UCRL 6810

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Ernest O. Lawrence Radiation Laboratory

PERFORMANCE TESTS AND LIFE DATA OF THE 36-MEGAWATT MODULATORS DEVELOPED FOR THE ASTRON 1000-MEGAWATT ELECTRON ACCELERATOR

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Contract No. W-7405-eng-48

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July 24, 1962

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by

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Summary

A 36-megawatt modulator, utilizing a Type 5949A hydrogen thyratron has been developed to pulse magnetic cores used in the 1000-megawatt peak-power Astron linear electron accelerator. The accelerator will be used for the injection of electrons into a thermonuclear fusion experimental device, called the Astron, which is now under construction at the Lawrence Radiation Laboratory in Livermore, California.

The type 5949A hydrogen thyratron is run at 32 kV, 2500 amperes peak current (5X rating), 0.4-μsec pulse length, and at 60 pps. The system requires 500 thyratrons operated in parallel which results in a peak-power output of over 15, 000 megawatts.

Data will be presented on the following subjects:

A. General description of the accelerator and modulator.

B. Performance tests of the 36-MW modulator.
   1. Peak current
   2. Hold-off voltage and tube aging procedure.
   3. Peak power.
   4. Average power.
   5. Trigger characteristics.
   6. Prefire characteristics.
   7. Output pulse shape.

C. Life data of the 36-MW modulator operated at 28 to 32 kV, 60 pps.
   1. Switch tube, Type 5949A, used at 2500 amperes peak.
   2. Pulse-forming network (RG-218/u at 32 kV).
   3. Load cables, RG-213/U.
   4. Connectors.

Introduction

A possible method to attain the long-sought goal of a controlled thermonuclear reaction is to utilize high-energy electrons to produce magnetic confinement and, simultaneously, heat the plasma by transfer of some of the electron energy to the plasma particles.

The Astron[1] thermonuclear fusion experimental device, (see Figs. 1 & 2) which is now under construction at the Lawrence Radiation Laboratory in Livermore, California, will be used to determine if these principles can be utilized to make a power-producing fusion reactor. A 1000-megawatt, linear electron accelerator[2-4] capable of producing a relativistic beam of electrons of high intensity and quality is required to perform these experiments. Table I lists the specifications for the accelerator.

TABLE I
Accelerator Specifications

Electron energy	5 MeV
Peak beam current	200 amperes
Peak beam power	1000 megawatts
Pulse length of ±0.5% flat portion	0.25 μsec
Repetition rate, variable	0 to 60 pps
Energy spread (during the pulse and/or from pulse to pulse, and at a variable repetition rate)	±0.5%
Beam diameter	~1 cm
Beam quality	$< 10^{-2}$ radian - cm

Development of Core Pulsing Requirements

After considerable study by the Physics Staff of the Lawrence Radiation Laboratory, it was decided to build an accelerator utilizing a basic induction principle,[5-7] known for many years, but never before employed in a practical linear accelerator. This basic principle is to use an accelerating induction electric field generated by changing the magnetic flux in a ferromagnetic material. This method is inefficient with low beam currents because of the extremely high exciting currents of known magnetic materials. An efficiency approaching 10% may be realized in the Astron accelerator when operating at beam currents of 200 amperes. An increase in the number of primary turns affects the input impedance, as in a pulse transformer, but results in a corresponding stepdown of accelerating potential. The Astron accelerator is designed[8] to utilize tape-wound, toroidal, doughnut-shaped, magnetic cores with the electrons accelerated through the center of the core. Figure 3 is a diagram of the principle using axial symmetry in the core material. A one-turn primary is used in order to keep the system voltage as low as possible. This results in a one-to-one pulse transformer and a large number of cores (429) are needed in series to obtain the required output energy.

The choice of magnetic material vastly affects the core modulator requirements because the pulse permeability[9] (at 0.4 μsec) can easily vary orders of magnitude depending on material composition, thickness of lamination, and annealing methods.

Many different materials were tested[10,11] and optimization studies were made comparing the combined costs of magnetic materials and pulse modulator systems. One-mil, 50% nickel-iron, tape-wound cores were found to represent a reasonable compromise. The final design uses two sizes of cores: The electron gun section uses forty-five 18-inch i.d. × 33-inch o.d. × 1/2-inch-thick cores; the eight accelerator sections (48 cores each) use 384 eight-inch i.d. × 24-inch o.d. × 1/2-inch-thick cores. See Fig. 4 for a side view of the complete accelerator.

The large cores will be pulsed to 16,000 volts and the small ones to 12,000 volts. Under optimum conditions this would yield an output of 5.32 MeV, however, beam loading effects and variations of the magnetic properties between cores (as much as ±30%) will reduce the output.

The electron injection requirements of the Astron dictate that a square-wave pulse voltage be developed across the secondary plates[12] of the accelerator. The waveforms of Fig. 5 show test results for gun and accelerator cores. The apparent core input impedance (primary voltage/input current) is shown in Fig. 6. These data reveal the need for a modulator that can deliver a constant voltage across a load impedance that varies approximately 4 to 1 during a 0.4-μsec pulse.

The core pulsing requirements for each type of core are summarized in Table II.

TABLE II
Typical Core Pulsing Requirements For a Single Core

	Item	Gun Core	Accelerator Core
1.	Peak primary voltage *	16,000 volts	12,000 volts
2.	Peak input current *	4,500 amp	1,800 amp
3.	Peak power input *	72 MW	21.6 MW
4.	Maximum input impedance	12.5 ohm	17.5 ohm
5.	Minimum input impedance	2.9 ohm	6.0 ohm
6.	Primary voltage rise time	40 nsec	40 nsec
7.	Secondary voltage rise time	40 nsec	40 nsec
8.	Primary voltage fall time	60 nsec	60 nsec
9.	Secondary voltage fall time	60 nsec	60 nsec
10.	Pulse duration over ±0.50% portion	0.25 μsec	0.25 μsec

* Measured at the end of the 0.25-μsec flat region of pulse

Description of Overall System

Discussion of System Requirements

A detailed review of core pulsing requirements reveals the need for a pulsing system capable of a peak power input of approximately 13,530 megawatts to the cores. The system chosen employs 519 line-type thyratron circuits, each one capable of 36 megawatts peak power with a combined peak power output of about 18,600 megawatts. There are unavoidable mismatches that result in losses which account for a peak power capability in excess of the core requirements. The system current rate of rise is approximately 1,000,000 amperes in 40 nsec or 25×10^6 amp/μsec at a maximum repetition rate of 60 pps.

The timing of the 519 thyratrons has to be held very precise because variations of anode delay will reduce available pulse width.

The Project schedule and budgetary considerations did not allow an extended research and development investigation. Therefore, the system was designed with existing commercial products.

A basic modulator channel, utilizing a Type 5949A hydrogen thyratron at five times rated peak current, was developed. The major problem has centered around the construction and operation of a system of over 500 thyratrons in parallel with stringent reliability and timing considerations.

A summary of test results and comments about various thyratron tubes is given in Table III. This work concluded with the choice of the Type 5949A tube.

TABLE III

Test Results of Thyratron Tube Testing (0.4-µsec Pulse)

		Rating				Tested At:							
MFG.	Type No.	Volts kV	Peak Current amp	Peak Power MW	P_B Factor $\times 10^{-9}$	Volts kV	Peak Current amp	Peak Power MW	P_B Factor $\times 10^{-9}$	Circuit Impedance Load + Source ohms	Rise Time 10 - 90% nsec	Approx. Cost in Large Quantity $	Comments
Kuthe	5C22	16	325	2.6	3.2	16	1600	12.8	1.5	10	60	21	Did not attempt higher voltage
Kuthe	6587	16	325	2.6	3.2	32	2240	36	4.3	14.3	40	40	Used a low inductance version & preaged at 35kV
Kuthe	1257	33	2000	33	20	32	3850	61	7.4	8.3	100	600	Rise time long
GE	GL7390	33	2000	33	30	32	3850	61	7.4	8.3	25	1200	High cost/amp
Kuthe	KU-74	33	2000	33	40	32	3850	61	7.4	8.3	25	1200	High cost/amp
Kuthe & Tung-Sol	5949A	25	500	6.25	6.25	32	2240	36	4.3	14.3	45	60	Prefire good, Low cost/amp

The voltage droop at the core (load impedance) due to the mismatch between the coaxial transmission line characteristic impedance and the core is eliminated by a pulse shaper located in the output circuit of the modulator. However, the flatness was obtained with a sacrifice in efficiency. The pulse shaper can be adjusted to produce an approximate ramp voltage to be transmitted to the core (see block diagram, Fig. 7). Secondary voltages from the cores have been observed with a ripple less than ±1/4% when the pulse shaper is properly adjusted.

The output pulse is positive and is taken from the cathode of the thyratron. A positive pulse improves the life of the RG-213/U transmission lines to the cores by at least an order of magnitude greater than when a negative pulse is used. The peak pulse voltage on the output cables can be 18 kV under maximum output conditions and pulse shaper adjustment. The cable can withstand many times (100 kV or more) this voltage under dc or long rise time pulse conditions. However, under fast pulse conditions, corona bursts occur during the rise and fall of voltage and holes are bored through from the braid to the inner conductor.[13]

The minimum electrical length of the transmission lines to the cores is set at one-half the pulse width (130 feet) in order to prevent reflections from arriving back during the pulse. The maximum length is limited by cable attenuation and will not exceed 200 feet. The final design utilizes 170-ft lengths. The pulse-forming network consists of three 260-ft reels of RG-218/U and one 130-ft length of RG-218/U to an isolating resistor which is connected to the high-voltage charging power supply.

The gun core, at an output of 16 kV, requires three times the peak power of the accelerator core. Three modulators in parallel will be used to power the gun core instead of using a different design modulator.

Detailed Description of System Under Construction

A simplified block diagram of the modulator system is shown in Fig. 7.

The PFN's consist of three 260-foot and one 130-foot reels of RG-218/U (see Figs. 8 and 9) per modulator channel. There will be over 2000 reels in the final system and Fig. 10 shows nearly half of the final installation.

The PFN's are charged by a pulse charging system of four 125-kW power supplies. They are charged up in approximately 2 milliseconds and discharged about 1 millisecond later (see Fig. 11). A de-Q'ing circuit,[14] plus hard-tube regulation, is used to obtain the ±1/4% regulation needed. The power supplies are still under construction, and, therefore, are not reported on in detail.

Each switch, the Type 5949A thyratron, is mounted in a low-inductance cast aluminum housing (see Fig. 12). The housing is incorporated in a chassis (see Fig. 13) which includes an adjustable trigger delay (short sections of RG-58A/U switched in or out), grid and cathode isolation, and a cathode monitor. A complete schematic of the switch chassis is shown in Fig. 14. The switch chassis is plugged in or out of a back panel (see Figs. 15 and 16).

The switch chassis is mounted on sliders in racks and plugs into a back panel (see Fig. 17). The PFN cables (RG-218/U) and load cables (RG-213/U) are permanently mounted in the connectors on the back panel. The switch chassis and pulse shapers are mounted in racks. Figures 18 and 19 show 40% completion of this layout.

Several varieties of co-axial connectors were designed to use with RG-213/U at high pulse voltages. The allowable spacings created a corona problem which was solved by using corona-resistant isomica (silicone bonded mica) shields. RG-213/U cable fails very rapidly when subjected to corona bombardment. This technique eliminates the use of oil and allowed use of a small, inexpensive connector (see Figs. 20, 21, 22, and 23).

Performance Tests of The 36-MW Modulator

The modulator specifications operating into a matched load are shown in Table IV. Waveforms under these conditions are shown in Fig. 24.

Peak Current

The peak current under matched conditions (Z_L = 50/7 ohm) is 2240 amperes. In the system the pulse shaper is added in parallel with a Z_L of 50/6 ohm. The current waveform, with the pulse shaper adjusted for a typical core, is shown in Fig. 25. The peak current through the thyratron is approximately 2830 amperes. This maximum is reached after 0.1 μsec and decreases to about 2200 amperes at the end of the pulse. The modulator performs satisfactorily in either case. No attempt was made to determine the maximum possible current pulse, however, it is possible to affect the current rate of rise by setting the reservoir too low. Waveforms of such conditions are shown in Fig. 26.

TABLE IV

Peak power	36 MW
Output voltage	8 to 16 kV
Output current	1120 to 2240 amp
Average power	680 watts
Load impedance	50/7 ohms ±2%
Average anode current	0.054 amp
RMS anode current	11 amp
Pulse length (flat region)	0.3 μsec
Rise time (10 - 90%)	50 nsec
Fall time (10 - 90%)	50 nsec
Pulse repetition rate	0 - 60 pps
Time jitter	±5 nsec
Pulse-to-pulse amplitude jitter	±0.25%
Pulse ripple	±0.25%

Hold-Off Voltage and Tube Aging Procedure

The anode voltage rises in about 2 msec and the thyratrons are fired about 1 msec after the peak voltage is reached. The modulator has worked well up to 32 kV under such conditions. In order to obtain such performance on 25-kV rated tubes, we have preaged the tubes. The aging process is a run-in time of 12 hours at 32 kV in a circuit with matched load conditions and at 60 pps. The anode voltage rises in 2 msec, however, it stays up about 10 msec before the tube is fired.

The optimum reservoir setting is determined during this aging process. In addition, cathode arcs to ground and prefires are monitored during the run. The prefires are of most concern in this system, because no attempt has been made to isolate PFN's other than by a 750-ohm resistor at the power supply to each PFN. This means about 125 PFN's are tied together and one early prefire could reduce the voltage on all the others. Ultimately it may be necessary to isolate each PFN, however, this will be costly.

Peak Power

The maximum peak power is approximately 36 MW and operation at 60 pps under such conditions was satisfactory. We have not attempted to make higher peak-power runs.

Average Power

Twelve test modulators have been run at an average power of 680 watts each, with a combined running time of over 20,000 unit hours.

Trigger Characteristics

We have experienced low jitter of the order of ±2 nsec when using a sufficiently high voltage trigger. However, the tube shows variations of anode delay of up to ±50 nsec over an operating time of 700 hours at 60 pps (see Fig. 27) and about ±20 nsec over short runs of 2 to 5 hours when anode voltage and repetition rate are varied. The anode delay drift has been negligible (±5 nsec) on short runs (2 to 5 hours) when anode voltage and repetition rate were constant. Variations occur slowly and can be taken care of manually by adjusting the delay in each switch chassis. The causes of these changes have not been determined.

The variation of anode delay vs trigger voltage of four tubes is shown in Fig. 28. A 50-ohm source trigger is used. It should be noted that the differential in delay is nearly a constant above 500 volts, the spread in anode delay is about ±70 nsec, and the variation in delay above 1500 volts is less than 3 nsec per 100 volts. A trigger voltage of 1500 to 1700 volts is used to minimize any effects from changes in trigger voltage.

Variations in anode delay are compensated by changes in trigger delay within each switch chassis. This method eliminates costly electronic delays and each chassis can be monitored and adjusted properly. However, the greater the variation of anode delay, the more delay required inside each switch chassis. Therefore, the anode delay (after the aging cycle of each tube) was measured in order to select tubes. The results of 222 tubes are shown in Fig. 29. All the tubes are from the same production run of one manufacturer. An initial variation of ±30 nsec can be achieved by using 2/3 of the run.

Prefire Characteristics

The anode voltage operation allows approximately 2 msec for a prefire to occur. A prefire is defined as a premature firing of a tube prior to the arrival of the trigger pulse. This phenomenon is not important in many applications because the rate is so low. However, in a system with many thyratrons in parallel and not completely isolated, a high prefire rate would make the system inoperable. In this system, because of protection devices, a single prefire will reduce the beam output considerably and require readjustment. Under such conditions a reasonable prefire rate should be under five per hour. Tests have been made that show an average prefire rate of about one per 2 hours at the end of a 12-hour period (see Fig. 30). Subsequent testing shows a further reduction of the prefire rate until the tube nears the end of life. We attempted to correlate these data with reservoir range (see Fig. 31), however, no direct conclusions were made.

Therefore, the system prefire rate could run as high as 250/hour, which is intolerable. This problem is obviously being given considerable study. It may be necessary to isolate each PFN and thyratron from the high-voltage power supply charging system and also isolate trigger inputs so that random prefires can be tolerated. Under conditions of proper isolation, a random prefire would reduce the beam output by only 0.2% and only occur about once per 1,000 pulses at 60 pps.

Output Pulse Characteristics

Rise times of 50 nsec (10 to 90%) have been realized into a load impedance consisting of seven RG-213/U cables (7.14 ohms). The waveforms (see Fig. 24) of primary voltage and current into the cores show the low ripple attainable with the system when the pulse shapers are properly adjusted. The secondary core voltages are almost identical because of the excellent coupling.

Life Data of the 36-MW Modulator Operated at 28 to 32 kV, 60 pps

Switch Tube, Type 5949A, Used at 2500-Ampere Peak

A single tube was run constantly at 28 kV for over 6000 hours. The tube apparently failed to hold voltage and was removed from the test setup. It was later retested and seemed satisfactory. This tube has been returned to the manufacturer for examination. These data seemed quite encouraging and the design continued around the Type 5949A.

The following test data are not quite as encouraging, but still show reasonable life considering the low cost of the tube. It is anticipated that a special tube may be designed specifically for this application.

No. Tubes	Hours of Life	Total Tube Hours
2	1180	2360
3	810	2430
2	710	1420
1	570	570
1	370	370
9		7150

The average life is about 800 hours. It is obvious from the above that it will be necessary to replace tubes on a maintenance schedule of 600 hours in order to obtain reasonable reliability for the operating system.

Pulse Forming Network (RG-218/U at 32 kV)

Twelve pieces of RG-218/U (nine 260 feet long and three 130 feet long) were run a total of 3200 hours at 32 kV, 60 pps. Three of the surviving pieces ran an additional 3300 hours before all had failed. This added to a total of 34,070 unit operating hours with three failures, or a MTBF of 11,290 hours. The wearout appears to be about 6500 hours. This life seems reasonable for an experimental system of this nature.

Load Cables, RG-213/U

Thirteen 2-foot sections of 213/U were tested at 30-kV pulses (two times actual expected voltage in service) and nine failures were experienced in 32,000 unit operating hours for an average MTBF of about 3600 hours. Individual 170-foot-long sections have been tested to 5650 hours at 16 kV, 60 pps.

Connectors

Nine sets of RG-213/U load cable connectors (Figs. 21 and 23) have been run a total of 20,800 unit operating hours with six failures, giving an MTBF in excess of 3400 hours. Measures were taken to eliminate early connector failures caused by:

(a) Poor connections of inner conductor pins.
(b) Nicking of polyethylene.
(c) Poor mica sleeves.

Conclusions

A compact, low cost, 36-megawatt modulator can be built utilizing a Type 5949A hydrogen thyratron for short pulses at five times rated peak current and attain the following:

(a) 800-hour tube life.
(b) Low anode delay drift of ±5 nsec at constant operating parameters.
(c) Low anode delay drift of ±20 nsec over a wide range of anode voltage and repetition rates.
(d) Long term (up to 800 hours) anode delay drift of ±50 nsec.
(e) Rise time of 50 nsec with low ripple in a 7-ohm circuit giving a current rate of rise of 50,000 amp/μsec.
(f) Positive output pulse without significant deterioration of the rise time.
(g) Prefire rates as low as one per 400,000 pulses.

Acknowledgments

The major portion of the life tests were performed by L. L. Steinmetz, H. M. Graham, and K. A. Saunders. This work was performed under the auspices of the U. S. Atomic Energy Commission.

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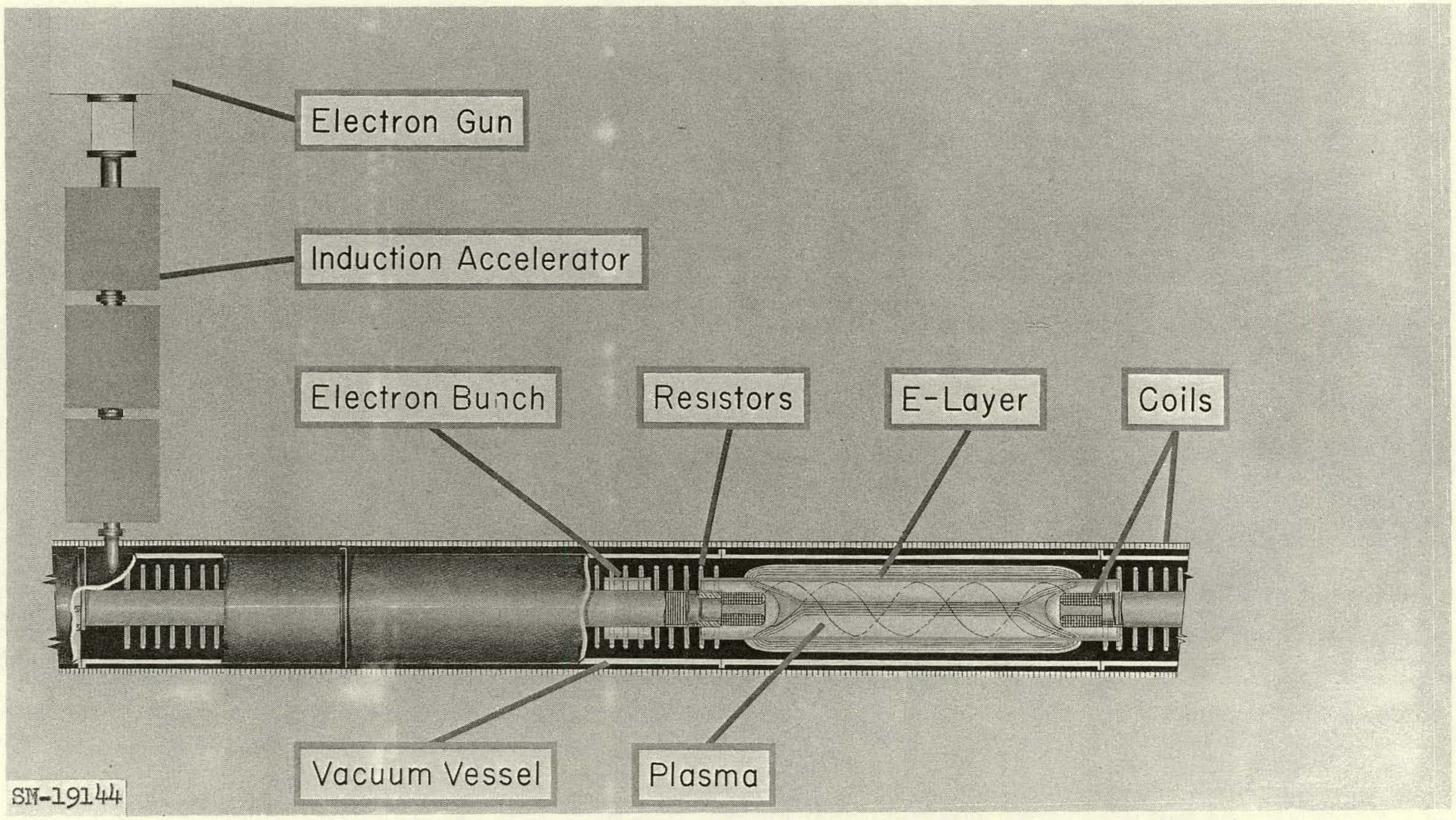

Fig. 1. Astron thermonuclear device.

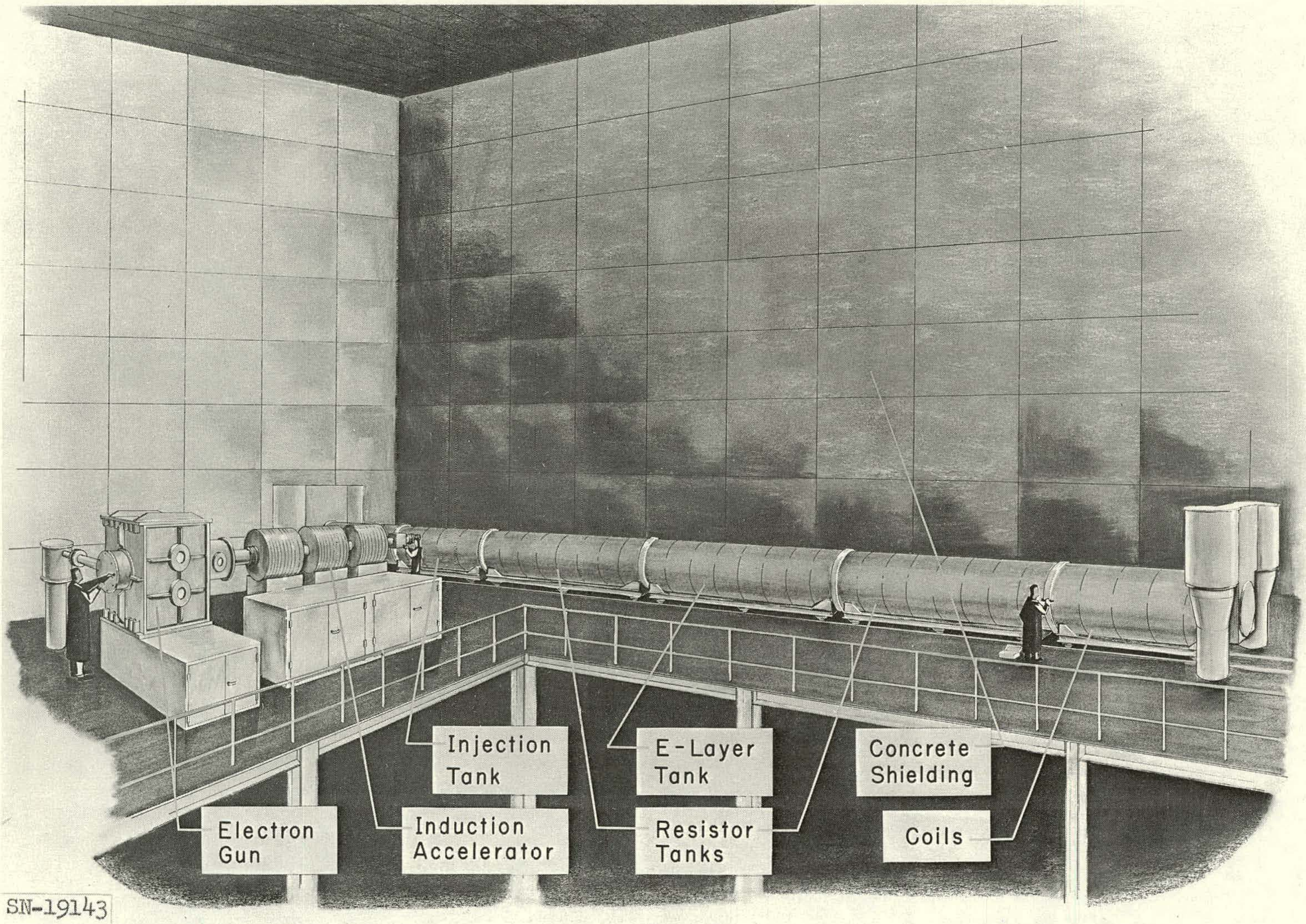

Fig. 2. Astron experimental facility.

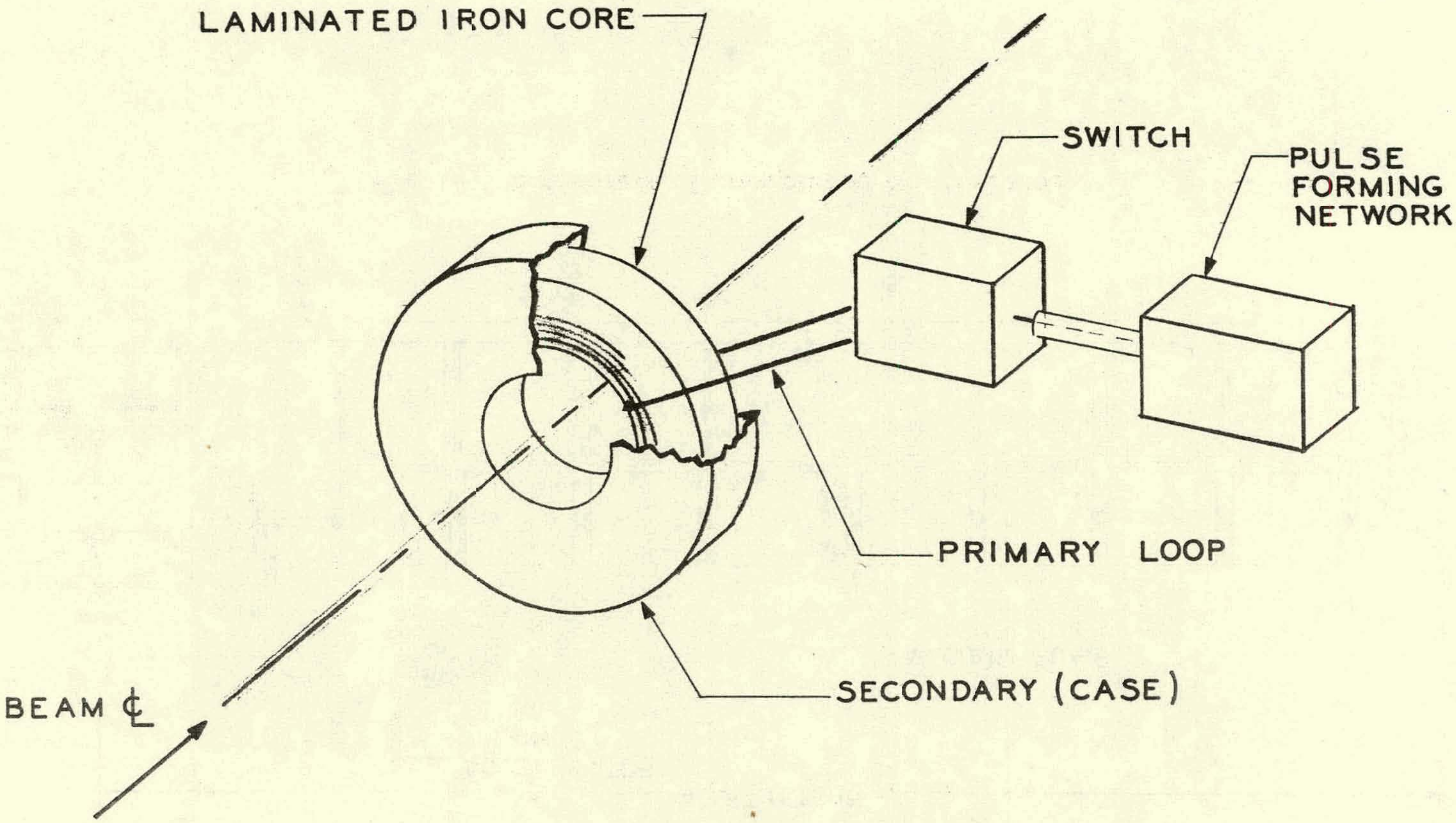

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Fig. 3. Induction accelerator principle.

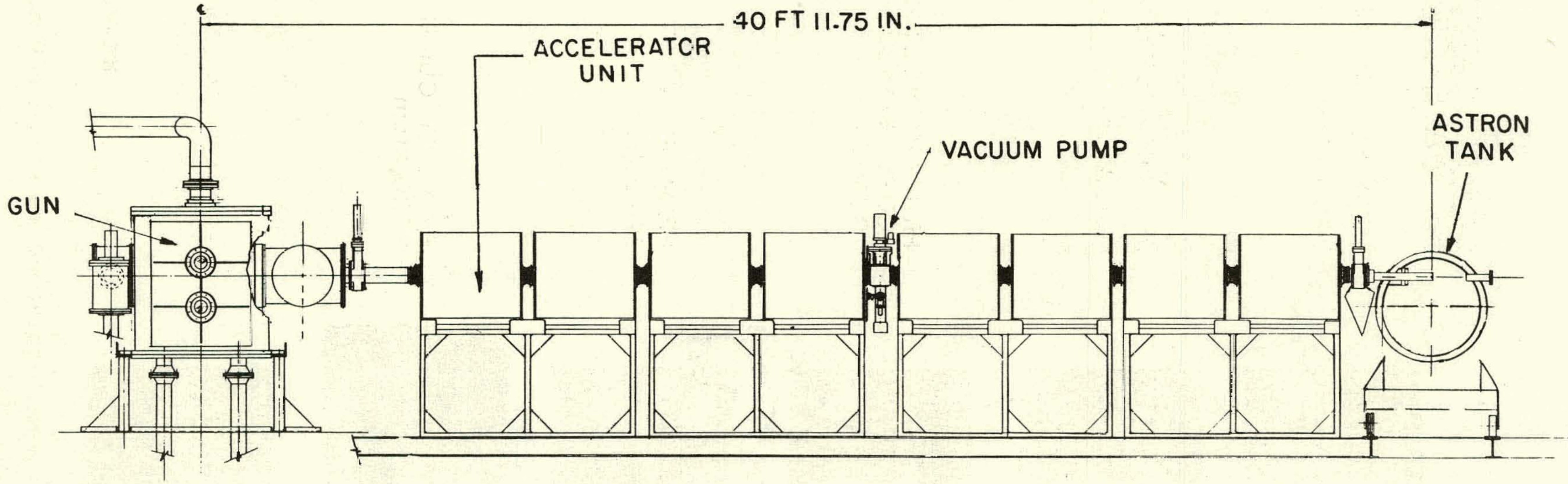

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Fig. 4. Side view of completed accelerator.

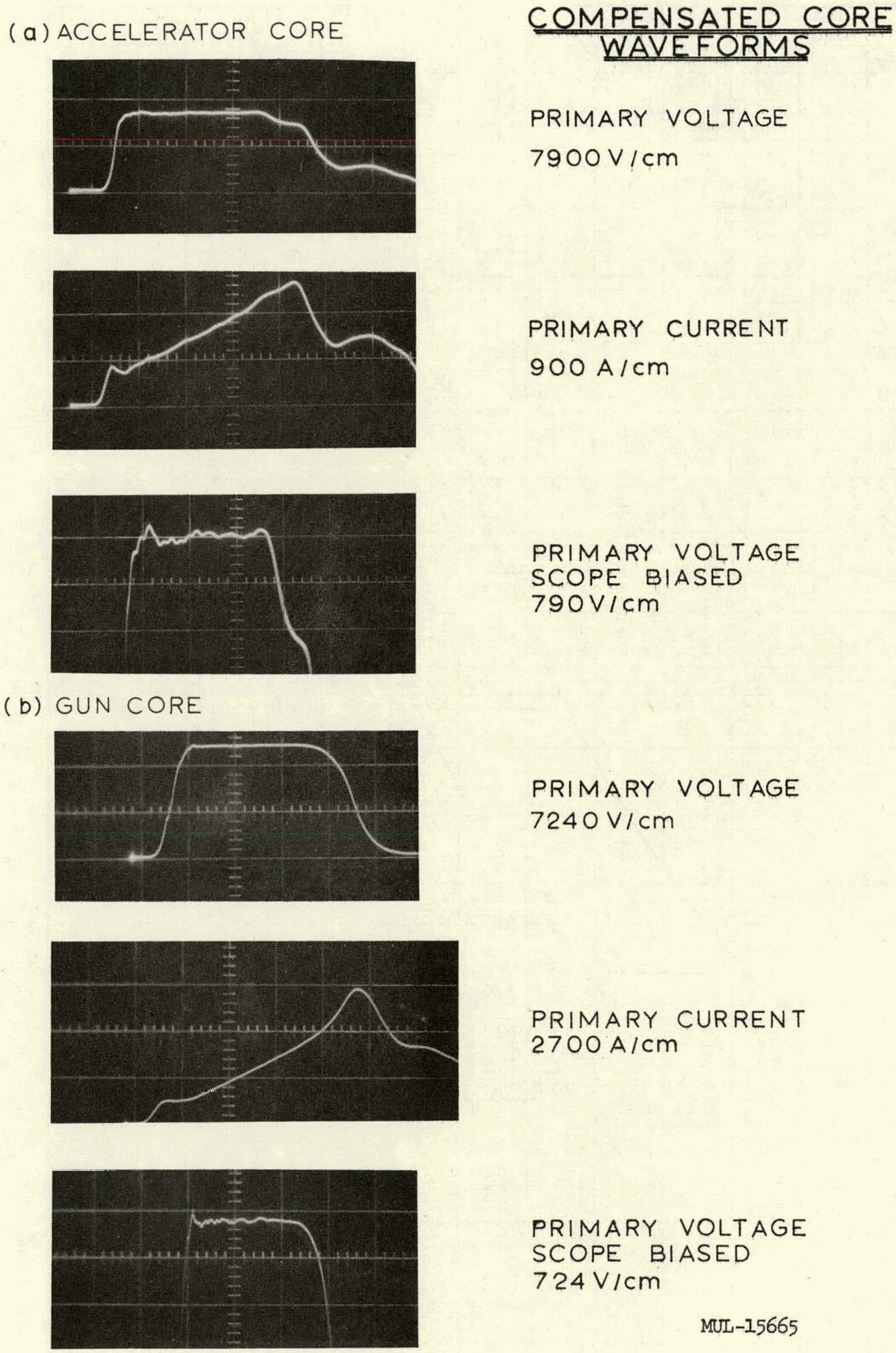

Fig. 5. Compensated waveforms; sweep speed 100 nsec/cm.

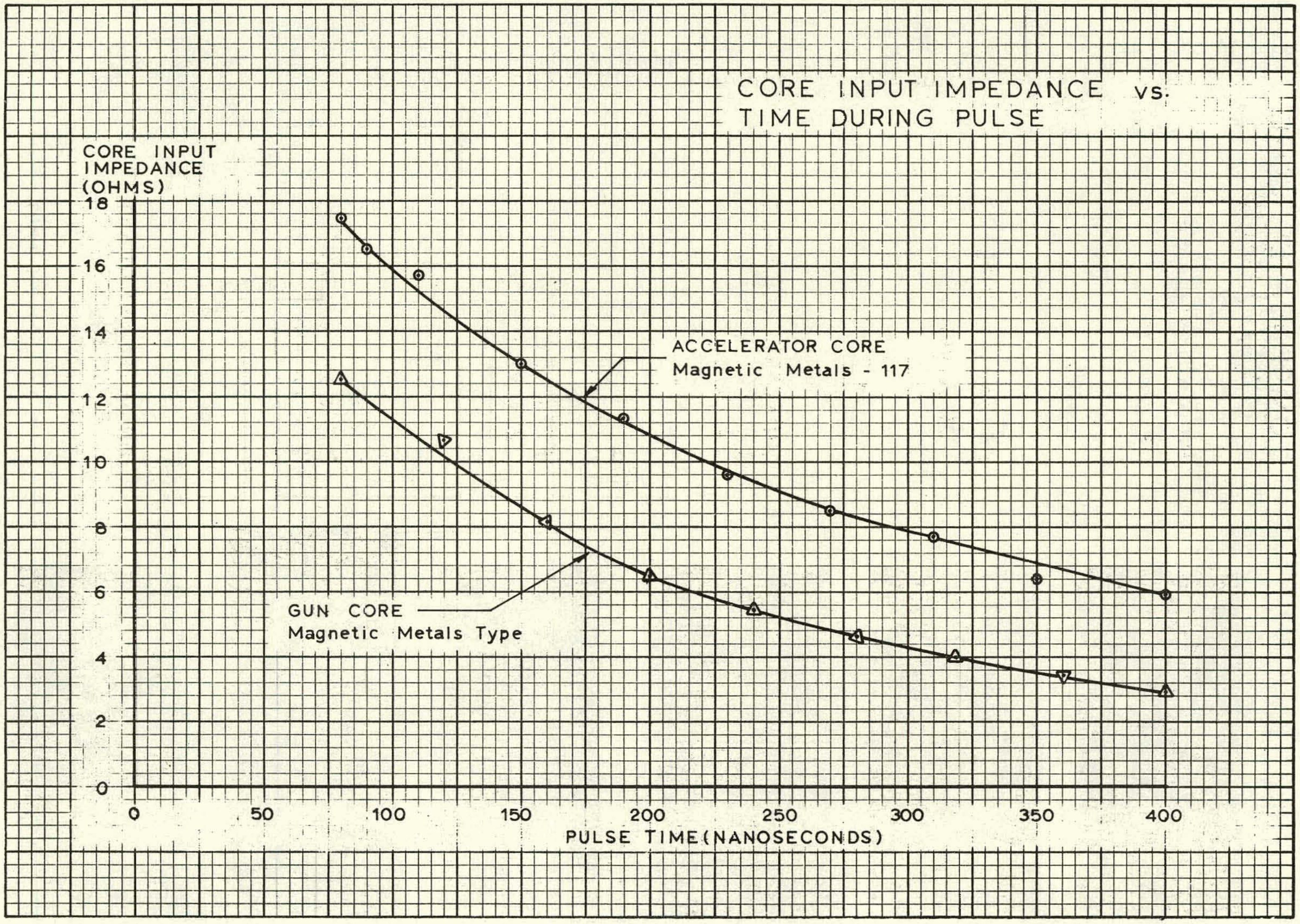

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Fig. 6. Input core impedance (primary voltage/primary current) vs time during voltage pulse.

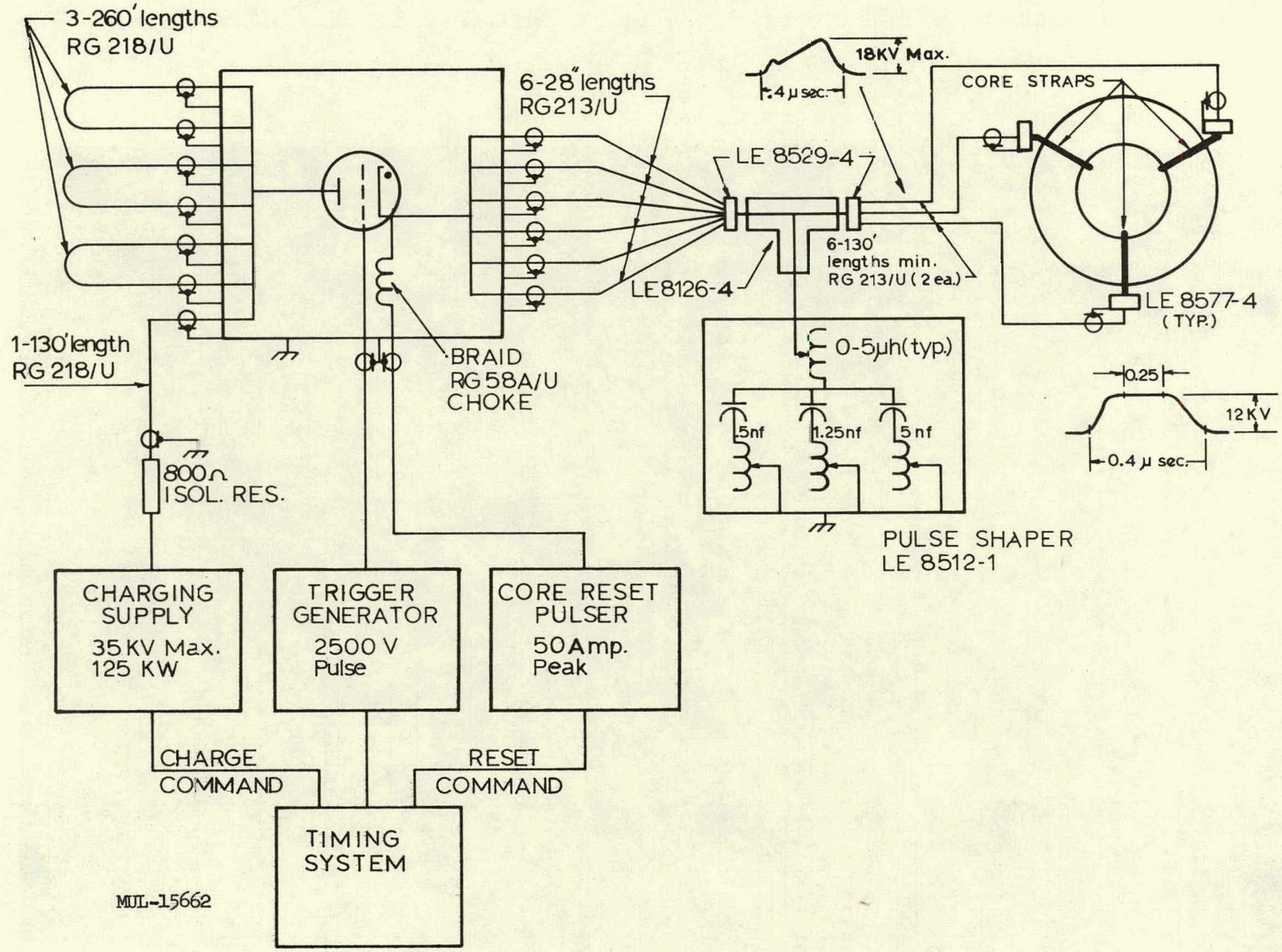

Fig. 7. Block diagram of modulator system.

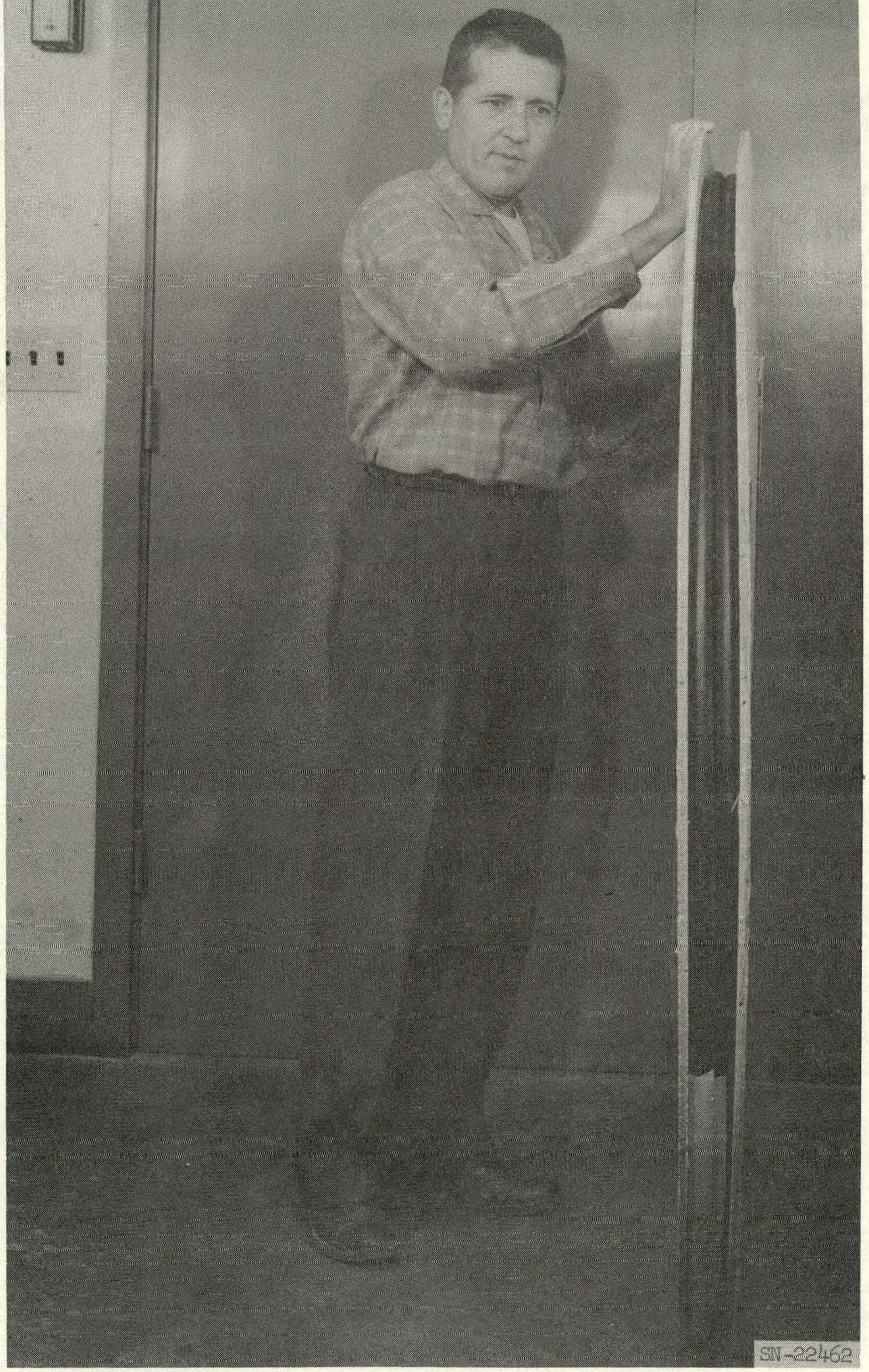

Fig. 8. One 260-foot PFN of RG-218/U.

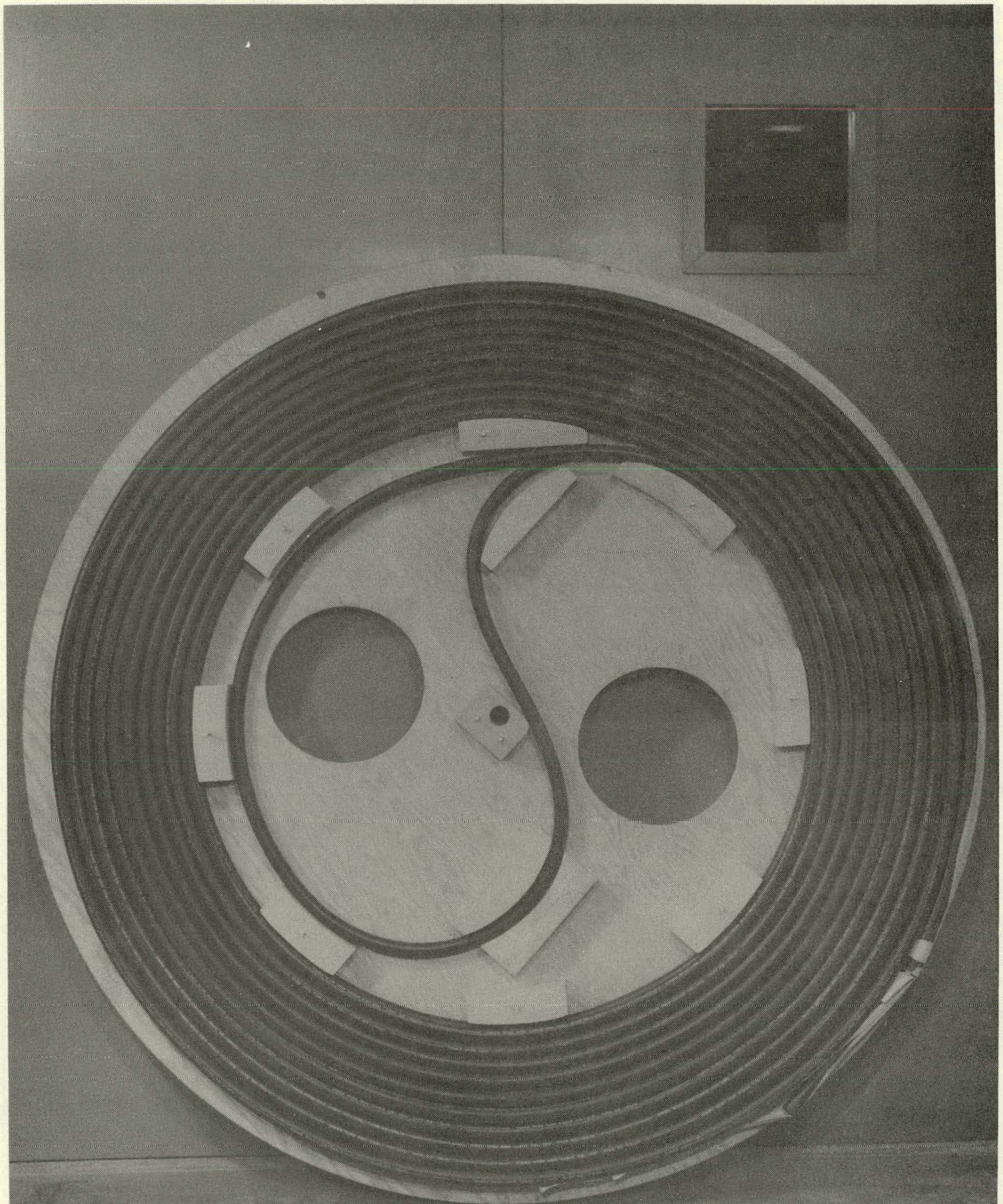

Fig. 9. Inside of PFN reel.

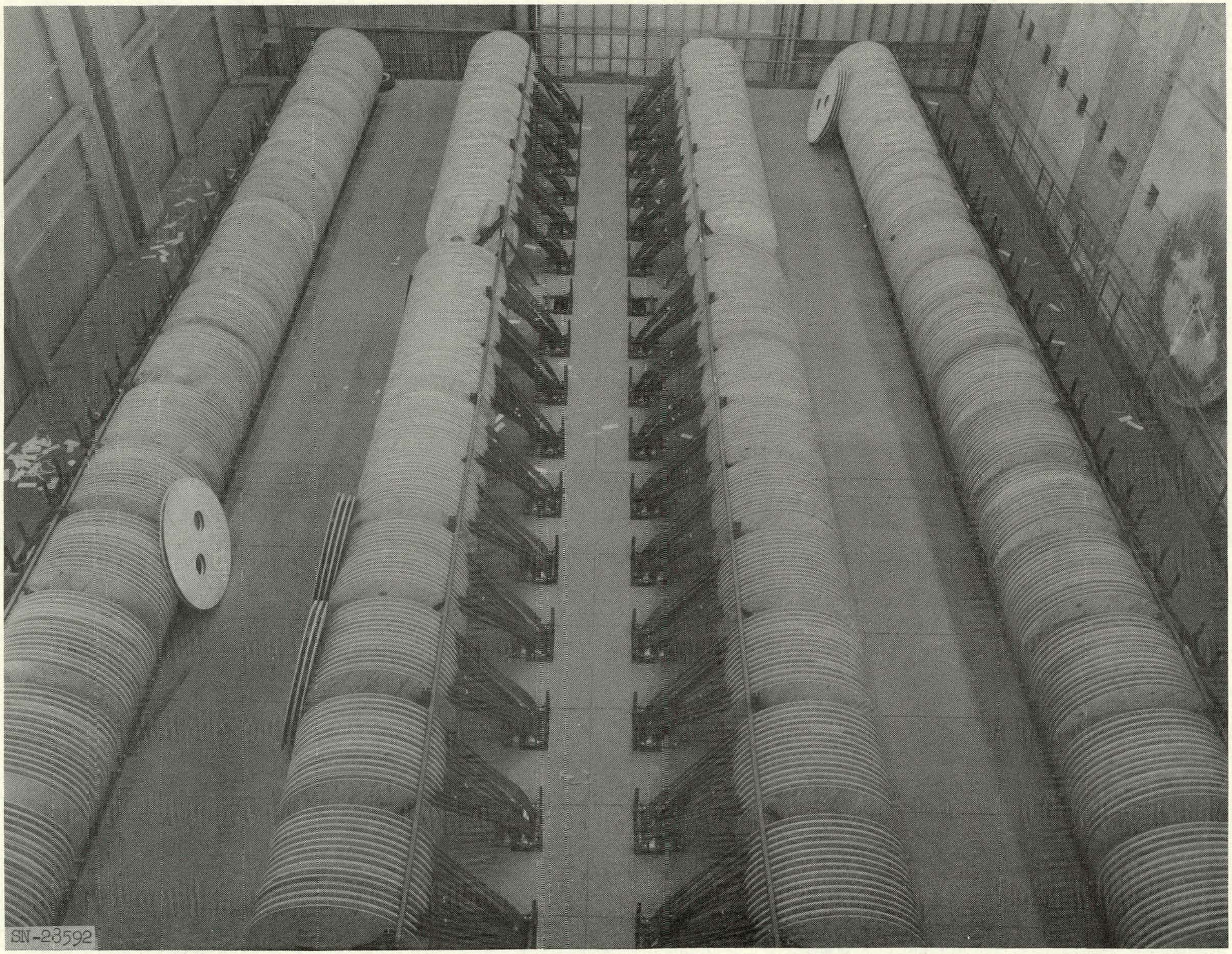

Fig. 10. Top view of 50% PFN installation.

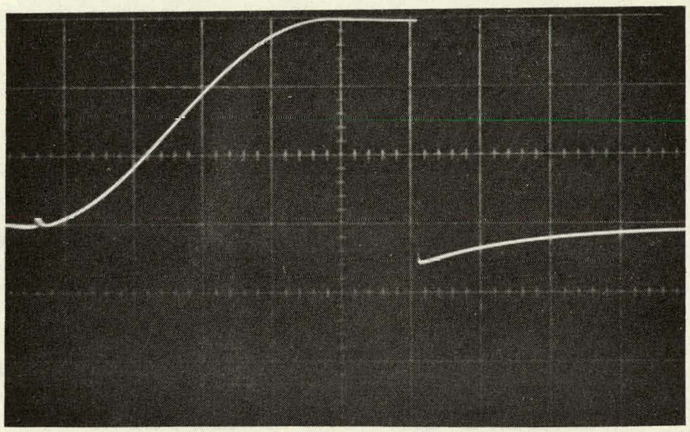

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Fig. 11. Waveform of pulse charging of PFN of modulator. Sweep speed 500 μsec/cm, vertical sensitivity 10,000 volts/cm.

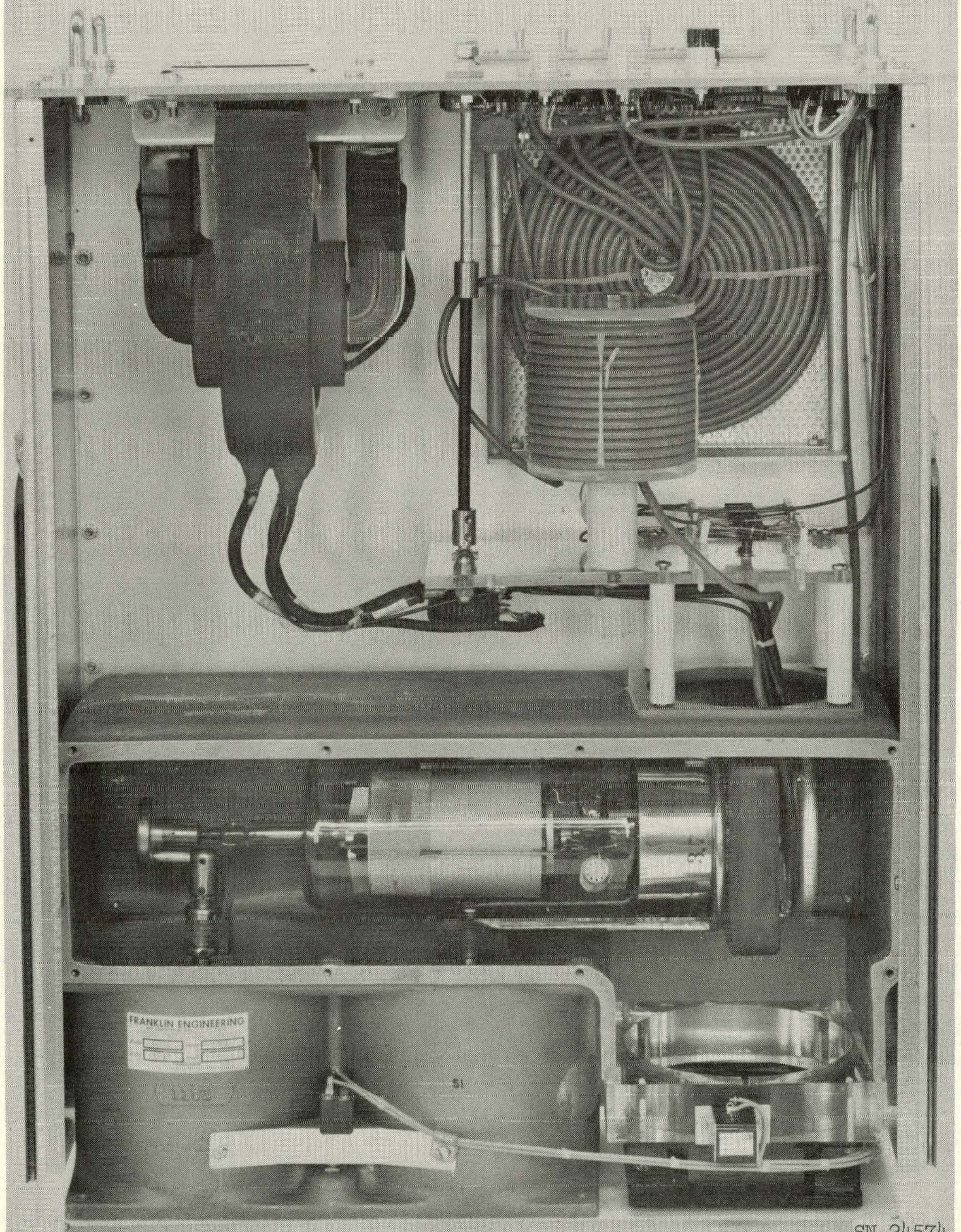

Fig. 12. Switch chassis, top view.

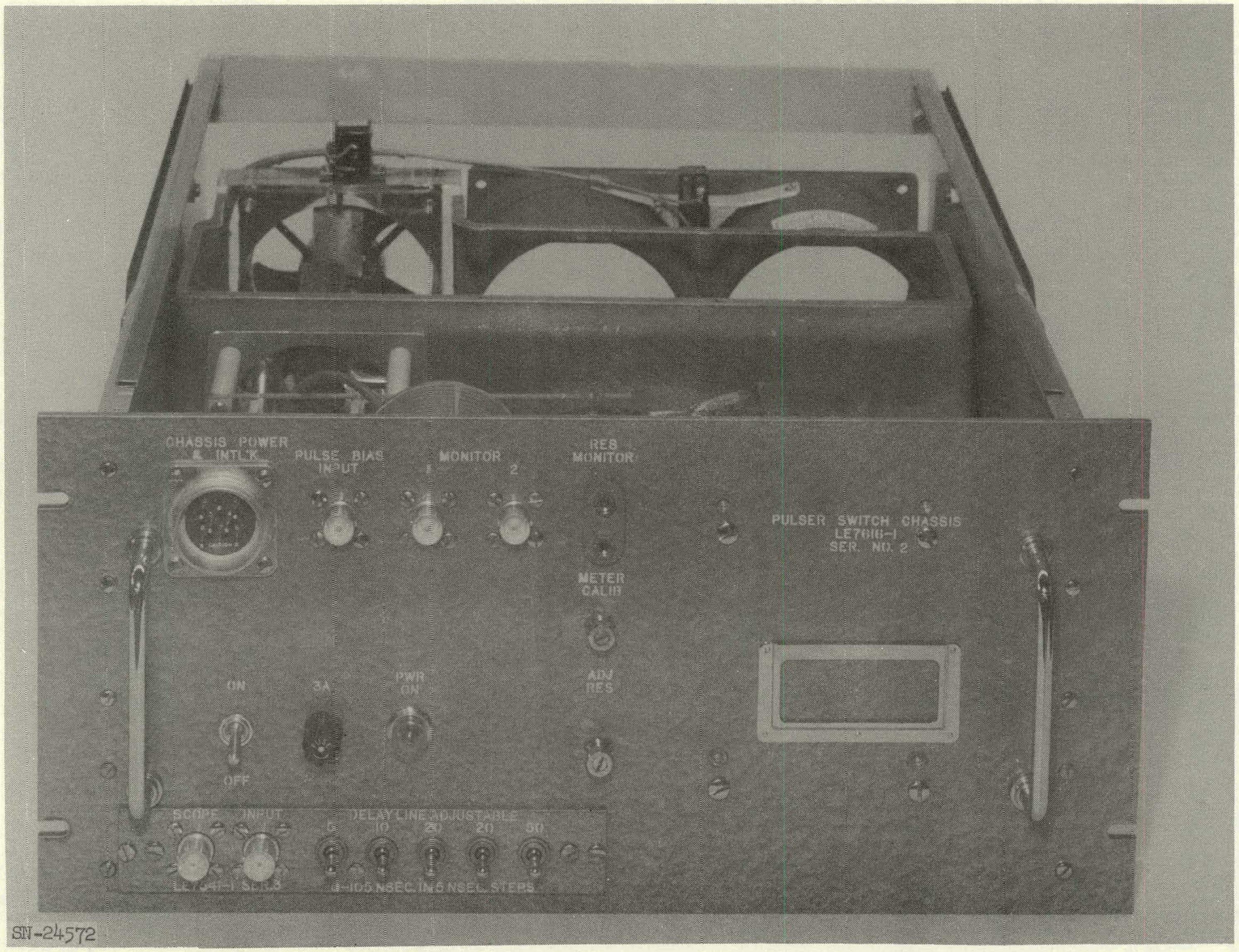

Fig. 13. Switch chassis, front view.

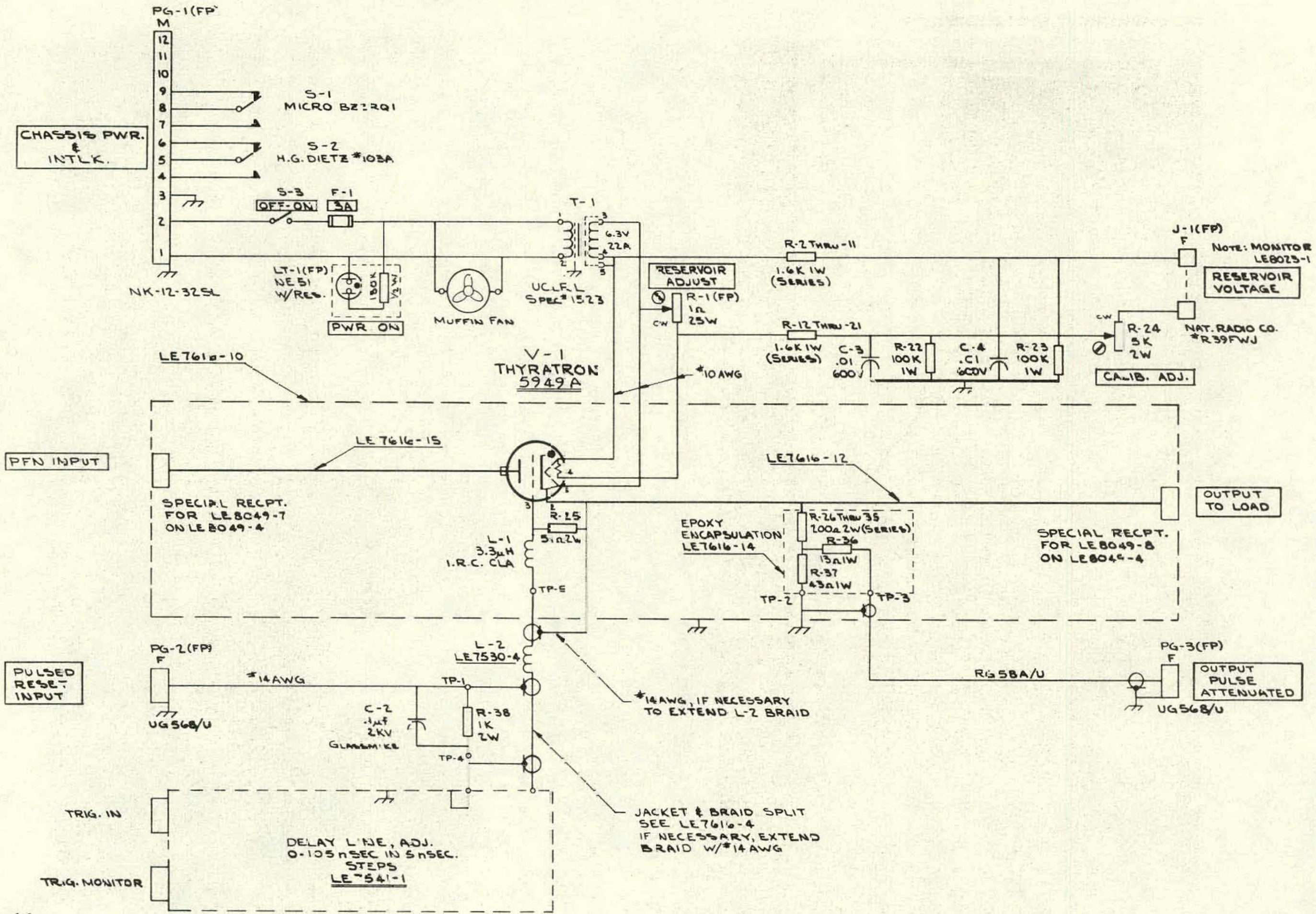

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Fig. 14. Schematic of switch chassis.

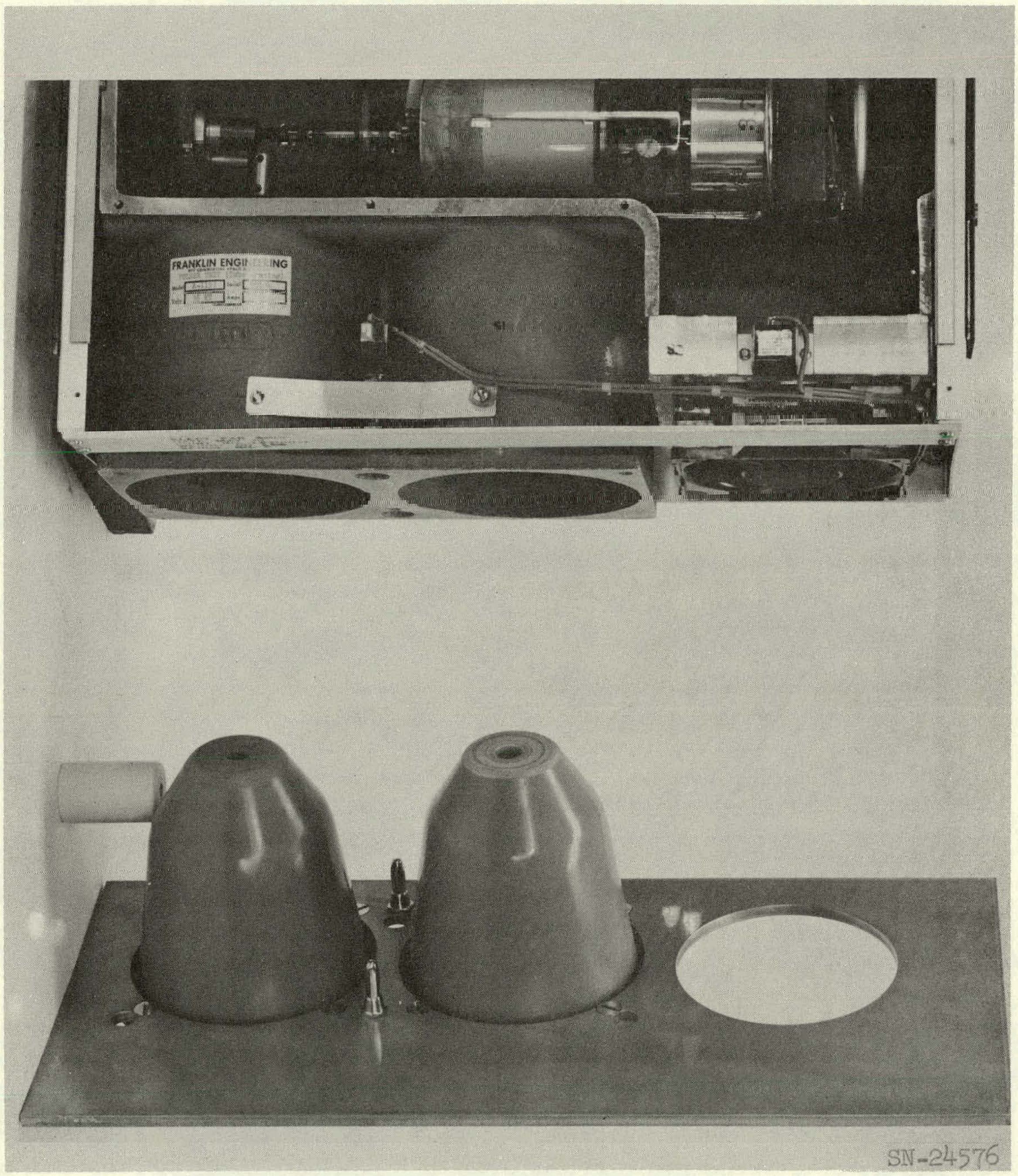


Fig. 15. Back panel plug-in connectors.

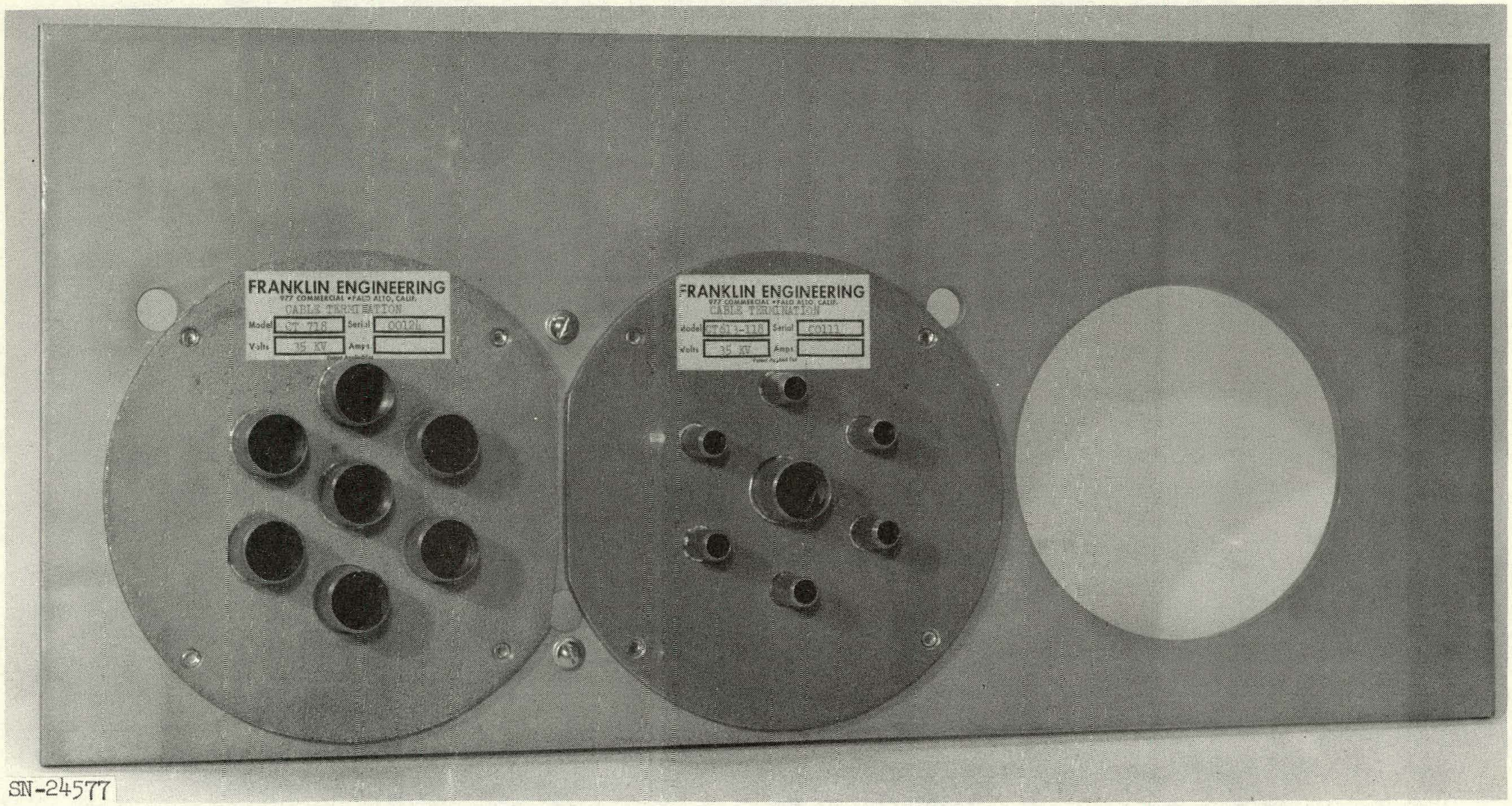


Fig. 16. Back panel, cable end.

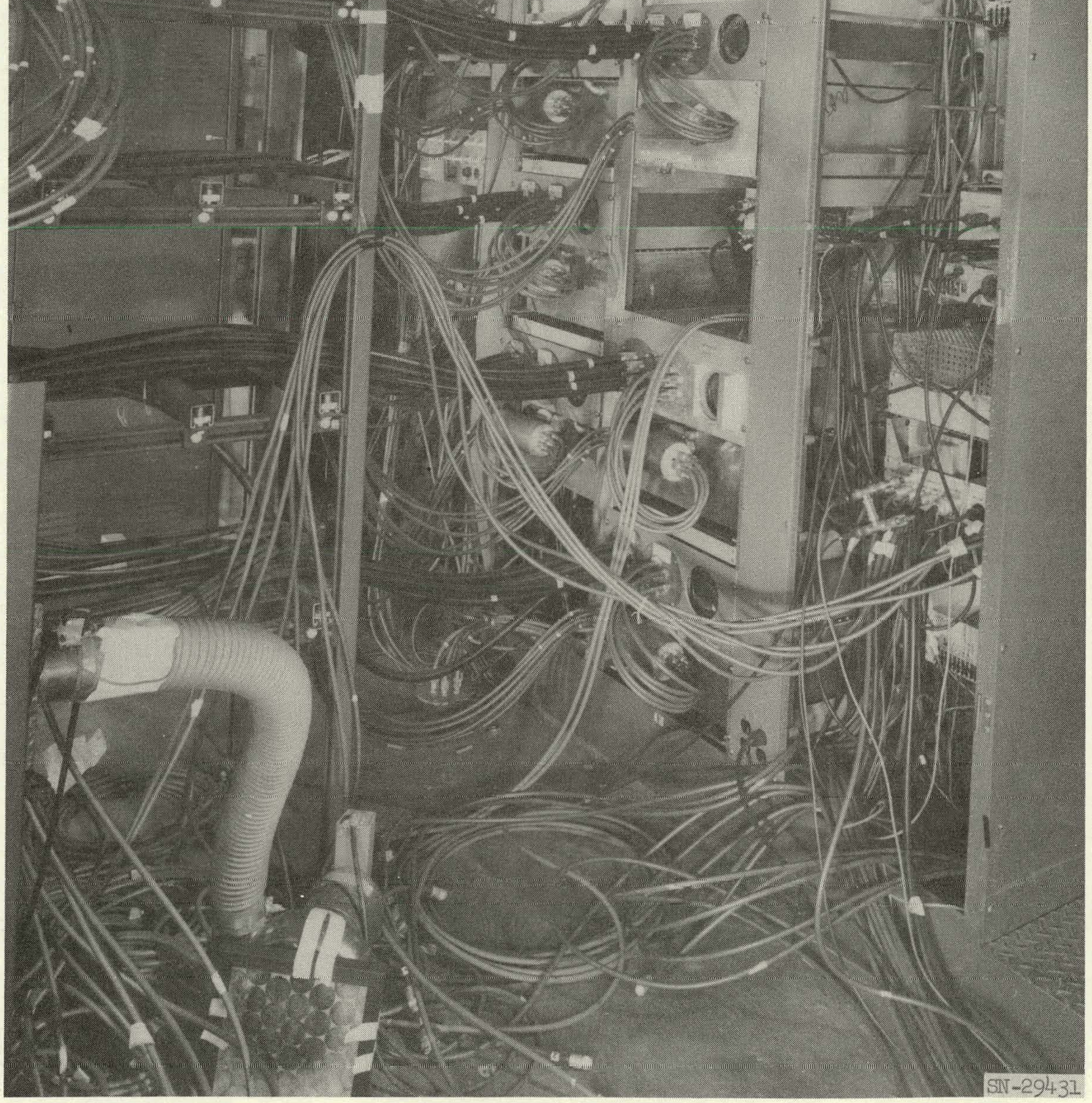


Fig. 17. Back view of eight pulsers showing cable connections to back panels and pulse shapers.

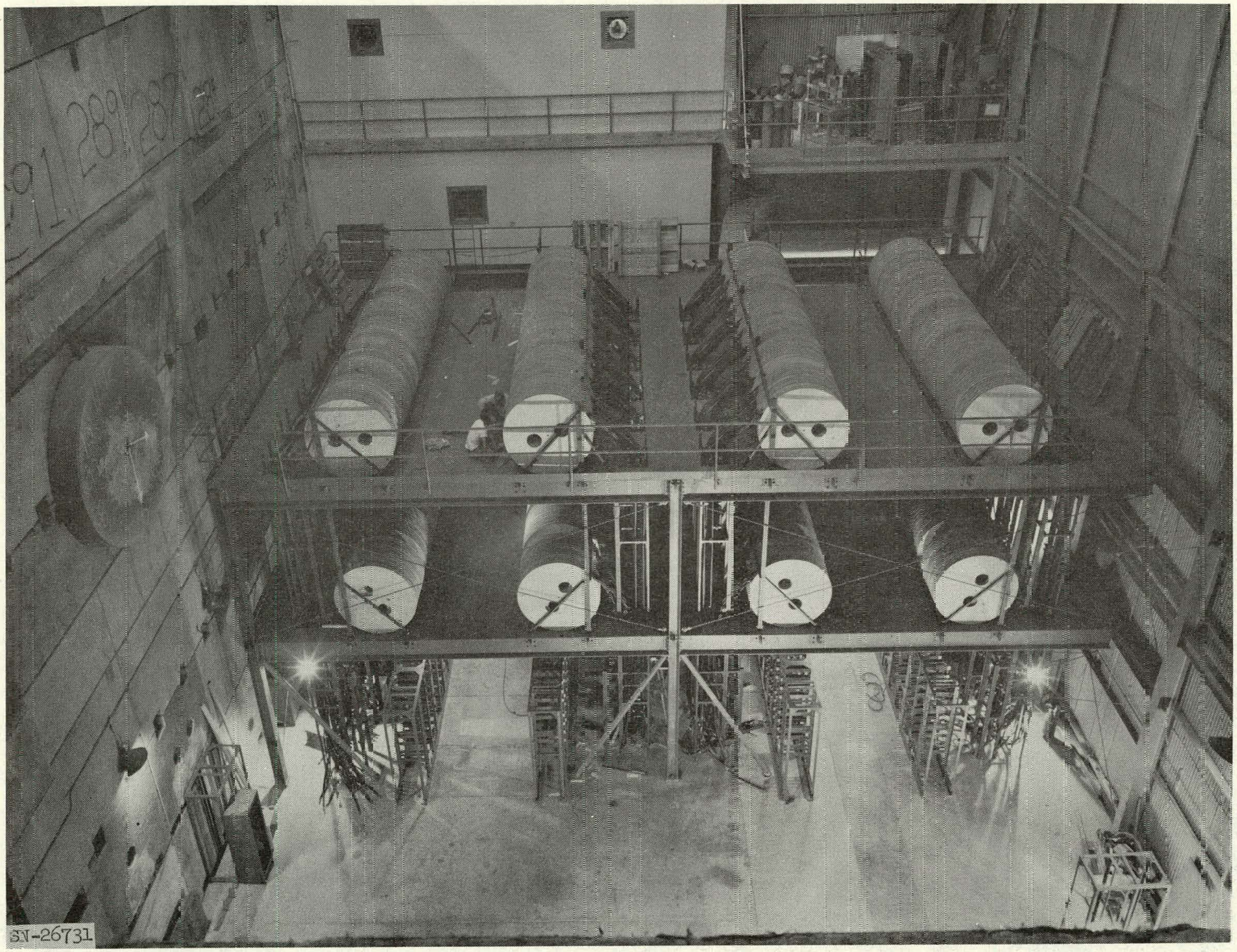


Fig. 18. Installation of PFN reels and racks for switch chassis (showing about 40% of the final system).

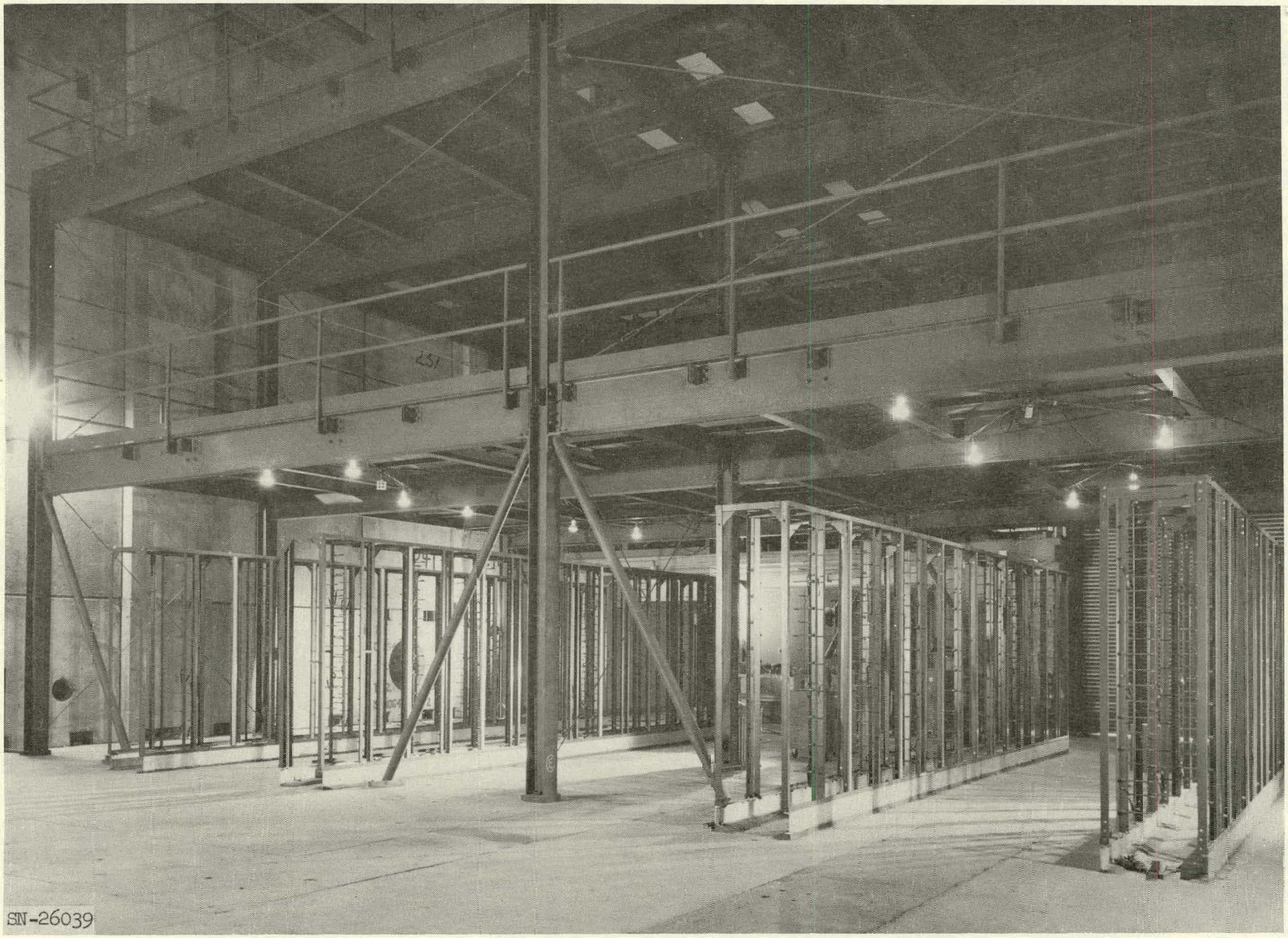


Fig. 19. Rack installation, 40% complete.

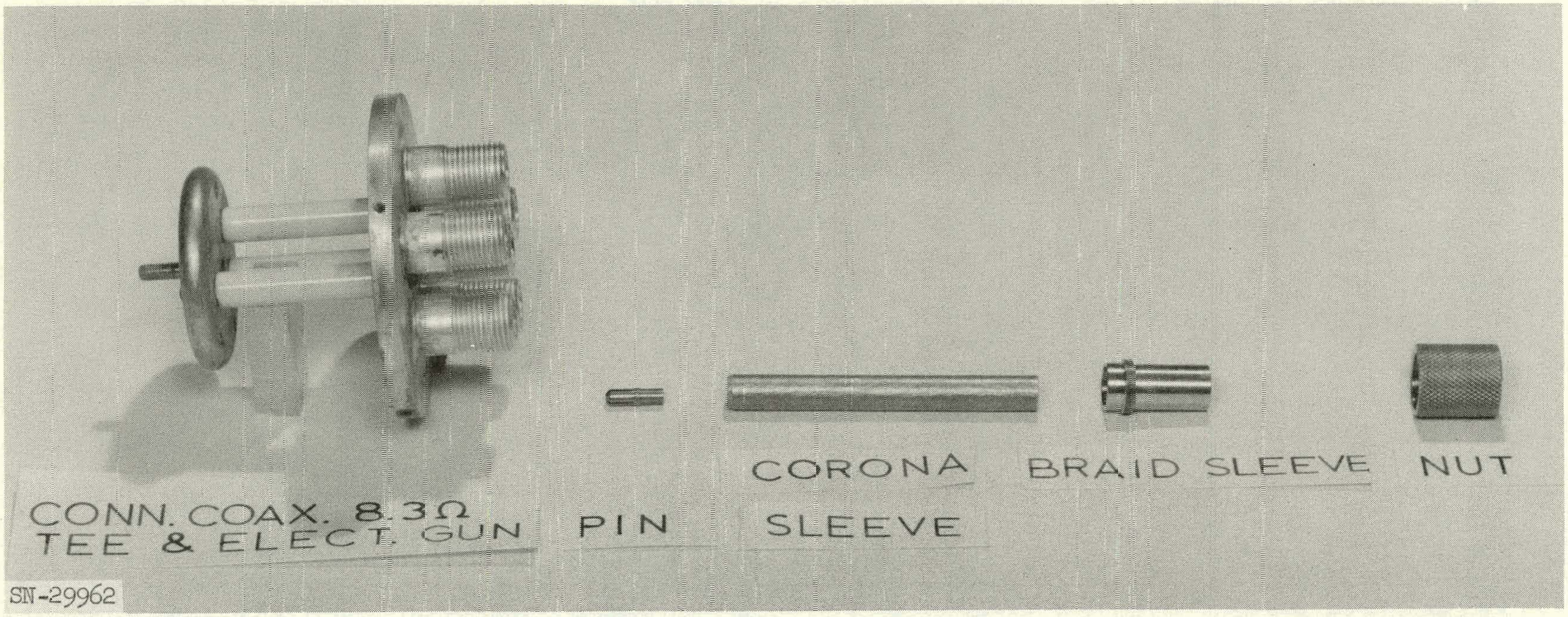


Fig. 20. Six-cable connector, parts.

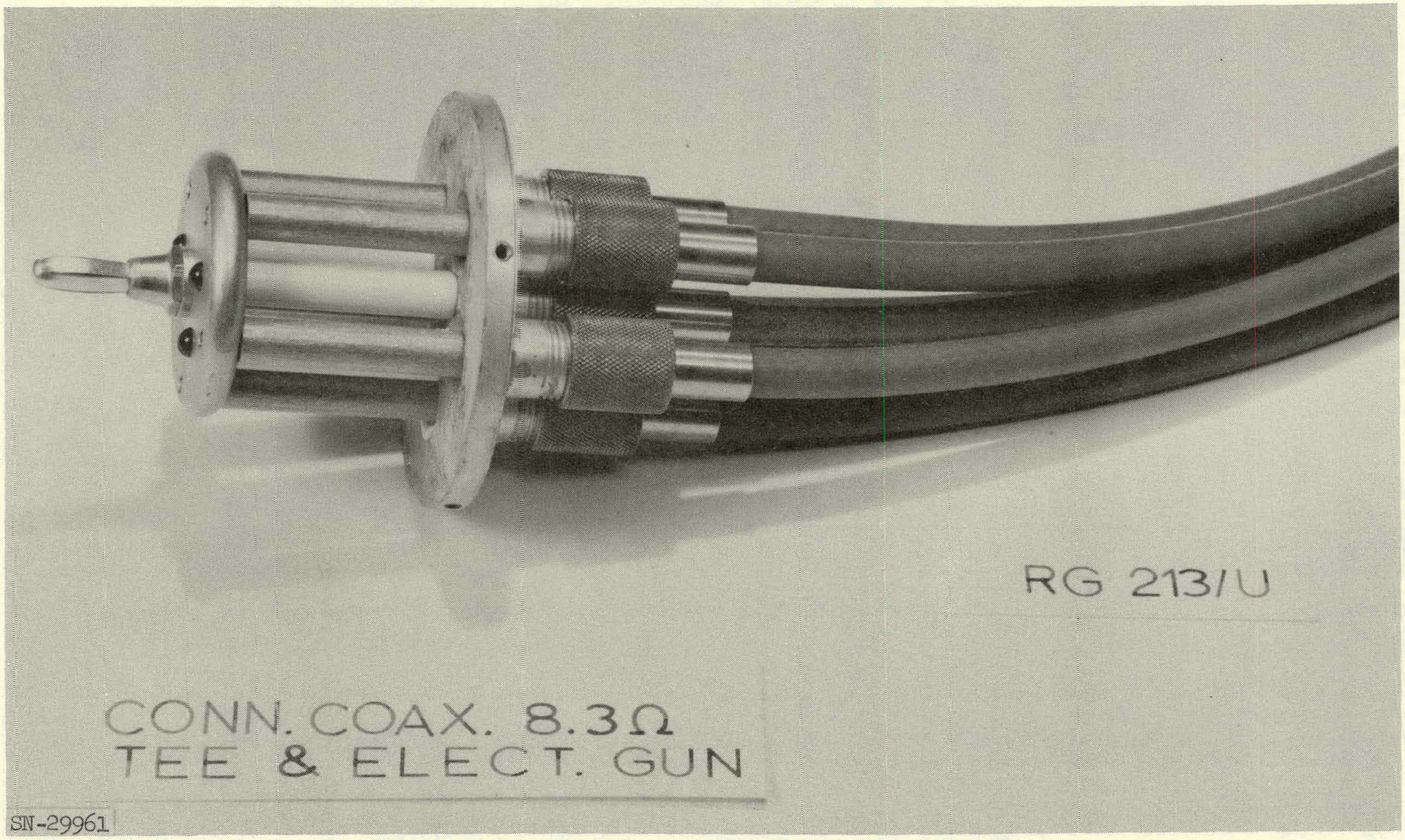


Fig. 21. Six-cable connector, assembled.

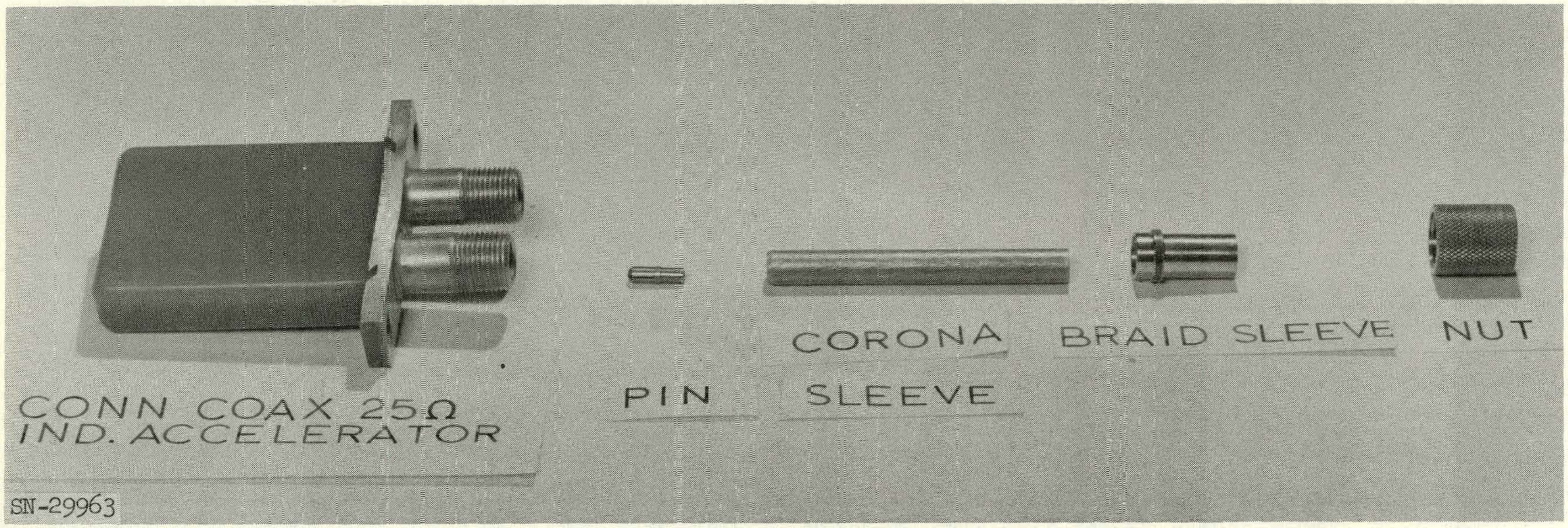


Fig. 22. Two-cable connector, parts.

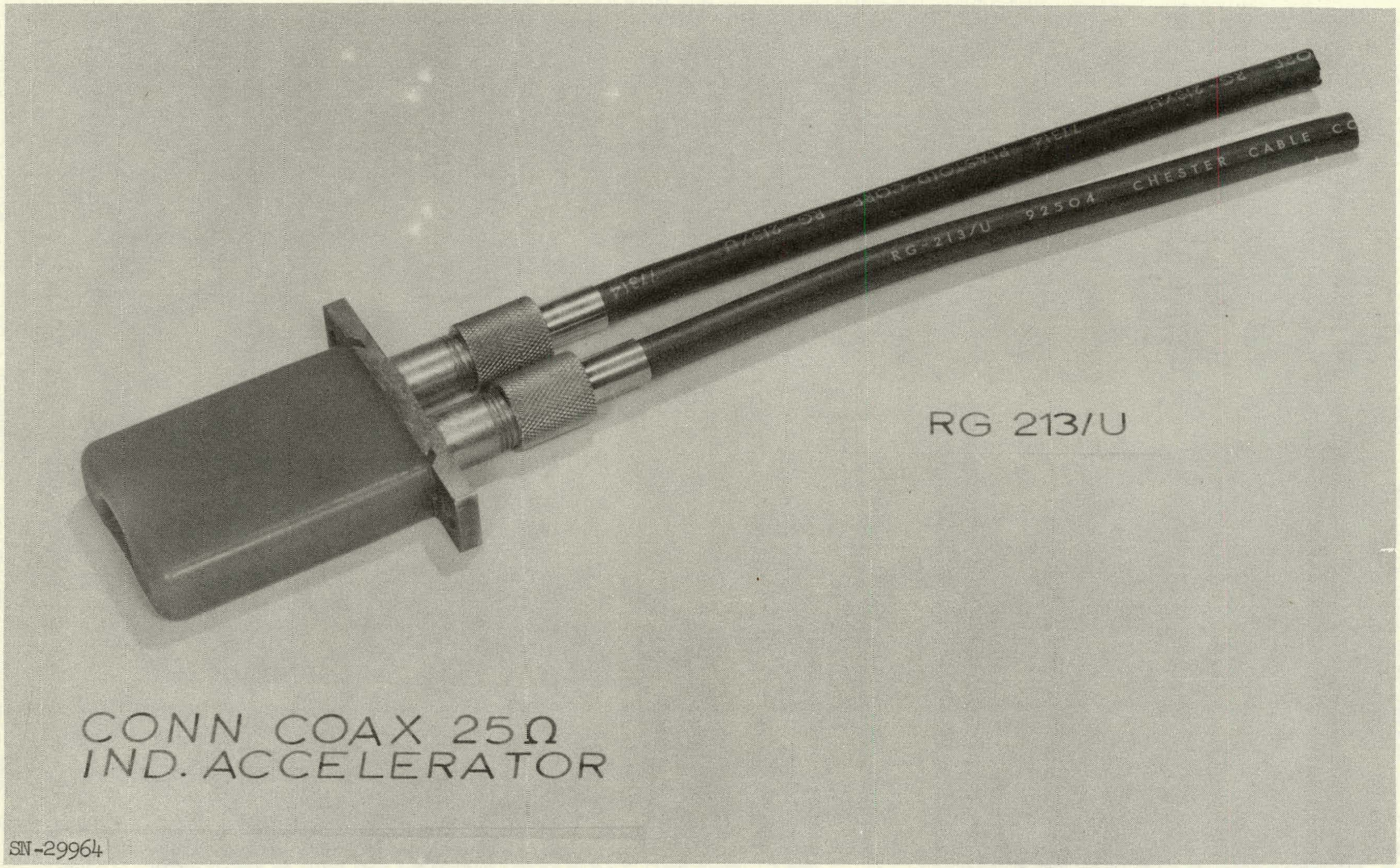
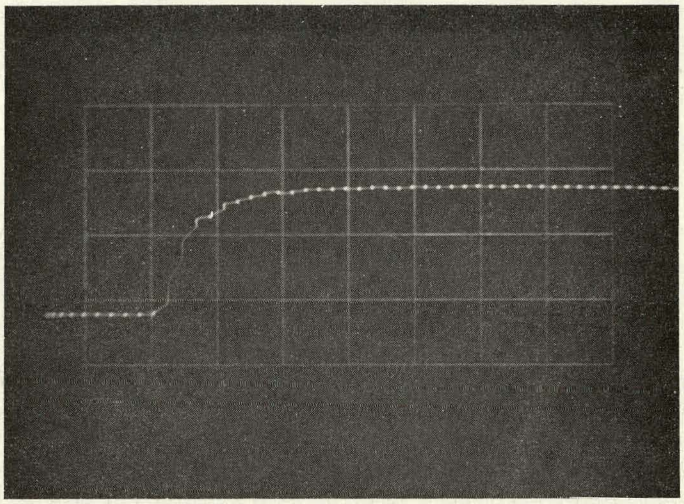
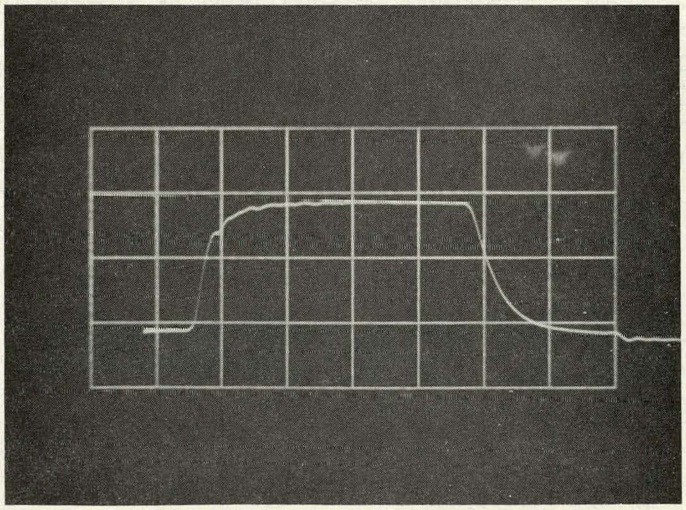


Fig. 23. Two-cable connector, assembled.



SWEEP SPEED: 50ns/cm
TIMING FREQ: 100mc
applied to Horizontal
Deflection Plates
("DOT ROSSI" Technique)



SWEEP SPEED: 100ns/cm

MUL-15666

Fig. 24. Waveforms of output of switch chassis terminated in a 7.14-ohm load.

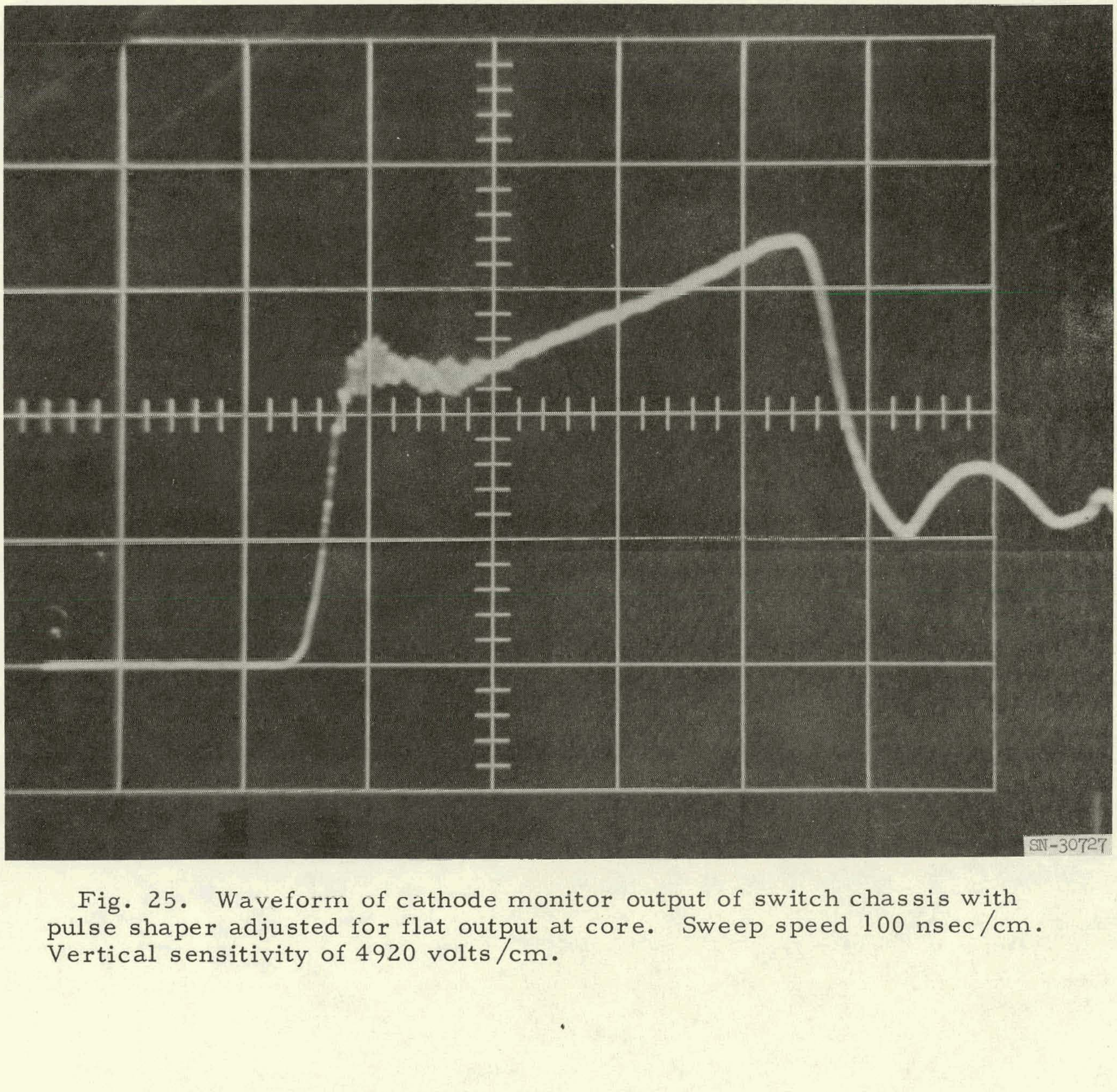
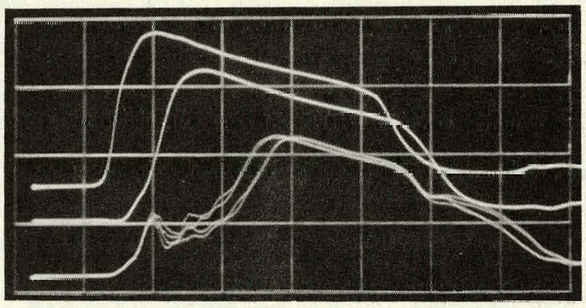


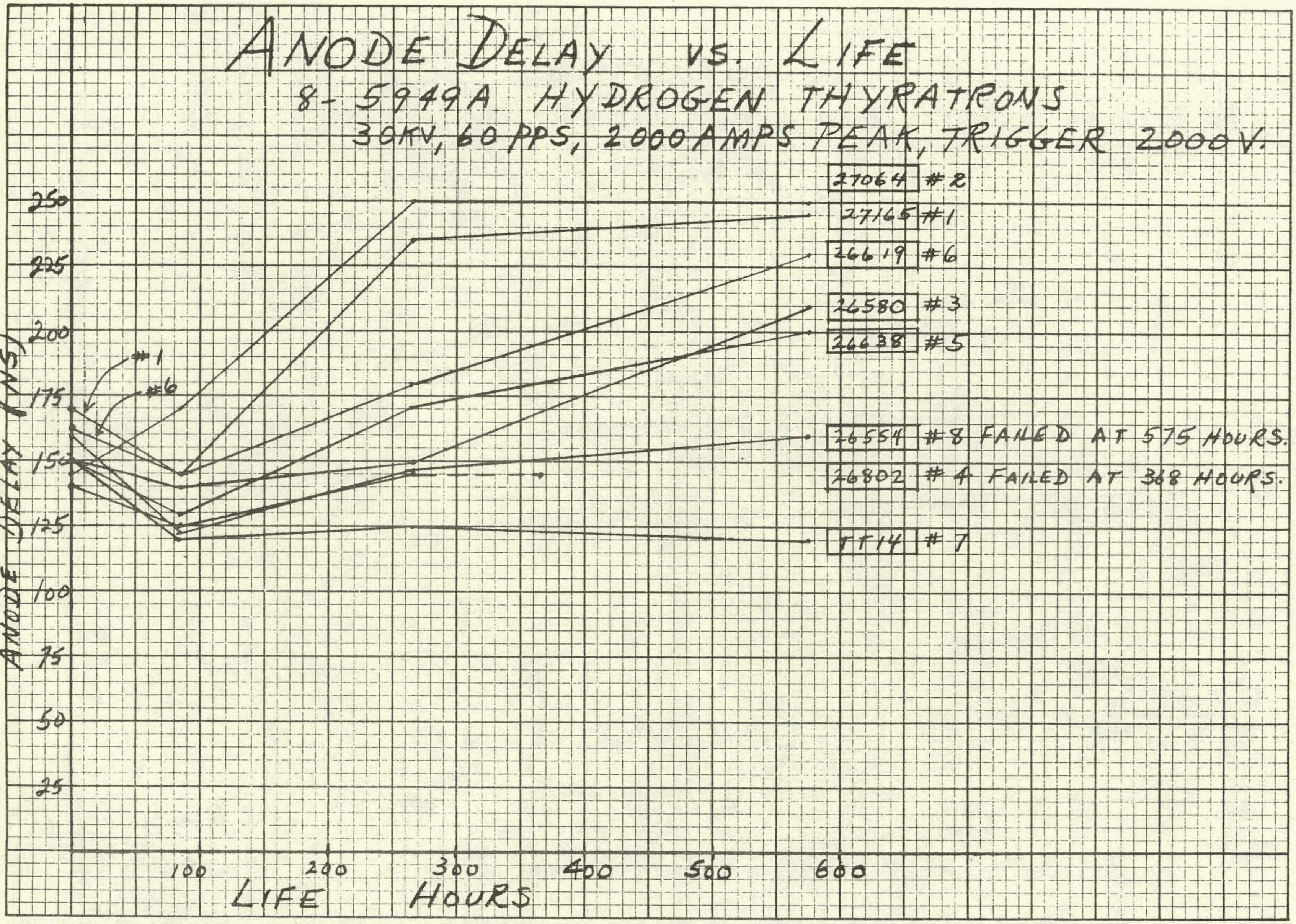
Fig. 25. Waveform of cathode monitor output of switch chassis with pulse shaper adjusted for flat output at core. Sweep speed 100 nsec/cm. Vertical sensitivity of 4920 volts/cm.



TOP TRACE: NORMAL RESERVOIR SETTING 5.1 V
CENTER TRACE: 30 sec. AFTER CHANGING RES.TO 4.4 V
BOTTOM TRACE: 2 min. AFTER CHANGING RES. TO 4.4 V

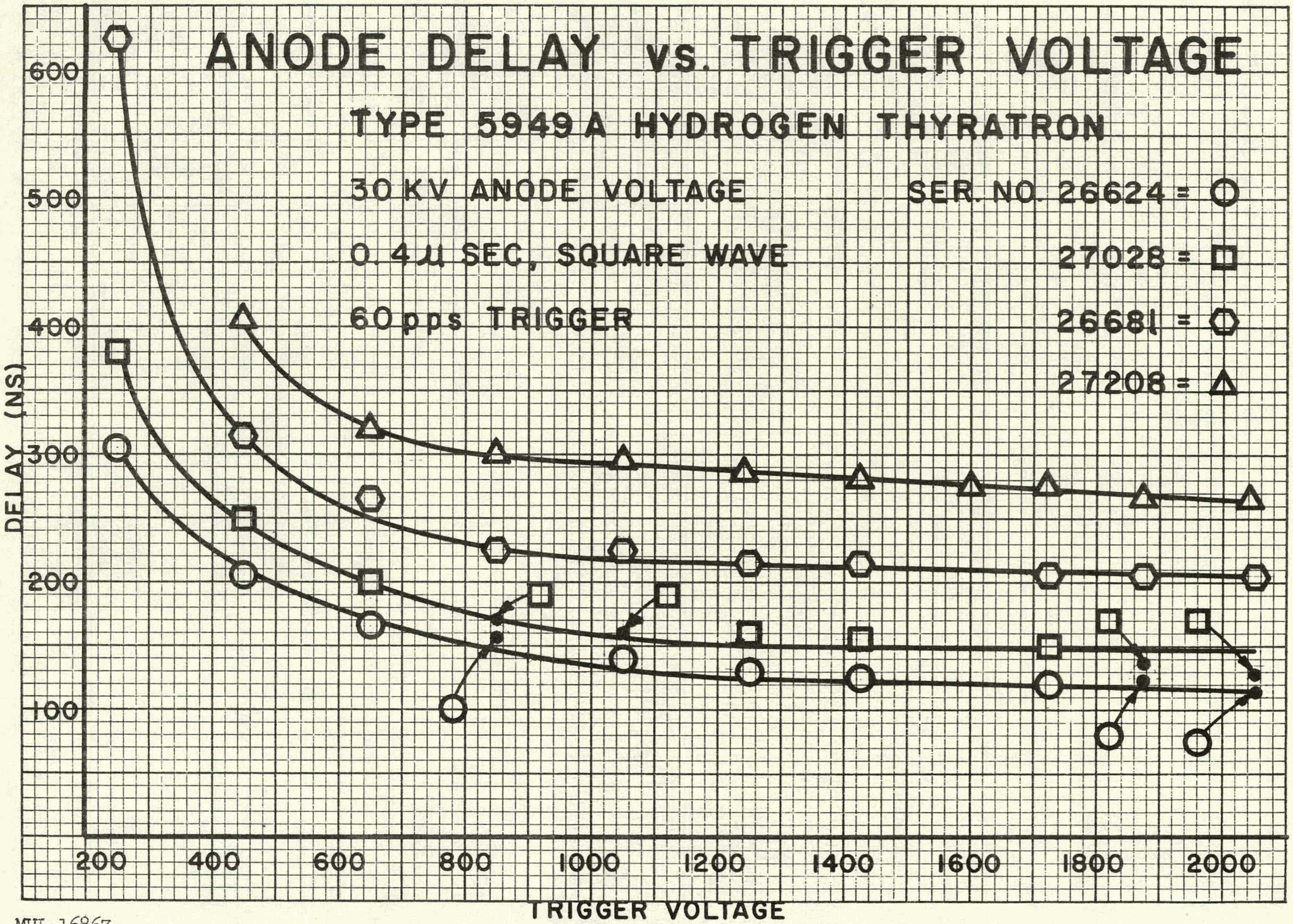
MUL-15664

Fig. 26. Waveforms of core output showing effects of low reservoir settings. Sweep speed 100 nsec/cm, vertical sensitivity 7,000 volts/cm.



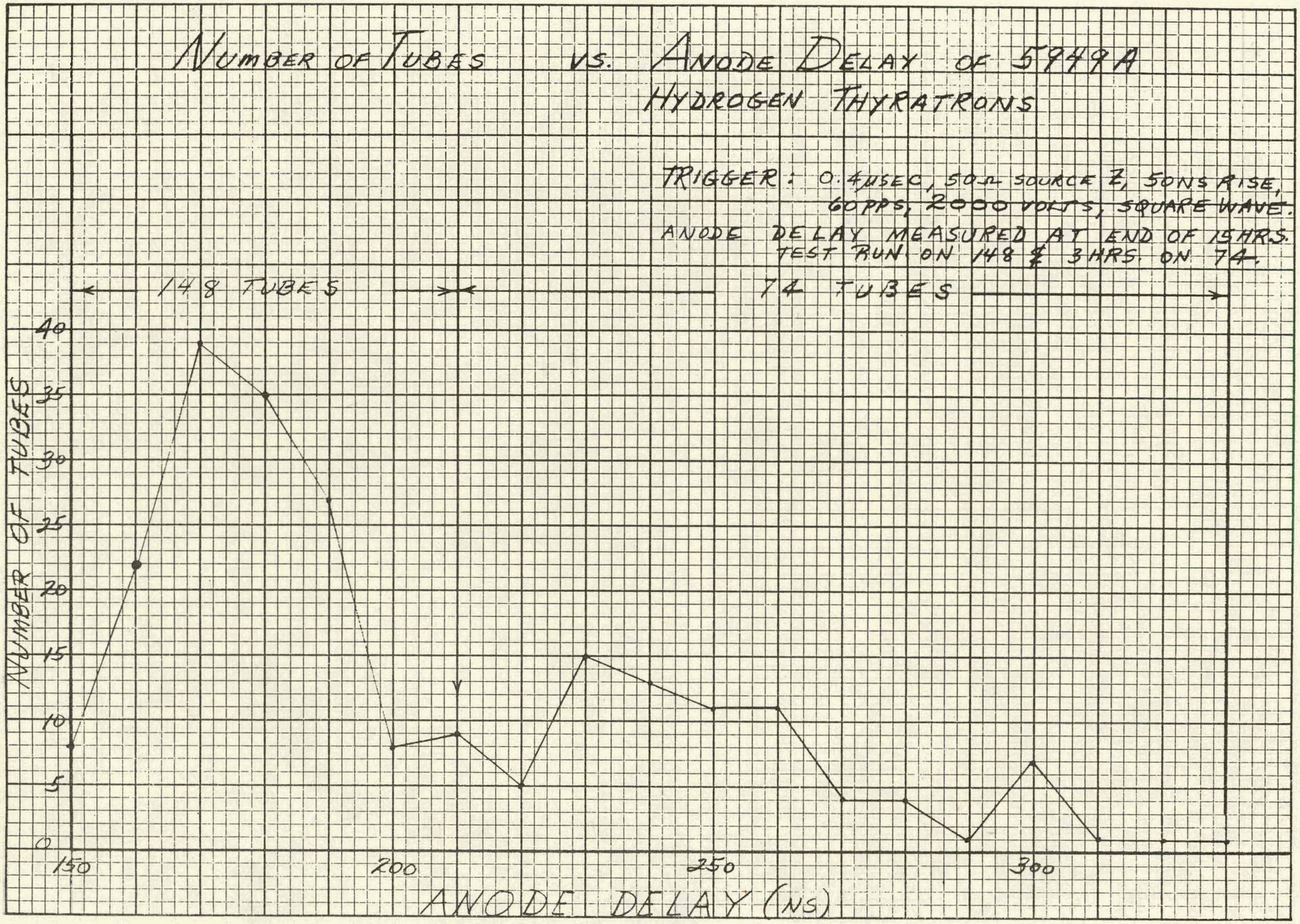
MUL-16866

Fig. 27. Anode delay vs life.



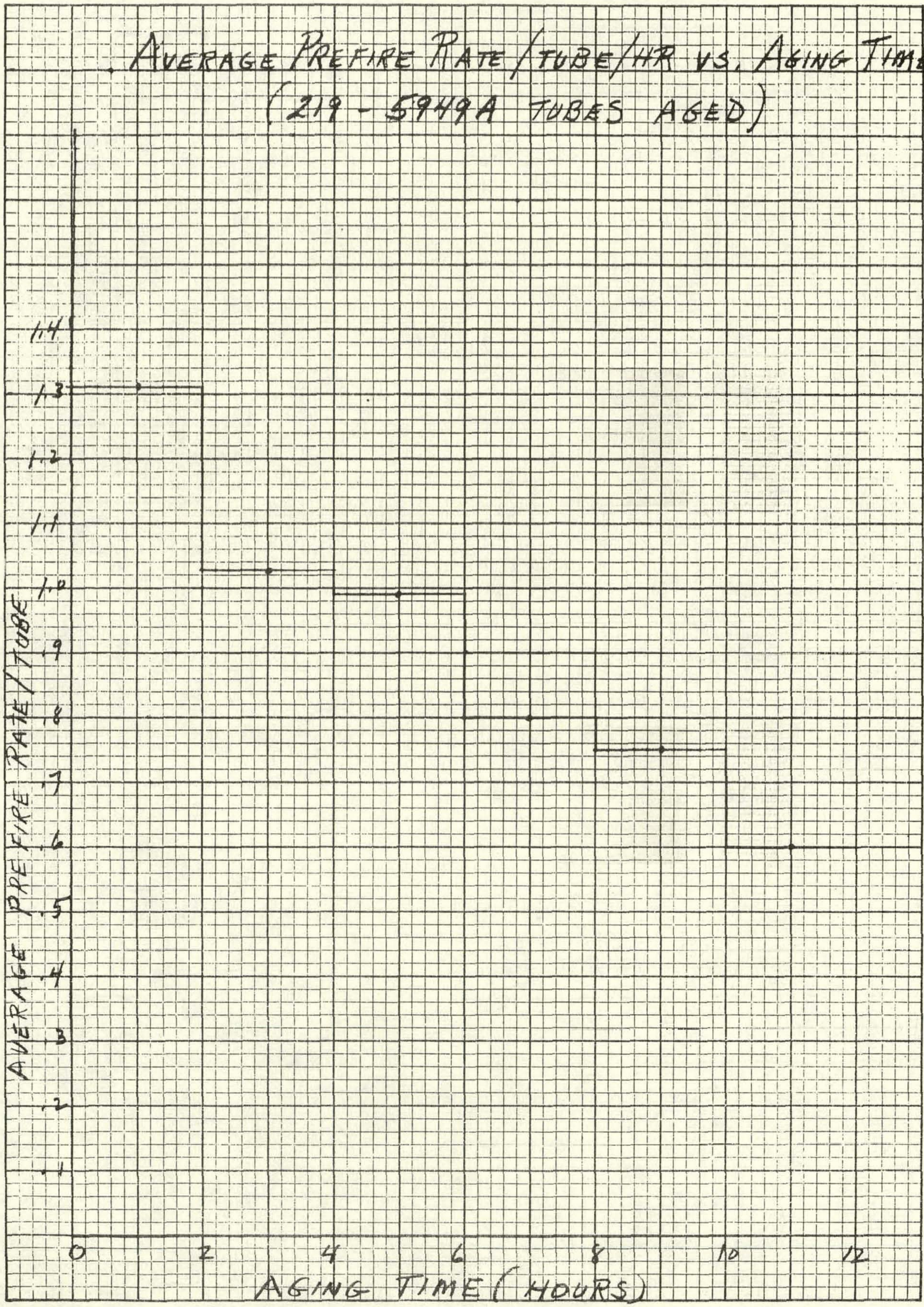
MUL-16867

Fig. 28. Anode delay vs trigger voltage.



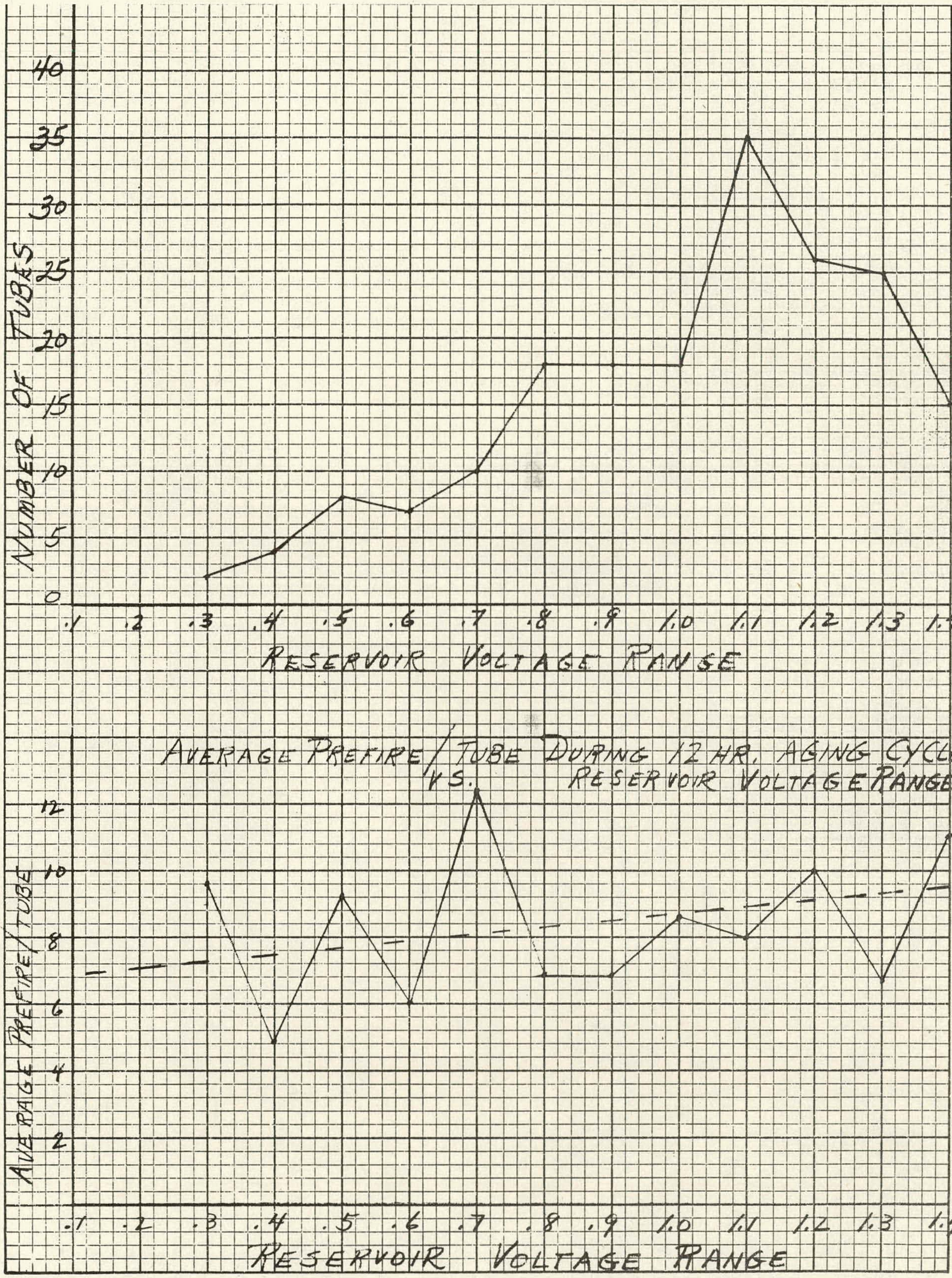
MUL-16863

Fig. 29. Number of tubes vs anode delay.



MUL-16865

Fig. 30. Average prefire rate/tube/hour vs aging time.



MUL-16864

Fig. 31. Top: Number of tubes vs reservoir voltage range.
Bottom: Average prefire/tube during 12-hour aging cycle vs reservoir voltage range.