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Properties of Ignitrons for 20 kv Capacitor Discharge Circuits

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Abstract

The properties of pulse Ignitrons are discussed. Measurements of delay, jitter, tube resistance and heating were carried out. In a reference list different makes of size A Ignitrons as well as some of the bigger diameter Ignitrons are compared with respect to their pulse behaviour.

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1. Introduction

During the past ten years the Ignitron has proved itself as a useful switch in high current discharge circuits up to 20 kv.

Numerous testing programs in research and industry laboratories in the USA (Los Alamos [1] , Livermore [2] , Princeton [3] , General Electric [4] , Westinghouse and National Electronics Laboratories), in France (Fontenay-aux-Roses, Schneider-Westinghouse [5]), in England (British Thomson Houston [6]) and Germany (Max-Planck-Institut für Physik [7,8,9] , Institut für Plasmaphysik [9,10] and AEG [14]) contributed to the development of special types of pulse Ignitrons or were carried out to find their pulse-behaviour.

Ignitrons of the seize A (2 inch tube diameter) can carry currents as high as 100 kA or even more at voltages of 20 kv. The life rates between 10^2 to 10^5 depending on the current ratings as well as on some constructional items (anode material).

In general data from manufacturers of Ignitrons are incomplete in many points of properties and as far as the life is concerned information is very poor. Therefore tests and measurements have been carried out to obtain a complete picture of Ignitron properties. The main effort dealt with the investigation of cathode temperature effects, the measurement of arc drop and the life for different current ratings. The investigation was carried out only with such types of Ignitrons which were promising for a use in condenser units of suitable energy content (e.g. 1 - 5 kJ) and voltages of 10 - 20 kv and whose prices would allow the use in a great quantity.

The following types have been tested -

GL 7703	(General Electric, USA)
WL 8306 = Wx4231	(Westinghouse, USA)
= Wx5018	
NL 1039	(National Electronics Laboratories, USA)
SAS	(Schneider-Westinghouse, France)

Additional information on the types NL 1037, Bk 178, Bk 194 was made available from other laboratories or was taken from industry data.

It was thought to be useful to add some data of the bigger size Ignitrons Bk 194, Bk 178 and WL 5555/B. The Ignitron can switch current pulses in the millisec range or will allow very high life rates (up to 3.10^5 pulses or more) when operated at moderate currents (e.g. 50 kA) of shorter duration (μsec). Their high price will not allow a more general use.

2. The Pulse-Ignitron

2.1 Mode of operation and constructional principles

The Ignitron has been developed as a controlled rectifier in welding apparatus. Because of its high hold-off voltage and its ability to carry high pulse currents it has been found as a very useful switch in condenser-batteries.

The Ignitron is a vacuum switch with two main electrodes (anode and cathode) and one (or more) auxiliary electrode (triggerelectrode), all mounted in a cylindrical discharge vessel as shown in fig. 1.

The cathode is a liquid mercury pool at the bottom of the container. The anode is a cylindrically shaped electrode of graphite or metal, which is hold in position by means of a glas seal and a threaded bolt.

American pulse-Ignitrons usually have an expoxy potting around the glas seal and this serves as a thermal insulation and mechanical reinforcement.

French types (SAS) or English ones (BTH, English Electric) have no potting whereas some others (NL 1039, NL 1037) have a silicon rubber potting.

In general pulse-Ignitrons do not need an additional cooling what is standard practice for welding-type Ignitrons.

In some cases it is wanted to control the cathode temperature (in case of high pulse rates or extreme low jitter) and this is easy arranged by an additional cooling clamp. For very high Coulomb ratings (Ignitrons Bk 178 or Bk 194) cooling is provided by a double-wall-system container.

Ignition is usually done via a semi-conductor rod which is tipping into the mercury. If a positive ignition current is sent through this rod (principle of triggering by Slepian and Ludwig [11]), field-emission of electrons and thermal heating in the zone of contact will generate charged particles and in consequence break-down in the cathode-anode space will occur. This principle has been adopted also for pulse-Ignitrons but certain requirements (intensity of current and pulse length) have to be fulfilled for save triggering.

The ignition of the Ignitron is only possible in one direction (i.e. when the anode has positive polarity). After a positive current (anode to cathode) has been established and generated enough charge-carriers (evaporation and ionisation of mercury vapour) current may now build up in both directions.

If the change of polarity is slow (e.g. at frequencies of 1 kcs or less) it may happen that all charge-carriers recombine to neutral gas, the "switch" opens then. This behaviour should be noted when the Ignitron is used in condenser batteries which have a low discharge frequency and as it will depend also on some other parameters such as voltage, intensity of current, and waveshape.

2.2 Survey on seize A Ignitrons for 2o kV operation

At present different types from several firms are available, the main difference being the choice of anode material. All types are interchangeable except the French type SAS which has a slightly different cathode mounting.

Cummings [2] and Boicourt [1] report on the improvement in Ignitron life when metal is used in place of graphite as anode material, what may be contributed to better cooling at the metal surface and thus less heating in the Ignitron interior. This is very important in the case of a ringing discharge in which during the period of negative current a cathode spot is formed at the anode surface. Ignitrons with graphite anodes also show a decreased hold-off voltage with increasing number of discharges. In such tubes a rough layer of sputtered graphite covers the internal surfaces and thus reduces the hold-off voltage. In addition, with metal anodes a certain "gettering" effect can be expected to improve the vacuum quality.

Different metals have been tried out. Best results so far were obtained with molybdenum (GL 77o3, NL 1o39). But the extra high costs of these tubes (factor 2 - 3 in comparison to graphite anode tubes) prevent a universe use of molybdenum. Good results were found also when using austenitic steels ([5], SAS "stainless steel") but a rapid decreasing in ignitor resistance was observed, as a consequence of ignitor wetting with mercury. This has been contributed to some components in the steel which favour the amalgamation process. Recently the use of very pure metals (e.g. iron) has been tried out. The life obtained with a few test samples are very promising, further tests will be necessary to establish the real life of these tubes. The price of "pure metal" anode tubes is between that of graphite and molybdenum tubes.

3. Properties

3.1 The ignition

The usual way of igniting an Ignitron is to apply a positive current pulse through the ignitor electrode to the cathode, this current is supplied from a thyratron-pulse-generator either direct or via a pulse transformer.

The anode current will start after a certain delay, which will vary from shot to shot. This effect is called jitter. In condenser batteries where many units are operated in parallel, the jitter may become important as it will influence the steepness of the voltage rise in the load.

3.11 The effect of trigger voltage

Warmoltz [12] found a strong dependance in the delay-triggervoltage characteristic. Also Cummings [2] proved that delay and jitter decrease by one order if the triggervoltage is increased from 1 to 5 kV. After his investigations there should be no influence of the anode voltage.

Measurements by Moustafa [8] show also a similar tendency.

The triggervoltage cannot be increased above a limit for following reasons:

- The triggercurrent shall be kept below a value (usually about 2oo - 3oo A) to avoid damage in the fragile semiconducter trigger rod.

- Flash over can occur at the outer trigger electrode connection (glasseal) at voltages above 1o kV.

For the mentioned reasons it has been found adequate that the trigger voltage (voltage of pulse generator) is 3 - 6 kV.

It has been shown, that Ignitrons, with lowered ignitor resistance as low as o.5Ω, can be triggered safely, if the trigger voltage is 5 kV.

The ignitor resistance (resistance measured between trigger connection and cathode) is decreased with increasing number of shots, this effect is specially true for Ignitrons with certain metal anodes but there is some indication that this also may happen with graphite anode tubes subjected to long current pulses due to arc spot migration to the stainless steel walls.

In Fig. 2 the decreasing in ignitron resistance is shown in dependance of the number of discharges.

The triggergenerator used for this and all further tests is shown in Fig. 3. It is a conventional thyratron pulse generator in which a o.5 μF capacitor is discharged through a HV-thyratron (PL 522 = 5C22) via a 5oΩ-cable and 1:1 pulse transformer into the ignitor system. A serie resistor will limit the current to a safe level. The test was started with the trigger voltage set to 3 kV, after 43oo pulses triggering failed. The ignitor resistance had changed to a value below o.5 Ω.

By increasing the pulse generator voltage to 5 kV and replacing the 1o Ω serie resistor by a 1Ω-resistor, triggering was possible again and no failure occured in the further run which was stopped at 2o,ooo pulses.

3.12 The effect of cathode temperature

The gas pressure in the Ignitron, which defines the break-down behaviour, is the pressure of the mercury vapour, i.e. a function of cathode temperature. Thus it may be expected that there is a strong relation between cathode temperature, breakdown voltage, ignition delay and jitter.

The higher the cathode temperature the lower will be the delay and jitter but the hold-off voltage (i.e. breakdown voltage) will be decreased too.

Thus the user of Ignitrons has to find the right compromise between cooling and heating the cathode. In cases where fast switching with low jitter are not important, the breakdown voltage can be raised by cooling the cathode (e.g. this way was chosen for a 300 kJ, 18 kv, condenser battery to supply a magnetic field coil, MPI). This cooling may become especially important with graphite anode ignitrons (WL 8306 = WX 4231).

Boicourt et al [1] advise in general to cool Ignitrons with respect to the rate of predischarges.

Measurements by Brandstetter [10] prove the expected dependence of delay and jitter from the cathode temperature. From these measurements one would expect an optimum temperature of 25 - 30°C. At this temperature the breakdown voltage is still high enough but delay and jitter have already reached low values. Own measurements found that different Ignitron types show different behaviour, which only may be contributed to differences in the ignitor construction. The Ignitron SAS shows very little temperature effect in contrary to the types GL 7703 and WL 8306 also tested by Brandstetter. This is clearly visible from oscillograms Fig. 4 a and Fig. 4 b which show the voltage rise in the load coil of a test circuit (see also Fig. 3). The results of these measurements are given in Fig. 5 a - 5 d (delay) and Fig. 6 (jitter) for different types.

The following interpretation for delay and jitter has been adopted:

Delay: Mean time (arithmetic mean value) from start of trigger current,(i.e. start of scope triggering) to the point where the load voltage has increased to 1o % of its maximum value.

Jitter: Difference between maximum and minimum delay as measured in at least 1o consecutive discharges.

The very different behaviour of the type SAS in comparison to others could have its origin in the use of a different semi-conductor material. The SAS tube and a GL 77o3 tube have been opened and compared but no marked differences in the construction could be detected.

The influence of the cathode temperature can be lowered by adding a certain amount of inert gas, this would guarantee a higher vapour pressure already at lower temperatures. Warmoltz [12] showed that adding of argon in a test Ignitron gave a decrease in delay. It is not known whether this method has been used with the SAS Ignitron.

The question whether cooling or thermo-control or neither of both is adequate is further connected with the problem of internal heat generation during a pulsing cycle. This has been investigated by measuring the heating of the Ignitron cathode. In a continuous test run at 2 pulses/min a GL 77o3 Ignitron was subjected to a 5o kA respective 9o kA, 13o kcs oscillatory discharge, 75 % current reversal. The Ignitron cathode stabilised at a temperature about 6°C higher than room-temperature (see Fig. 7), for the 9o kA discharge cycle.

This means that in most cases where Ignitrons are used in thermonuclear research, an additional cooling is not necessary because of the low repetition rate of operation.

3.2 The Ignitron resistance

A finite conductivity in the discharge channel is responsible for the arc drop when current is passing the Ignitron. In welding type Ignitrons and small currents in this application the arc drop is constant (Arends [13]). In pulsed discharges the ohmic arc drop is current dependent (Nittrouer [3], Cummings [2]). Nittrouers measurement was carried out with slow current pulses (msec-range) but only up to 6 kA in a seize A Ignitron (555o).

Cummings investigation with a glas Ignitron found a rather high value fo arc drop (1ooo V) for a 2oo kcs, 2o kA discharge.

Own measurements were carried out in a 1.2 kJ, 18 kV capacitor unit with different Ignitron types (WL 83o6, GL 77o3, NL 1o39).

A direct measurement of the voltage drop in the Ignitron would be correct in the point of current maximum ($\frac{di}{dt} = 0$) as the inductive voltage drop is then 0 and the measured voltage

$$U_M = U_{arc} = R_{arc} \cdot \hat{i}$$

The better method is to compensate the inductive component of the signal by introducing an additional voltage which is a pure inductive one and of opposite polarity to the original inductive voltage drop. This method has been verified by inserting a pick-up coil in the measuring circuit and by variation of the geometrical position of this coil with respect to the main discharge circuit the amount of compensation was controlled (fig. 8). As the absolute value of compensation voltage is not known in advance, the compensation was found by observing the phase angle between the measured voltage and the discharge current. The point of best compensation is reached when the phase shift between both signals becomes zero. The measured voltage is then called the resistive arc drop of the Ignitron. In fig. 9 the resistive arc drop and the tube current are shown.

The high voltage of the discharge circuit was suppressed by an additional measure as shown in fig. 8. The potential at point A is measured through a HV-diode which only will close when the potential A has fallen below the bias potential B.

Fig. 1o shows the ohmic arc drop in dependence of the tube current. Some values which could be taken from literature are added for completeness.

The ohmic resistance of the Ignitron can now be defined -

$$R_{Ign}(i) = \frac{U_{arc}(i)}{i} \qquad i = i(t)$$

This definition cannot describe the resistance when the current is passing through zero. In fast ringing discharges, the charged particles in the discharge channel will not recombine i.e. the resistance will be maintained at a finite value.

Fig. 11 shows the Ignitron resistance in dependence of tube current. It can be seen that above 2o kA the resistance is varying only slightly and it settles at a constant value. The influence of cathode temperature is a small one, no marked difference could be measured in the resistance for three different temperatures 15°, 20° and 30°C.

3.3 The self-inductance

The self-inductance of an Ignitron is given by the magnetic flux between internal current path (discharge channel) and the current in the outer connections, i.e. it will be minimized in the case of a coaxial connection.
The inductance has been calculated for the case that the discharge column has the same diameter as the anode. This seems to be justified as optical measurements by Cummings [2] show that the discharge channel is filling nearly almost the internal cathode to anode space.

The calculated self-inductance thus is easily found:

$$L \doteq 3o \text{ nH} \quad \text{(GL 7703, coaxial mounting)}$$

Measurements in a condenser discharge circuit gave a value of about 4o - 45 nH. It should be noted that the self-inductance is not a constant though it is convenient to take a mean value for circuit calculations. At the start of breakdown in which the discharge channel is anchored only at a small cathode spot, higher values of inductivity can be expected.

3.4 The current and voltage ratings

3.41 The hold-off voltage

Small Ignitrons with a simple construction i.e. without the use of potential grids will usually be limited to an operational voltage of 2o kV. Some Ignitrons of larger construction may hold 25 kV or more (e.g. Bk 178 or Bk 194) but for use with higher voltage special Ignitrons with built-in control-grids are available (e.g. General Electric Z 5234 for 8o kV). Ignitrons of this type have not been investigated.

Before an Ignitron is put into service some preconditioning is necessary.

a) Mercury droplets on the internal surface of the anode glas seal can cause voltage breakdown and local damage on the glas surface. Therefore by heating of the upper part and simultaneous cooling of the lower part (cathode) a distillation of mercury will remove it from the anode region. It is clear that from this further on the Ignitron should be kept in an upright position.

b) Residual gas can be removed by low energy discharges the effect of which is binding the gas molecules to the surface of electrodes (gettering). A small condenser (e.g. o.1 μF) is charged via a high ohmic resistor and is discharged through a limiting resistor into the Ignitron. The voltage of the DC-supply has to be high enough for self-ignition of the Ignitron and this charge--discharge cycle should be maintained over a suitable period until the breakdown voltage has improved to its final value. Normally with graphite anode Ignitrons (WL 83o6 = WX 4231) the breakdown voltage of a new and conditioned tube should be above 25 kV, whereas tubes with metal anodes can reach values up to 4o kV. This only can be contributed to much better electrode surface and better vacuum for the metal anode Ignitron. In fig. 12 the statistical distribution of breakdown voltage measured for 76 Ignitrons (WL 83o6) is shown.

During the normal operation with high currents the breakdown voltage decreases with increasing number of shots as a consequence of vacuum degrading and surface roughening. Besides this, occasional prefires occure after which normal voltage holding is regained. This rate of self-ignition is of great importance when many units shall be operated in parallel in a large capacitorbank. In fig. 13 some data on self-ignition in dependence of current are shown. Best values are obtained with metal anode tubes SAS "pure metal" and GL 77o3 and results range from 1 to 1o prefires in 1o,ooo discharges.

3.42 The tolerable current and the effect of its waveshape

The current intensity and its waveshape are determining factors for the life of an Ignitron. To classify different Ignitron types it has proved useful distinct between:

a) The maximum operational current

This shall be called the current intensity for which a sufficient life can be expected. Its value is connected with the waveshape, i.e. whether it is a ringing discharge or a single pulse (crowbar, critically damped). At the end of this report values will be listed for different types. In general the cheaper graphite anode tube will withstand less current than metal anode ones.

b) The maximum fault current

This current should not be exceeded because it will be the limit of current above which the Ignitron will become faulty within a small number of shots.

c) The total charge

The total charge given by the integral $Q = \int i \, dt$ for one pulse, it defines the capability of a certain ignitron to carry the operational maximum currunt during the given period. Though the available data on this items are rare, the following ratings may be taken as a guide:

Size A	Ignitrons (graphite) (WL 8306, NL 1037)	10-15 coulombs
Size A	Ignitrons (metal) (GL 7703, NL 1039,SAS)	20-30 coulombs
Size D	Ignitrons (Bk 178)	200 coulombs
Size E	Ignitrons (Bk 194)	400 coulombs

d) The effect of the current waveshape

The current waveshape in a capacitor discharge circuit will be either oscillatory or a single pulse (e.g. crowbarpulse, fast rising, slowly decaying).

All Ignitrons are suitable for both types of waveshapes but for two reasons a limitation in the current duration is necessary:

a) A limited internal heat capacity.

b) the arc transfer to the Ignitron walls.

If the allowable total charge and the peak current are known, it is easy to find the corresponding values for frequency, current reversal, and time constant (in the case of a single pulse). Values found by this method have been calculated and are given in the reference list. The maximum pulse duration should not be exceeded even if calculation for smaller currents would suggest so. Cummings [2] measured the arc to wall transfer time in a 5550-Ignitron (e.g. Wx4231) and found that the arc transfers within 1 millisec from the cathode to the wall in a 10 kA discharge. Though the pulse duration is acceptable as far as the charge is concerned (10 As), the arc transfer would cauce vacuum degrading and thus such a long pulse has to be avoided.

3.5 The Ignitron life

The life of an Ignitron will be called the total number of shots for a given current, waveshape and charge found in a test. The end of life is indicated:

a) when the breakdown-voltage becomes insufficiently low or,

b) when triggering fails.

Both kind of faults have been observed.

Life figures obtained by testing only one sample have to be taken with some precaution, as the spread in life from sample to sample can be great. But tests of this kind are time-consuming and expensive and therefore it was impossible to carry out large scale lifetests with all tubes in question.

Fig. 14 shows a typical distribution of life for graphite anode Ignitrons WL 8306 obtained by testing two batches (batch A 14 Ignitrons, batch B 8 Ignitrons[x)]) tested at the same current (50 kA) but two different voltages (batch A at 18 kv, batch B at 10 kv). The end of life with WL 8306 tubes in all cases was a rapidly increasing rate of prefire and finally loss in voltage hold-off. Thus a mean life (50% probability) of 6000 - 7000 pulses has been found for both conditions.

x) Testresult by van Mark, IPP

Further test results:

Test I GL 7703

130 kcs, 3 pulses/min voltage 18 kv:

Test stopped after 22,000 pulses, as the demanded life (life should be greater than 20,000 pulses, which is a typical requirement in plasma research) has been reached. No decrease in hold-off voltage could be detected, but a decrease in ignitor resistance was observed. Triggering was maintained by raising the trigger voltage (see also section 3.1).

Total number of prefires: 14

Test II GL 7703 x)

Current: 27 kA, crowbarred (T_{cr} = 50 µsec)
Voltage: 10 kv 12 pulses/min

Tube	No 1	 71,400	discharges
	No 2	 39,291	"
	No 3	 20,045	"
	No 4	 17,723	"
	No 5	 3,718	"

End of life: triggering failed in all cases, no prefires observed.

Test III NL 1037 x)

Current: 27 kA
Crowbar shape T_{cr} = 50 µsec
Voltage: 10 kv, 12 pulses/min

2 samples tested each 200,000 discharges. Test stopped as original condition (life greater 200,000) was achieved. No prefires observed.

x) Test by J. Reinke, Max-Planck Institut für Physik, München

Test IV SAS "pure metal anode"

Comparison test to test I:

Current: 90 kA, voltage 18 kv

Test stopped after 20,000 discharges as the requirement was satisfied. Total numbér of prefires: 12 .

Test V SAS "pure metal anode" (Lit. [5])

Current: 79 kA, ringing discharge 90 kcs
Voltage: 18 kv
8,000 discharges, 1 prefire.

4. Ignitron reference list

In this list Ignitrons used during past years, or expected to be of interest for future applications are listed. Most of the data has been established by experience with discharge circuits in research laboratories or testing programs in industry.

5. Acknowledgement

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Fig. 13 Rate of Self-Ignition

Fig. 14 Statistical Life of WL 83o6

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IGNITRON - REFERENCE - LIST

Ignitrontype	GL 7171	WX 4231 = WX 5018 = WL 8306	GL 7703	SAS stainless steel	SAS pure metal	NL 1037	NL 1039	Bk 178	Bk 194
Manufacturer	GE	W	GE	SW	SW	NE	NE	BTH	BTH
Size (Diameter) Anode material	A (2") Graphite	A (2") Graphite	A (2") Molybden	A (2") stainless Steel	A(2") "pure"Metal	A (2") Graphite	A (2") Molybden	D (5 1/2 ") Graphite	E (9") Graphite
Peak Anode voltage (kV)	10	20	20	20	20	20	20	25	25
Peak Current (kA)	35	35 (50*)	100	50	50 (90*)	100 (50*)	100	40	80
Fault Current (kA)	60-90*	60-90*	120*	90*	120*	90*	120*	100	150
Peak charge/pulse (As)	15*	18 (15*)	30 (20*)	17	17	45 (15*)	45 (20*)	200	400
Oscillation: Current (kA)	35	35*	100	50	50 (90*)	50*	100	40*	80*
Oscillation: Period (µsec)	200	240 (200*)	140	160	160 (90*)	160	140	2300	2300
Oscillation: Current reversal (%)	85	85	85	85	85	85	85	85	85
Single Pulse: Current (kA)	35	35	35 (60*)	50	50	50	50	40	80
Single Pulse: Time Constant (e-Decay) (µsec)	430	510 (430*)	850 (330*)	340	340	900 (300*)	900 (400*)	5000	5000
Max. Pulse duration (msec)	1,5	1,5	3 (2*)	1,5	1,5	3 (1,5*)	3 (2*)	150 (20*)	150 (20*)
Pulses / minute	1	2	2 (3*)	5 (3*)	5 (3*)	2*	2	12	12
Resistance (m Ω) (current peak)	6	6	3	5	5 (3*)	not known	3	not known	not known
Inductance (nH) minim.	40	40	40	40	40	40	40	80 - 100	80 - 100
estim. Life at peak current (pulses)	10^4	10^4 (5.10^3)	2.10^4	2.10^4	2.10^4	2.10^4	2.10^4	2.10^4	2.10^4

Abbreviations:

GE General Electric USA
W Westinghouse USA
SW Schneider-Westinghouse France
BTH British Thomsen Housten England

NE: National Electronics USA
* : Own measurement or estimate

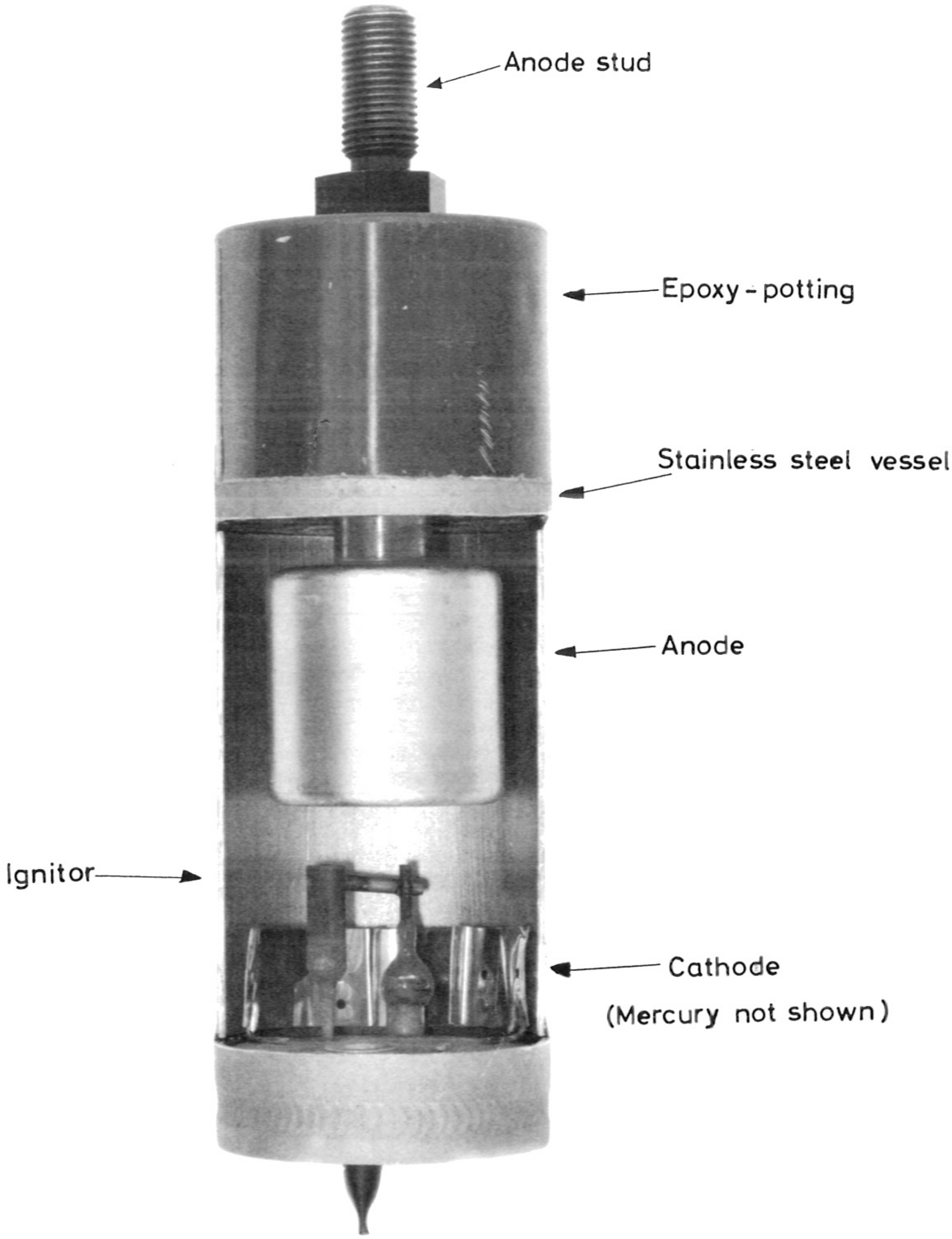


Fig. 1 Typical construction of a Pulse-Ignitron

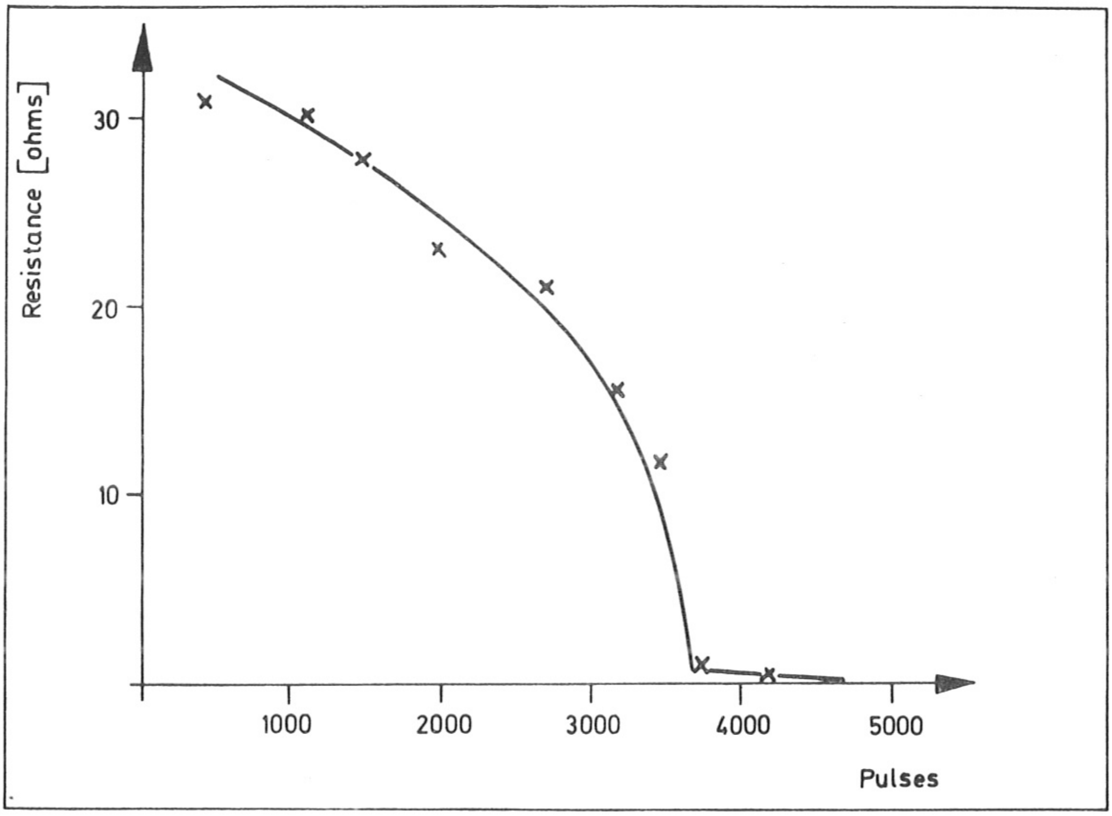


Fig. 2 Change of Ignitor - Resistance
Ignitron GL 7703 90 kA 130 kcs damped

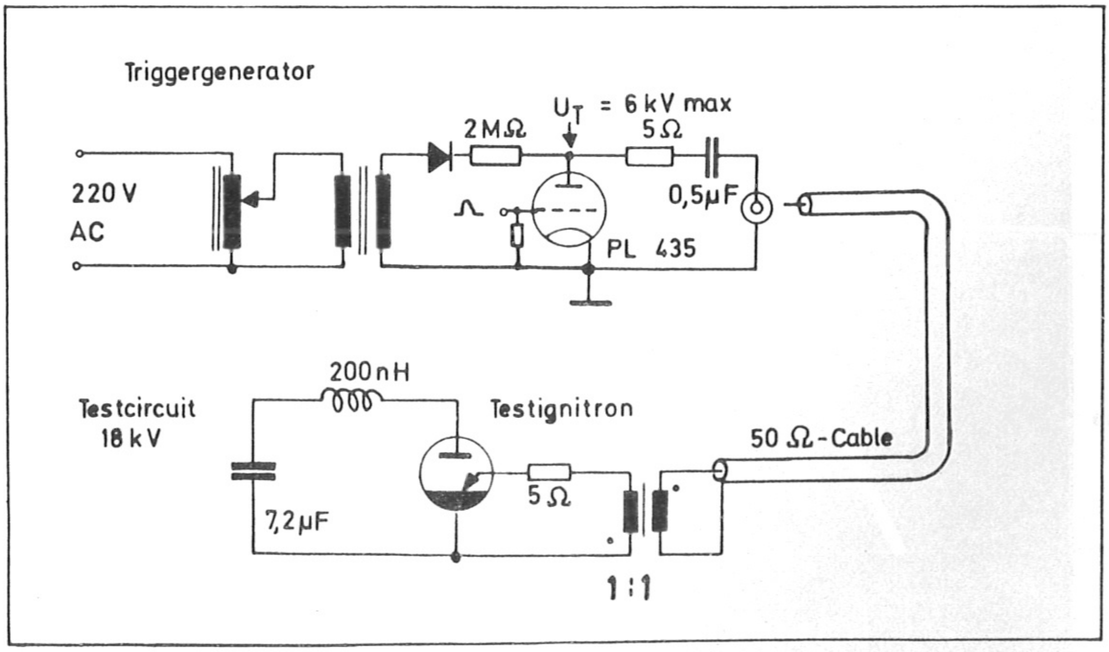


Fig. 3 Ignitron Triggercircuit

Fig.4a Voltage on load inductance

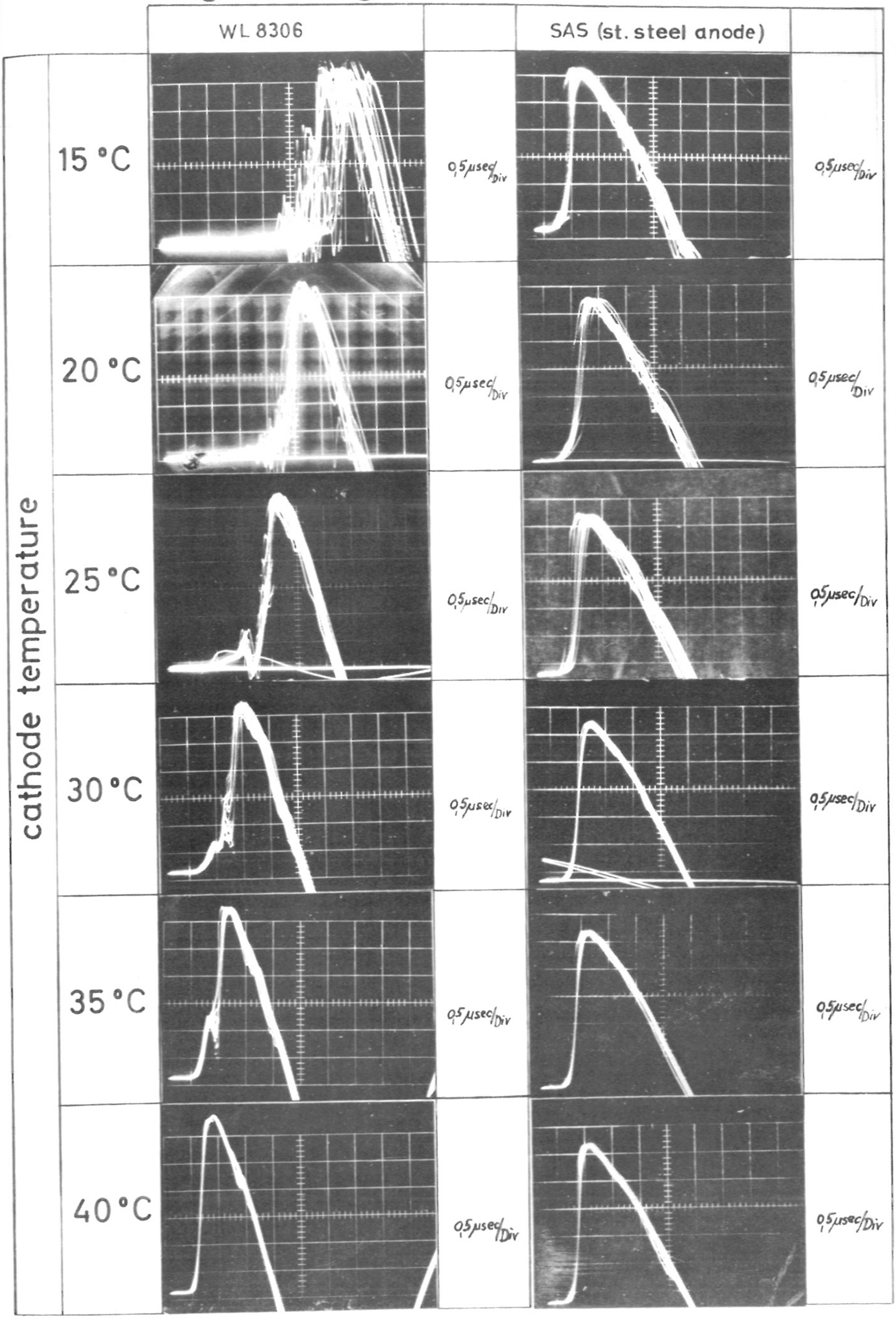
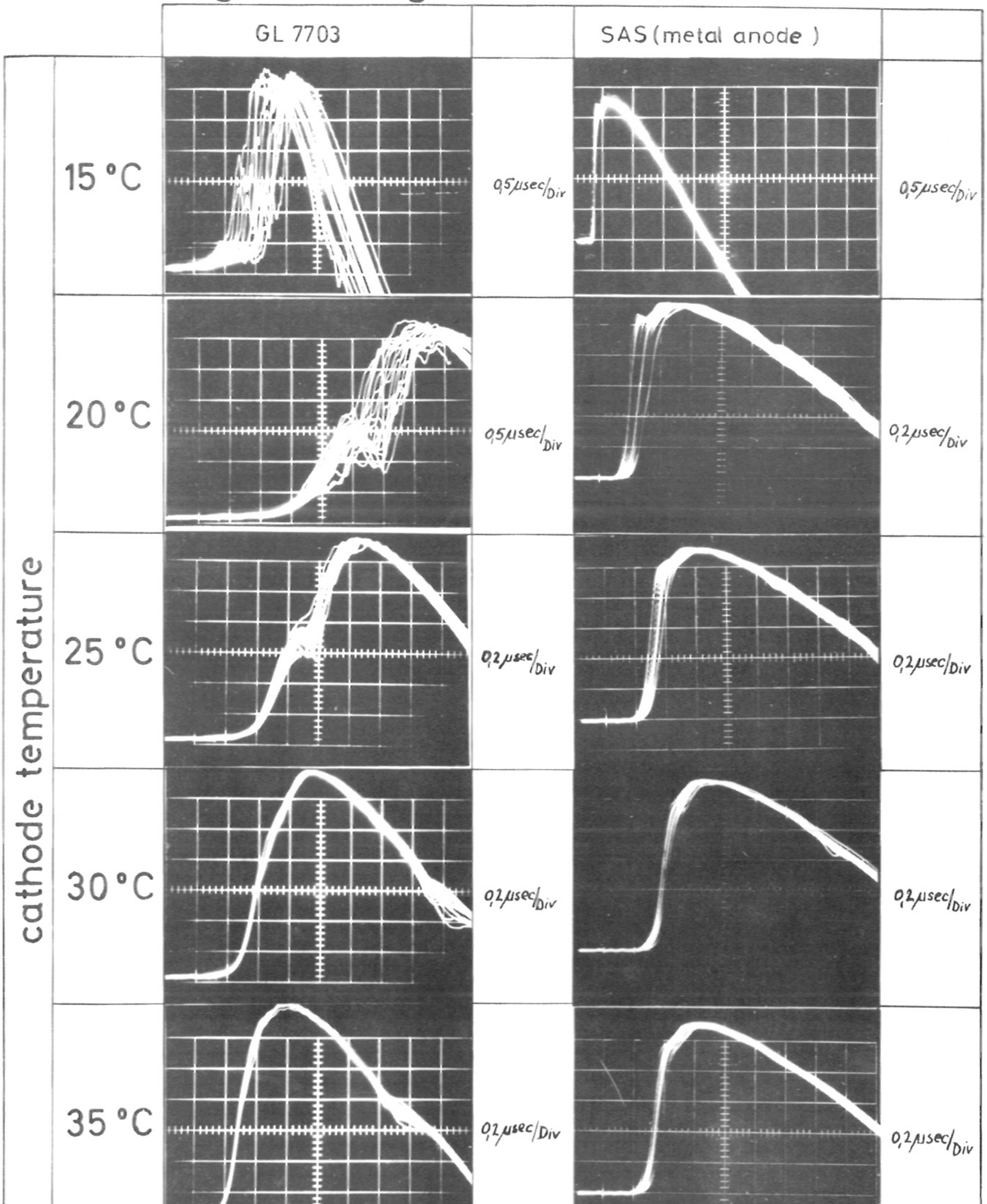


Fig. 4b Voltage on load inductance



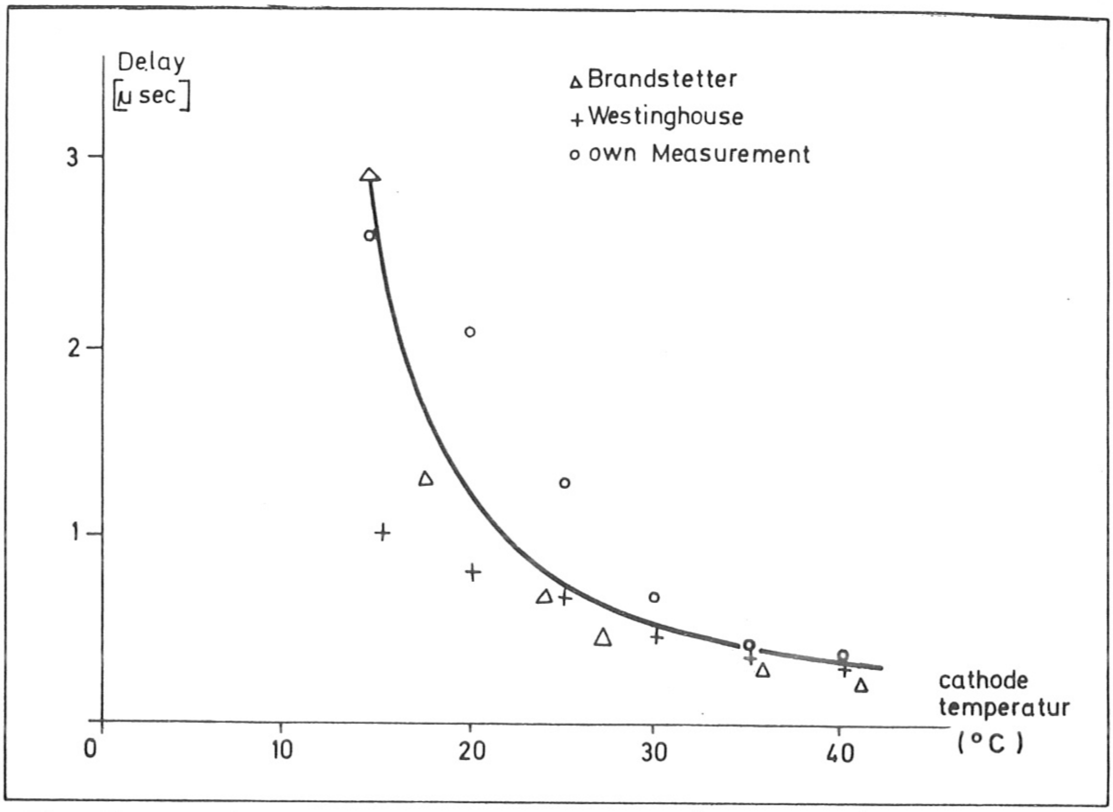


Fig. 5a Ignition Delay of WL 8306 (WX 4231) Ignitron

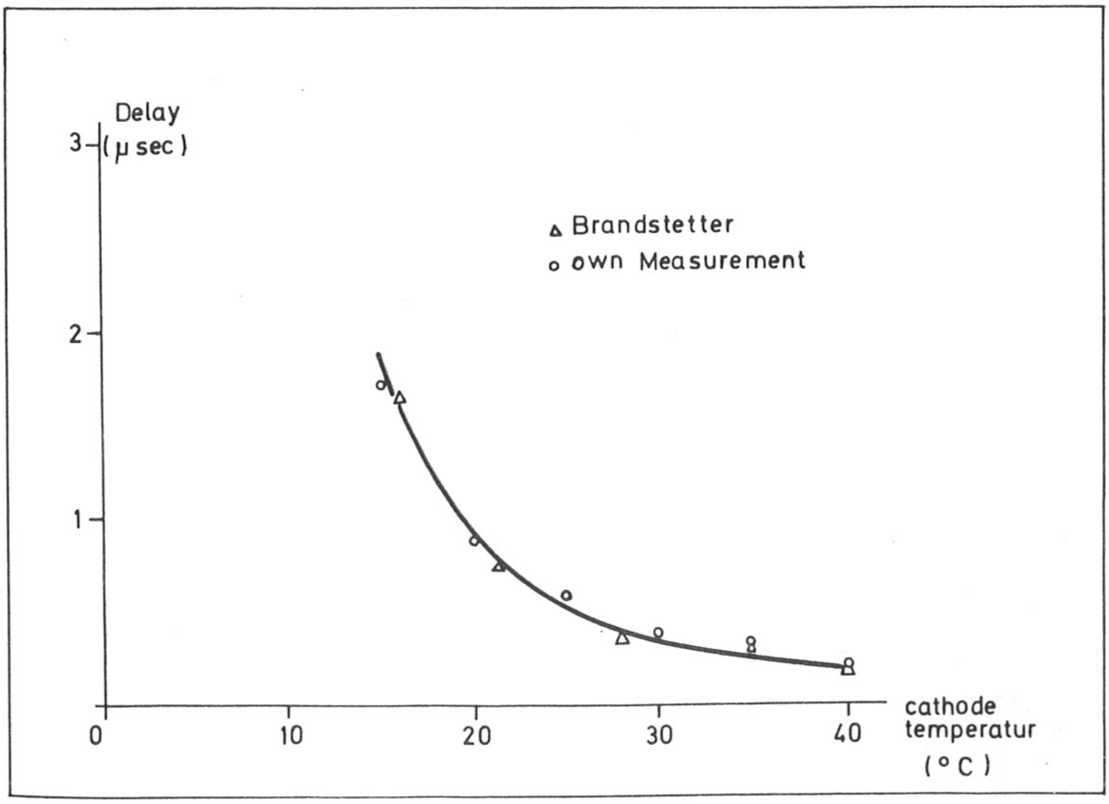


Fig. 5b Ignition Delay of GL 7703 Ignitron

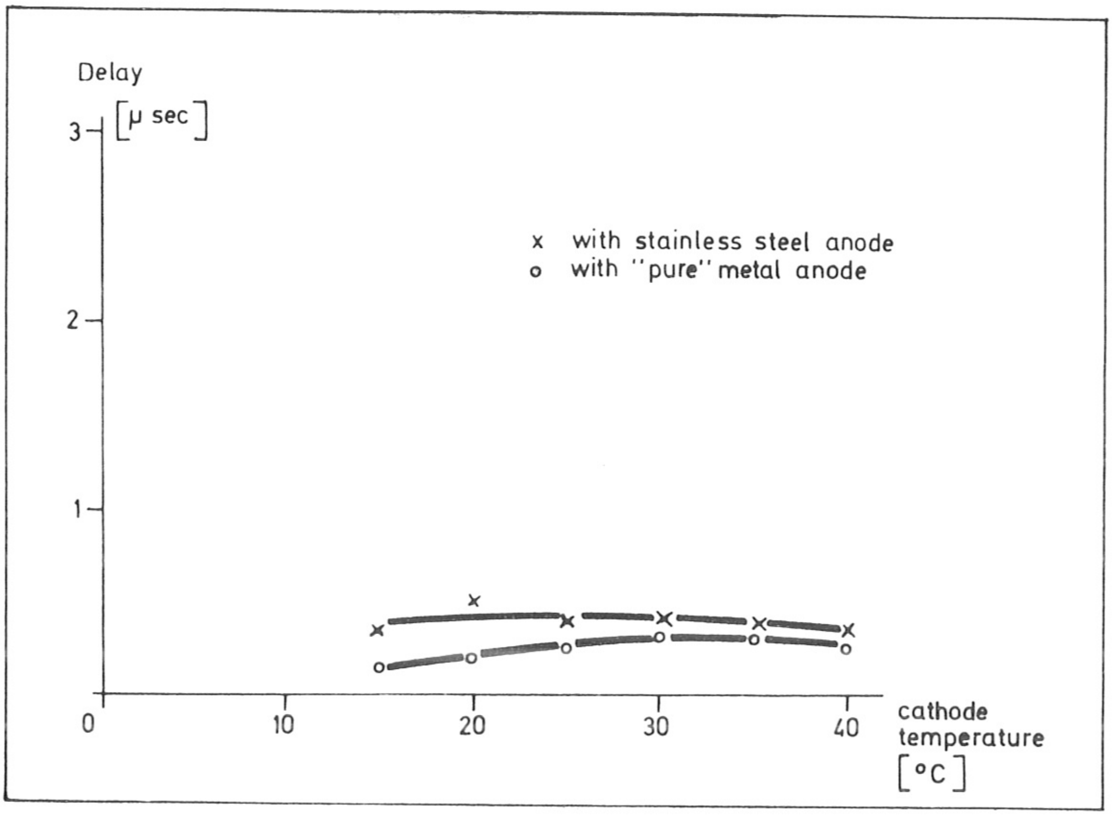


Fig. 5c Ignition Delay of SAS – Ignitron

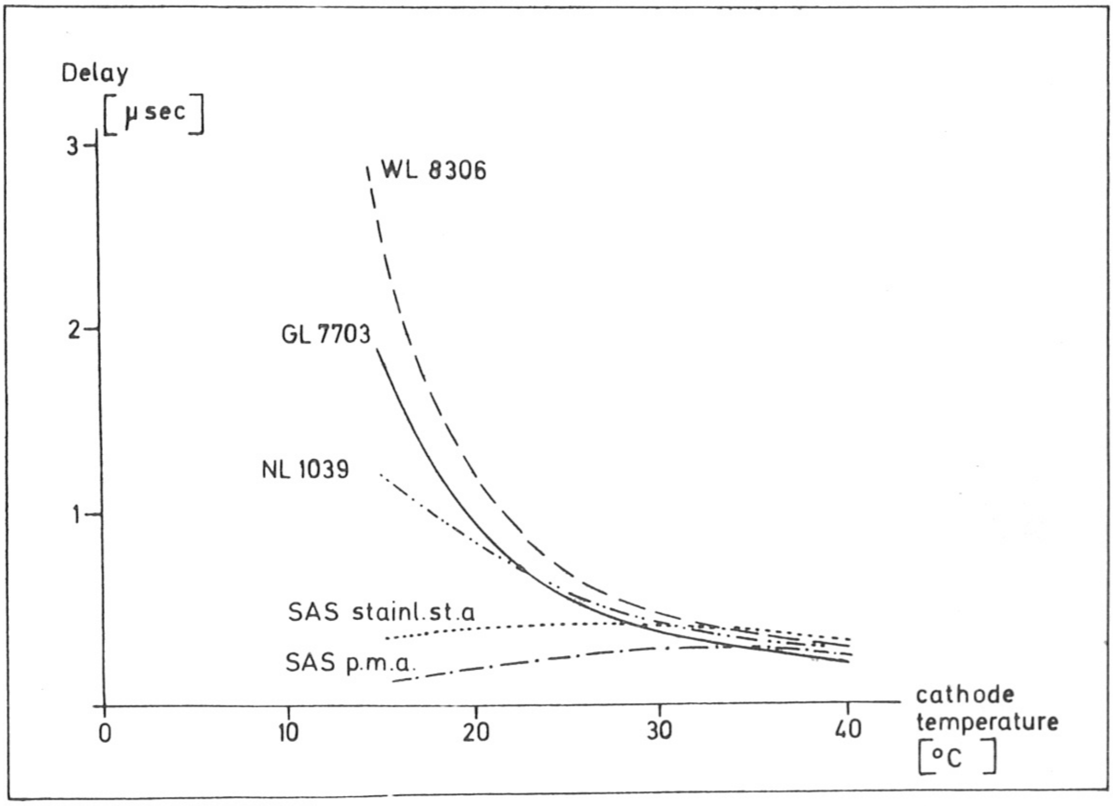


Fig. 5d Ignition delay in dependance of cathode temperature for different makes of size A Ignitrons

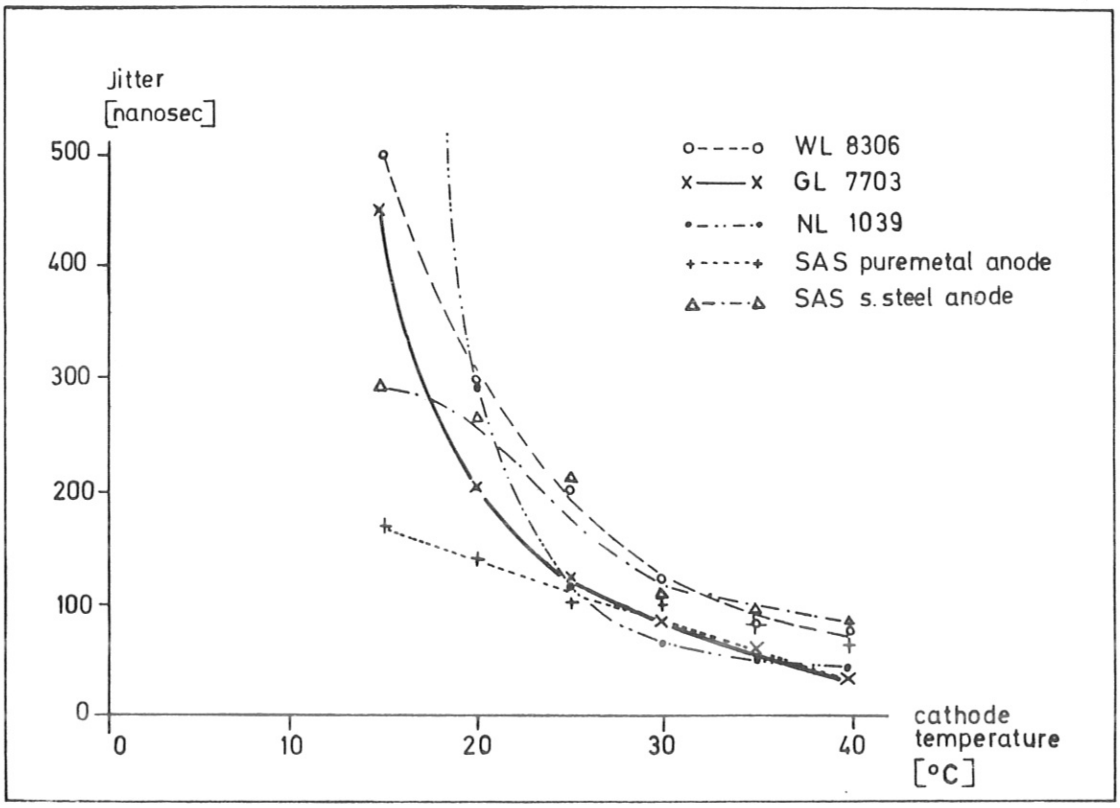


Fig. 6 Jitter in dependance of cathode temperature for different makes of size A Ignitrons

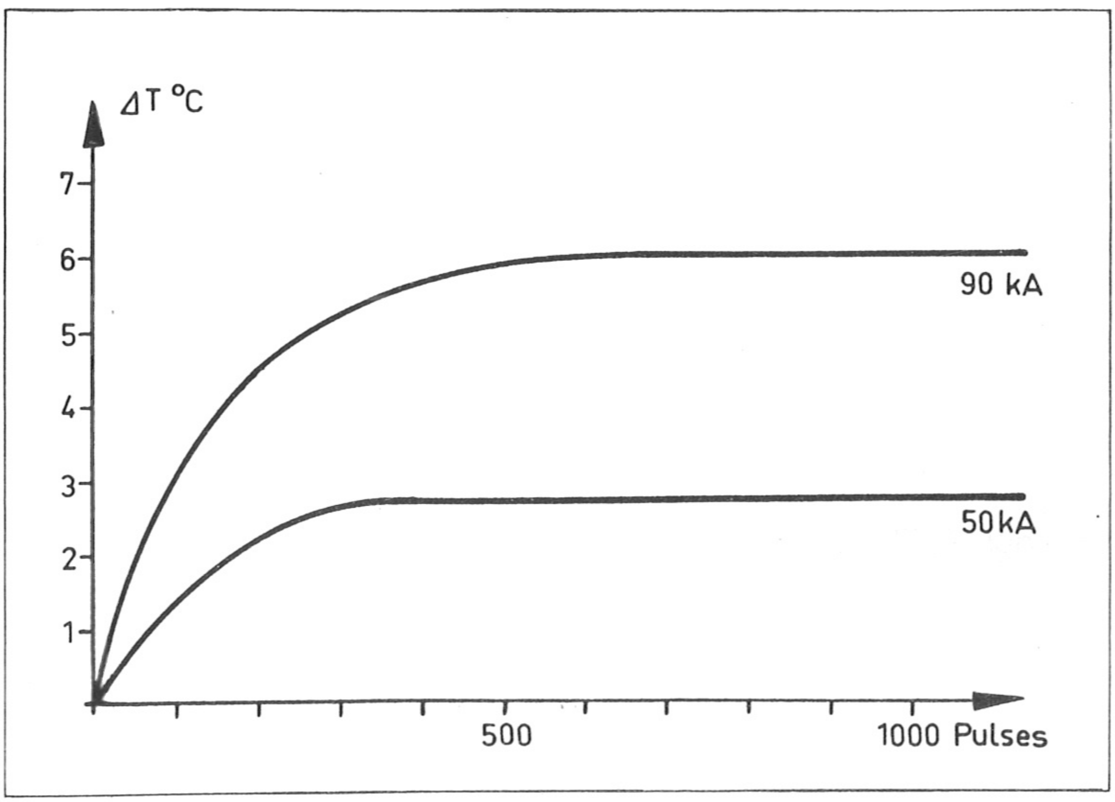


Fig. 7 Heating of ignitron cathode in pulsed operation (pulse sequence 30 sec.)

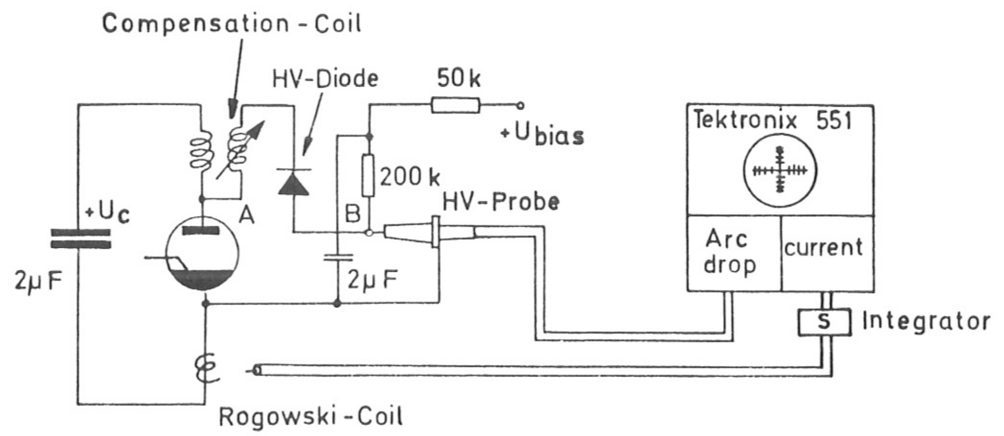


Fig. 8 Measurement of arc drop in the Ignitron

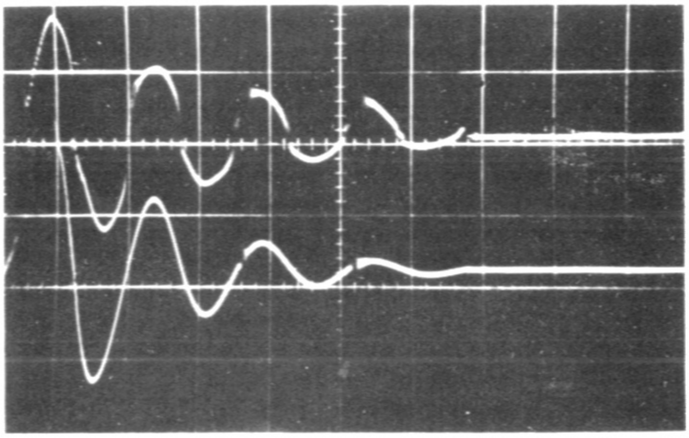
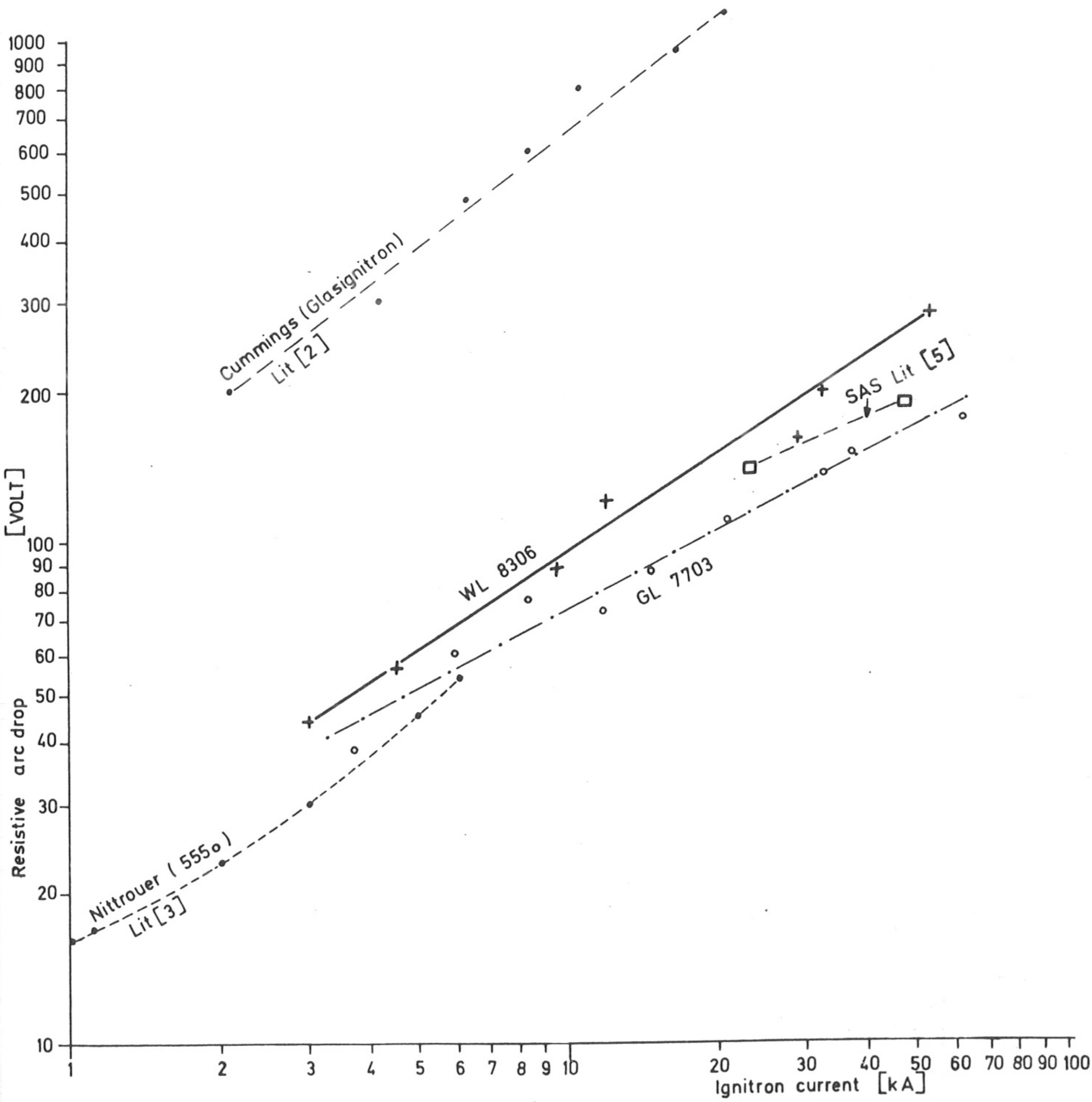


Fig. 9 Measurement of arc drop in the GL 7703 Ignitron

Fig. 10 Resistive Arc drop in the Ignitron



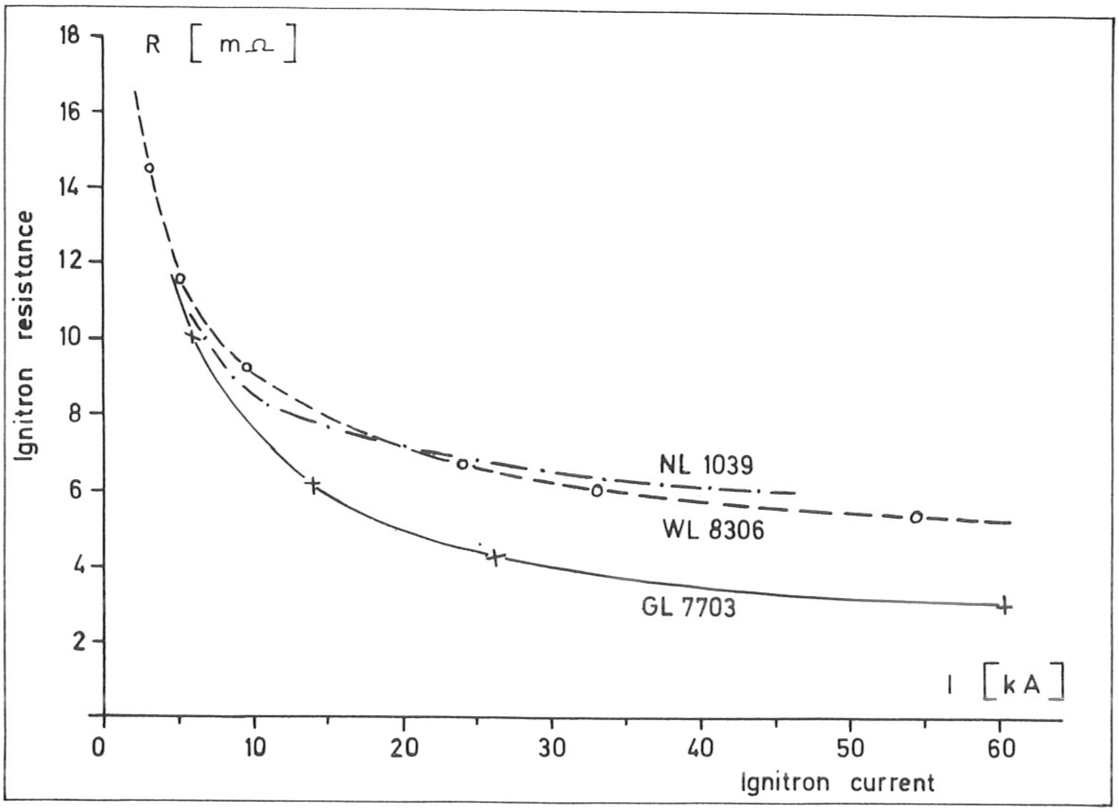


Fig. 11 Internal Ignitronresistance

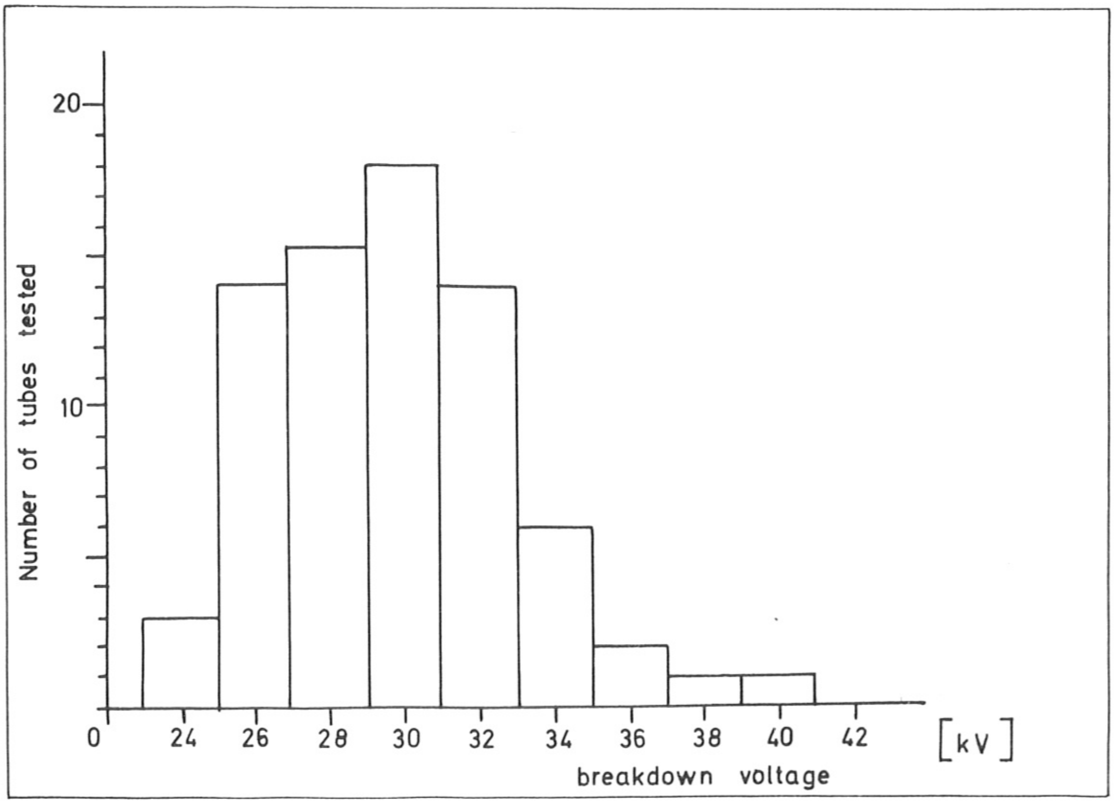


Fig. 12 Distribution of breakdown voltage measured for 76 tubes WX 4231 (WL 8306) after conditioning and before applying high current

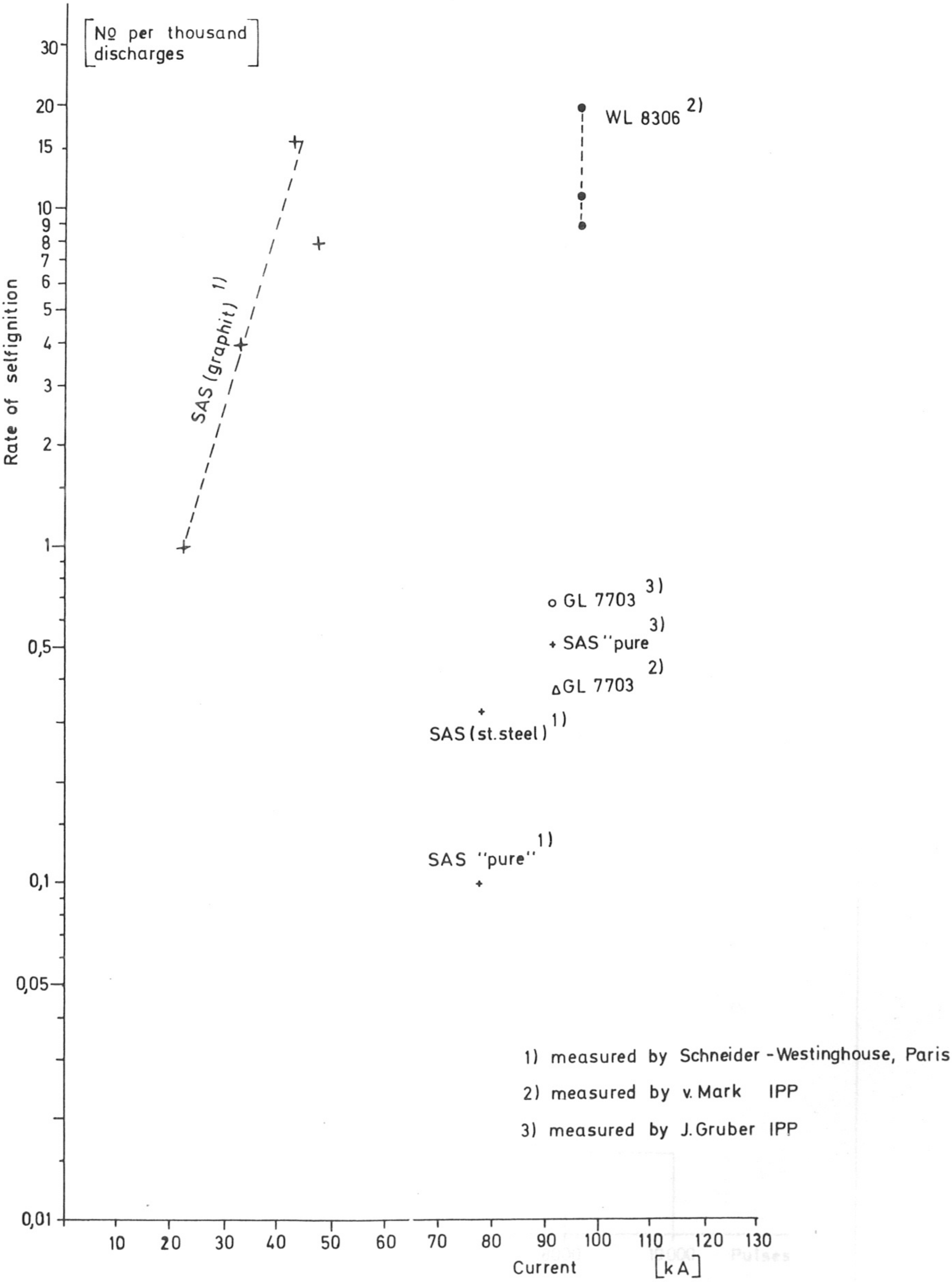


Fig. 13 Rate of selfignition for oscillatory current and 18 kV bank charging

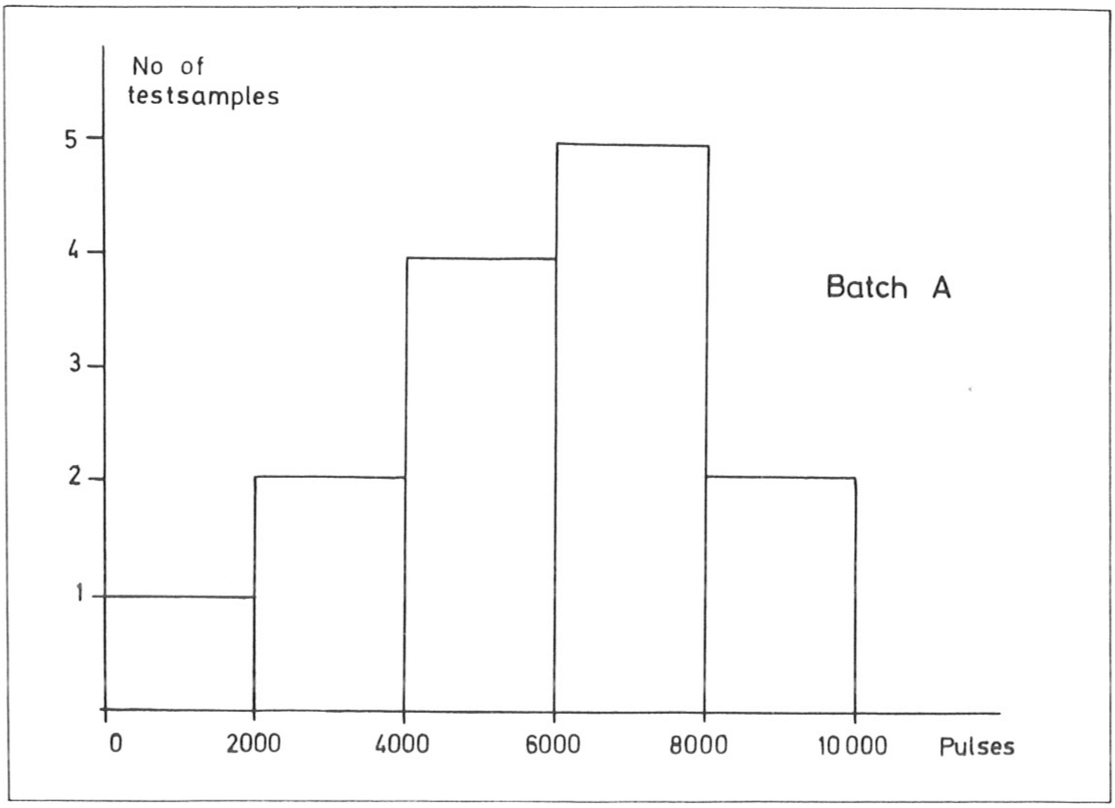


Fig. 14a Life of WL 8306 (WX 4231) Ignitron
48 kA 18 kV crowbared

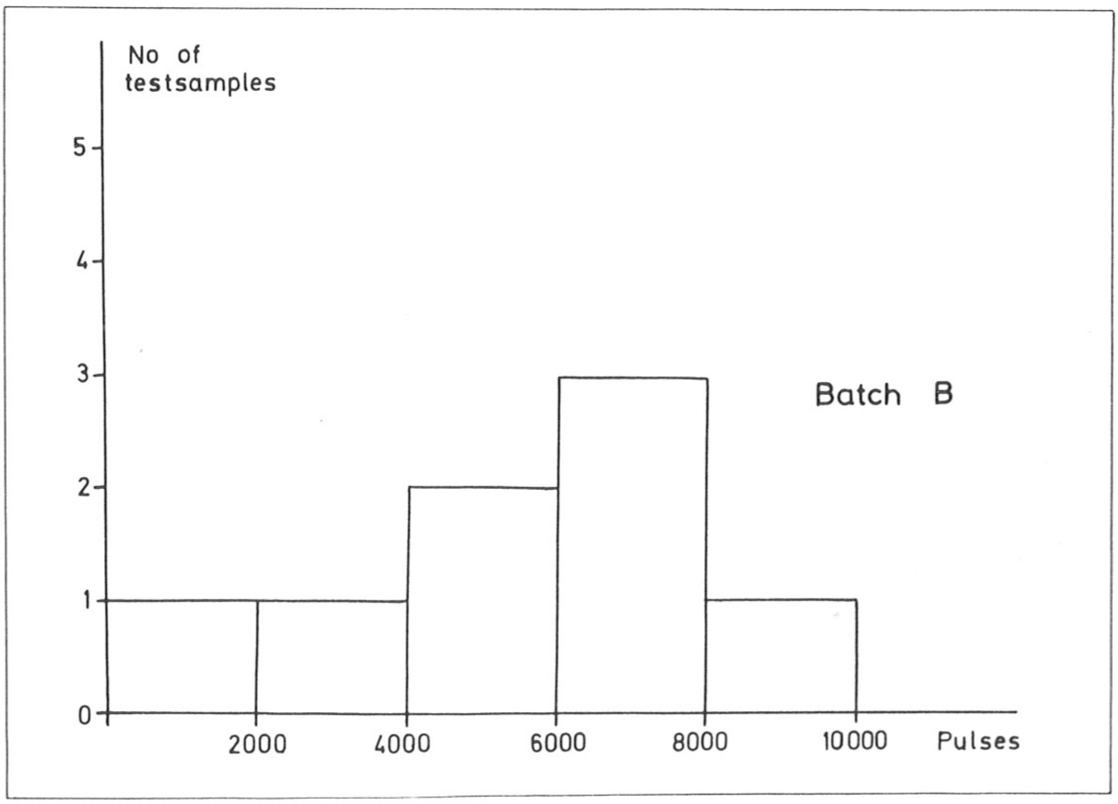


Fig. 14b Life of WL 8306 (WX 4231) Ignitron
50 kA 10 kV ringing

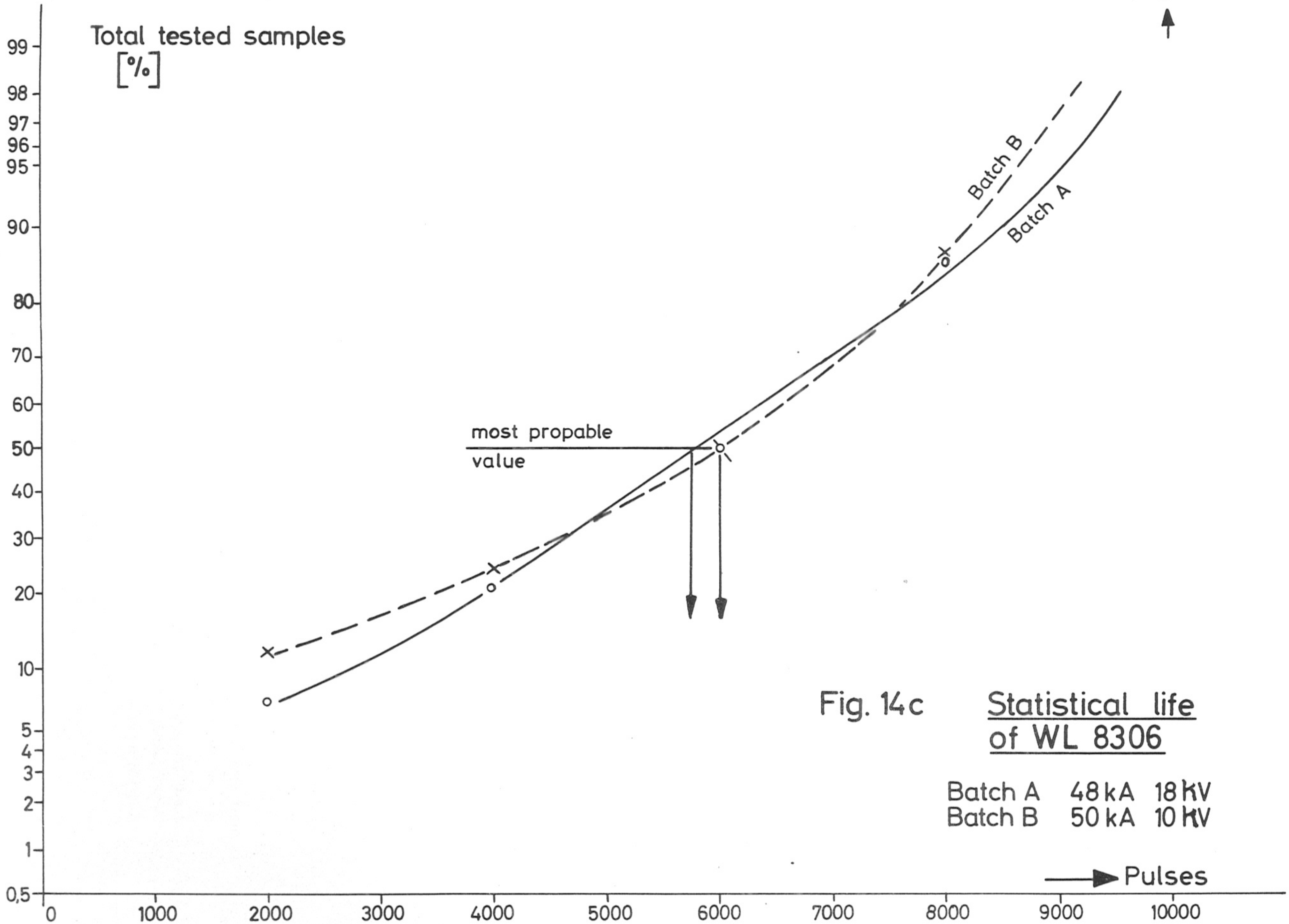


Fig. 14c Statistical life of WL 8306