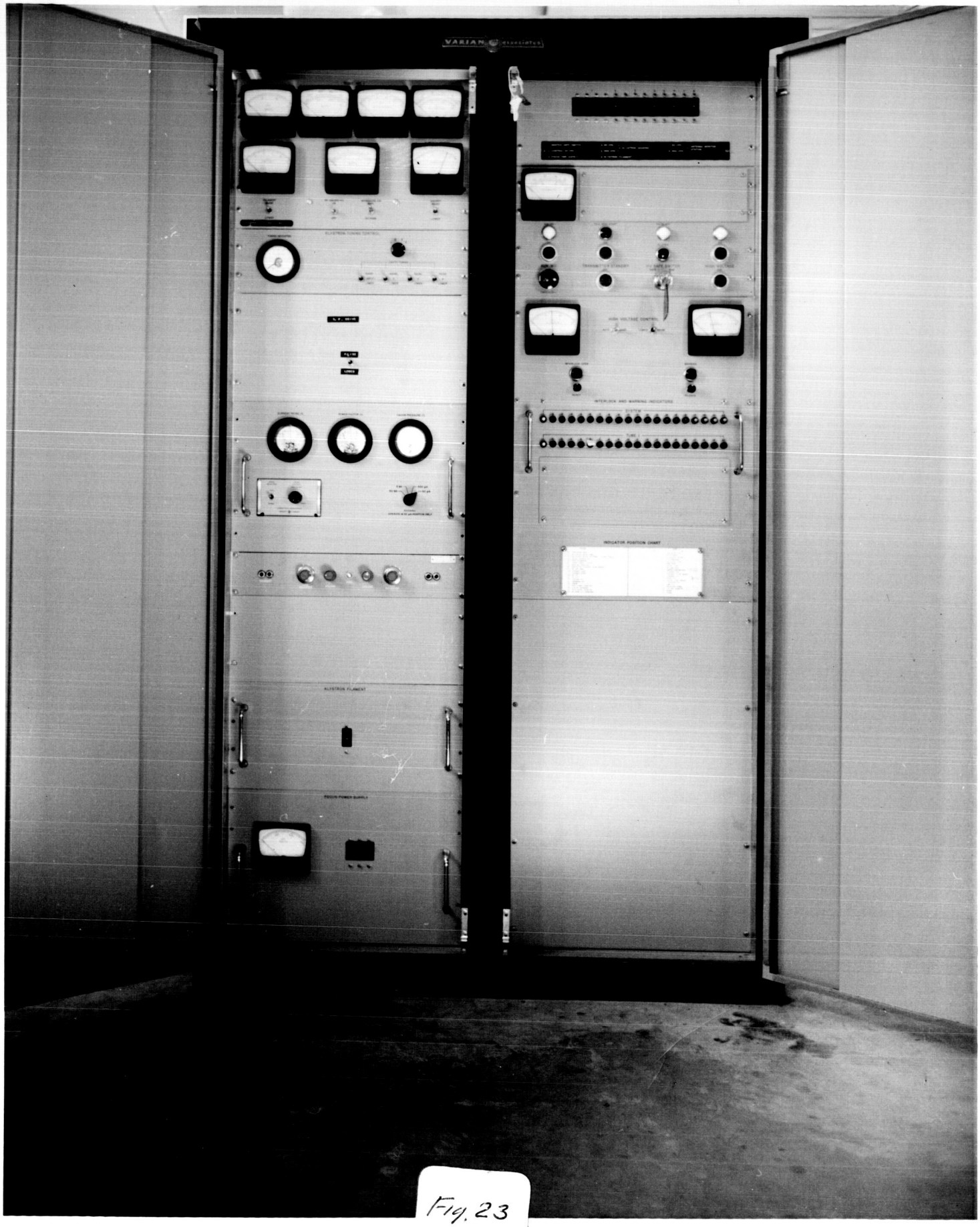

VARIAN
INTERLOCK AND WARNING INDICATORS
INDICATOR POSITION CHART

Fig. 23

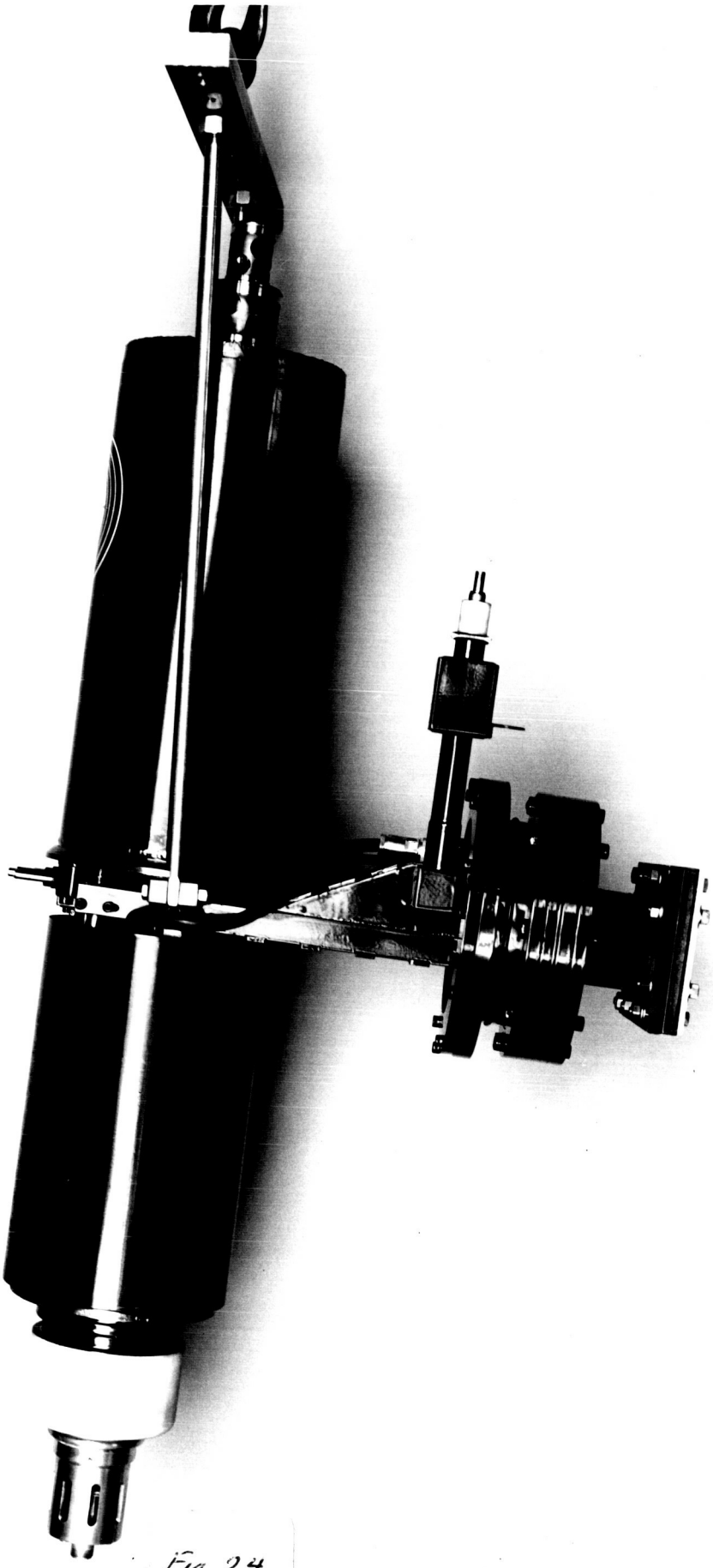
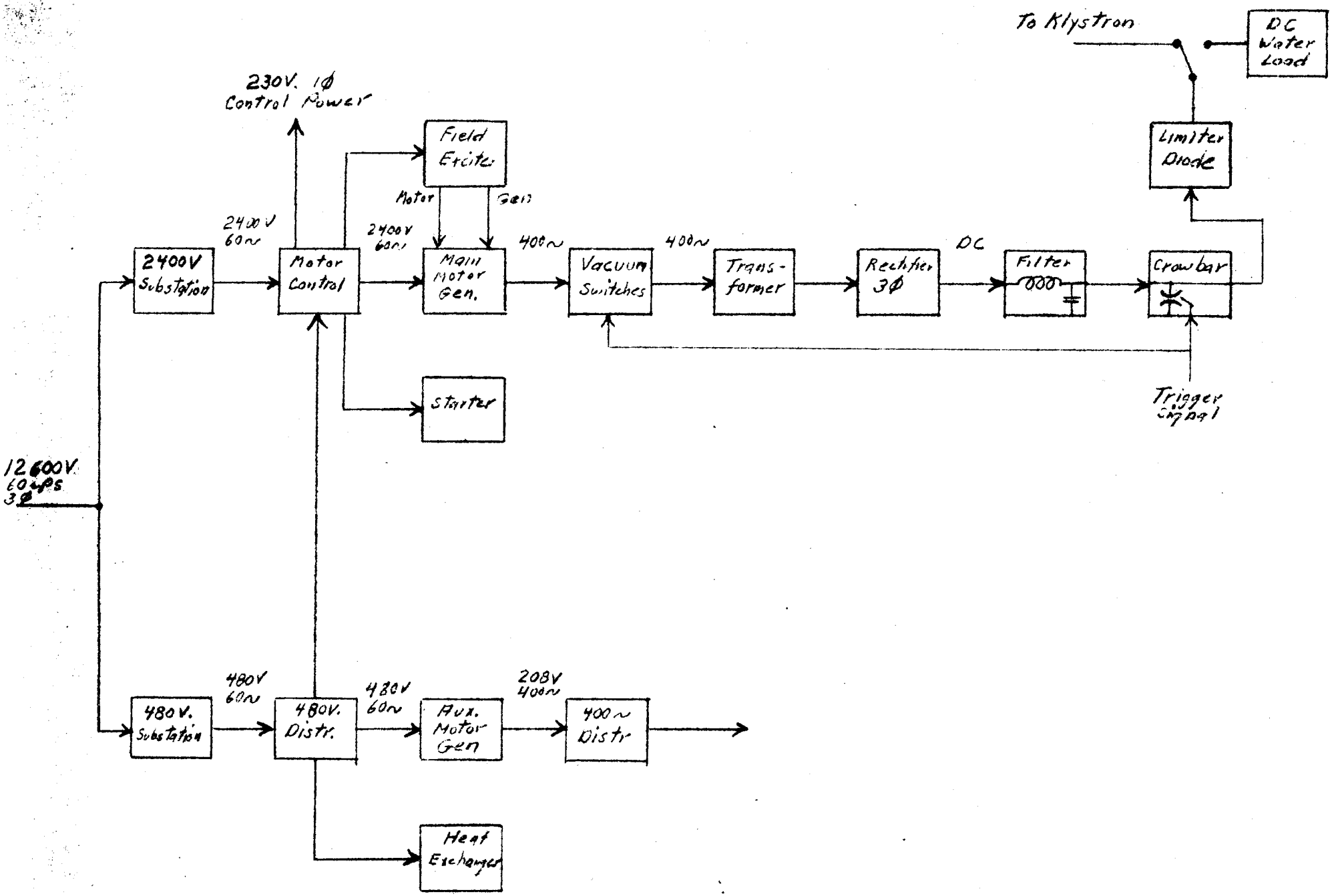


Fig. 24



Power Supply Block Diagram

Fig. 25

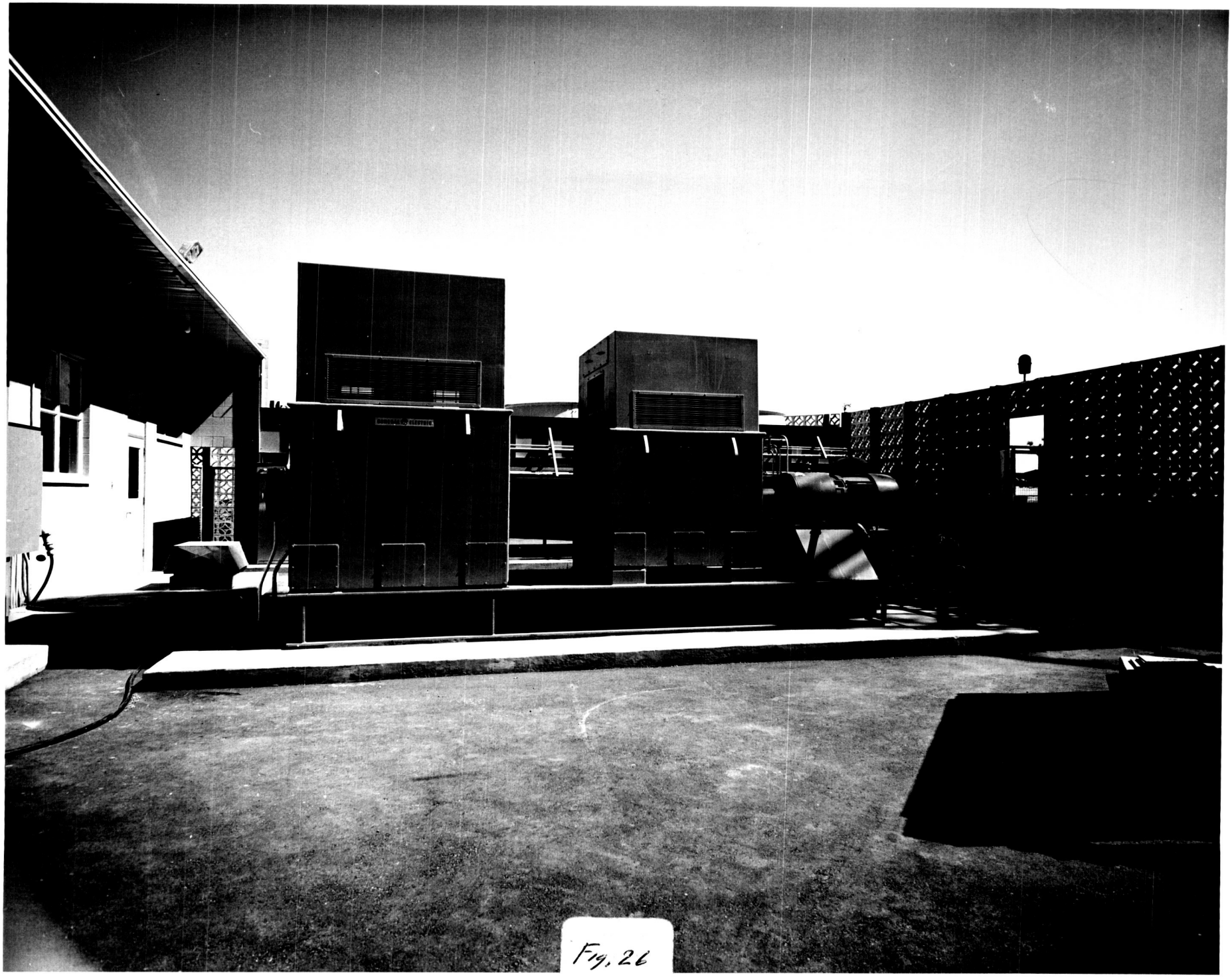


Fig. 26

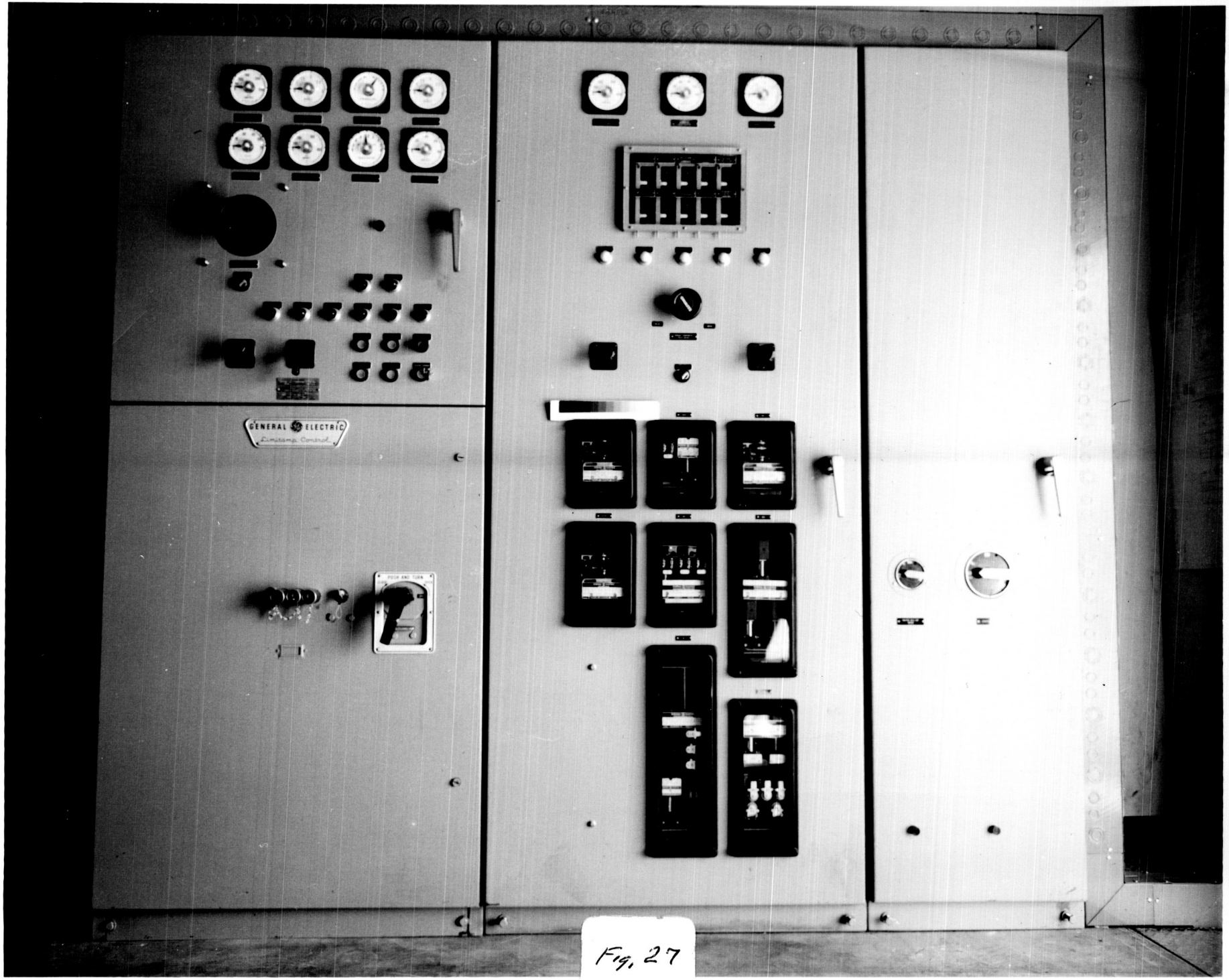


Fig. 27

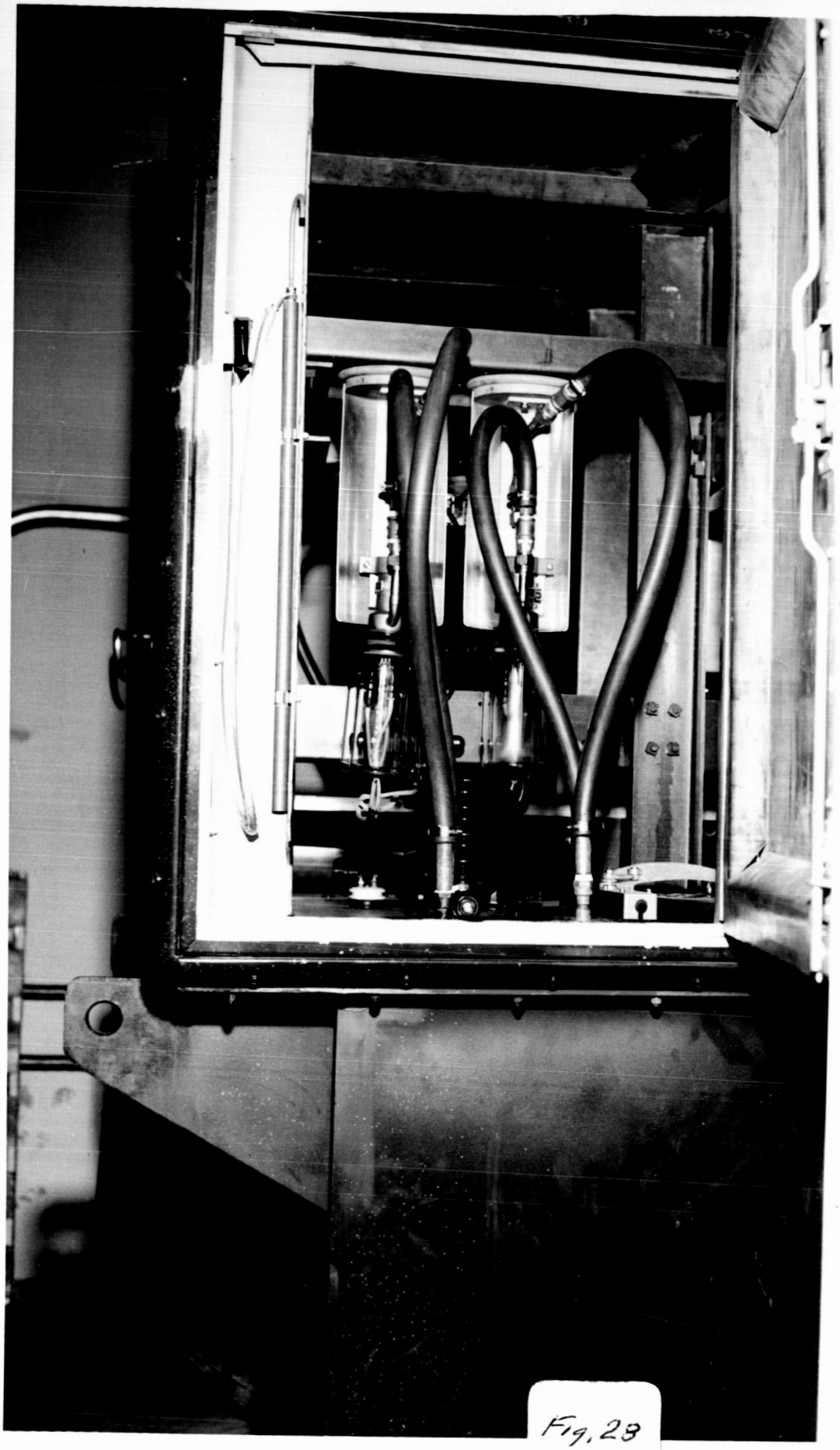


Fig. 23

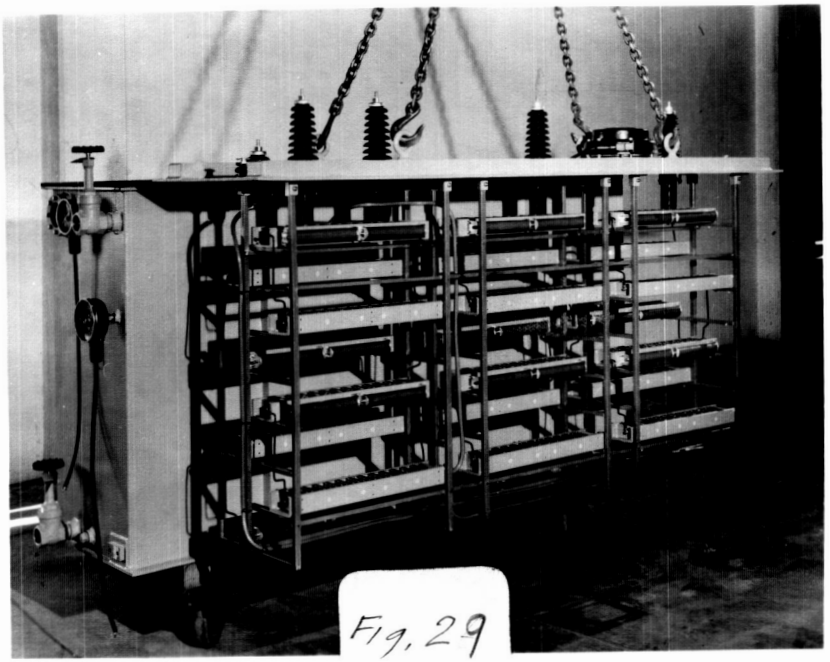


Fig. 29

Fig. 29



Fig. 30

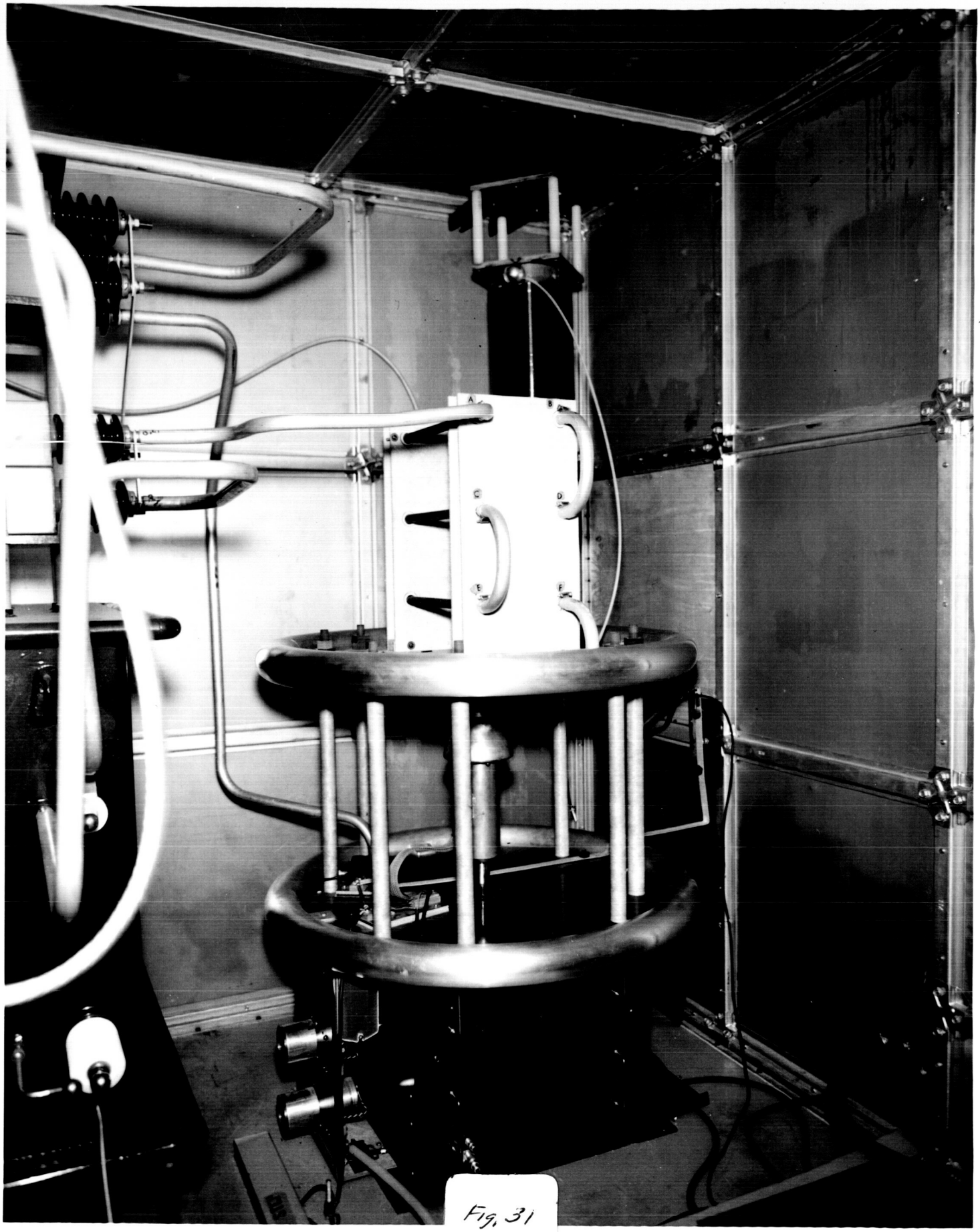


Fig. 31

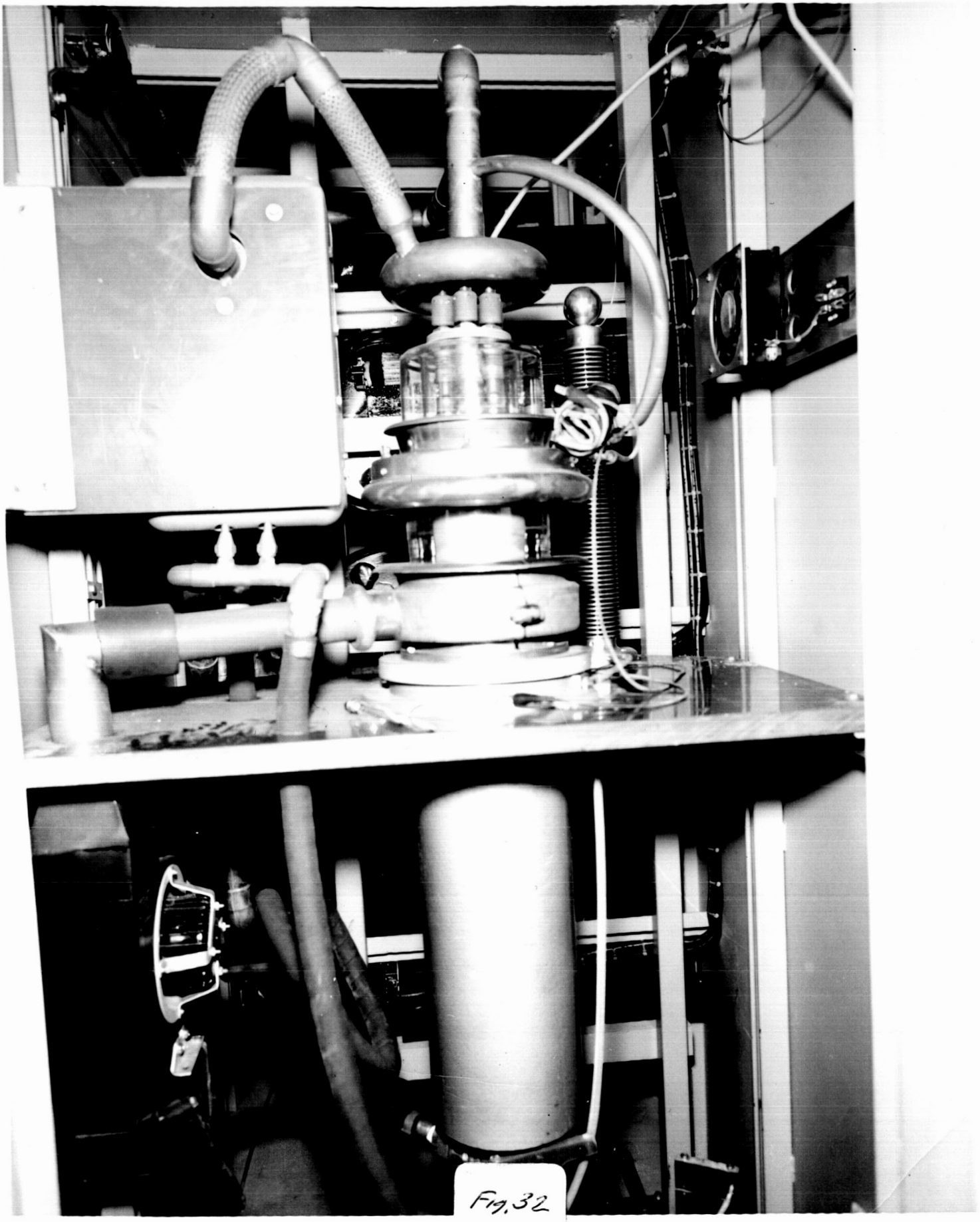


Fig. 32



Fig. 33

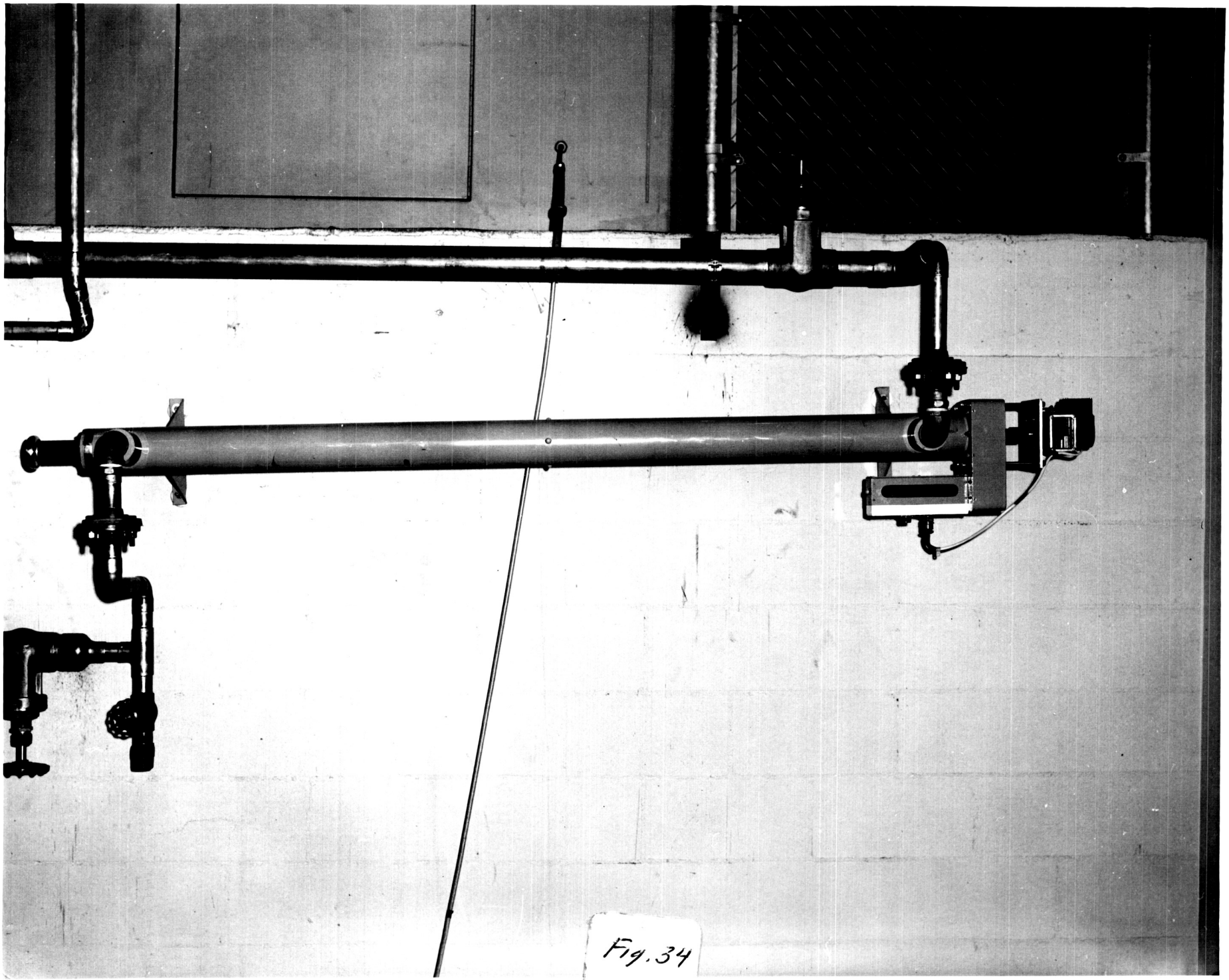
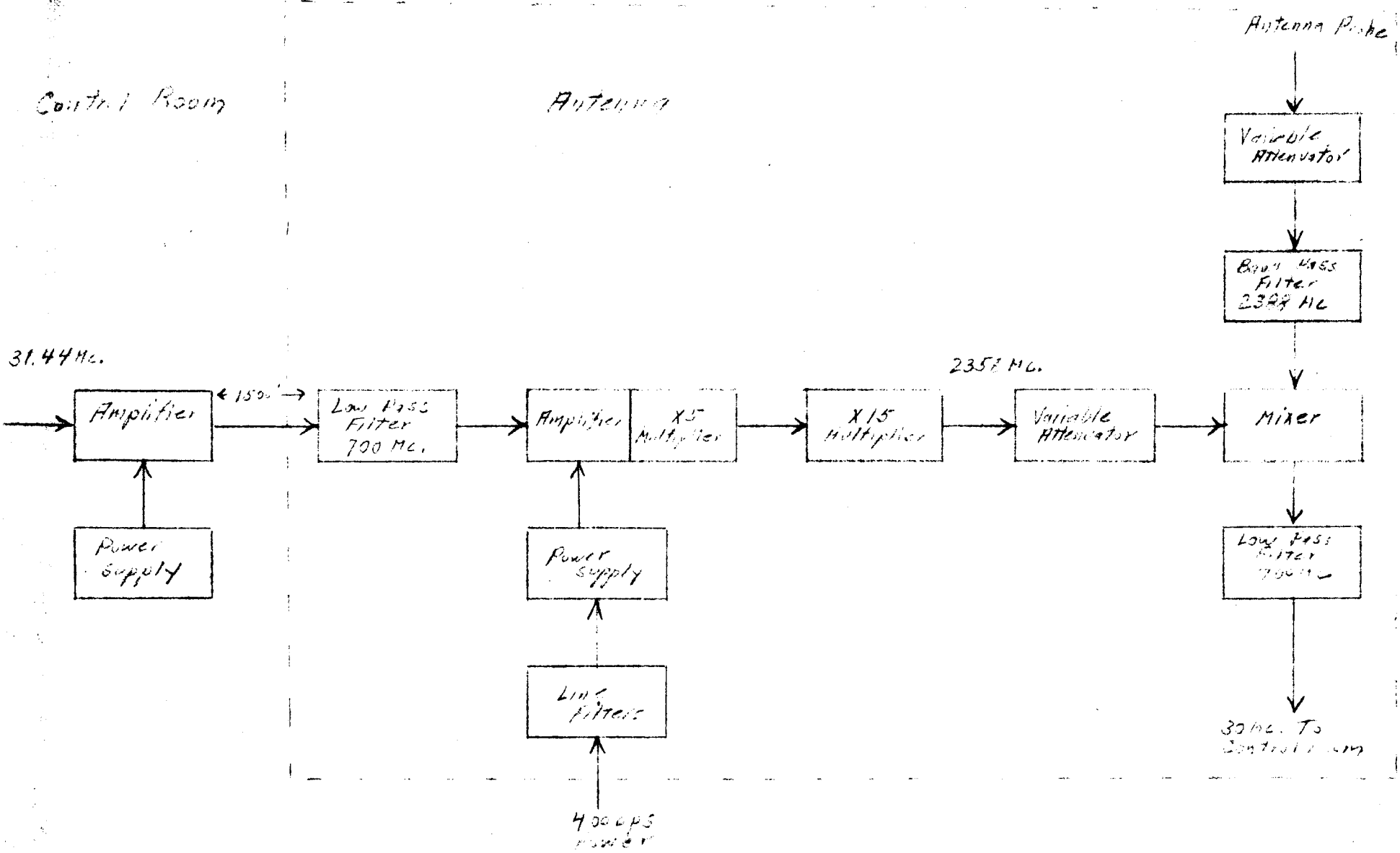


Fig. 34



Transmitter Monitor Frequency Converter

Fig. 35