Measurements of time constants on cascade d.c. arc in nitrogen

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MEASUREMENTS OF TIME CONSTANTS ON CASCADE D.C. ARC IN NITROGEN

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Measurements of Time Constants on Cascade D.C. Arc in Nitrogen

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Measurements of Time Constants on Cascade DC Arc in Nitrogen.

Abstract.

Results of measurements on a cascade arc in local thermodynamic equilibrium with 5 mm bore diameter in nitrogen are presented. Electrical time constants up to 50 amp d.c. current were derived for 1 atm nitrogen pressure.
Two exponentials were found, in general, in the decay of the voltage response on a current step (with exceptions of small arc currents).
Relations between different definitions of time constants and arc current are graphically illustrated.
These measurements were carried out in the laboratory of The High Voltage-High Current Institute of The Technological University Eindhoven (The Netherlands) under guidance and counsel of its head:
Prof.Dr. D.Th.J. ter Horst.

1. Introduction.

A circuit breaker clearing a section of a transmission system in case of a fault separates its contacts under current flow, leading to an electrical discharge. This discharge should be cleared as soon as possible.

In many cases this discharge can be seen as an arc in local thermodynamic equilibrium. The study of electric conductance of the arc and its variation as a function of temperature and pressure became a topic of investigations. Due to its heat content the arc shows a certain delay in changing the arc voltage when the arc current varies. This fact has a direct relation with the reignition of the a.c. arc during the time immediately after current zero.

The time delay is characterized by a thermal time constant.

It is not so easy to measure the thermal time constant directly. Usually this thermal time constant is obtained from an electrical time constant θ. In order to derive θ the method of analyzing of the voltage response on a sudden current change was used by many investigators (ref. 2-5).

This paper tries to bring forward some more details about the relations between the time constant and arc current.

2. Time Constants Measuring Methods.

The response of a steady d.c. arc in local thermodynamic equilibrium (L.T.E.) to a current step is a sudden voltage change which after a certain time returns to the value given by the static UI characteristic. The current step perturbation must be so steep, that the arc under investigation remains in L.T.E. during the time the perturbation step is growing. In this case the increase of the arc voltage due to a sudden current change is given by the arc impedance at the given point of the UI characteristic and the amplitude of the current step ΔI only. The initial voltage response U_1 decreases slowly to the value U_∞ given by the steady UI arc characteristic for the current ($I + \Delta I$).
The rate of decay of the voltage response is given by arc properties such as accumulated heat Q_o and heat loss N. For this reason a time constant θ_T was defined by Mayr (ref. 1) and later by Yoon and Spindle (ref. 2) as $\theta_T = Q_o/N$. These investigators suppose a simple exponential decay of the voltage response only. In this case θ_T can be derived by measuring the time T after which the curve of the voltage response reaches again the value U_o (see fig. 1).
The time constant θ_T can be derived from T by means of the following equation (ref. 2) :

$$\theta_T = \frac{T}{\ln \frac{U_o I_\infty - U_\infty I_o}{I_\infty (U_o - U_\infty)}} \qquad (1)$$

Here is

U_o - steady state voltage at the time t = 0
I_o - steady state current at the time t = 0
U_∞ - new steady state voltage
I_∞ - new steady state current.

In case the voltage response consists of a simple exponential decay, plotting as a function of time in a semi-log scale should lead to a straight line, the slope of which determines θ_s.
However, Pflanz (ref. 3), pointed out that, in general, there is at small values of time an other exponential voltage decay superimposed on the straight line. From this latter decay a second time constant $\theta_f < \theta_s$ can be derived.
Pflanz (ref. 3) demonstrated the relation between the properties of the arc shell and θ_s and the arc core and θ_f. Later Edels and Graffmann (ref. 4) found also in some cases two time constants, but these authors limited their further work mainly to cases where only one time constant should be found.
Pflanz (ref. 3) has derived the following expression for obtaining the time constant θ_s (under the condition that $t_A, t_B \geqq 3\,\theta_s$)

$$\theta_s = \frac{t_A - t_B}{\ln \dfrac{U_B - U_\infty}{U_A - U_\infty}} \tag{2}$$

Here is

U_A - voltage at the time t_A
U_B - voltage at the time t_B

In order to find out to what difference (1) and (2) lead we shall introduce the modulation ratio $m = \frac{\Delta I}{I}$. We suppose also that in the small region of the arc current within the limits I and ($I + \Delta I$) the following equation holds (ref. 2) :

$$U\, I^{a} = \text{const.} \tag{3}$$

In that case the equation (1) can be rewritten as:

$$\frac{1}{\theta_T} = \frac{1}{T} \ln \frac{(1+m)^{a+1} - 1}{(1+m)\left[(1+m)^{a} - 1\right]} \tag{4}$$

Introducing the same conditions in eq. (2) i.e. for $t_B = 0$ is $U_B = U_o\,(1 + m)$ and for $t_A = T$ is $U_A = U_o$, we obtain

$$\frac{1}{\theta_S} = \frac{1}{T}\ln\frac{(1+m)^{a+1}-1}{(1+m)^{a}-1} \tag{5}$$

Comparing (4) and (5) we arrive at

$$\frac{1}{\theta_T} = \frac{1}{\theta_S} - \frac{1}{T}\ln(1+m) \tag{6}$$

Assuming $m \ll 1$ both equations (4) and (5) lead to the result

$$\theta_T = \theta_S \simeq \frac{T}{\ln(1+\frac{1}{a})} \tag{7}$$

3. Derivation of α.

The time constants mentioned above are based on the validity of eq. (3). In order to check whether this equation holds within the limits I_o and $(I_o + \Delta I_o)$ we measured the static UI characteristic (fig. 2). Fig. 3 shows the comparison of our measurements with the results obtained by other investigators (ref. 3, 6, 7) under similar conditions. There seems to be more or less agreement.
Admitting the validity of (3) for $I_o < I < (I_o + \Delta I_o)$ we can derive α from the voltage response in the following way:
The voltage amplitude due to current step modulation at the time $t = 0$ is $\Delta U = U_o.m$. With the values of $(U_1 - U_o)$ and $(U_o - U_\infty)$ obtained from oscillographic records we arrive at

$$\frac{U_o - U_\infty}{U_1 - U_o} = \frac{1}{m}\left[1 - \frac{1}{(1+m)^{a}}\right] \tag{8}$$

5. Electric circuits.

The feeding circuit for currents between 4 and 50 amp. is shown in fig. 8. The arc current could be set in steps by variation of the resistance R or continiously by variation of the output voltage of the d.c. generator 500 V/200 amp. For currents below 4 amp. the generator voltage was too low. Therefore a 10 kV d.c. source (fig. 9) was applied, obtained by six-phase rectifying of a 500 c/s a.c voltage and using LC filter of 2 x 110 μF/1 H.

The maximum voltage over the arc chamber was limited to 3 kV by means of a spark gap.

Particular care was given to the modulating circuit.

For the generation of current steps a separate modulating circuit was designed in such a way (fig. 10) that it enabled us to keep the impedance of the feeder circuit so high that the modulating current was only negligibly influenced by the feeding circuit.

The current step should be as steep as possible and its value should remain constant during the whole decay of the voltage response.

Therefore the modulating circuit itself should show as small an inductivity as possible.

For this reason the circuit was designed as a coaxial structure. The capacitance C was obtained from a parallel connection of 12 coaxial capacitors of 0,25 μF/3 kV, the resistors R_1 and R_2 were of "morganite" type. The capacitors C_c were used with small arc current. They improved the steepness of the modulating step. The steepness of the current step was influenced favorably by locating the capacitor C between the resistors R_1 and R_2 ($R_2 = 2 R_1$).

Records of voltage responses and modulating currents were obtained with a Tektronix type 555 C.R.O. During some measurements the two traces of the osciloscope were used for current step and voltage response, in other cases the voltage response was recorded with a different time basis (e.g. 5 us/div and 50 us/div). In such a way it was possible to obtain as well the amplitude at the beginning of the voltage response with a reasonable accuracy as the amplitude towards the end.

6. Experimental Results.

Some 3000 voltage responses have been recorded photographically and plotted in semi-log scale. This fairly large number of measurements kept the accuracy of the measuring results within the limits of 5%. Typical records are shown in fig. 11a and 11b, the plotting can be seen in fig. 12 (the maximum amplitude was put equal 100%). From the slope of each voltage response the time constant θ_s and the amplitude A were derived. The time constant θ_f was obtained by replotting the difference Δ between the straight line and the real response in semi-log scale (comp. fig. 13).

From the photographic record the time T and the values ($U_o - U_\infty$) and ($U_1 - U_o$) were also measured, so that the values of θ_T and α could be derived. Average values of all variables versus the arc current are given in fig. 14 - 18.

For currents below 1,6 amp. only one time constant θ_s could be found. The voltage response of arcs with larger currents showed two time constants θ_s and θ_f.

At low currents the time constant θ_s increases with increasing current up to about 3 amp., then it decreases with arc current up to about 18 amp. and afterwards it begins to increase again. In fig. 14 our measurements are compared with those of Pflanz (ref. 3) and Edels and Graffmann (ref. 4). At the arc current of 18 amp. the curves of θ_s, θ_f, T and θ_T show a minimum. It is interesting to notice that Maecker (ref. 6) found for his channel-model arc in nitrogen, where constant electrical conductivity and temperature were supposed, a curve for the effective radius of the conductive zone which shows a maximum at about 3 amp. and a minimum at about 17 - 18 amp. This is in agreement with our curve for θ_s (fig. 14).

Comparing the curves of θ_s (fig. 14) and θ_T (fig. 16) we can see agreement between both time constants up to 1,6 amp.

Further increase of the current reveals that the difference between θ_s and θ_T becomes larger ($\theta_T < \theta_s$). The explanation is as follows. With larger currents the voltage response consists of two exponentials. The derivation of θ_T is based on the assumption that only one exponential exists. The maximum amplitude of the voltage response is given by the arc impedance and the modulating current step.

By measuring the time T we measure a value which depends on both exponential decays and is no longer characteristic for θ_T.
As $\theta_f < \theta_s$ the measured time T must be shorter than the time T' that could be found if only one exponential was present in the voltage response. Thus the following conclusion could be made: The voltage response has a simple exponential decay as far as θ_s is equal to θ_T.
The dividing point was found in our measurements at $I = 1,6$ amp.
The influence of the faster time constant θ_f on the decay of the voltage response can be easily observed in fig. 18. Up to about 1,6 amp. θ_f can be hardly mentioned because its amplitude is smaller than 5% of the total deflection and so it falls within the limits of the measuring faults. The value of 1,6 amp. seems to be the origin of the core formation (in our conditions) as the observations of θ_f show.
With the increasing arc current the influence of θ_f increases rapidly and at 40 amp. the amplitude of θ_f is as high as 60% of the amplitude of θ_s.
The influence of flow velocity on the time constant θ_s was investigated shortly and the results are given in fig. 19. The percentual decrease of θ_s with the arc current corresponds with a curve given by Yoon and Browne (ref. 5).
The arc current of 17 - 18 amp. seems to be typical for all the curves derived from the experimental data. The investigation of this phenomenon is now under way.

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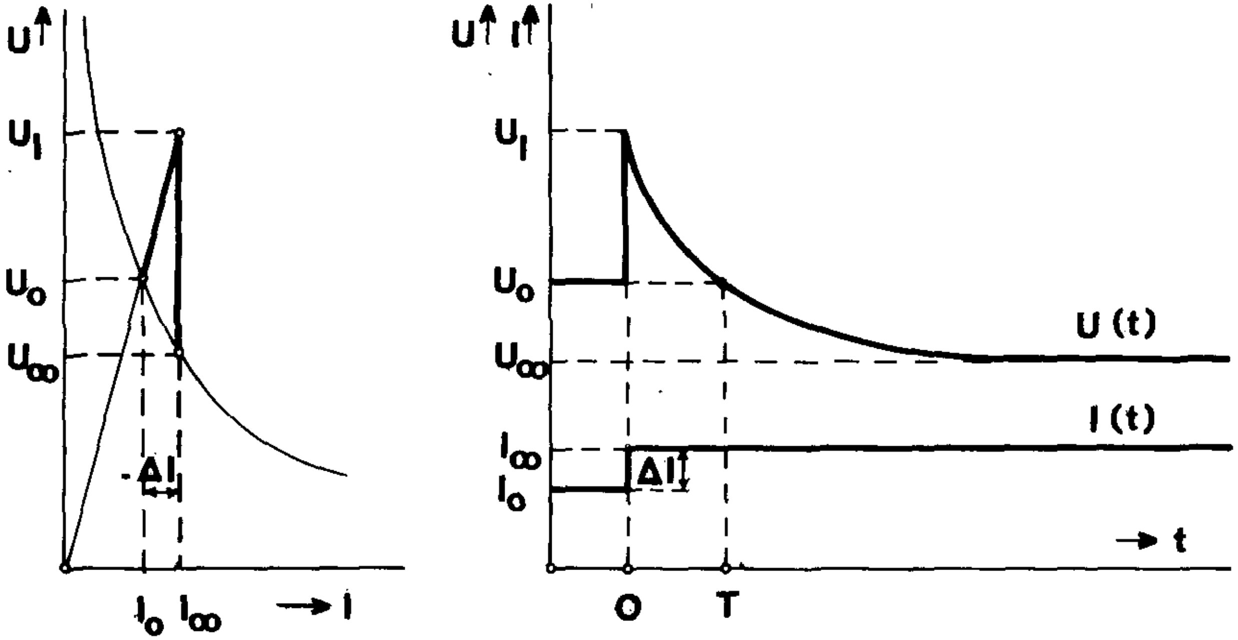


FIG. 1.

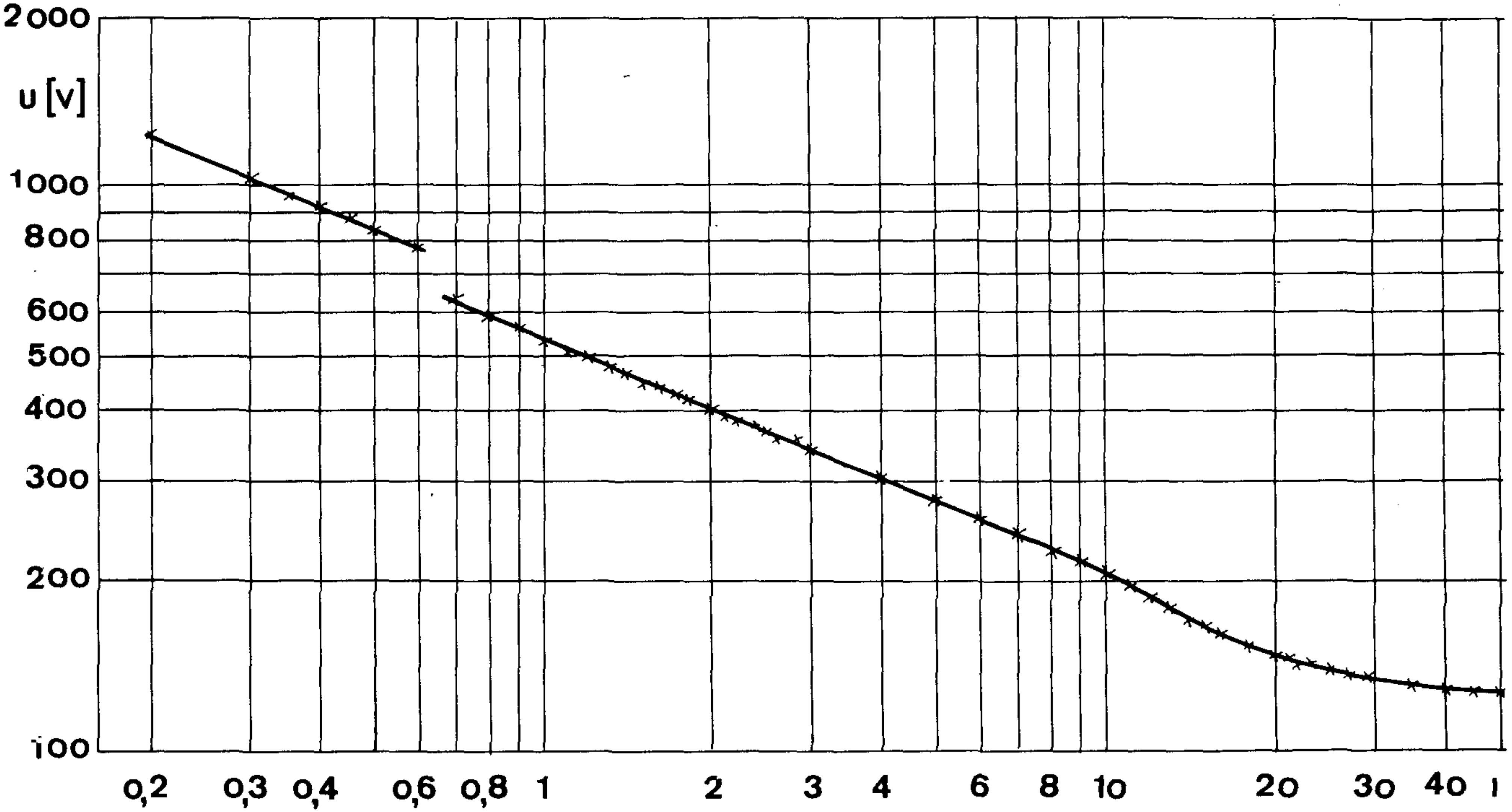

2000
u [v]
1000
800
600
500
400
300
200
100
0,2
0,3
0,4
0,6
0,8
1
2
3
4
6
8
10
20
30
40
I

FIG. 2.

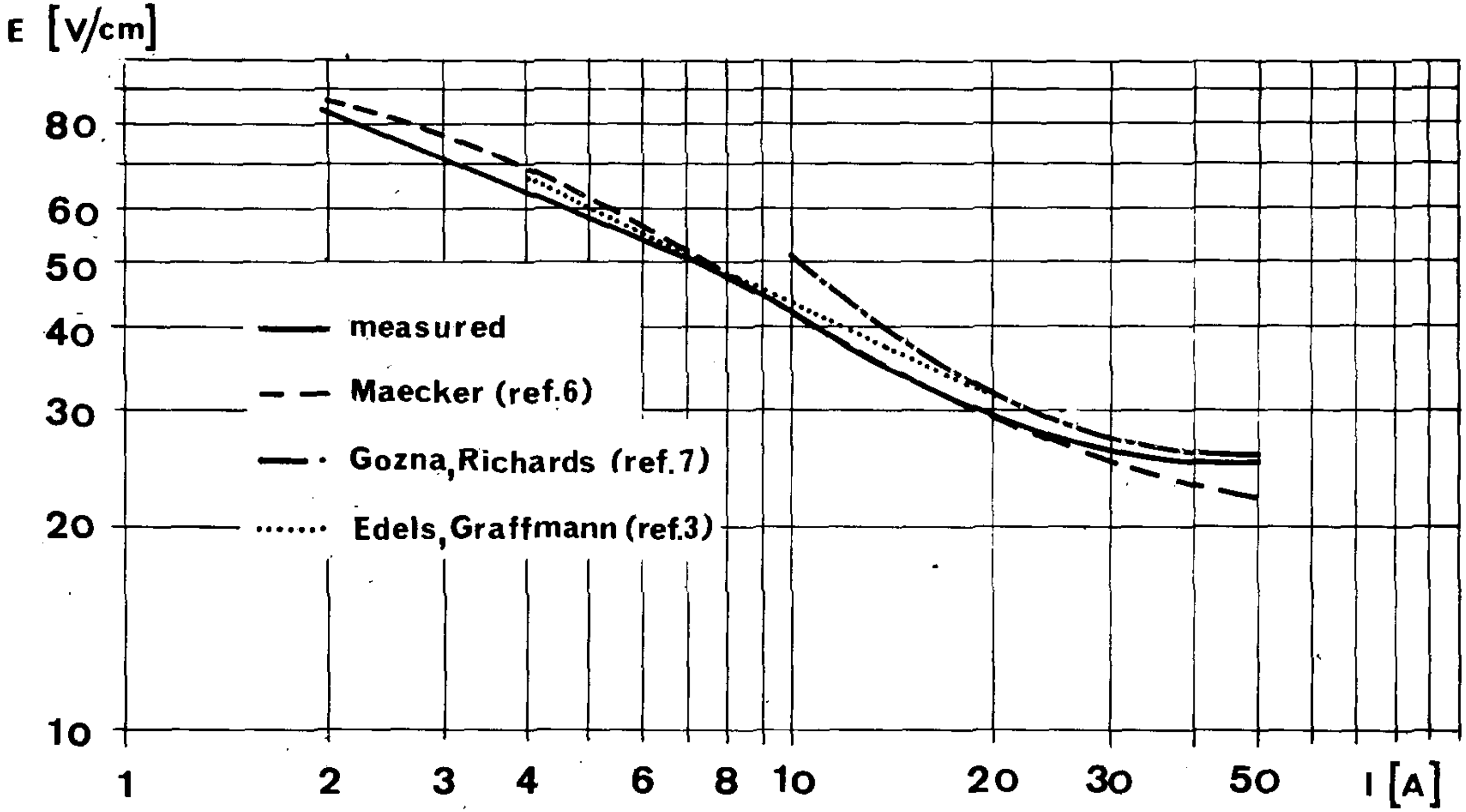

E [V/cm]
80
60
50
40
30
20
10
1
2
3
4
6
8
10
20
30
50
I [A]
measured
Maecker (ref.6)
Gozna, Richards (ref.7)
Edels, Graffmann (ref.3)

FIG. 3.

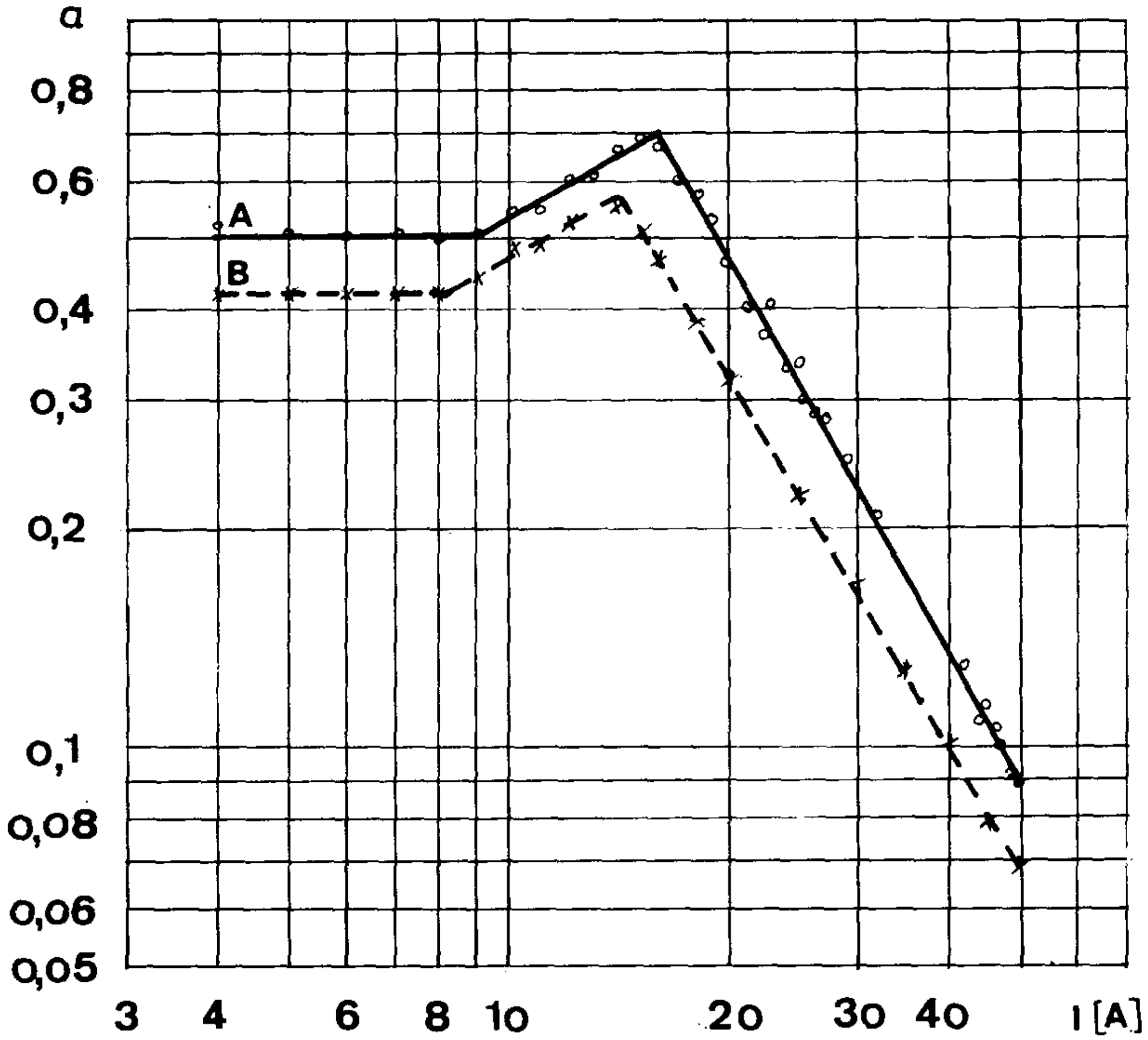


FIG. 4.

A according eq (9)

B graphically from fig 2

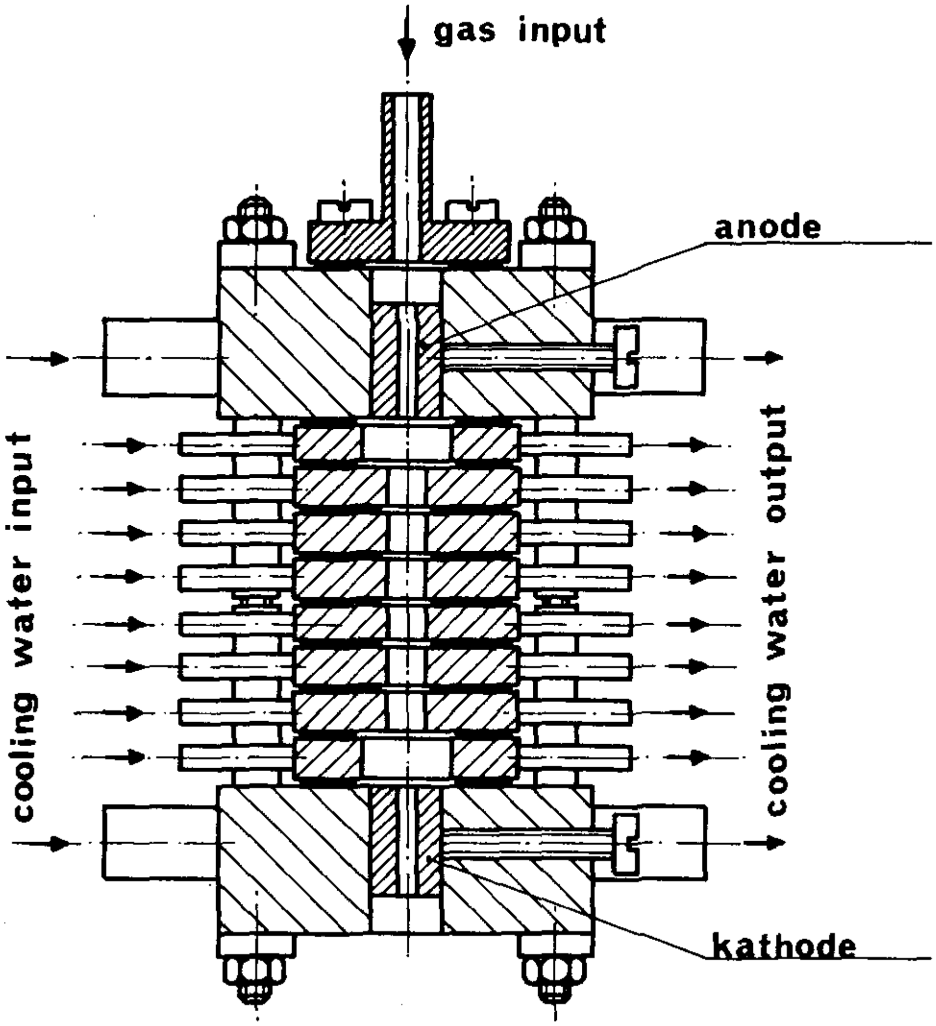

gas input
anode
cooling water input
cooling water output
kathode

FIG.5.

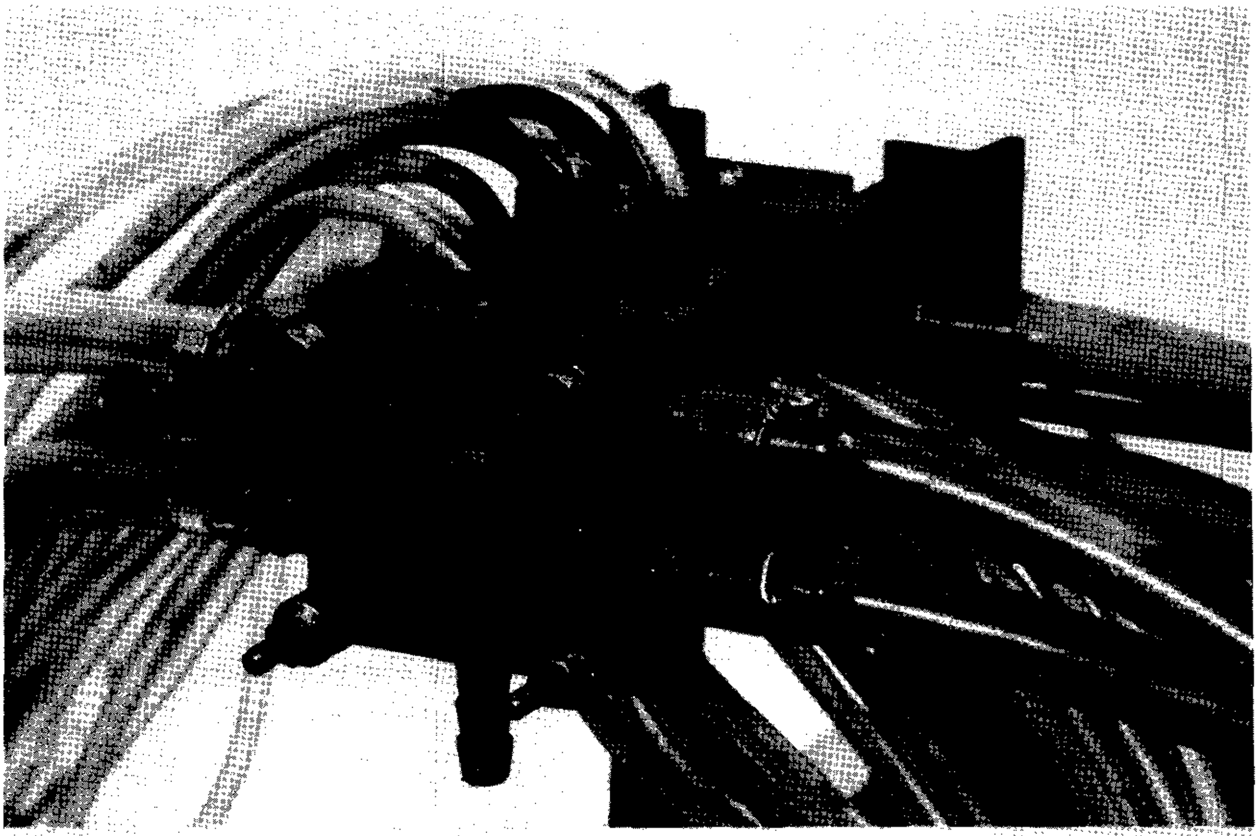
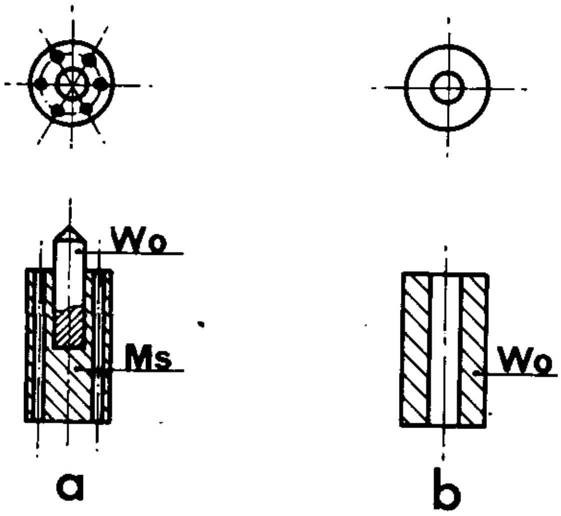


FIG. 6.



a

b

FIG. 7.

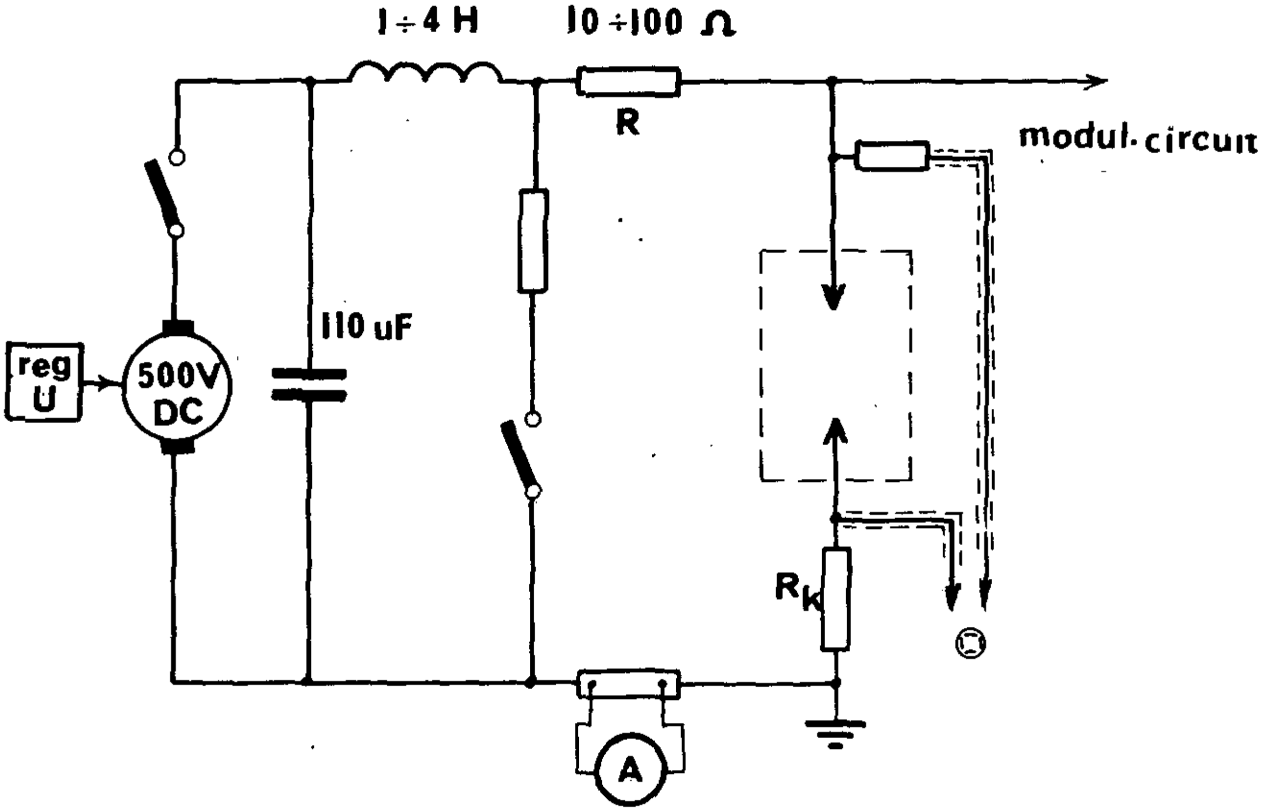

1÷4 H
10÷100 Ω
R
modul. circuit
110 uF
reg U
500V DC
R_k
A

FIG. 8.

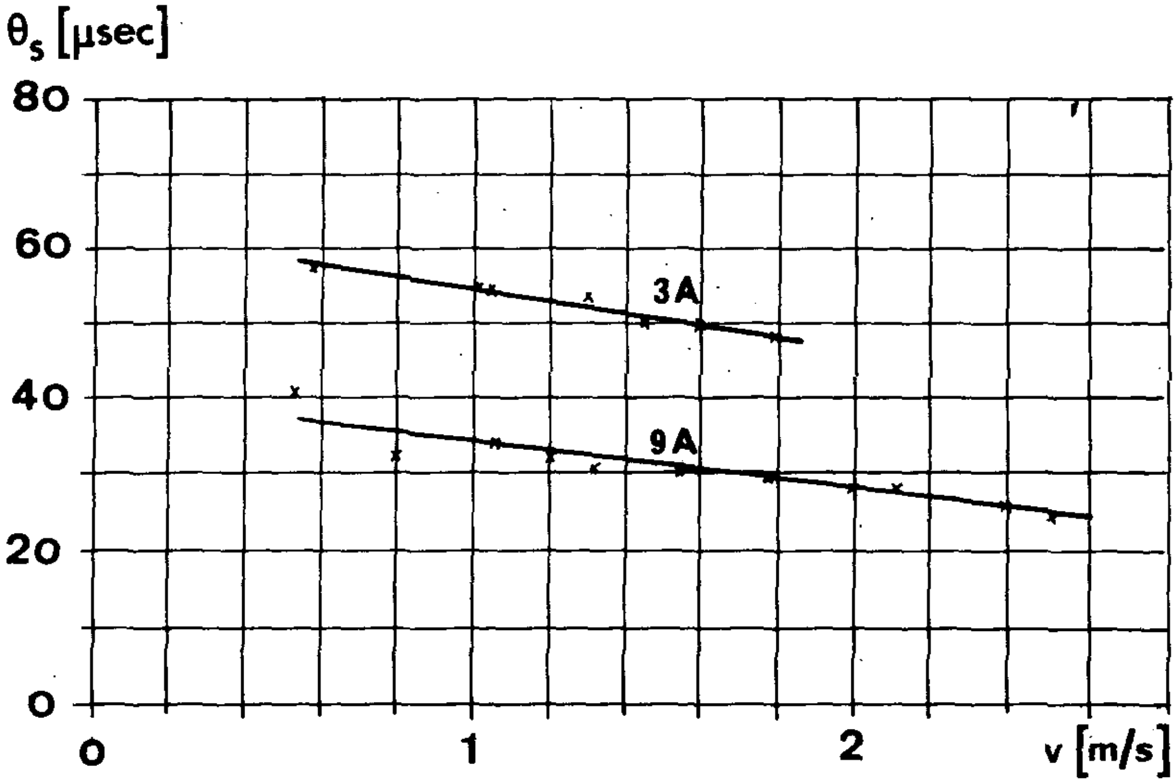

θ_s [μsec]
80
60
40
20
0
0
1
2
v [m/s]
3A
9A

FIG. 19.

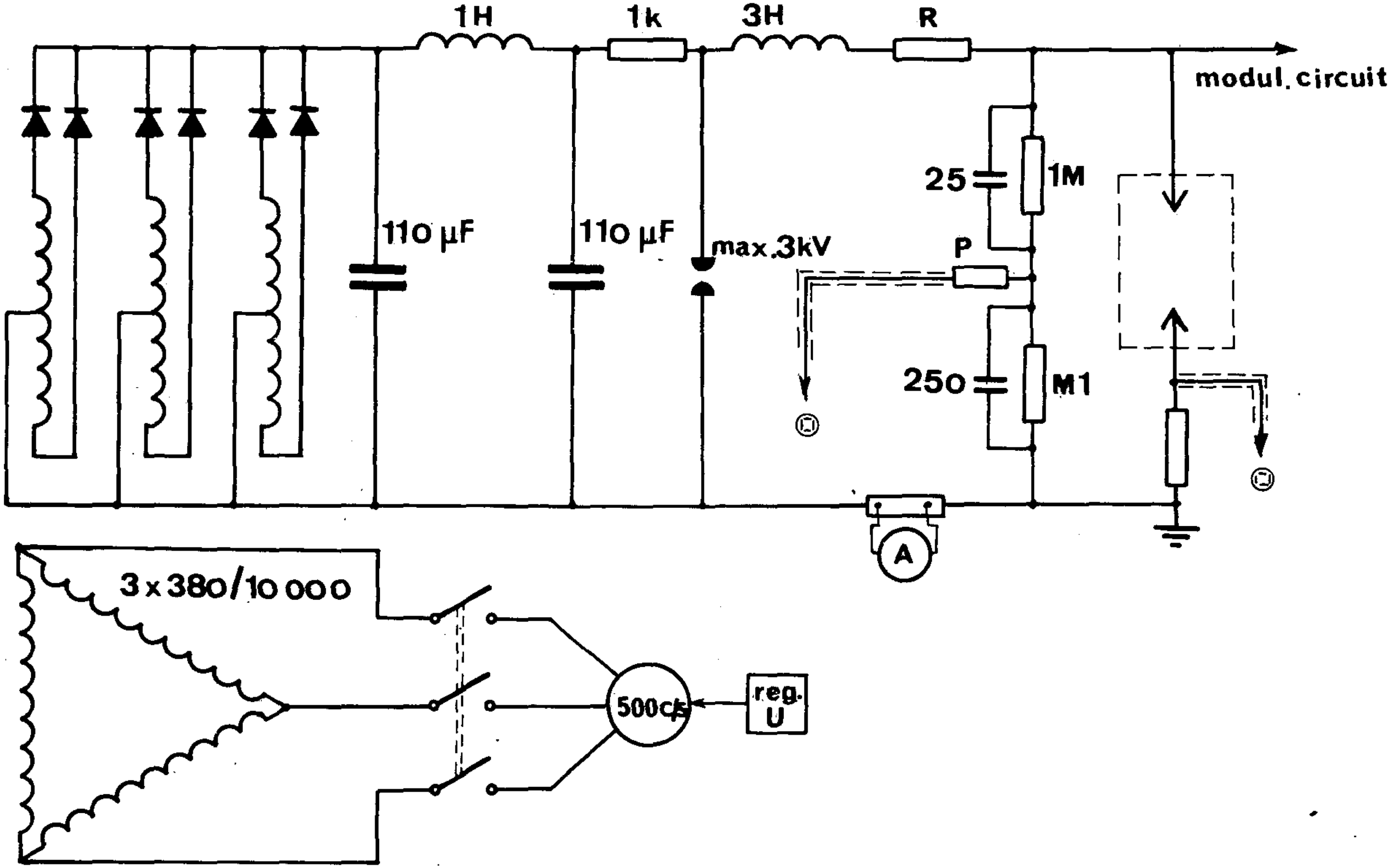

1H
1k
3H
R
modul. circuit
110 µF
110 µF
max.3kV
25
1M
P
250
M1
A
3 x 380/10 000
500c/s
reg.
U

FIG. 9.

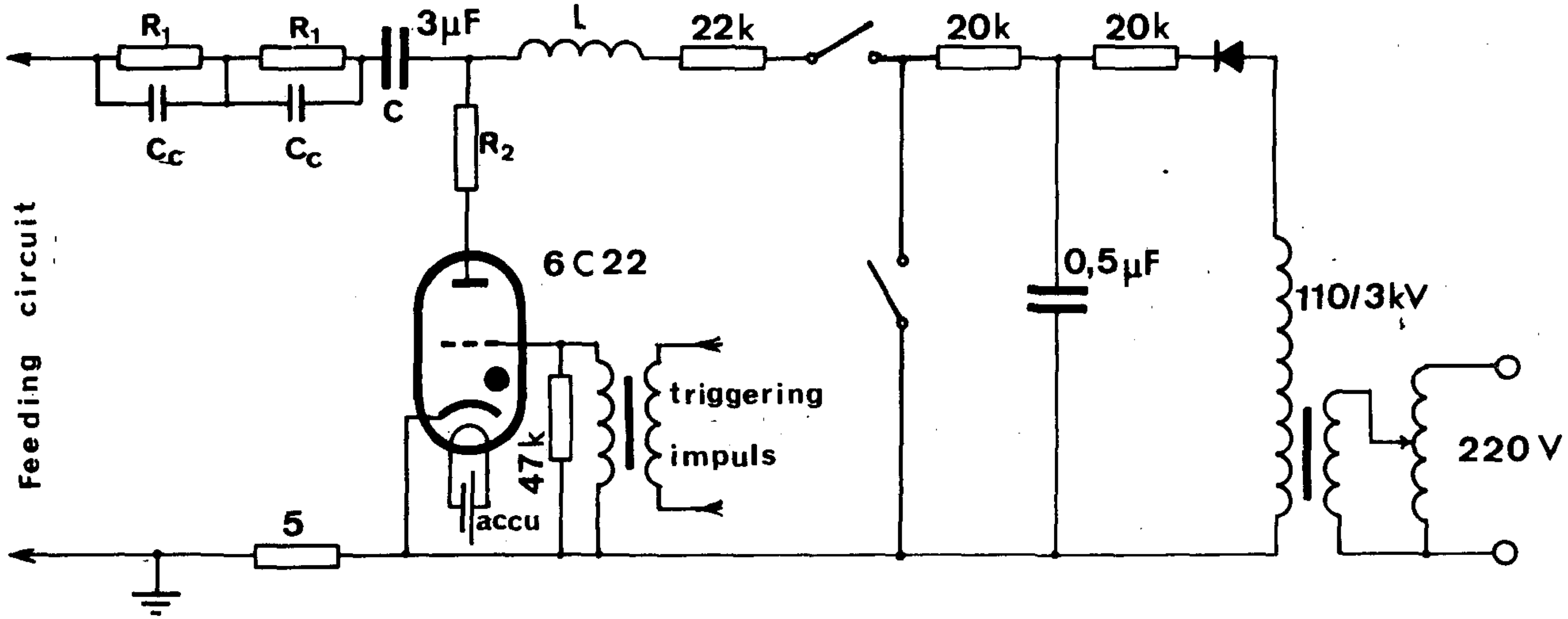

Feeding circuit
R_1
R_1
C_c
C_c
C
3µF
L
22k
20k
20k
R_2
6C22
0,5µF
110/3kV
triggering
impuls
47k
accu
5
220V

FIG. 10.

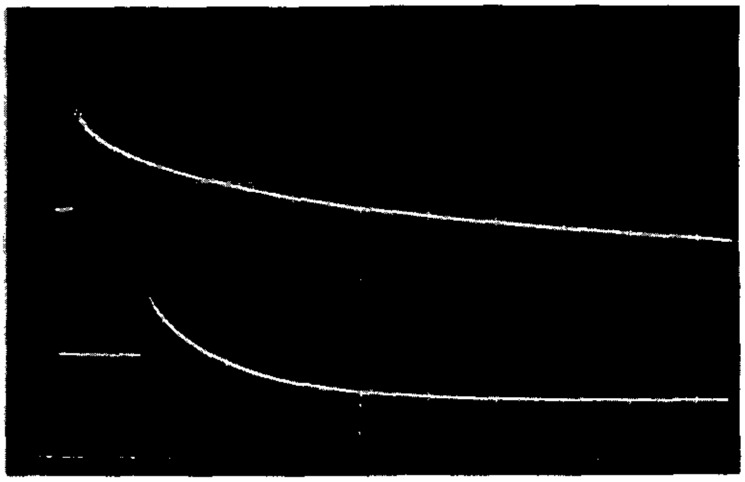


FIG. 11a.

Voltage response

Trace 1 : time basis 5 μsec/div

Trace 2: time basis 20 μsec/div

Arc current 12 amp

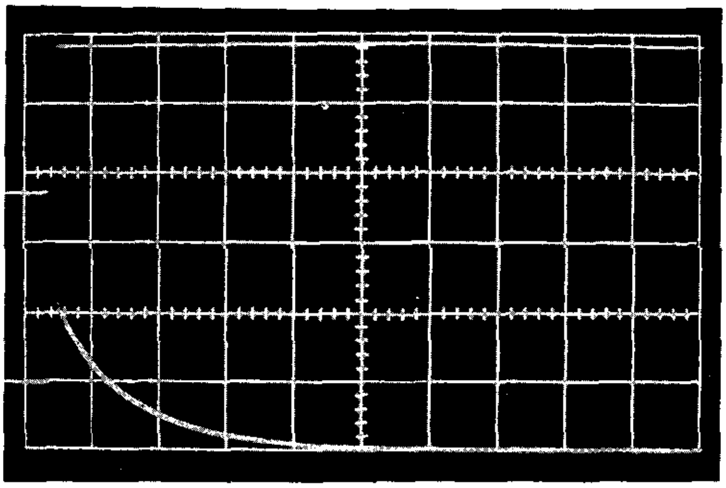


FIG. 11b.

Trace 1: modulating current

Trace 2: voltage response

Time basis 50 μsec/div

Arc current 5 amp

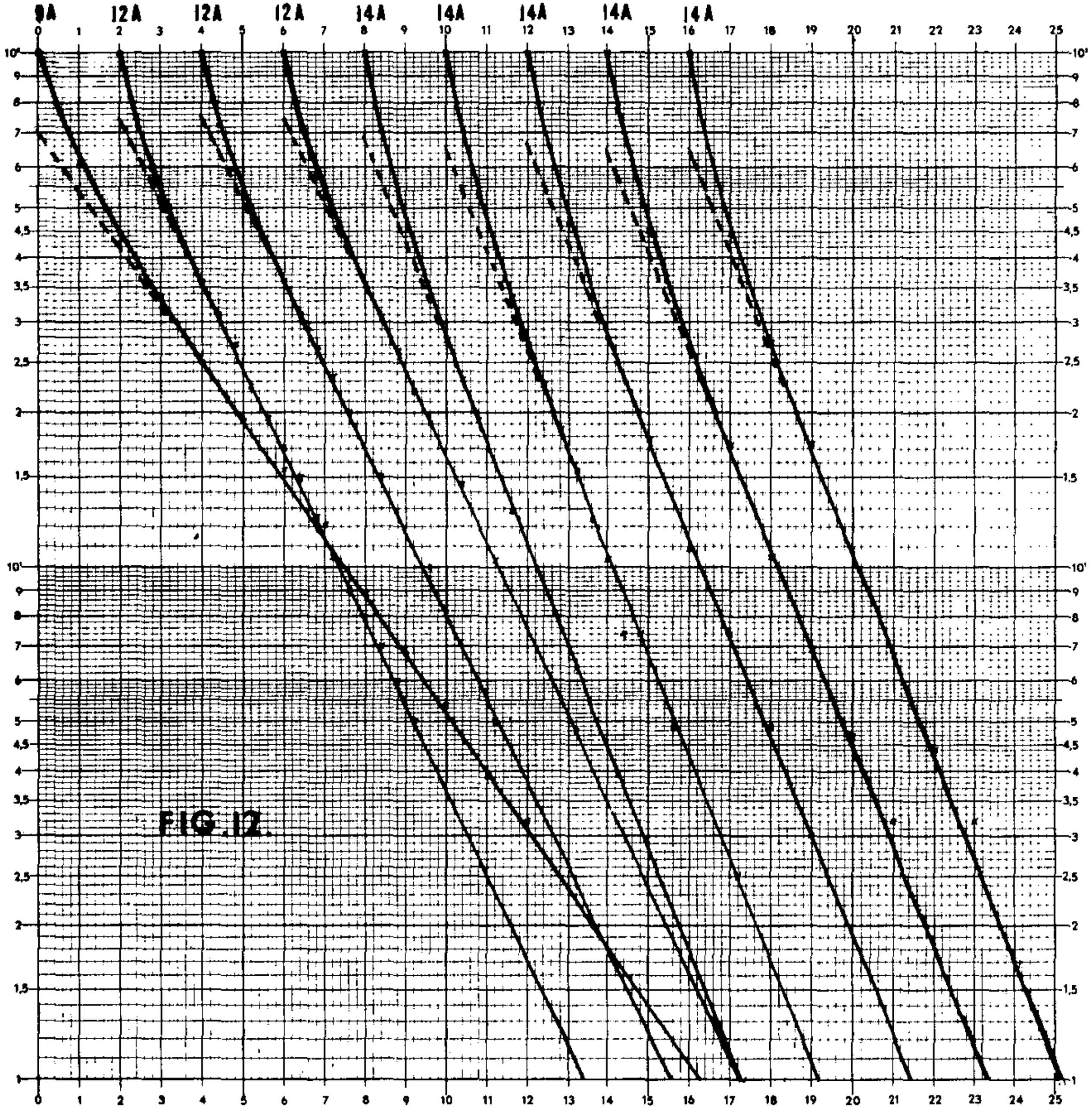


FIG.12.

N.V. Drukkerij „Mercurius", Wormerveer No. 2 x-as verdeeld in 2 mm y-as log. verdeeld 1-10² Eenheid 125 mm

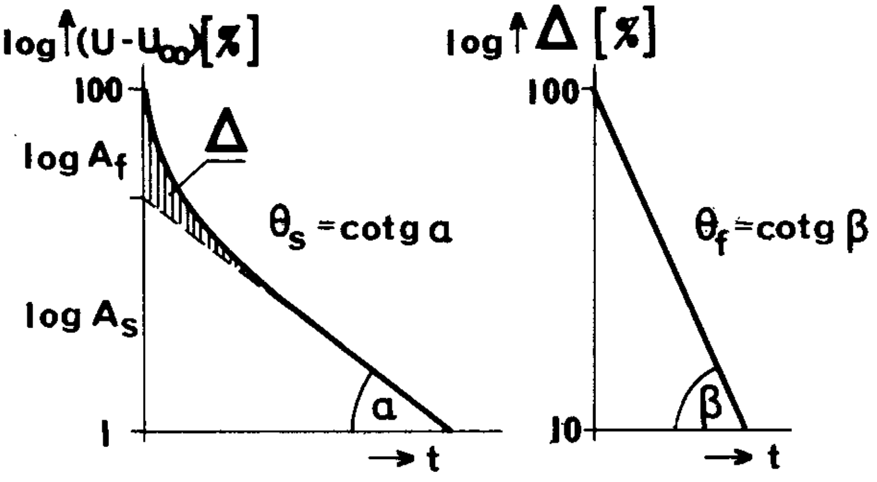


FIG. 13.

× measured

△ Pflanz (ref.3)

∘ Edels (ref.4)

FIG. 14.

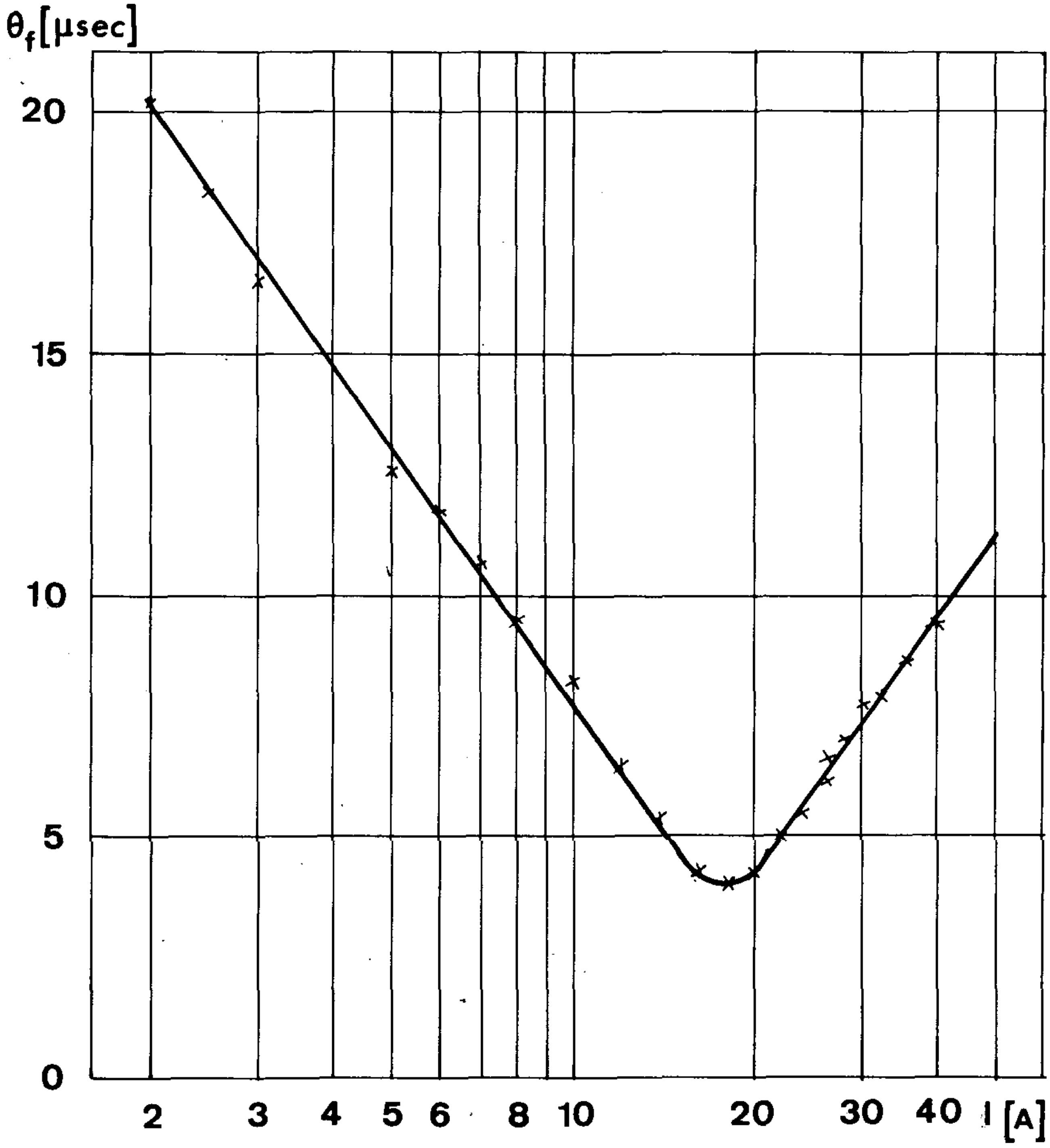


FIG. 15.

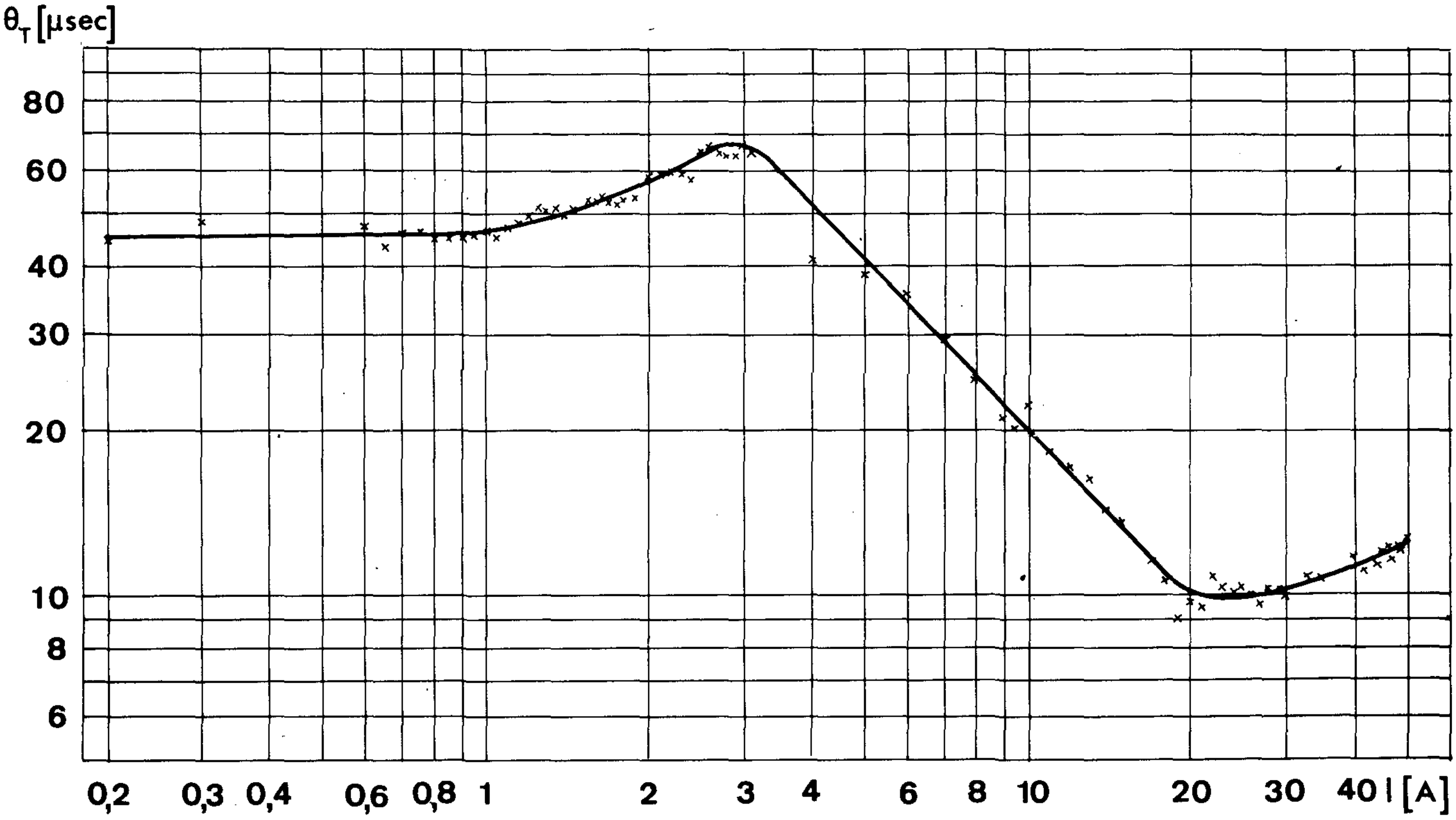


FIG. 16.

FIG. 17.

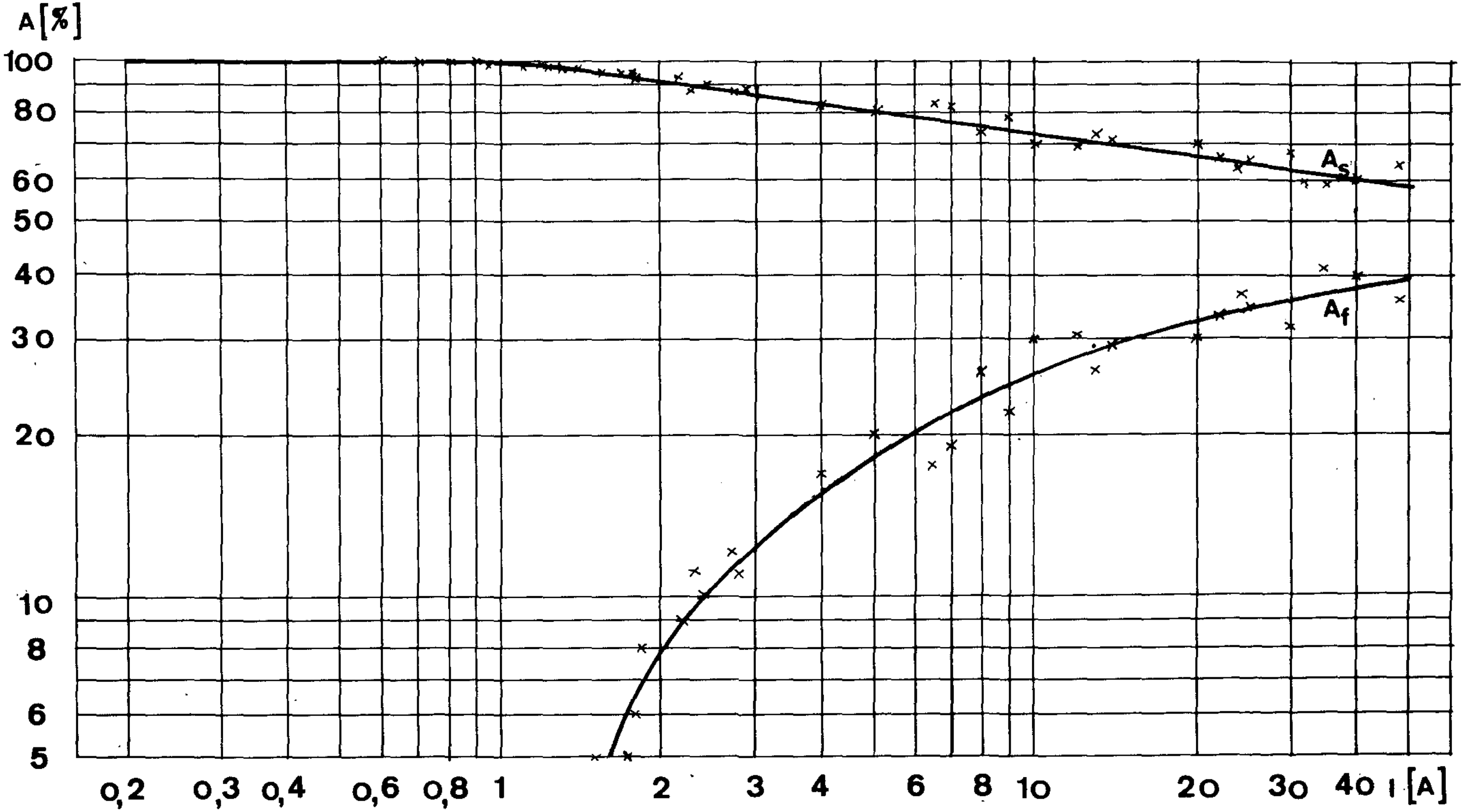

A [%]
100
80
60
50
40
30
20
10
8
6
5
0,2
0,3
0,4
0,6
0,8
1
2
3
4
6
8
10
20
30
40
I [A]
A_s
A_f

FIG. 18.