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DEVELOPMENT OF SWITCHING COMPONENTS
FOR CONTROLLED FUSION RESEARCH

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DEVELOPMENT OF SWITCHING COMPONENTS FOR CONTROLLED FUSION RESEARCH[†]

by
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ABSTRACT

Components for switching large stored energies have been under development at the University of California Radiation Laboratory at Livermore. Applications and problems are discussed. Work has been done on a low inductance ignitron. A test and development program of 5550 type 2" ignitrons has led to a tube good at 10 kv for pulses of 30 ka with a decay time of 500 μ s. Times for transfer of the arc to the wall have been measured for several types of ignitrons. A 4"-insulated cathode ignitron has been developed for pulses of 10 ka for 20 ms. The firing delay and jitter of 2" ignitrons has been found to be as low as 0.25 μ s and 0.06 μ s, respectively.

I. INTRODUCTION

In both the Pyrotron (Mirror Machine) and Pinch and Collapse programs at this Laboratory intense magnetic fields are required. This requires the rapid transfer of large amounts of energy. Voltages as high as 300 kv, currents up to 3×10^7 amp and powers up to 10^{11} watts are required. Conduction periods range from microseconds to seconds. No commercial switching components could be used within their ratings except in great numbers. It was necessary to find out how much abuse various components could take and to improve or modify them.

II. APPLICATIONS AND PROBLEMS A. INITIAL APPLICATIONS

In 1953 and 1954 the first Pyrotrons (Mirror Machines) were built at Livermore using the type of circuit shown in Fig. 1. A typical circuit of larger capacitor banks is shown in Fig. 1a. A simpler circuit is shown in Fig. 1b from which circuit operation can be more easily seen. It is also the circuit used for small ignitron tests (See III B). The capacitor bank is charged up slowly and then discharged into the magnet coil by firing V_1 (series tube). At the end of 1/4 cycle V_2 (crowbar tube) is fired and the magnet coil current circulates through V_2 decaying with an L/R time constant. See Fig. 2.

The first Pyrotron, Table Top I, was built with both spark gaps and ignitrons. However ignitrons performed better and gaps were not used thereafter.

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The 5" diameter (size D) 5555 ignitron was selected as a compromise between commercial voltage and surge current ratings. In other applications spark gaps are still used for very large currents of short duration.

It should be emphasized that the ignitron is a very good, reliable tube for industrial use. These applications greatly exceed normal ratings, and depend on tube parameters not normally controlled.

Table I. Initial Pyrotron Applications

	Table Top I		Toy Top I	
	Series Tube	Crowbar Tube	Series Tube	Crowbar Tube
Standoff Voltage	+ 13 kv	- 21 kv	+ 20 kv	- 20 kv
Peak Current	17 ka ^a	17 ka	150 ka	150 ka
Period	$\frac{T}{4} = 500 \mu s$	$\frac{L}{R} = 9 ms$	$\frac{T}{4} = 100 \mu s$	$\frac{L}{R} = 2 ms$

^a ka = kiloampere, ms = millisecond, and μs = microsecond.

The few ignitrons used initially were selected, conditioned tubes. It appeared that the 5555 was good at 21 kv for 17 ka for 9 ms. This experience was used in designing larger capacitor banks where the weakness of the sampling showed up. The typical 5555 cannot always be used above 10 kv and seldom reliably above 15 kv (maximum rated voltage 3 kv peak). Some fail very rapidly and all have limited life even with special, frequent conditioning.

Use was later made in the Livermore Pinch and Collapse Program of clusters of 2" diameter (size A) 5550 ignitrons in similar circuits for currents up to 30 ka for 10's of microseconds. It was established that they are seldom reliable above 15 kv (maximum rated voltage 6 kv) or for long conduction times at high currents.

B. CIRCUITRY PROBLEMS

All applications of this type have been at very low repetition rates, 1 pulse per minute (1 ppm), and the desired life has been low (10^5 operations) in comparison to industrial usage. Initially reliability was secondary, however, as capacitor banks became larger and the destructiveness of failures increased, reliability became more important. Some of the factors affecting life and reliability follow.

The rise times are less than the decay times which usually makes the series tube application less severe. A series tube must be able to hold a high voltage throughout the charge time. On large capacitor banks many sections of capacitors are connected to a common load with individual series tubes. This insures parallel operation but if all tubes do not fire it changes the capacitance of the circuit. On very fast capacitor banks or on small capacitor banks the stray inductances (L_1 and L_2 of Fig. 1) are not negligible compared to the load inductance. In the test bank of section IIIB $L_1 + L_2$ is about 20% of L_3 . This produces the oscillations of Fig. 3. The energy stored in L_2 prevents deionization of the series tube. The bank oscillates through the crowbar tube and modulates the load current. The frequency and amplitude of this modulation depend upon (neglecting R_1 , R_2 and R_3)

$$\sqrt{\frac{L_3 + L_2}{L_3(L_1 + L_2) + L_1 L_2}}$$

and $L_2/(L_3 + L_2)$, respectively. The length of time which this continues depends

upon $\frac{L_1 + L_2}{R_1 + R_2}$. In Fig. 3b it is over in about 3 cycles. The series tube must

carry reverse current forming arc spots on the graphite anode. On the third and subsequent odd half cycles the arc spots form on the steel wall instead of the mercury pool where the arc spot has had time to extinguish. This oscillation, where not quickly damped, can shorten series tube life.

It is desirable to maintain magnet current as long as possible making the crowbar tube application very severe. They must stand a high inverse voltage applied very rapidly. If one fails at this time it draws the short-circuit current from the capacitor bank. They must fire rapidly on low voltage in order to operate in parallel to keep to a minimum the amount of isolating inductance necessary to permit them to fire and share current. They must also have a low voltage drop in order to make L/R large.

C. IGNITRON PROBLEMS

A basic limitation of commercial ignitrons in high power switching is the transfer of the arc from the mercury cathode to the steel wall. In time one of three results will cause failure: (a) The arc will melt the wall and liberate gas. (b) Steel vapor will coat the ignitor seal and prevent ignitor firing. (c) The arc may melt a hole through the wall. See Fig. 4.

Even without arc transfer gas can be liberated if the current density is high enough, long enough. Tubes can be improved in voltage holding by applying a high dc or ac potential periodically to clean up gas.

III. DEVELOPMENTS AND TESTS

A. LOW INDUCTANCE IGNITRON DEVELOPMENT

The proportions of a conventional ignitron are not those of an inherently very low inductance device. The path for internal current conduction is many times as long as it is wide. E. C. Hartwig of this Laboratory in 1955 began work on a low inductance ignitron. See Fig. 5.

By making the conduction path many times as wide as it is long it was hoped to achieve a very low inductance. A grid was used to reduce the spacing for voltage holding and to decrease the firing delay and jitter. Along with the change in size comes a high current capacity.

Work was done initially at UCRL Livermore on a 16"-diameter demountable continuously pumped version with a fused quartz wall. Efforts to fabricate the fused quartz piece were unsuccessful. The tube was completed with a Lucite wall in order to test the ideas of interest.

In addition, a contract was let to develop a sealed-off 12" diameter version with a 15" diameter Kovar-glass seal for the wall.

Table 12. Low Inductance Ignitron Data (Internal Version)

(Grid 1/4 inch thick with 1/16 diameter holes)

Grid Firing Data	; Delay $\leq 0.05 \mu s$	
	Jitter $\leq 0.02 \mu s$	
Inductance (inductance)	8×10^{-9} henries	
Voltage Drop	Peak current	Peak voltage drop
	A	volt
	70	110
	100	140
	220	220

Difficulties were encountered on the contract version in making the top and bottom plates rigid enough to avoid sagging during exhaust bake-out. This sagging stresses the glass seal and of the two models delivered so far neither held vacuum long enough for testing at Livermore. These tubes are to be operated with continuous pumping to obtain performance data.

B. SMALL IGNITRON DEVELOPMENT

Some variable success had been achieved using the 5550 ignitron. A test program on 5550 type ignitrons was begun by H. W. VarNes, of UCRL, Livermore, to: (a) Get comparative data on tubes from different manufacturers, (b) Obtain application information, (c) Develop better tubes. It was thought anything learned could be applied on the larger, more expensive tubes.

The tubes were tested as crowbar tubes on a small capacitor bank at 10 kv. The test was arbitrarily chosen to use available components and give a life of 10 to 100 pulses on standard tubes. The tube passes 10 coulombs per pulse. Wave shapes for this bank are shown in Fig. 3 and explained in section 11A and 11B.

First each tube is tested to obtain the breakdown voltage with and without a small capacitor in parallel. Most of the tubes tested have epoxy potting around the anode seal, and external flash-over seldom occurs. The usual range is 20 kv to 45 kv. Baking the anode seal region 1/2 hour at 110°C will improve breakdown voltage 5 to 15 kv, especially if there are mercury droplets or films in this region. The igitor resistance is then measured with an ohmmeter. The tube is conditioned by running 5 times each at 2 kv steps up to 10 kv. The test is ended if the tube fails to hold inverse voltage once even if it is good afterwards.

Table III. 2" Diameter Ignitron Life Data

Manufacturer and application	Life on initial samples		Life on best type produced		
	Operations	Coulombs	Operations	Coulombs	
A	Crowbar Tube	18	340	>1500	$>2.4 \times 10^4$
	Series Tube	-	-	1412	8.5×10^3
B	Crowbar Tube	9	170	323	5.2×10^3
	Series Tube	-	-	-	-
C	Crowbar Tube	52 [*]	980	369	6×10^3
	Series Tube	-	-	-	-

* Equivalent.

DISCUSSION

There were three main sources of failure: (a) In some first tubes the graphite anode burned loose. (b) The most common failure was due to the liberation of gas. (c) Failure due to mercury-wetting or condensation of the glass anode seal.

It was discovered that tubes without potting (mica-filled epoxy encapsulation around the anode seal) would fail soon after resumption of testing after a long shutdown, but potted tubes did not. The potting keeps the anode seal warmer and prevents mercury condensation there as the tube cooled. The average life of tubes from manufacturer C was increased from 811 to 5980 coulombs when potted. The internal construction and the processing were supposedly unchanged. Possibly the dielectric properties of epoxy resin also change the electrostatic fields at the anode seal beneficially.

Many of the tubes that went more than 100 pulses showed bombardment on the upper surface of the ignitor support. The metal had been melted and flattened out especially toward the center of the tube. The texture and degree of attack varied between manufacturers even though almost identical alloys were used. This effect was proportional to the number of operations. On tubes from manufacturer C the thickness was reduced about 50% after 1500 operations. Measurements of ignitor current show no evidence of any arc transfer to the ignitor support. It is believed that the effect is due to ion bombardment of this part acting as a low impedance probe. On recent designs the ignitor support has been removed from the center of the tube by locating the ignitor close to the ignitor seal.

It was noticed during the test that sometimes the crowbar tube would fire at the proper time without any triggering pulse. It is very likely that the ignitor support remained hot enough between pulses to initiate ionization.

Various modifications have been tried to improve the performance of tubes. Among the variations tried have been liners of refractory metals and graphite, use of refractory metals and vacuum-melted metals in the ignitor supports, the use of refractory-metal-covered metal anodes, and variations of contours and electrostatic shields to reduce electrostatic stress at the anode seal. The latter approach has resulted in tubes which have a voltage breakdown 20 to 30% higher than the conventional tube. However, the greatest success on improving life has been with a tube of conventional design but improved processing and quality control. It has been necessary to work with each manufacturer to determine which parameters are important in stored energy switching.

C. LARGE IGNITRON DEVELOPMENT

It became obvious that arc transfer was a major problem in crowbar tubes. One solution is to separate the wall electrically from the mercury pool. The only limitation would be at higher current levels where multiple series arcs might form. Work was begun toward this end.

It was desired to: (a) Measure the arc transfer time of standard tubes, both large and small. (b) Test available insulated cathode tubes. (c) Develop new designs of insulated cathode tubes.

1. Arc Transfer Measurement

When connection is made to the cathode of an ignitron and the arc transfers from the mercury pool to the wall the current is conducted by the wall which produces voltage drops of the order of 0.01 to 1.0 volts.

These tests were performed using two 300-kw selenium power supplies which can be pulsed to about 15 ka total. The pulse was begun by pulsing the tube and ended by opening contactors in the primaries of the supplies. The impedance level of these 150-volt power supplies is such that the change of arc drop when the arc transfers usually produces a noticeable change in current. These changes correlate with the tube wall voltage on transfer time. A repetition rate of about 2 min. between pulses was used. See Fig. 6 for wave shapes. The graphs in Figs. 7-10 show the times for four different types of tubes. The limits on the points show the extremes of data taken. Fig. 11 shows a typical distribution of data.

Significance of Data. The data shown are probably a fundamental limitation on the application of tubes to stored energy switching. If the tubes are applied under the curves shown it is likely that trouble will be avoided. It does not mean that going above the line slightly will cause the tubes to fail. However, going far above the lines has been shown by experience to cause trouble. This data correlates with the results on the small ignitron life tests, which showed no indication of arc transfer to the walls. See III B. Although the wave shape is not a simple one the probable equivalent point for a square wave is just below the curves.

2. Tests of Insulated Cathode Tubes

The same test setup was used as described above. The tubes were pulsed 5 times per minute at 10 ka with a pulse length of approximately 20 ms. Periodically the breakdown voltage was measured.

Only one type of insulated cathode rectifier was available as a standard commercial item. This tube has an internal wall of cooling tubes electrically insulated from the outer vacuum wall. The arc was retained on the mercury pool by a fused quartz ring. Two samples were given 10,000 operations each with similar results. The tube was only slightly damaged. However, the breakdown voltage which initially was over 20 kv gradually dropped to approximately 8 kv.

Two types of insulated cathode ignitrons were built by manufacturer C. They had a glass seal in the wall of a 5555 ignitron which was protected from the arc by a fused quartz ring. The second type, with no graphite arc baffle performed better. These tubes went 10,000 operations but the breakdown voltage gradually dropped from >20 kv to 11 kv. A tentative conclusion is that an intense arc breaks down quartz into silicon and oxygen which is born out by an apparent attack of the quartz surface.

An insulated cathode ignitron was made by manufacturer B. This type is a 4"-diameter tube insulated with a glass seal protected with molybdenum shields. See Fig. 12. The results of these tests are given in Table IV. These tubes appear attractive for use at 10 kv. There was no evidence of arc damage.

Table IV. 4"-Diameter Insulated Cathode Ignitron, Life Data.

Tube #	Breakdown Voltage		Wall to Cathode Resistance Lowest	Operation	
	Before ± kv	After ± kv		10 ka 20-25 ms	15 18 ka 5 10 ms
1	^a 20	^a 20	140 kΩ	10,000	
2	^a 20	25	20 kΩ	10,000	1500 Accidentally ruined
3	27	^a 20	7 mΩ	10,000	2650
4	^a 20	25	1 kΩ	10,000	

Voltage drop: 10 ka 28 v.
14 ka 36 v.

Repetition rate: 4 ppm at 10 ka.
2-3 " " 15-18 ka.

^a Limit of power supply available.

D. MECHANICAL SWITCHES

One remedy for arc transfer is to relieve the tube with a mechanical switch before arc transfer. A switch was built for 20 ka and is being used. Because a mechanical switch accelerates slowly the firing of the capacitor bank is synchronized to the closure of the switch. Work is progressing on mechanical switches for 200 ka and to hold 40 kv 500 μs before closure.

E. FIRING DELAY AND JITTER MEASUREMENTS

In some fast capacitor banks it is very important to have rapid, simultaneous firing of tubes. Tests were necessary to measure firing delay and jitter and to find out how they might be reduced. These tests were begun by H. W. Van Ness of this Laboratory.

These were performed on 2' ignitrons in a coaxial geometry discharging a fast capacitor into the igniter with a mechanical vacuum switch. The anode circuit is likewise a fast plastic capacitor in a coaxial geometry. By using pickup loops it is possible to measure with accuracy the beginning of current conduction in each circuit and to measure the time delay between these two events. There is variation between tubes and between individual tubes of one type. Fig. 13 shows a typical result.

IV. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

A reliable 2' ignitron has been developed for use at currents of 30 ka for 500 μ s as a crowbar tube. The life expectancy is at least 1,000 operations and possibly more than 10,000 operations. It is likely that this tube can also be used as a series tube where there is not substantial current reversal. However, the problem cannot be considered solved as yet for the series tube where there is substantial current reversal.

A 4' insulated cathode ignitron has been developed for currents of 10,000 amperes for 20 ms. The life expectancy at this level is over 10,000 operations. It is considered almost certain that this tube can be used reliably at 10 kv, however, it has not actually been tested in a capacitor bank at this voltage. It is also known that the tube can be used at 15 ka or more with a pulse length of 5 ms. The ultimate abilities of the tube are not yet known.

B. FUTURE DEVELOPMENT WORK

The ultimate capabilities and application data are being determined for the tubes mentioned above. Arc transfer information is being extended to higher currents on a capacitor bank.

Work is underway to extend the useful voltage level of these types to 20 kv and to adapt them to series tube use with current reversal. It is likely that this will call for design modifications.

It is hoped to produce a useful version of the low inductance tube of paragraph IIIA. This type of tube may eventually be more successful in a smaller version possibly with non-conducting walls as was done at Livermore. It appears to be more like the ultimate type of tube: i.e., no arc transfer problem, low ind. L , r , short spacing and hence high breakdown voltage, and a short, wide discharge with the lowest possible arc drop.

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(a)

SIMPLIFIED

(b)

Fig. 1. Circuits for capacitor banks with crow-barred magnet load, (a) typical and (b) simplified.

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Fig. 2. Wave shapes (idealized, i.e., $L_1 = L_2 = R_1 = R_2 = 0$).

Fig. 3. Wave shapes - small ignitron test bank.

Fig. 4. Detailed drawing of arc transfer effects on 5555 ignitron.

Fig. 5. Low inductance ignitron - contract version.

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Note:

Typical for 6 ka with 5550 type Ignitron with stainless steel wall.

$$\tau = 1.1 \text{ ms}$$

MUL-1006

Fig. 6. Wave shapes - arc transfer measurements.

Fig. 7. Arc transfer time - 5550 type ignitron (average of 6 tubes).

Fig. 8. Arc transfer time - 5553 B ignitron (one tube).

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Fig. 9. Arc transfer time - 5555 ignitron (average of 4 tubes).

Fig. 10. Arc transfer tube - 622R/506 ignitron (one tube).

Fig. 11. Typical spread of transfer time data from one 5550 type ignitron.

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Fig. 12. Cross section of 4-inch-diameter insulated cathode ignitron.

Fig. 13. Typical ignitor characteristics -- 5550 type ignitron (30-ohm ignitor).

END