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A 550-Megawatt Pulse Modulator

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ABSTRACT

The development of a 1000-ampere electron gun made a modulator necessary to supply pulse power to the gun. The stringent requirements imposed on the pulse characteristics by the gun preclude a run-of-the-mill type of modulator. These requirements are: peak voltage in excess of 500 kv, flat top less than one microsecond in length with a flatness of 1% for at least 150 ns, and a rise and fall time less than one microsecond. A modulator has been developed and tested which meets or exceeds these requirements. An 0.5-μf capacitor and an 0.3-μf capacitor, each built up of silvered Mylar sheets, are contained in a hermetically sealed tank and form part of a two-section network. The housing of a triggered spark gap acts as a low-impedance transmission line to connect across to another hermetically sealed tank containing a transformer and having on it a flange for attachment of the gun. The transformer has a single-turn primary and a 31-turn secondary. The leakage inductance of the transformer and its leads, which has to be small, is 0.12 μh. To match properly with this, the inductance of the 0.5-μf capacitor plus its connection to the 0.3-μf capacitor is held below .06 μh. The pulse repetition rate is one per second.

PROBLEM STATUS

This is a final report on one phase of the problem; work is continuing on other phases.

AUTHORIZATION

NRL Problem H02-21
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A 550-MEGAWATT PULSE MODULATOR

GENERAL DESCRIPTION

A pulse modulator capable of supplying the required pulse power to a 1000-ampere electron gun has been developed. The gun (1) supplies 1000 amperes at 550 kv, which gives a load impedance of 550 ohms and a peak pulse power of 550 megawatts. Primary considerations in the design of a modulator at this power level are that the voltage stepup ratio (n) of the transformer be large and that the pulse length be short. The large voltage gain is necessary in order to reduce the dc supply voltage to a reasonable level. A short pulse length will lessen voltage breakdown problems and will increase the operating life of the gun. Figure 1 is a view of the modulator showing the tank containing the two capacitors, the spark gap housing, and the removable spark gap adjusting wheel and showing the transformer tank with the flange for attachment of the gun. When in an operating state the two tanks will be hermetically sealed by means of gasketed covers.

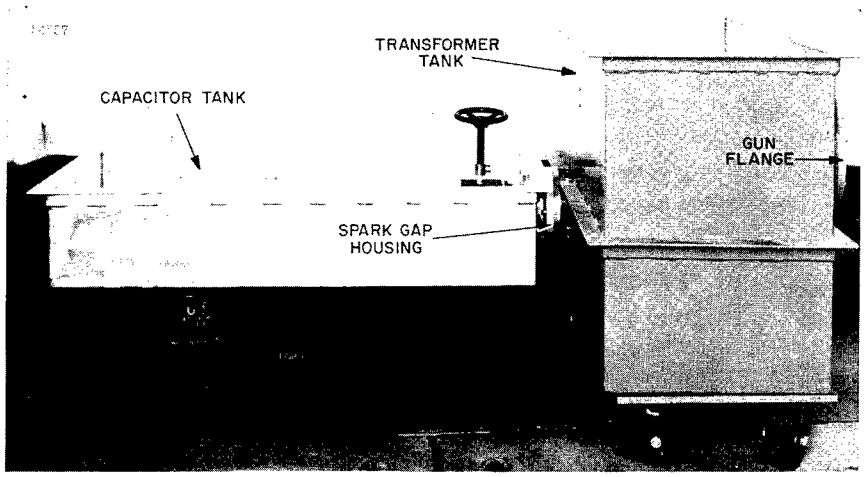

Fig. 1 – Side view of the modulator (without covers)

CIRCUIT CONSIDERATIONS

Figure 2 shows the equivalent circuit of the modulator. The pulseforming network consists of two sections (C_1 and L_1 in one section and C_2 and L_2 in the other section) in which the leakage inductance of the transformer is included in L_2, and R_p is the load resistance referred to the primary or R_L/n^2. For networks whose values for L_1 and L_2 are quite small the internal inductances of C_1 and C_2 (L_{C1} and L_{C2}) are not negligible, and their effect on the pulse shape must be considered (2).

An understanding of the behavior of the pulse-forming network has been greatly enhanced by the use of a digital differential analyzer. This device solves the differential equations which are derived from the equivalent circuit of the network and plots their

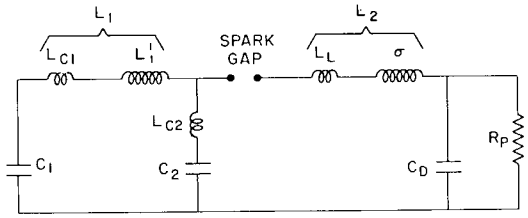

Fig. 2 – Equivalent circuit of the modulator. C_D is the distributed capacity of the transformer referred to the primary, and L_1' is the inductance of the connection between C_1 and C_2.

solutions in the form of a curve. This curve can then be compared to the experimental pulse shape as observed on an oscilloscope, and the parameter values of the computer program can be adjusted until the two curves agree. It has been determined by this method that the internal inductance of C_2 (L_{C2}) has considerable influence on the pulse shape; It is responsible for the departure from the theoretical 4/3 ratio of C_1/C_2 for optimum pulse shape. Within limits, this ratio is proportional to L_{C2}, so that if L_2 is of the same order of magnitude as L_{C2}, C_2 must be correspondingly reduced.

Factors which determine the pulse length and the high-voltage stand-off ability of the transformer are interdependent. For a two-section pulse former (3) the length of the pulse at the base is given by $t_0 = (3\pi/2)\sqrt{L_2C_1}$ and the network impedance by $Z_0 = \sqrt{L_2/C_1}$. Since the reflected primary impedance R_p is the small value R_L/n^2 (≈ 0.6 ohm), then in order to match Z_0 to R_p, either L_2 must be small or C_1 must be large. But an increase in C_1 will increase the pulse length, which is undesirable. Thus, attention must be given to reducing L_2 to its smallest possible value.

Consider L_2 to be the sum of the transformer leakage inductance σ and the inductance of connecting leads L_L. From the relationship $\sigma = (\mu_0 N_p^2 V)/\lambda^2$, where N_p is the number of primary turns, V is the volume between windings, and λ is the winding length, which is fixed by the core dimensions, it is seen that a reduction in $N_p^2 V$ will give a reduced σ.* A further decrease in σ is achieved by the method of transformer connections as shown by Fig. 3(a). The split primary windings are in parallel, thus reducing the effective leakage inductance (σ) by a factor of 2, since the leakage inductances of the individual windings (σ_1 and σ_2) are equal, so that $\sigma = \sigma_1\sigma_2/(\sigma_1 + \sigma_2)$ becomes $\sigma = \sigma_1/2$ or $\sigma_2/2$.

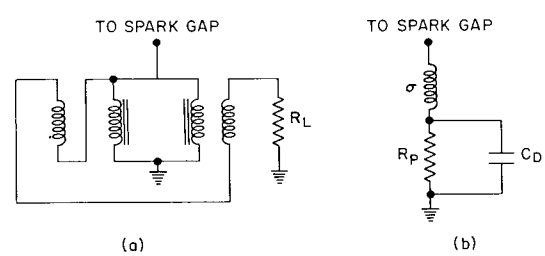

Fig. 3 – (a) Transformer schematic and (b) equivalent circuit

TRANSFORMER DESIGN

The transformer, as constructed, has the lowest possible value for N_p^2, that is, a single primary turn as shown in Fig. 4. The secondary has 30 turns with an additional turn arising from connecting the primary to the secondary as depicted in Fig. 3(a). Figure 5 shows the complete transformer including a secondary bifilar winding used to carry the filament current for the electron gun. A modification, not shown in the photograph, has

*A limit to the amount that V can be reduced is set by the breakdown between windings.

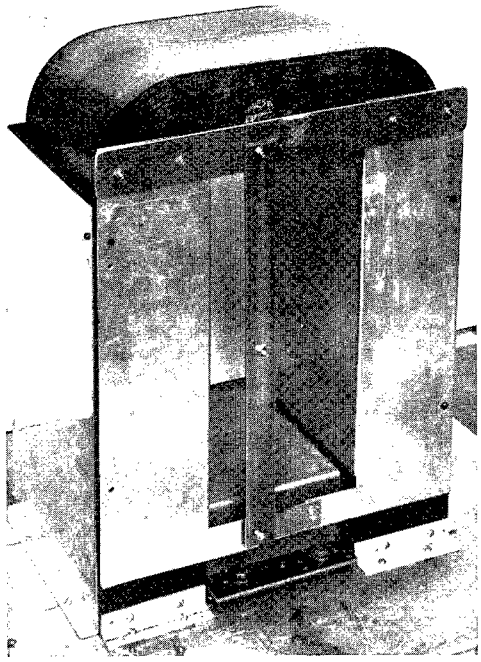

Fig. 4 – Single turn parallel primary around the core of the transformer

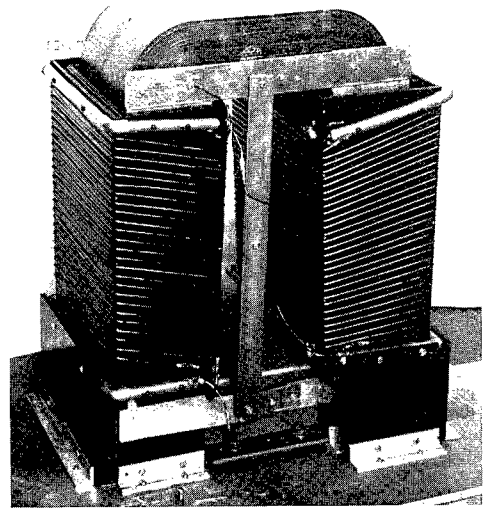

Fig. 5 – Complete transformer (see text for modifications)

the last high-voltage turn displaced about 2 inches from the winding to reduce the probability of voltage breakdown. The method of connecting the pulse-forming network to the primary has also been modified, as shown in Fig. 6. The secondary winding has a tapered construction which is effective in reducing the volume between windings and hence the leakage inductance. Calculations for σ based on the dimensions of V and λ give a value of 0.05 μh. Using the Q-meter method of measurement gave the value of σ as 0.045 μh, an excellent agreement (see the Appendix).

The short pulse length which is desired implies a relatively short rise time. The rise time response of a pulse transformer is proportional to $\sqrt{\sigma C_D}$, where C_D is the distributed capacity of the transformer.* C_D is mainly that due to interwinding capacities in which the windings act as parallel plates. In the process of reducing the interwinding volume to obtain a small σ, the rise time is adversely affected by the increase in capacity, so that a reduction in V is not all profit. Since the interwinding capacity is multiplied by n^2, a large stepup ratio such as is used in the transformer under discussion will increase the rise time by the factor n. If a short rise time is to be maintained, the product (σC_D) can be reduced only by reducing the factor σ. This, again, emphasizes the need for a very small leakage inductance. C_D is also effective in determining the flatness of the pulse; an excessive C_D will reduce the flatness so that the shape approaches that of a sine wave.

The necessity for a small L_2 and the fact that L_2 includes the inductance of connecting leads have been pointed out. Because of the large spatial dimensions of the transformer and its finite separation from the network, a simple direct connection between the two would result in a prohibitive amount of inductance. A low-impedance transmission line method of connection is used, therefore, to reduce this inductance to an acceptable value.

*If C_D did not exist, the rise time would be governed by 2.2 σ/R_p and would be approximately 220 ns.

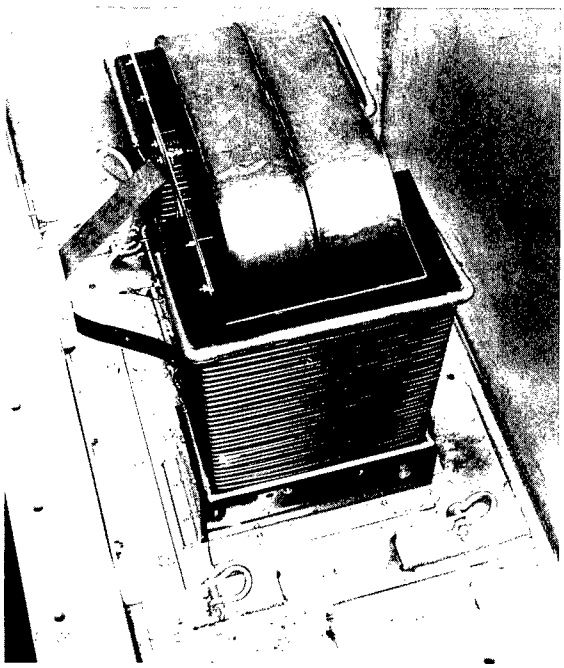

Fig. 6 – The transformer in its tank and the connections to the transmission line. The stripped RG8/U cable carries the fast-rising positive pulse of relatively low voltage to the spark gap trigger left of the tank.

Using the output pulse rise time as a basis for calculation, one finds the value of L_2 to be 0.12 μh. It follows that the lead-in inductance (L_L) is $L_2 - \sigma = 0.07 \mu$h.

Experiments were conducted to determine the breakdown characteristics of several Dow Corning fluids, and these results were compared to those of a similar experiment using regular transformer insulating oil. No significant difference was found as far as breakdown at low repetition rates was concerned; hence the insulating oil was chosen because of its lower cost. Attention was then given to the selection of the dielectric to be used for the winding forms. Ideally, the dielectric constant of this material should be the same as that of the insulating fluid so as to minimize the setting up of high potential gradients between them. Two such materials, polystyrene (whose dielectric constant is 2.3) and polyethylene (whose dielectric constant is 2.25 to 2.3) proved unsatisfactory. Polystyrene will craze at high voltages (jagged paths are formed in the material due to current flow) and it cracks up when in contact with oil over a period of time. Polyethylene suffers no apparent damage under these conditions, but arcing occurs along its surfaces, even at relatively low voltages. Although Bakelite has a dielectric constant which is higher than that of oil (5 as compared to 2.24 for the latter), it has proved to be satisfactory as far as dielectric strength and resistance to oil are concerned and is used in the final design.

The transformer cores are made of 2-mil highly-grain-oriented silicon steel–Silectron. Using a saturation flux density of 10,000 gauss, a simple calculation shows that the unbiased cores will accommodate a pulse length up to 1 μsec at 550 kv before saturation occurs.

CAPACITOR DESIGN

For two-section pulse formers a ratio of $L_2/L_1 = 2/1$ can be used to give the desired pulse shape, that is, a flat top, if other parameters are correct.* L_1 should therefore be

*Theory (3) predicts that this ratio should be 4/3 but computer studies and experiment seem to favor the 2/1 ratio.

0.06 μh. Referring to Fig. 2, one sees that L_1 will include the internal inductance of C_1. This means that the inductance of C_1 cannot exceed 0.06 μh and should be somewhat less in order to permit some adjustment of L_1. Capacitors that meet the requirements of low internal inductance, high voltage stand-off, and proper spatial configuration are not commercially available; therefore, it has been necessary to design and construct them within our group (4). Their physical description and method of construction are as follows.

The capacitors are built up of stacks of four sheets of silvered Mylar, each stack having a capacity of 4880 pf. The 0.30-μf capacitor required 64 stacks and measured 0.298 μf at 3 Mc. The 0.50-μf capacitor required 108 stacks and measured 0.501 μf at 3 Mc.

The dielectric is du Pont Mylar Type A polyester film, 0.0075 inch thick and 19 inches square, having a conducting silver coating 15 inches square centered on both sides of each sheet. This leaves a 2-inch border around the silver; this border is necessary for corona suppression and avoidance of surface tracking when the capacitors are immersed in an insulating fluid. The capacitors are contained in a vacuum-tight aluminum tank, in which they are evacuated and then immersed in Dow Corning Type 200 fluid. This method of packaging allows for the removal of all trapped air and its replacement with the insulating fluid. The tank is hermetically sealed.

Contact to the silver on each stack of four sheets is made by means of a sheet of 0.0014-inch copper foil 15 inches wide and 23 inches long which runs under the stack and extends 2 inches beyond the edge at one side of the stack. Contact to the top of the stack is made the same way, but the foil runs at right angles to the first foil. As the stacks are assembled, the foil strips on any one side come from every second stack and, by joining these ends, all stacks are connected in parallel. The first and last sheet of each orientation of foils are replaced by plates of 1/2-inch aluminum, 15-1/2 inches wide and 23 inches long. Copper spacers 1/2 inch wide and 15 inches long by 0.080 inch thick are placed between adjacent foil sheets at each end so as to provide positive contact between foils. Brass bolts (1/4"-20) are run through the aluminum plates so that the copper spacers and the foils are all bound into a rigid assembly.

The preceding applies to the construction of the 0.30-μf capacitor; its size is 23 by 23 inches by 6-1/4 inches high. The 0.50-μf capacitor is assembled the same way except that the alternate aluminum plates and copper foils are 15 inches wide but only 19-1/2 inches long. This is done since connection is required at one end only. This capacitor is 23 by 21 inches by 4-1/2 inches high. The top and bottom aluminum plates operate at ground potential and also serve as mechanical supports.

The calculated internal inductance of capacitors of this type of construction is in the picohenry range, about 20 ph. The lead inductance is about 26 nh for each lead. The sum of these two Inductances is difficult to measure directly because of the long leads that are required to connect to any measuring device, but a relative value can be determined by comparing the experimental pulse shape to that generated by the computer. Similar shapes were obtained when the known ratios of L_1/L_2 and C_2/C_1 were used in the computer program with L_{C1} and L_{C2} set to zero; hence the shunt-branch inductance can be entirely neglected.

These capacitors are designed to operate at 50 kv peak charging voltage with a breakdown voltage in excess of 80 kv. The anticipated life is about 300,000 discharges at a peak voltage of 50 kv. They should have a considerably longer life, since they will be operated at a lower voltage during most of their use.

The pulse shape of the experimental pulse may be compared to that derived from the computer by comparing Figs. 7 and 8. The only unknown parameters necessary to program the computer are L_{C1} and L_{C2}. Only by setting L_{C1} and L_{C2} to zero was the computer pulse made to agree with the experimental pulse. The close agreement is readily apparent by the two figures.

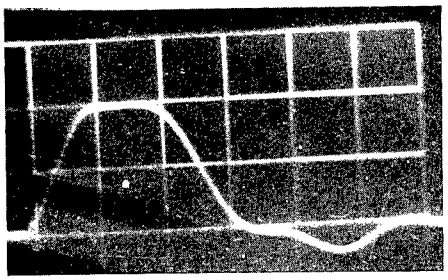

Fig. 7 – Modulator pulse. The sweep speed is 500 ns/division.

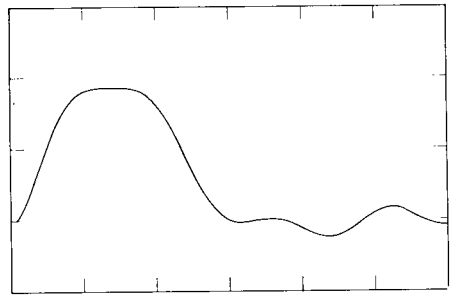

Fig. 8 – Computer pulse. Each division is equivalent to 500 ns.

SPARK GAP DESIGN

A cross section of the spark gap and its housing is shown in Fig. 9. The gap anode is shown in Fig. 10. Brass was selected for the electrode material, as it is easily machined and has shown an ability to withstand the pitting action of the discharge to a satisfactory degree. The trigger electrode is similar to one which is used by the Plasma Physics Branch at this laboratory. It consists of a copper pin, encased in a ceramic sleeve within the cathode as shown in the diagram. Gap breakdown is accomplished by adjusting the spacing of the gap just beyond that at which breakdown without triggering occurs and then applying a fast-rising positive pulse to the trigger electrode. Because the cathode is at a large negative potential, a relatively low trigger voltage will produce breakdown of the gap. Isolation of the trigger generator from the charged network is necessary when the breakdown occurs. This is achieved by the insertion of a 100-ohm resistor in series with the trigger lead.

The gap housing in conjunction with a polyethylene sleeve constitutes a low-impedance transmission line, thereby reducing the effective inductance compared with that of a direct connection. The outline of the transmission line can be seen in Fig. 9.

Figure 11 shows C_2, part of C_1, and the gap adjusting mechanism. The short length of braid connecting the two capacitors is L_1'. It offers a convenient means of adjusting the pulse shape within a limited range. A small increase in length (an inch or less) will lengthen the pulse and will produce a pronounced ripple on the flat top. A small decrease will shorten the pulse but will cause an excessive droop.

Because of the high pressure engendered by the gap discharge and the formation of corrosive gases, venting holes are placed around the periphery of the gap housing.

SUMMARY OF MODULATOR PARAMETERS AND EXPERIMENTAL RESULTS

Peak power output	550 megawatts
Peak output voltage	550 kilovolts
Peak output current	1000 amperes
Ratio of output voltage to dc voltage	13/1
Pulse repetition rate	1 per second
Type of charging	Resistive
Step-up ratio	31/1

Cores (two required)	Arnold Engr. Co., AL-1079
Length of pulse flat top	500 ns
Flatness of pulse top	within 1% for at least 200 ns
Pulse rise time (10% to 90%)	300 ns
C_1	0.5 μf
C_2	0.3 μf
Transformer distributed capacity (C_D)	0.3 μf
Transformer leakage inductance (σ)	0.05 μh
Internal inductances of C_1 and C_2	Negligible
Load impedance (referred to primary)	0.6 ohms
Load impedance	550 ohms
Network impedance	0.6 ohms
Jitter	None discernible on 100 ns/cm scale

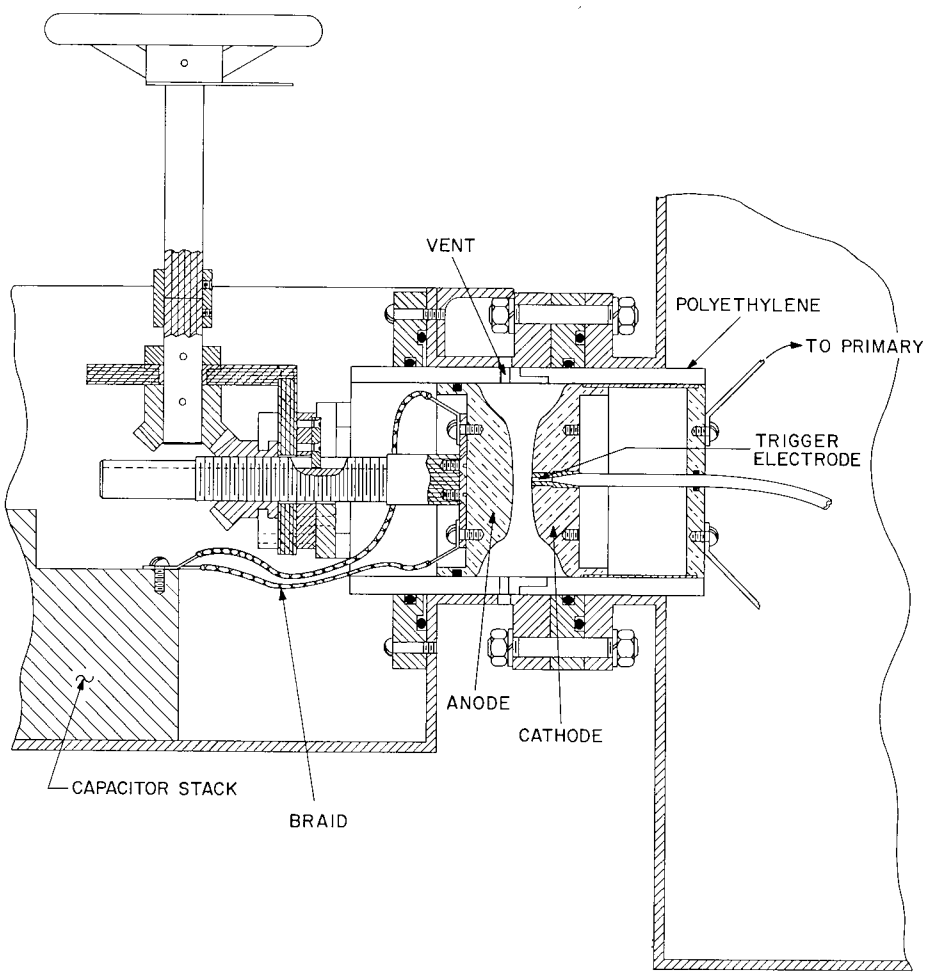

Fig. 9 – Spark gap assembly

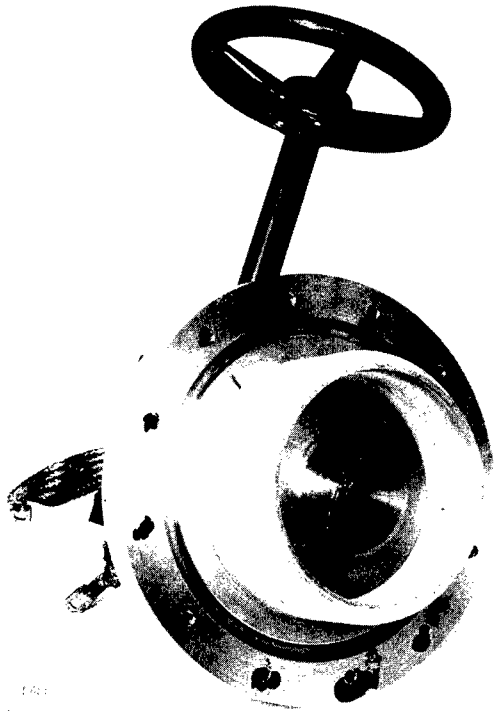

Fig. 10 – Spark gap anode

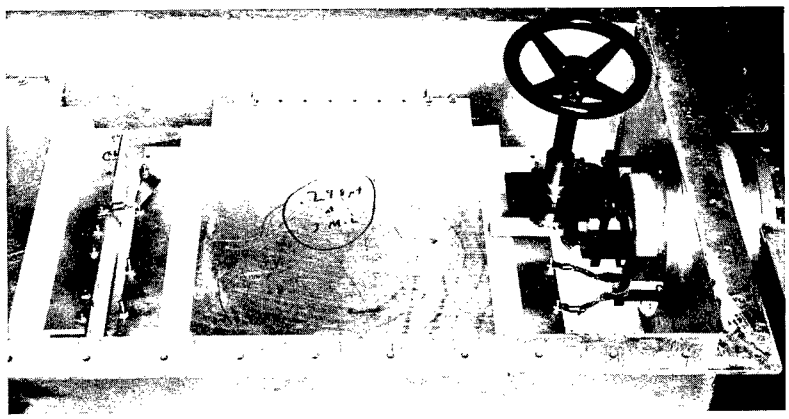

Fig. 11 – Capacitors in their tank before filling with Dow Corning-200 fluid

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APPENDIX

Q-METER METHOD OF MEASURING σ

When σ is very small ($\approx 0.05\ \mu h$), the usual method of shorting the secondary and measuring σ direct on a Q-meter is not accurate due to the inductance of connecting leads. A better method is to short the primary and measure the inductance of the secondary σ_s. Then σ may be determined by dividing by n^2; that is, $\sigma = \sigma_s / n^2$. Greater accuracy is obtainable by taking several measurements and plotting $1/\omega^2$ against C (as read on the Q-meter). The resultant curve will be a straight line with a slope σ_s and an intercept C_o. (The equation is $1/\omega^2 = \sigma_s C + \sigma_s C_o$.) Then C_D may be found by $C_D = n^2 C_o$.