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LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

DEVELOPMENT OF RELIABLE 20 KV, SIZE A IGNITRONS FOR THERMONUCLEAR RESEARCH

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DEVELOPMENT OF RELIABLE 20 KV, SIZE A IGNITRONS FOR THERMONUCLEAR RESEARCH

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ABSTRACT

On October 21, 1957 a research and development contract was given to the General Electric Power Tube Department at Schenectady, New York. The technical direction was supplied by the Los Alamos Scientific Laboratory. The initial goal of the contract was to develop ignitrons which could be used reliably as high voltage, high current switches in thermonuclear research. Later the contract was directed to develop an ignitron for Zeus. The Zeus application is: $V = 20$ kv, $I_{peak} = 30{,}000$ amperes ringing at 5 kc with an 85% voltage reversal. The General Electric Z-5385 size A ignitron was developed under this contract and meets the Zeus application with a 99.9% reliability factor. During the evaluation of tubes it was shown that cooling the cathode of an ignitron greatly improved the tube's high voltage reliability. The contract was terminated October 31, 1959.

ACKNOWLEDGEMENTS

The authors wish to express their profound appreciation to the people who worked with them at the General Electric Power Tube Department in Schenectady, New York. We would like to single out H. E. Zeuvers, J. L. Zehner and A. F. Juckett for particular thanks.

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A WORD OF EXPLANATION

The size A ignitron is a small tube as power handling tubes go. The 5550 tube is designed to handle 300 kva. Maximum ratings for capacitor discharge service are peak current 500 amps, peak volts forward 6000, peak volts inverse 3000. We have asked this tube to handle 1,200,000 kva, with peak currents of 60,000 amps and forward voltages of 20,000. It is small wonder that these tubes have sometimes failed after a few shots; rather it is astonishing that they functioned in this operation at all.

I. INTRODUCTION

Thermonuclear research requires the production of large magnetic fields and high current discharges. The most common source of energy for this application is a capacitor bank switched with spark gaps or ignitrons. The most efficient use of the capacitors requires a switch capable of reliable operation at the maximum capacitor voltage. In late 1957 the voltage ratings of capacitors far exceeded the abilities of ignitrons. For example, the first ignitron used at Los Alamos was the size A-5550. This tube was used primarily with 20 kv capacitors. Maximum recommended voltage for the 5550 was 6 kv. However, experience showed that this tube would operate with reasonable reliability to about 14 kv.

On October 21, 1957 a research and development contract was given to the General Electric Power Tube Department at Schenectady, New York, to develop ignitrons for application in thermonuclear research. P-Division of the Los Alamos Scientific Laboratory handled the general administration of the contract. Specific technical direction and design evaluation were performed at Los Alamos by personnel in Group W-7, W-Division.

Thermonuclear research at Los Alamos uses capacitors and ignitrons in ringing discharge service. Therefore, it was decided to evaluate all ignitrons in this type of operation. The initial goal of the contract was an ignitron satisfying the following minimum requirements:

1. Reliable operating voltage >20 kv
2. Peak current >10 ka
3. Life >1000 shots

II. EVALUATION TECHNIQUES

Several tests to determine ignitron high voltage characteristics were examined. They were AC Hy-Pot, DC Hy-Pot, Q-Pot and capacitor bank tests.

A. AC Hy-Pot (Fig. 1)

This test applied 18,000 volts rms at 60 cycles across the tube. The leakage current through the tube is measured. A gassy tube is indicated by excessive current. This test tends to "clean up" the tube electrically.

B. DC Hy-Pot

The DC Hy-Pot is the standard manufacturer's high voltage test. When the tube breaks down, only a few milliamperes are allowed to pass. The manufacturers believed that higher currents could damage the tube. Type 5550 tubes on DC Hy-Pot tested from about 30 to 50 kv. Since this ignitron was known to be unreliable above 14 kv, this test was discarded as a measure of quality. The Q-Pot test was devised to replace it.

C. Q-Pot (Fig. 2)

The Q-Pot test is somewhat closer to actual application. It was believed that on a DC Hy-Pot an imminent failure might not become actual due to lack of available charge to develop a cathode spot. The Q-Potter has a capacitor which supplies the necessary charge. It was found that this test did give a more accurate index of tube performance and in general was a measure of the best performance which could be expected from the tube. However, a tube which would Q-Pot to, say, 20 kv would not operate reliably at 20 kv in a bank.

It was noted that the Q-Pot produced a "clean up" in the tube under test. That is to say, the tube would show initial failures at low voltage gradually "cleaning up" to hold 20-30 kv. A graph of this electrical aging process is shown in Fig. 3. The electrical aging tended to standardize the tube for later bank testing.

D. Capacitor Bank Testing

The true quality of a tube is determined by its performance in a bank. Thus the merit of a design was evaluated from its test bank performance.

In the course of testing, four banks, A, B, C, and D, were used. Table I gives the electrical constants of these banks. Bank A was constructed to get an initial feel for tube performance in ringing application. Bank B was constructed to test tubes specifically for Zeus application. The Zeus bank calls for a tube able to hold off 20 kv and to carry 30 ka for a period of approximately 200 μsec. Both banks A and B used 7.5 μf, 20 kv capacitors. Capacitor failures made it virtually impossible to run these banks longer than 50 consecutive shots.

By this time an improved 15 μf, 20 kv capacitor had become available. It was decided to construct a new test bank from these longer lived capacitors. Bank C was designed to roughly double the service needed for Zeus. The capacitors ranged in capacity value between 14.1 and 15.8 μf. Therefore, the capacity of banks C and D has ranged from 115 to 121 μf.

Capacitor life in bank C with its 93% voltage reversal was about 1200, 20 kv shots. Bank D, designed for 85% reversal, extended capacitor life to about 4000 shots. It should be noted that this change from bank C to D changed the capacitor cost per 20 kv shot from about $1.20 to about $0.36.

A block diagram of a test bank showing the layout of the power supply, firing set and basic test circuit is shown in Fig. 4. The operation of the test bank is as follows: The high voltage power supply charges the capacitor bank to a voltage V. When the voltage reaches V, a mercury switch in the recorder is tripped initiating the firing pulse. The ignitron fires discharging the bank. The cycle is then repeated. The recorder provides a record of the voltage at which the tube fired on each shot.

It was discovered early in the work that heating the anode stud of the ignitron while cooling the cathode prior to bank testing made a distinct improvement in the early bank failure characteristic. Mercury globules hanging in the throat of the tube form points of small radius of curvature. These points have high electrostatic fields and cause breakdowns. The mercury is driven away by the heat and is condensed on the cooled cathode where it belongs.

The present order of testing is as follows:

1. The tube is tested on AC Hy-Pot.
2. The tube is put in an 8 hr., 125°C anode stud bake.
3. The tube is tested on AC Hy-Pot to determine if the heating has gassed up the tube.
4. The tube is tested on Q-Pot.
5. The tube is placed in test bank and run.

III. TUBE DEVELOPMENT AND EVALUATION

The development of improved tubes was based on the critical evaluation of previous designs. Critical evaluation included preliminary high voltage testing, bank testing and a post-mortem on the remains. The bank test failure rate was considered the most important figure of merit for a design. A summary of bank performance for the designs tested is given in Tables II and III.

The first tube tested in bank A was a GL-5550. This tube was run at 10 kv bank voltage with a peak current of 36 ka. The tube ran for 1004 shots without a failure. When the tube was cut open two things were noted: The ignitor support was badly damaged (Fig. 5) and a carbon deposit appeared on the glass pantleg in the throat of the tube. The resistance from the pantleg to the cathode was 2 megaohms.

This initial test indicated that our test voltage was too low. It was decided to raise the voltage for subsequent tests.

Visual observation made while Q-Potting the 5550 indicated that breakdown occurred in the throat of the tube. The Z-5282 was built with a ceramic sleeve around the anode stud to prevent this breakdown. Two tubes of this type were received from General Electric Company. The Q-Pot data on both indicated that they were certainly no better than the 5550. One of the tubes was run in bank A at 15 kv and a peak current of 54 ka. The analysis of the recorder chart showed 197 failures below 15 kv in the first 526 shots and all subsequent shots were failures until the tube was removed at 658 shots.

The next four tubes were tested at 20 kv in bank B. They were a General Electric Z-5253, a General Electric Z-5280, a Westinghouse WX-3815 and a GL-5550. The Z-5253 was a 5550 design with special high vacuum processing during manufacture. It was run about 200 shots and had a failure rate of 18.7%.

The Z-5280 was the first attempt to change the configuration in a size A ignitron (Fig. 6). This design featured an enlarged glass seal, upper and lower static shields and a semi-contoured anode. The static shields were designed to optimize the throat spacings with respect to Paschen's Law. Pachen's Law is an emperical law relating breakdown voltage with the product pressure times electrode spacing. The tube which was tested was poorly made with some obvious sharp corners. It showed a failure rate of 32% in 400 shots. The tube died after 400 shots, i.e., it was not able to reach 20 kv again.

The Westinghouse WX-3815 was an improved 5550 similar to the Z-5253. The tube had only 16 shots at 20 kv. It collapsed at 40 shots (all shots were failures below 10 kv).

The GL-5550 was tested to establish a base line on the performance of the standard commercial tubes. It had only 11 shots at 20 kv but occasionally reached 18 kv beyond 400 shots.

Bank C was put into operation at this time. The first three General Electric tubes tested in this bank were a 5550, a Z-5253, and a Z-5280. All had a failure rate above 50% and a life of less than 125 shots.

Four tubes of National Electronics type NL-1333 were tested. This tube was designed to compete with the Z-5253 and the WX-3815. The four had failure rates greater than 50% and lifetimes between 50 and 125 shots.

Two National NL-1338's were tested. This design had a shaped anode. Their failure rates were 0 and 4.9% but their lifetimes were 31 and 41 shots respectively.

Eight Westinghouse WX-3943 tubes were then tested. The WX-3943 design featured a higher temperature (for Westinghouse) vacuum bake of the carbon anode prior to fabrication. More gas was driven from the carbon and a cleaner tube resulted. Life of the group ranged between 19 and 28 shots with an average of 23 shots. Two of these tubes failed because the anode stud melted through.

It should be emphasized that bank C pushed 59 ka through the tubes with a voltage reversal of 93%. The tube was the main resistance in the circuit and dissipated most of the bank energy in the form of heat. The wall temperature of the tube rose to over 200°F. With the hearty approval of the General Electric engineers, it was decided to try cooling the cathodes during operation. A copper cooling block with circulating water was attached to the cathode of the tubes.

Four more WX-3943 tubes were then tested with cooling. The cathodes were at roughly 20°C. The results were as follows:

Tube	Shots	Breakdown Failures	Cause of Ultimate Failure
WX-3943-1	406	7	Anode stud melted off
WX-3943-2	22	3	Anode stud melted off
WX-3943-3	230	3	Anode seal glass cracked
WX-3943-4	126	11	Anode seal glass cracked

The WX-3943 design was fairly standard and its uncooled performance in the bank was not outstanding. The effect of cooling is dramatically shown by the comparison of cooled and uncooled life. Later tests showed that high voltage breakdown failure rates were decreased a factor of 10 by cooling. Subsequently, all testing was done with cooled cathodes except where noted.

The bank test was reappraised at this time. It was decided to reduce the bank voltage reversal to 85%. (Bank D, Table III). This had two effects: It lowered the power dissipated in the tube and extended capacitor life as noted earlier. All remaining tests except 30 kv runs were done on bank D.

Westinghouse WX-3904B

The Westinghouse WX-3904B is similar to the General Electric Z-5380. It has shaped static shields and a contoured anode designed to conform to Paschen's Law. Five tubes were tested, one on bank C (Table II) and four on bank D (Table III). Their failure rates ranged from 10% to 17% with a life of less than 1000 shots. The WX-3904B showed a peculiar characteristic not exhibited by the Z-5280. The Westinghouse tube tended to have failures at very low voltage, less than 1 kv, following a 20 kv firing. All five tubes showed this. The high failure rate of the WX-3904B showed them to be unsuitable for Sherwood use.

National-1333

This type was tested uncooled in bank C. Tests were made on three cooled tubes. The cooled tubes showed an average failure rate of 12% with a short life and were judged unsuitable.

General Electric Z-5280

Another Z-5280 was run cooled. This tube's uncooled performance has already been mentioned. Its failure rate dropped from 32% uncooled to about 6% cooled. After the first 200 shots, the failure rate dropped to 3%. The tube was run over 1000 shots. Since Zeus bank operation requires a failure rate of less than 0.1%, further bank testing of this type was discontinued. Q-Pot tests were continued but definitely showed that the tube did not live up to theoretical expectations.

Westinghouse WX-3962

In tests of the WX-3943, anode stud melting had been encountered. The Westinghouse WX-3962 had an enlarged anode stud, otherwise it was the same as the WX-3943. This tube was run in the bank for 1179 shots and showed a total failure rate of 2.2% and a 1% failure rate after a 44 shot break-in period. However, attempts to test two more tubes of this type failed. One tube became too gassy to hold voltage after the anode bake. The second tube arced over the anode seal a number of times while in the bank, and it became impossible to tell which shots were internal failures and which external. These tubes did not have potting around the anode seal and an external breakdown was not considered a tube failure.

General Electric GL-7171

The GL-7171 is a clean 5550 without a glass pantleg in the throat. Three tubes of this type were tested with the following results:

	Total Shots	Percent Fail Total	Percent After Break-In
1.	261[x]	12.2%	6%
2.	1059[t]	1.5%	0.5%
3.	1052[**]	1.7%	1.2%

[x] Tube was good to shot 206, then was off four days; no good when testing was resumed.

[t] Still good.

[**] Tube was good to shot 1042, then went sour.

General Electric Z-5333

The Z-5333 was made with a semi-contoured anode, an integral static shield, and an enlarged and elongated throat. It was hoped that some of the benefits of an improved Paschen's Law configuration could be realized in an economical design. General Electric engineers added the elongated seal for manufacturing reasons. Under bank test all these tubes became gassy and investigation revealed that the glass throat was crazed and cracked. A probable explanation is that long path discharge, as predicted by Paschen's Law, occurred across the seal. Since other designs were showing promise no short seal modification was tested.

General Electric Z-5349

The General Electric Z-5349 was the same as the Z-5333 except that it was equipped with a ground plane design. The ground plane in this case was an extension of the cathode body of the tube up past the glass seal. The intent was to keep the electric field lines radial by terminating them on the ground plane rather than being concentrated at the metal in the metal glass seal (Fig. 7). Since the Z-5349 had the same long throat as the Z-5333, it suffered from the same glass crazing and cracking. Therefore, the ground plane idea also lacks experimental evaluation.

Westinghouse WX-3993A

The Westinghouse WX-3993A is the same physically as the WX-3962. The carbon anode in the WX-3993A had been subjected to a higher temperature vacuum bake than was the case for the WX-3962. Bank tests showed no real difference in performance from the WX-3962 and the WX-3943.

National 1471A

The National 1471A differs from the National 1338 only in that the carbon anode has been subjected to a higher temperature vacuum bake. Tests showed that this tube type had a failure rate of approximately 0.6% but that the life of the tube was decidedly below the required 1000 shots.

General Electric Z-5329 (Fig. 8)

This design was suggested by the engineers at General Electric. It employed a double pantleg glass insulator in the throat of the tube. This design has proven successful in hydrogen thyratrons.

Bank tests at LASL showed that the failure rates were not as good as the GL-7171; however, there was one very encouraging peculiarity. The Z-5329 did not show the usual initial break-in failures all other tubes had shown. The original design of the Z-5329 had a hollow anode stud with holes to allow better outgassing. It was believed that the higher failure rate could be explained by mercury vapor boiling out of the holes and changing the conductivity of the anode cathode space. Mercury vapor would enter the stud while it lay idle overnight and come out when testing was resumed the next day. Elimination of the hollow stud did indeed cut the failure rate down to the range 5% - 0.5%. The Z-5329 had a shortened body; the body was lengthened to the dimension used in the 5550, in hopes that this would cut the failure rate still more.

General Electric Z-5329A

The Z-5329A was the lengthened Z-5329. Two of these tubes were tested. They showed failure rates of 0.6% and 0.8%, not significantly different from most of the solid anode stem Z-5329's.

General Electric Z-5329C

The next modification was to slope the top of the anode to facilitate the removal of mercury droplets from the anode. This tube was the Z-5329C. The tube ran with a failure rate of 2%.

General Electric Z-5328

The Z-5328 was the same as the Z-5329 but it had no potting on the anode seal. Bank tests showed it to be electrically equivalent to the Z-5329 but the glass had to be covered with apiezon to prevent external breakdown.

General Electric Z-5328A

The Z-5328A had a small ring of potting around the base of the anode seal. It was found that this did not provide sufficient protection against external breakdown at the altitude of Los Alamos. At this time it was decided that only a potted tube would be feasible at Los Alamos.

The double pantleg design was closely evaluated for several reasons. It gave very encouraging data on the Hy-Pot and Q-Pot tests. It always began its bank life test without a series of initial breakdowns. Its life was very good and its failure rate constant throughout the run, although much too high for use in large banks.

Several tubes of this type were cut open after testing. A black conducting deposit was observed on the inner pantleg. It was conjectured that this deposit was carbon knocked off the anode during the discharge. General Electric made flux plots that showed such a deposit would spoil the good high voltage characteristics of the double pantleg.

General Electric Z-5382

This tube had a metal sputter shield attached to the outer glass pantleg to prevent material from depositing on the interior of the insulator. One tube was run and showed a failure rate of 20%.

General Electric Z-5385

The Z-5385 has the same configuration as the Z-5329, but the anode is made of molybdenum. Molybdenum was used because it is highly refractory, has few impurities after refinement and is less damaged by arcs. The first tube of this type ran

6803 shots with only one failure. Present data show that the Z-5385 averages less than one failure per 5000 shots in bank D. This tube is being installed in Zeus.

General Electric Z-5384

The Z-5384 was the same as the Z-5385 except that the anode was titanium instead of molybdenum. This was an attempt to reduce the cost of the tube. The first Z-5384 was run 5010 shots and showed four failures, all at 19.9 kv. The second tube showed no failures in 1010 shots. The four failures on the first tube indicated that titanium was not quite as good as molybdenum. The titanium used was not as pure as the molybdenum. The cost of purer titanium is about the same as molybdenum so investigation of titanium tubes was discontinued.

General Electric Z-5389

The Z-5389 was another attempt to reduce tube cost. It used the 5550 configuration with a molybdenum anode. The first tube of this type showed no failures in 1000 shots while the second had only one. However, the third had 24 and the fourth 79 failures through 1000 shots. The last two were cut open and shown to have exposed threads at the anode-anode stud junction. More tubes of this type were ordered from General Electric. One more was run at 20 kv with such a poor performance that the test was discontinued after 500 shots. Comparison tests at 30 kv have shown that the Z-5389 is inferior to the Z-5385.

General Electric Z-5399

The Z-5399 represents another attempt to reduce the cost of the double pantleg metal anode tube. The Z-5399 is the same as the Z-5385 except it has a stainless steel anode instead of molybdenum. Three of these tubes were tested. Data show that this type, while not good enough for Zeus bank operation, is far superior to carbon types. It could be used for smaller banks.

Westinghouse WX-4138

By the time, word of the success of metal anode tubes had spread throughout the industry and Westinghouse entered the WX-4138. The WX-4138 was a standard configuration tube having a sintered molybdenum anode. Two of these tubes became gassy on bake out. The gas may have been caused by failure to outgas the sintered molybdenum anodes sufficiently. The two tubes run in the bank performed well with respect to high voltage failure but not as well as the Z-5385 type. However, the ignitors of WX-4138's were so wetted by mercury during the test that the tubes sometimes failed to fire.

National 1640

The National Electronics type NL-1640 had the same configuration as the NL-1338, but the anode was sintered molybdenum. These tubes had a higher percentage of high voltage breakdowns than the Z-5385; their life was short and their anode stem threads tended to melt.

General Electric Z-5393

The Z-5393 is a Z-5389 configuration with a titanium anode. One model was tested. This tube confirmed both the inferiority of impure titanium and the Z-5389 configuration. It showed a failure rate of 7%, by far the worst performance of a General Electric metal anode tube.

General Electric Z-5414 and General Electric Z-5415

The Z-5414 and Z-5415 were tubes similar to the Z-5389 but having a 1/4 in. radius at the base of the throat. The Z-5414 had a molybdenum anode and the Z-5415 a stainless steel anode. The two 14's and one 15 were tested. Failure rates were high and life short.

Bank Testing at Voltages Higher than 20 kv

The upper limit of the type Z-5385 had not been reached at 20 kv, so a new bank was built to operate at higher voltages. The bank used a series parallel hookup of 20 kv, 15 μf capacitors. The electrical constants were:

$C = 30\ \mu f$

$T = 195\ \mu sec$

$V_{max} = 40$ kv

$I_{peak}(30 \text{ kv}) = 29$ ka

Voltage reversal = 96%

No attempt was made to reduce the voltage reversal. This tended to heat the tube under test much more than would be reasonable in actual service. Two Z-5389's were run at 30 kv in this bank. Their failure rate was high (18% and 17%) and their life short, about 200 shots. A Z-5397 tube, similar to the Z-5385 but having a longer anode cathode spacing, was run 1014 shots in this bank; its failure rate was 1.5%. A Z-5385 was run in the 30 kv bank for 1000 shots. This tube showed a failure rate of 1.2%. The same 5385 was subsequently run in the 20 kv bank for another 1000 shots and showed no failure.

IV. DEVELOPMENTAL WORK ON OTHER THAN SIZE A IGNITRONS

General Electric Z-5355

Ignitrons are often used to short-circuit the load current and minimize the ringing of the bank. Figure 9 shows a typical circuit and current waveforms in the circuit. The crowbar tube S-2 is turned on at the start of the second quarter cycle and keeps the current in the bank from reversing. In this service the tube must withstand high inverse voltage and carry unidirectional current for a relatively long time. When a tube carries current for times of the order of milliseconds, the arc transfers from the mercury pool to the metal wall. If the arc rests too long on the wall it will burn through, destroying the tube. One method of preventing this is to use a nonconducting wall.

The Z-5355 is a ceramic walled tube with a titanium anode and a dielectric starter. The dielectric starter works as follows: A fast-rising high voltage pulse is applied to one side of a dielectric, a high field is produced on the other side and if mercury is in contact with this side a cathode spot is formed.

Two of these tubes have been tested. The first one withstood fifty 20 kv, 30 ka shots before shorting out. Investigation revealed that the wall was coated with metal reduced from the ceramic wall. The second tube was made from an improved ceramic. This one required only four shots in bank D to kill it. However, there is some evidence that ceramic tubes may prove very effective for voltages in the 50-100 kv range at reduced currents.

V. HIGHER VOLTAGE TUBES

Cavity Grid Tube (Fig. 10)

The need for higher voltage switches prompted the investigation of the cavity grid tube. The cavity grid is modeled after high voltage thyratrons. These tubes rely on a region of ionization between the grids to give fast, low jitter current rise and use the anode-grid and grid-cathode regions to hold off the required voltage.

A demountable cavity grid tube has been under test at General Electric, Schenectady. The tube does not operate as a cavity grid, i.e., there is no evidence of ionization in the center cavity. This is probably due to the low gas pressure in the tube relative to the pressure in a hydrogen thyratron.

However, it does act as a conventional gradient grid, the potential being divided by the interelectrode capacities. The tube has been fired several times at 32 kv carrying 32 ka. Pitting on the graphite electrode was evident and carbon deposits made the glass conducting. The electrodes were replaced with stainless steel. Further tests showed the tube to be reliable up to 65 kv.

"Stacking" is another approach to a high voltage tube hold off. Here two or more ignitrons would be stacked in series to obtain higher voltage hold off. It should be noted that the Z-5385 is capable of use at, at least, 30 kv under quite severe current conditions. Two Z-5385 tubes were stacked and operated for 100 shots with 30 kv across one and 50 kv across the other. These were low current shots but the experiment gives an indication of a promising field for development.

VI. HIGH PRESSURE TUBES

An experiment to test the feasibility of using high pressure as a means of obtaining high voltage dependability was carried out at General Electric. A Z-5329 type tube was fitted with a tubulation and argon was admitted to pressure up to 110 psi. The result was a Paschen's Law breakdown characteristic but at too low a voltage for practical use. It was noted that the tube could not be fired with the ignitor.

VII. JITTER

At the start of the contract work it was believed that jitter should be improved. However, the development of a reliable 20 kv tube had first priority and since Zeus bank operation did not require a better jitter characteristic, little was done to improve it in a concrete way.

Early in the testing program. jitter measurements were made on a number of GL-5550 tubes using triggering equipment of the type then in current use in Sherwood. These measurements showed that an improved jitter characteristic was obtained with higher voltage ignitor pulses and higher anode voltages. Later measurements indicated that part of the measured jitter is due to less than optimum design in the firing circuits. Measurements at General Electric have shown that a dielectric starter ignitor fires on rate of rise. Since these starters have low capacity, fast rates of rise can be easily obtained. Therefore theoretically a tube employing a dielectric starter would have low jitter.

VIII. IGNITOR WETTING

A triggering problem has developed in regard to the metal anode tubes. With use the resistance of the ignitor in these tubes drops to very low values, in some cases to zero. It appears that metal from anode or wall deposits on the ignitor and then this metal is wet by the mercury. No triggering trouble was experienced with General Electric tubes, if they were not moved from their original installation positions. However, if the tubes were shaken severely the ignitors shorted out.

Several designs were fabricated at General Electric to combat this problem. The first approach was to groove the standard ignitor. The second design featured a bonnet over the ignitor and the third design used the grooves with the bonnet. Tests on the simple grooved ignitor (Z-5385-1) and on the grooved ignitor with a bonnet (Z-5385-3) showed that these designs did not solve the wetting problem.

It should be noted that the tubes presently installed in Zeus show no indication of ignitor wetting after 1000 shots. The ignitor wetting problem does not appear to be a serious problem at peak currents of 30,000 amperes with 85% voltage reversal.

IX. SERIES-CROWBAR TUBE

Design studies are being carried out on a combination series-crowbar tube. This tube would utilize separate anodes and a common cathode pool. One model has been built and awaits evaluation.

X. CONCLUSION

Los Alamos began to use small ignitrons for capacitor bank switches soon after controlled fusion research began in 1951. However, the operating characteristics and limitations of ignitrons in this application were not investigated until this contract was initiated. It was quickly established that the size A ignitron was satisfactory at 10 kv but the upper limit was less than 15 kv. Since the most reliable capacitor available at that time was rated at 20 kv that voltage was chosen as the first goal. Typical bank application dictated a peak current rating of more than 10,000 amperes ringing with an 85% reversal.

All ignitron manufacturers improved the performance and reliability of their Sherwood ignitrons by better processing at manufacture. Early testing showed that the ignitor support was directly in the arc stream and would eventually be eroded away. Its relocation contributed to longer life of ignitrons in this service.

One perennial problem of ignitrons is the identification of bad tubes before they are put into service. The Q-Potter has proven to be the most reliable test so far developed for preliminary evaluating of ignitrons.

Cathode cooling gave the first dramatic improvement of ignitrons in Sherwood application. Cooling raised the reliable operating voltage by several kilovolts and increased the average life of all tubes. Cathode cooling lowers the gas pressure by removing heat from the walls. It also provides a proper place for the mercury to condense, keeping it out of the critical throat region. Cathode cooling should be standard practice for best operation of ignitrons in capacitor bank application.

The metal anode design, which was developed under this contract, has been the most rewarding improvement in the development of ignitrons for capacitor bank application. It was always appreciated that the carbon anode was an excellent sink for residual gases but experience in the early 1930's had shown that metal anode tubes had short lives. Of course these ignitrons were used in 60 cycle rectifier service. The metal anode was initially an attempt to sustain the excellent early performance of the double pantleg design.

The first Z 5335 ran for 7000 shots at 20 kv passing a peak ringing current of 59,000 amperes and had one probable prefire. It was still good when it was removed from testing. This tube marked the beginning of a series of old designs with metal anodes.

Subsequent tubes have proven that the first tube was no fluke. The Z-5385 has proven reliable with and without cooling at 20 kv. It operated with a low failure rate at 30 kv with only moderate cathode cooling. It performed satisfactorily at 20 kv uncooled passing a peak ringing current of over 300,000 amperes. Two tubes were stacked in series and withstood 100 kv in a pulse charged capacitor discharge test. In the test bank evaluation of 20 kv and 59,000 amperes the Z-5385 has proven to have approximately one prefire per 5000 shots. At the present time over 300 Z-5335's are installed in Zeus. One hundred and twenty eight of these tubes in parallel have consistantly operated at 20 kv with less than one prefire per 100 shots. The Z-5385 is the most expensive but the most reliable ignitron tested at this laboratory to date.

The Z-5385 is an expensive design for two reasons. The vacuum melted molybdenum anode is an expensive material and the double pantleg glass throat is quite complicated.

Several attempts were made to lower the cost without sacrificing performance. The anode material was changed to titanium in the Z-5384, to stainless steel in the Z-5399 and to sintered molybdeunum in some open throat designs from other manufacturers. The titanium apparently was too impure for use in ignitrons. Acceptable titanium is as costly as molybdenum. The stainless steel showed some promise and may be adequate for a less severe application. However, it did not perform as well as the Z-5385 in our tests. The sintered molybdenum anode in a standard throat design was tested and proved unsatisfactory.

The Z-5389 had a standard open throat with a molybdenum anode. It was definitely inferior to the Z-5385. The Z-5414 with a modified open throat and a molybdenum anode proved unsatisfactory in our tests.

All metal anode tubes were evaluated under identical conditions except special tests of the Z-5385. It must be emphasized that these conclusions are for tubes tested at 20 kv, in the series ringing application passing 59,000 amperes peak current. The Z-5389, Z-5399 and possibly the Z-5414 may perform satisfactorily at a lower peak current or at lower voltages. Our tests show that we have yet to learn the ultimate performance for the Z-5385.

The contract was used to investigate several other approaches to Sherwood ignitrons. Three ceramic wall ignitrons were made. While they proved unsuccessful in the tests, they do suggest several interesting designs. The multi-stage cavity grid tube has not been evaluated but its early performance at holding off 100 kv is significant. The unusual rectifying property of metal anode ignitrons has been applied in one experiment to decouple a capacitor bank from the load after passing over 7000 amperes in the forward direction. This characteristic of metal anode ignitrons could lead to uni-directional switches. The ignitor wetting problem with metal anode tubes could prove serious in some severe applications. Dielectric starters for this application may be necessary and possibly more desirable than the present ignitor.

CTU 80252 was directed to develop a 20 kv ignitron for Sherwood application. That has been accomplished. A number of other new ideas were investigated. Future work will evaluate the significance of these ideas.

TABLE I

Characteristics of Test Banks

	A	B	C	D
Capacity µf (average)	195	60	118	118
Period µsec	344	200	250	250
Maximum voltage kv	20	20	20	20
Maximum current ka	72	39	59	59
	(36 ka at 10 kv) (54 ka at 15 kv)			
Voltage reversal	90%	88%	93%	85%
Rep rate per hour	30	60	60	60

TABLE II

Test Data Banks A, B, and C

Tube Type	No. Tested	Best Life	Worst Life	Failure Rate Percent			Voltage of Test	Total Shots [β]
				Best	Worst	Ave.		
				Bank A				
GL-5550	1	S.G.[t]				0	10 kv	1004
Z-5282	1	440				29	15	658
				Bank B				
Z-5253	1	S.G.	S.G.			18.7	20	193
Z-5280	1	375	375			61	20	596
GL-5550	1	32	32			65	20	541
WX-3815	1	21	21			14.3	20	130
				Bank C (Uncooled)				
Z-5253	1	126	126			42	20	211
Z-5280	1	15	15			33	20	239
GL-5550	1	23	23			35	20	218
WX-3904B	1	15	15			13.3	20	207
WX-3943	8	47*	22	14	45	27	20	955
NL-1333	4	125	50	33	60	47	20	868
NL-1338	2	41	31	0	4.9	2.5	20	252
				Cooled				
WX-3943	4	403	22	1.8	9.1	5.8	20	806

* Run at slow repetition rate

t S.G. Still good

β Total shots includes shots on tubes after tubes were considered dead

TABLE III

Test Data Bank D

Tube Type	No. Tested	Best Life	Worst Life	Failure Rate Percent Best	Failure Rate Percent Worst	Failure Rate Percent Ave.	Voltage of Test	Total Shots β
				Bank D Cooled				
Z-5280	1	S.G.[t]	S.G.			5.8	20 kv	1012
Z-5328	8	S.G.	30	0.56	13.3	5.8	20	6602
Z-5328A	4	S.G.	227	5.7	26	15.2	20	2909
Z-5329	10	S.G.	12	0	36	8.9	20	8708
Z-5329A	2	S.G.	S.G.	0.63	0.8	0.72	20	2118
Z-5329C	1	365	365			1.9	20	404
Z-5333	5	108	73	2.6	6.3	4.3	20	544
Z-5349	4	102	83	1.2	8.8	4.2	20	402
Z-5382	1	S.G.	S.G.			20	20	1079
Z-5384	2	S.G.	S.G.	0	0.08	0.04	20	6020
Z-5385	8	S.G.	S.G.	0	0.2	0.02	20	14004
Z-5385-1	1	S.G.	S.G.			0.1	20	1052
Z-5385-3		S.G.	S.G.			0	20	1063
Z-5389	5	S.G.	498	0	7.5	3.2	20	4731
Z-5393	1	S.G.	S.G.			7.3	20	1000
Z-5397	1	S.G.	S.G.			52	20	956
Z-5399	3	S.G.	S.G.	0.097	0.49	0.36	20	5346
Z-5414	2	778	211	9.3	13.3	11.3	20	1113
Z-5415	1	150	150	No fail in 150 shots			20	210
GL-7171	3	S.G.	205	1.5	12.2	5.1	20	2372
WX-3904B	3	906	107	10.3	17.2	13.1	20	2340
WX-3943	1	935	935			2.6	20	949
WX-3962	1	S.G.	S.G.			2.2	20	1179
NL-1333	3	600	227	5.8	15.4	11.8	20	2100
NL-1471A	3	689	568	0.6	0.9	1.4	20	2099
NL-1640	3	S.G.	67α	0	3.0	1.7%	20	1934
WX-4138	2	S.G.	S.G.	0	.3	.15	20	2000
WX-3993A	2	S.G.	S.G.	2.7	2.7	2.7	20	2001

TABLE III
(continued)

Test Data Bank D

Tube Type	No. Tested	Best Life	Worst Life	Failure Rate Percent Best	Failure Rate Percent Worst	Ave.	Voltage of Test	Total Shots β
				Bank D (uncooled)				
Z-5385	3	S.G.	S.G.	0.07	0.65	0.34	20	3135
Z-5389	2	230	53	0	2	1	20	417
Z-5393	1	591				6.7	20	623
Z-5397	1	S.G.	S.G.			8.9	20	993
Z-5399	1	S.G.	S.G.			0.093	20	1072
WX-4138	2	S.G.	928	0.32	2.5	1.4	20	1926
NL-1640	1	S.G.	S.G.			1.7	20	982

t S. G. Still good

α Tube with worst life also had best failure rate, its anode melted off

β Total shots includes shots on tubes after tubes were considered dead

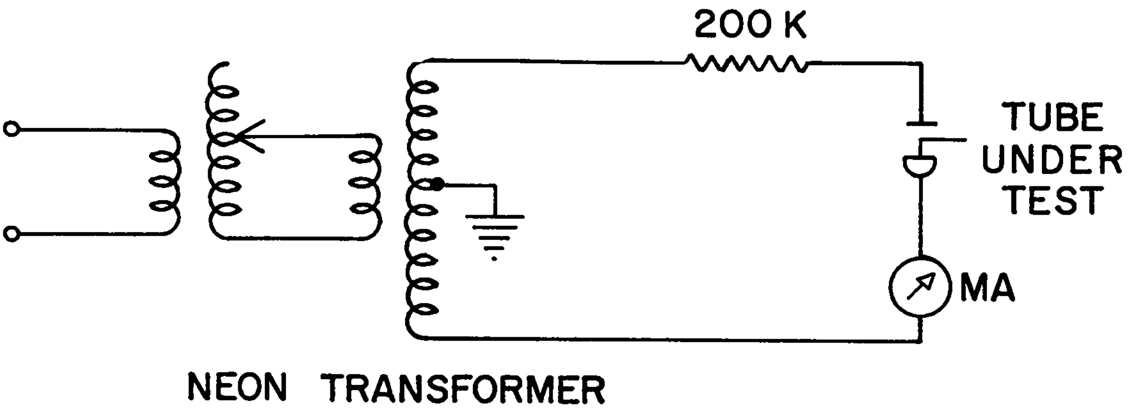


Fig. 1. AC Hy-Pot circuit

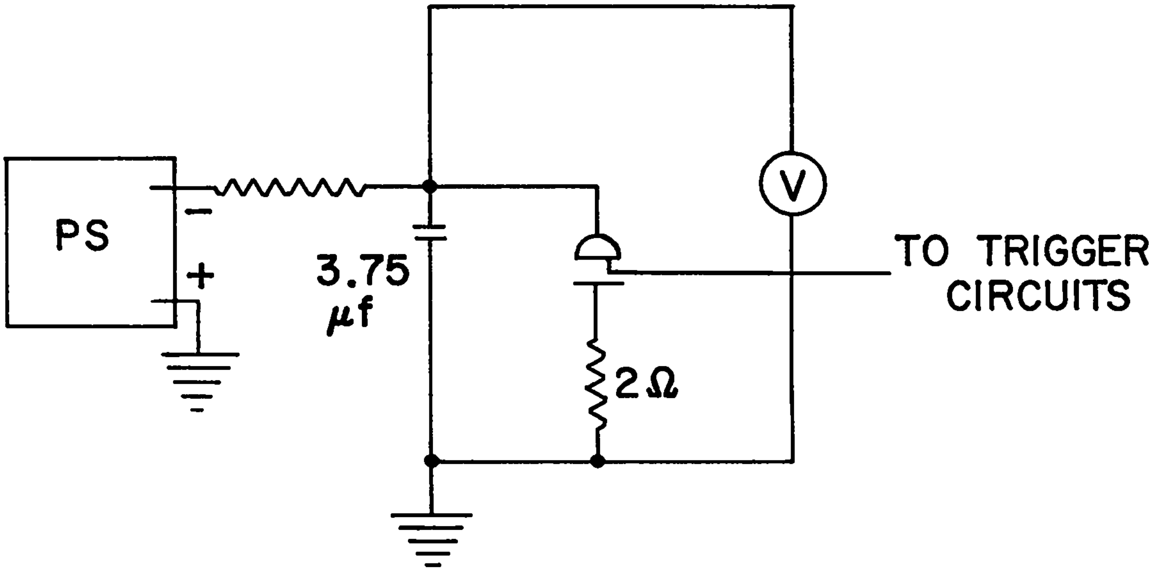


Fig. 2. Q-Pot circuit

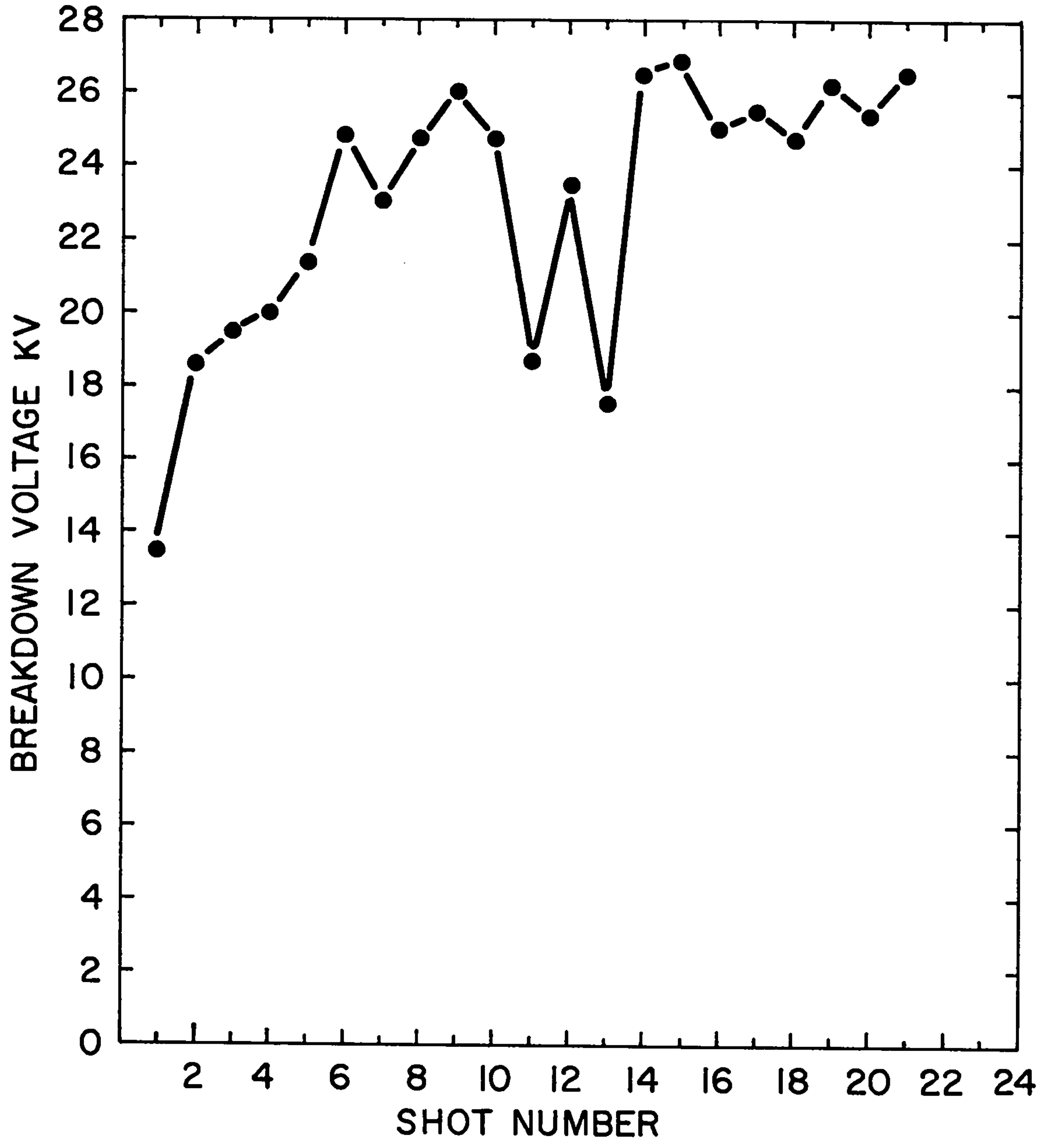


Fig. 3. Typical Q-Pot data plot

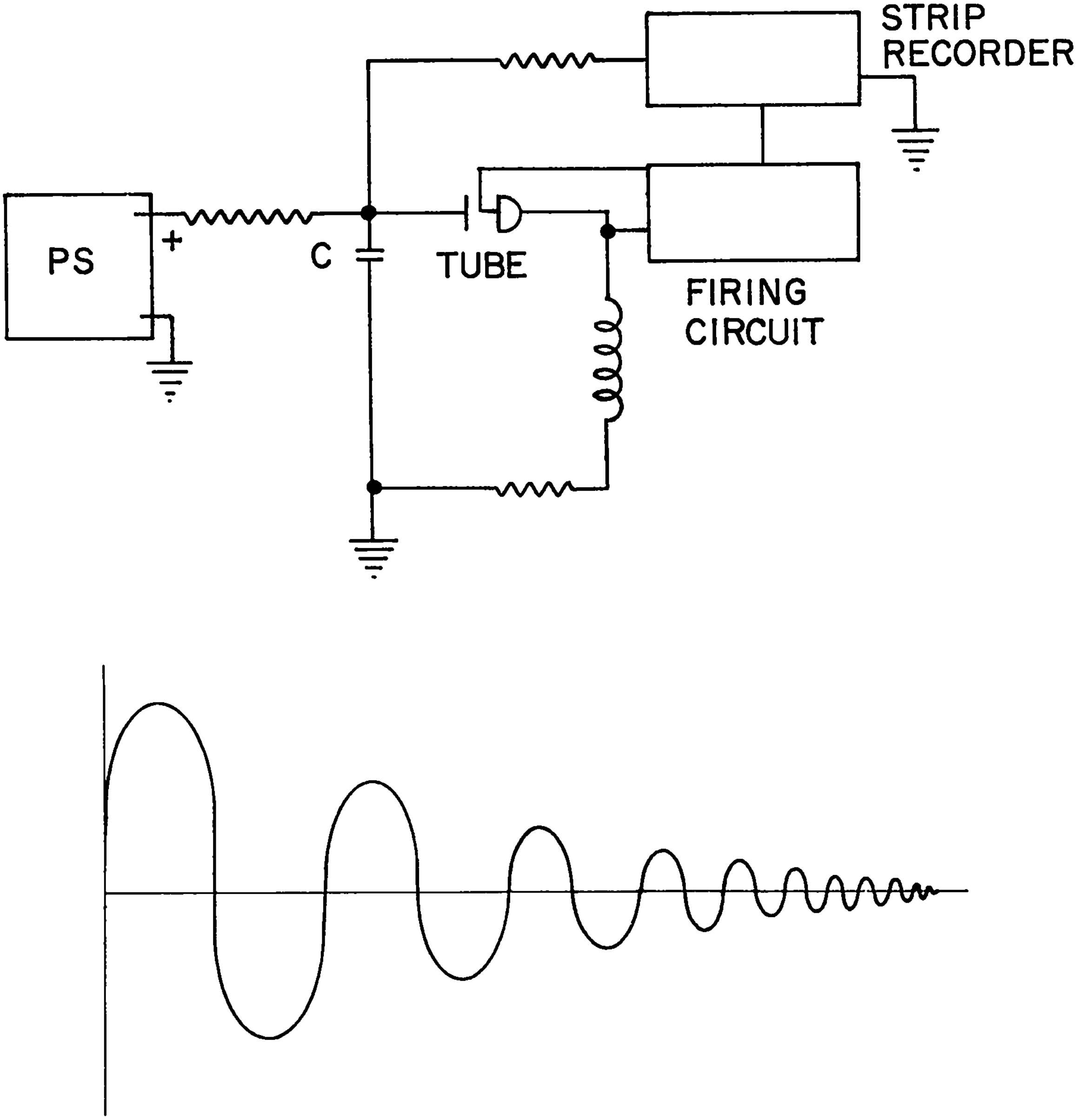


Fig. 4. Test bank and test bank current

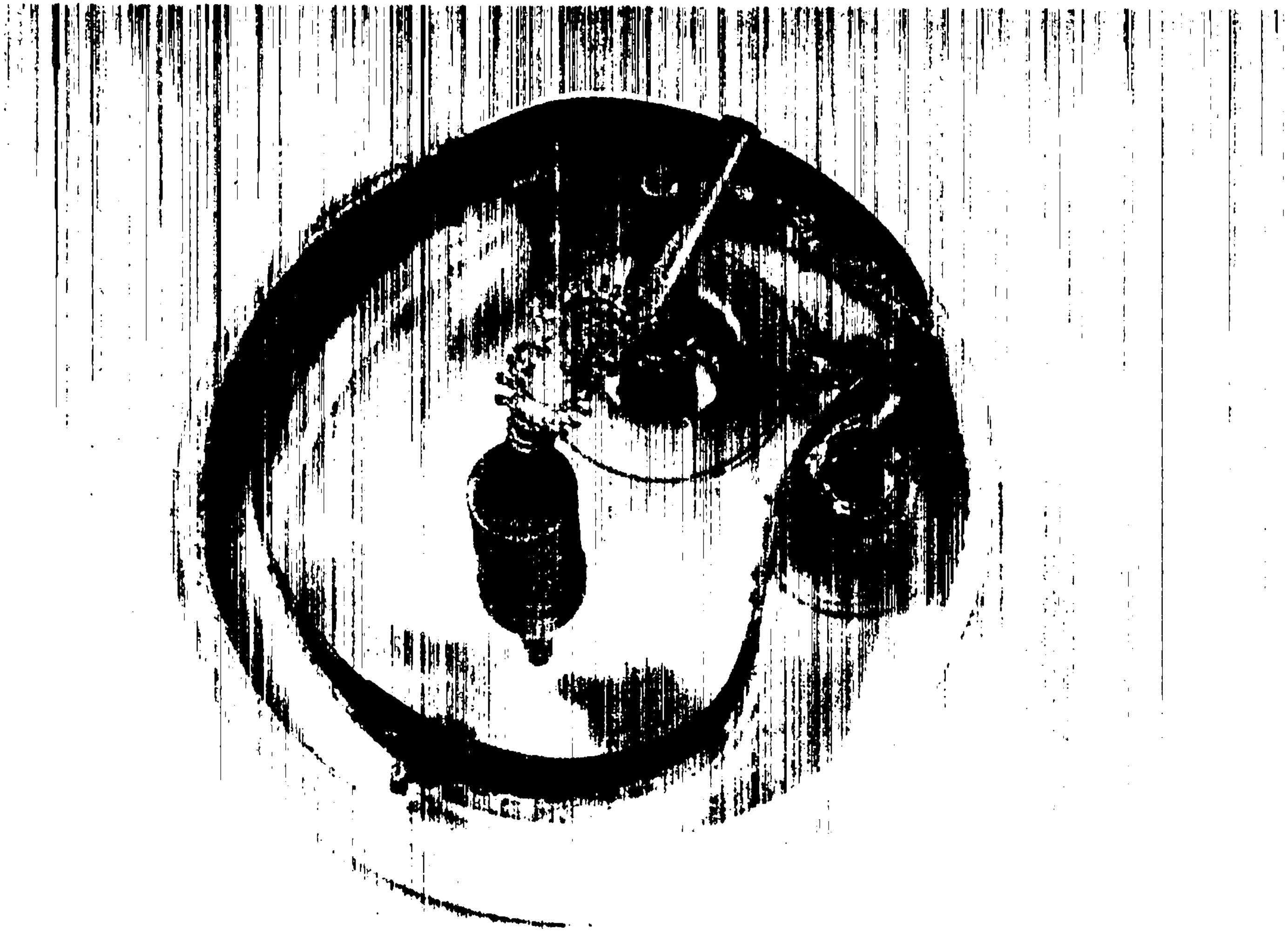


Fig. 5. Ignitor structure damage on a GL-5550

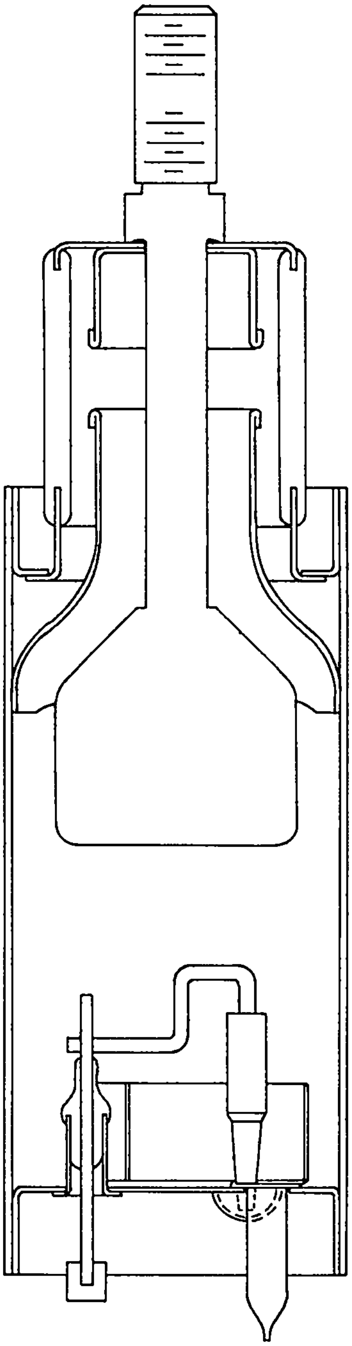


Fig. 6. Z-5280 outline

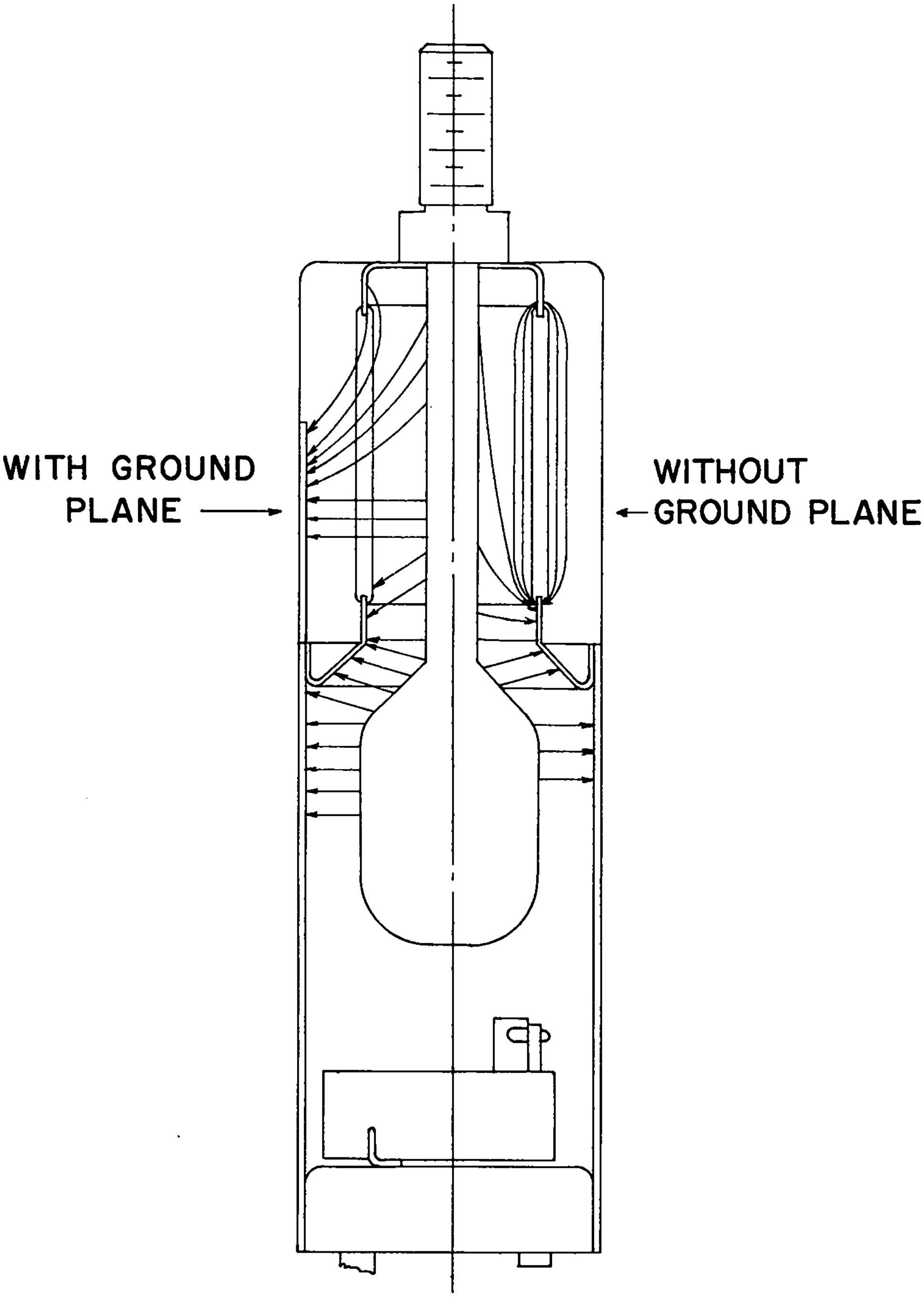


Fig. 7. Flux plots with and without ground plane

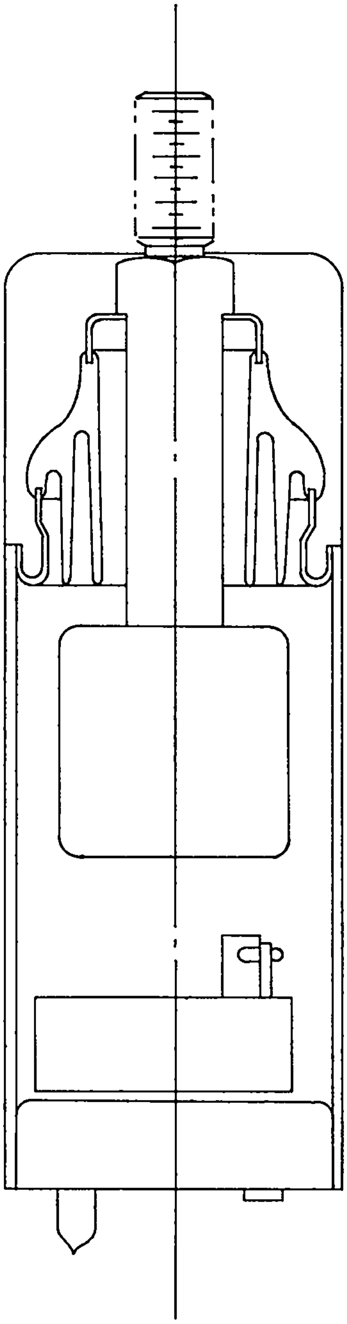
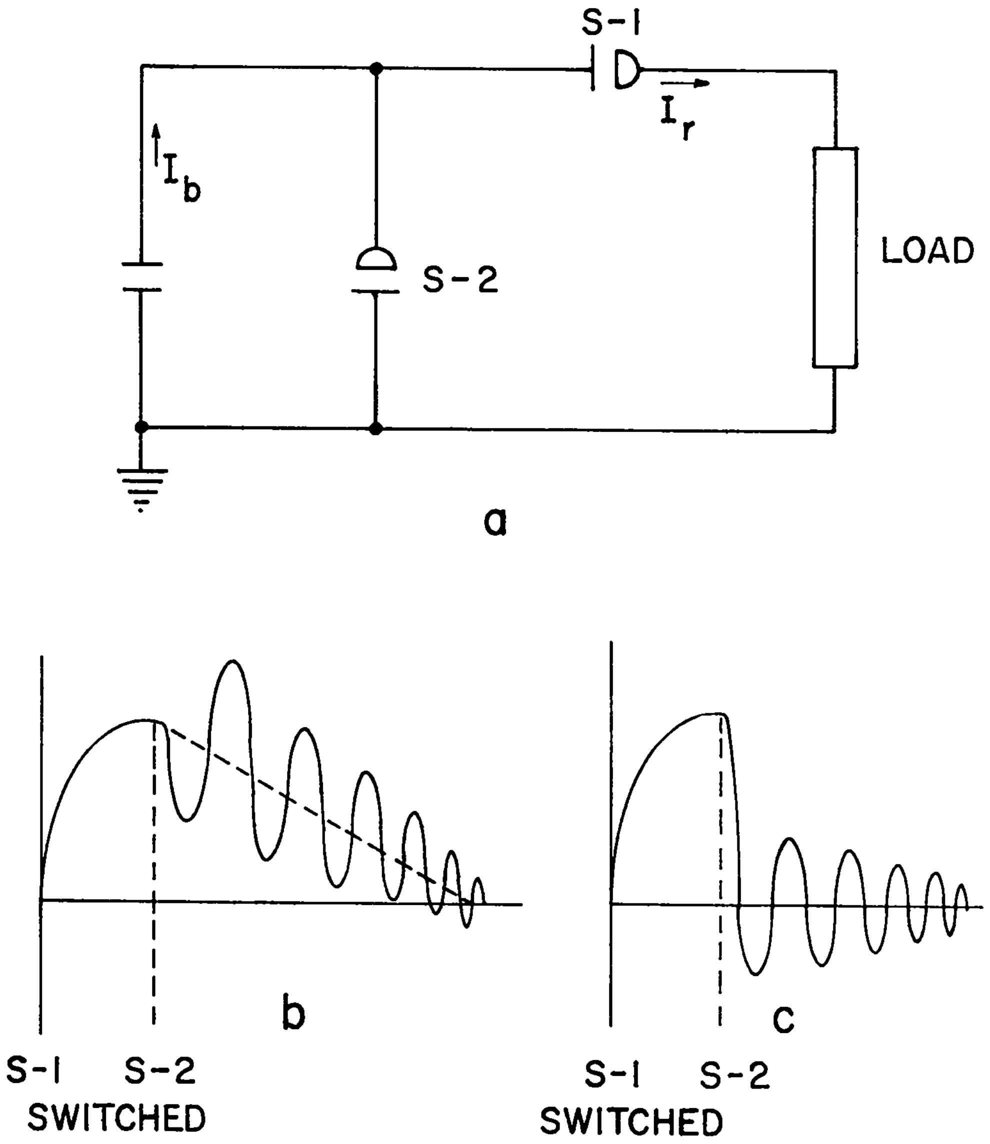


Fig. 8. Z-5329 outline



a. CROWBAR CIRCUIT

b. LOAD CURRENT

c. BANK CURRENT

Fig. 9. Gradient grid tube

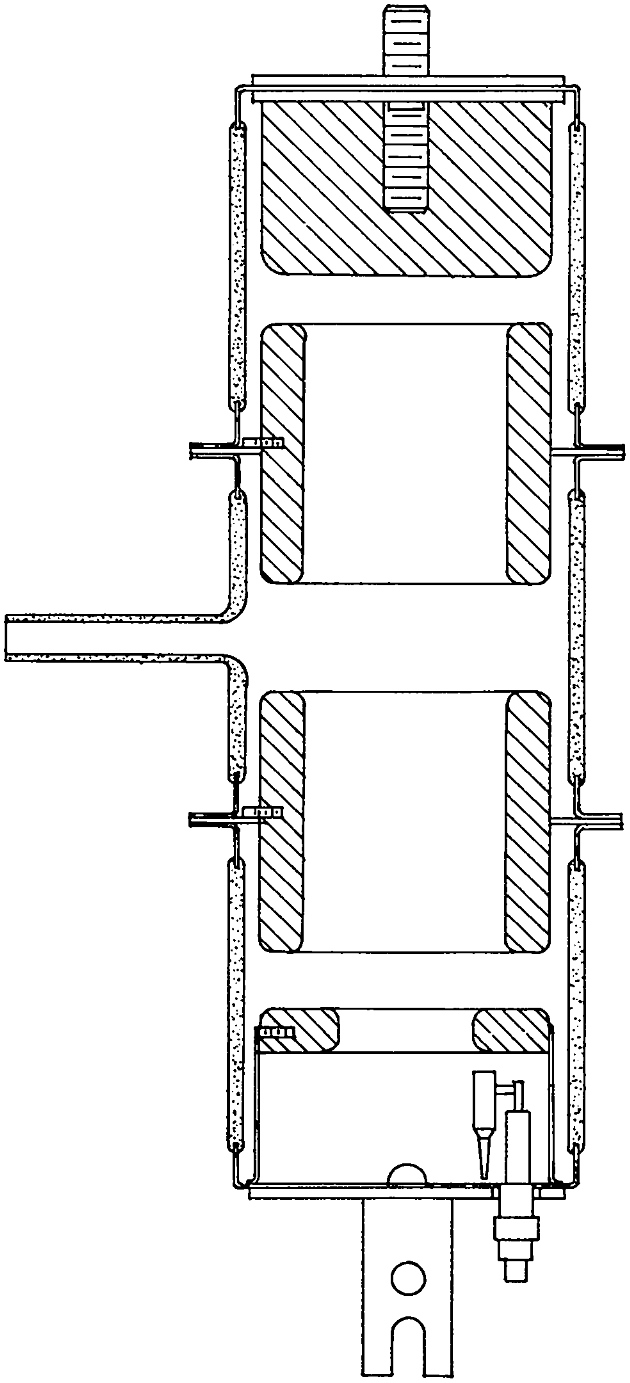


Fig. 10. Operation of crowbar bank

XI. TUBE INDEX

General Electric Tubes

TUBE INDEX