I^2t VALUES OF REAL AND IDEAL SEMICONDUCTOR FUSES

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INTRODUCTION The semiconductor fuses (SF) are genuine current-limiting devices. Their following parameters at a.c. short-circuit interruption may be among others mainly interesting for users:

i the cut-off currents,
ii the generated overvoltages,
iii the I^2t values, pre-arcing and total.

Unfortunately, these parameters of real SF are very scattered. On the other hand the withstand of semiconductor devices (SD) against mentioned parameters is very scattered too. Therefore any reasonable interchangeability between SF and SD delivered by different manufacturers is practically out of consideration. That's why the parameters comparison of real and ideal SF is very actual in order to show the desirable SF development directions to get in the future at least a satisfactory SF interchangeability.

Because the cut-off currents and overvoltages are approx. similar for SF made by several manufacturers, these parameters practically do not limit interchangeability of these fuses. Therefore it's main problem is the interchangeability of I^2t values.

To some extent the real and more ideal SF parameters may be calculated using dependences such as e.g. given in [1,2,3] for cut-off current and pre-arcing I^2t value or in [4] for arc peak overvoltage.

But the analytical estimation of the very important I^2t value for real SF is practically very difficult. On the contrary it

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is very easy for an ideal SF.

That's why the I^2t parameters comparison for ideal SF will be based on calculations and for real SF on the data given by manufacturers information sheets.

WHAT IS AN IDEAL SF? As an ideal SF let understand the one with following features:

1 The shape of the arc voltage e_a is a rectangular one (fig.1).
2 The whole range of different fuse-links rated currents is homogeneous in respect to IEC Specification[5].
3 The changes of the fuse-link rated current is achieved by monotonous change in number of fuse-element stripes.
4 The mutual thermal and arcing influence of the several fuse-element stripes is neglected.
5 The arc burning process in each stripe is this same.
6 The notched parts of the fuse-element are of uniform--section.

THE SHORT-CIRCUIT PARAMETERS OF AN IDEAL SF The worst case is when the instantaneous value of applied voltage is troughout the arcing period as large as possible. For a sinusoidal a.c. voltage this implies that the entire arcing period t_a shall extend equally on both sides of the maximum value of the applied voltage E_m (fig.1).

During the typical short-circuit current interruption by SF the operating time is in order of 1:10 part of one half-period. Than, with a practically nonresistive circuit, the onerous interrupting conditions are with short-circuit making angle abt 90 el.deg. after voltage zero. This angle gives the maximum prospective current rate of rise, maximum value of the cut-off current and maximum magnetic field energy $Li_o^2/2$.

Because of the very short operating time we may assume a maximum value of the applied voltage be constant throughout the whole operating time. Than the mode of SF operation in the worst conditions may be shown by fig.2.

From recent papers[6,7] one may conclude that in some cases for SD protection there are better the I^3t values instead I^2t. Therefore in the following relations we use notation I^mt. The pre-arcing and arcing I^mt values for ideal SF, operating as it is shown in fig.2, are as follows:

$$J_1=\int_0^{t_1} i^m dt=\frac{E_m^m}{L^m}\,\frac{t_1^{m+1}}{m+1} \qquad (1)$$

$$J_2=\int_{t_1}^{t_2} i^m dt=\frac{E_m^m}{L^m}\,\frac{t_1^{m+1}}{m+1}\,\frac{1}{n-1} \qquad (2)$$

and

$$\frac{J_1}{J}=\frac{n-1}{n} \qquad (3)$$

where $m \neq -1$, $J=J_1+J_2$ and $n=e_a/E_m$ - the overvoltage ratio. So we see that the ratio J_1/J is not dependent from the power m.

In any making angle instant other than 90 el.deg. the ratio J_1/J will exceed the values of $n-1/n$. It means, that for given n and J_1 the maximum of J_1 may be calculated from equation (3) only.

The influence of the overvoltage ratio n on I^2t is significant (fig.3). By changing the ratio n from 1 to 2 the ratio J_1/J rise from 0 to 0.5. Only with $n \rightarrow \infty$ we can get $J_1/J \rightarrow 1$. It means, that with extra high overvoltages the arcing I^2t is negligible.

Furthere, from[4] we know

$$n=\frac{\rho_o l}{E_m}\sqrt{\frac{i_o}{S}} \qquad (4)$$

where l means the short-circuit length of the fuse-element, i.e. the sum of the length of the fuse-element notched parts, ρ_o - the disrupted fuse-element resistivity at the moment t_1

(fig.1), S - the cross-section area of the notched element.

Under circumstances of an ideal SF for any rated current of a fuse-link I_n with current density $j=const$, we have

$$I_n = S j$$

and

$$n = \frac{\rho_o l}{E_m}\sqrt{\frac{i_o j}{I_n}}$$

therefore

$$\frac{I_n E_m}{2} = \frac{\rho_o l}{n}\sqrt{\frac{I_n j i_o}{2}} \qquad (5)$$

where $I_n E_m / \sqrt{2}$ we call as the rated power of a SF at the rated applied voltage $E_m / \sqrt{2} = U_n$.

For $m=2$ it is well known that

$$i_o = c_1 I_n^{1/3} \qquad (6)$$

and

$$t_1 = c_2 I_n^{2/3} \qquad (7)$$

These dependences are correct for linear rise of prospective currents only.

Because for $m=2$

$$J = \frac{E_m^2}{L^2}\,\frac{t_1^3}{3}\,\frac{n}{n-1} \qquad (8)$$

than from (5) to (8) it follows

$$\frac{J}{I_n U_n} = \frac{\sqrt{2}}{3}\,\frac{E_m^2}{L^2}\,\frac{1}{\rho_o l \sqrt{j}}\,\frac{n^2}{n-1} = const \qquad (9)$$

for a given circuit and for given homogeneous series of fuse--links. Dependence (9) shows, that the relation total $I^2 t$ to rated power of an ideal SF is constant.

Furthermore, the ratio J/P is very interesting too, where P are power losses at the rated current of a SF. The P value may be calculated from equation

$$P=I_n \rho l j \qquad (10)$$

where ρ - the fuse-element material resistivity. Than from (7), (8) and (10) one can get

$$\frac{J}{P}=\frac{1}{3}\frac{E_m^2 I_n}{L}\frac{1}{\rho l j}\frac{n}{n-1}=CI_n \qquad (11)$$

It means that dependence of J/P versus the rated current of an ideal SF is linear.

THE SHORT-CIRCUIT PARAMETERS OF REAL SF In figures 4 to 9 are shown the parameters for real SF manufactured in 1975 by six European firms. It is evident, that these real short--circuit parameters are very scattered, indeed. They are very far to a desirable situation, when for a given SD the SF rated current of any manufacturers product should be the same.

For instance, from fig.4 it is obvious, that the majority of real pre-arcing I^2t are greater than I^2t withstand of manufactured SD. Than, only abt 15 % of examined real SF have convenient total I^2t values suitable for correct coordination with I^2t withstand of 50 % SD with those same rated currents of the SF and SD (fig.5).

By present state of real I^2t withstand of SD the pre-arcing I^2t of SF by very common $n=1.5$ should be not greater than the values indicated by line a (fig.4) or line b. The lower line (a) corresponds to the 99 % correct coordination with SD I^2t withstand and the upper line (b) - to the 50 % correct coordination. It means, that practically all or 50 % of SD will be correctly protected by SF, if their pre-arcing I^2t are not greater as stated correspondingly by line a or by line b.

Fig.6 shows that the real SF J/J_1 ratio is greater than the correspondent ratio for an ideal SF by e.g. $n=1.5$.

The comparison of results given by dependence (9) and fig.7 shows, that the ratio $J/I_n U_n$ of a real SF is not constant. The real ratios are growing with the rated currents and they are very scattered. It seems, that the greatest influence not satysfying the dependence (9) are coming from:

i the mutual heating of the stripes is homogeneous multi-stripe fuse-elements,

ii the approx. trapezoidal instead rectangular shape of e_a.

The real values of $J/P=f(I_n)$ (fig.8) are very scattered too. The mean line of the real spread zone shows a greater rate of rise than calculated from dependence (11). This difference could find an explication in two reasons mentioned just above and additionally in:

iii the manufacturers tendency to keep the same value of the peak arc overvoltages throughout the whole range of the fuses independing from their rated currents.

It means, that the total length of all notched parts is growing with the rated current.

The next fig.9 shows the tendency to rise the ratio J/V with the rated current, where V - the external volume of the fuse-link excluding contact blades.

<u>CONCLUSIONS</u> The presented comparison of I^2t values of real and ideal SF shows that we are still far away from a well arranged SF.

The desirable situation in this field is to have the I^2t values of a real SF like those for an ideal SF and their pre-arcing I^2t values situated not higher than the line a indicated in fig.4.

Afterwards, the ratio J_1/J should be alike for the ideal SF too, given by relationship (3) for rectangular shape of the arc voltage and for the said value n=e.g. 1.5.

The simple analytical solution for J_1/J ratio (relationship 3) is practically the same as the calculation results obtained by authors[6] using the computing calculator.

In order to get interchangeability between SF and SD delivered by different manufacturers it is necessary:

i The SF manufacturers should deliver the SF with pre-arcing and total I^2t values respectively not lower and not greater then the values specified by standard for given rated currents.

ii The SD manufacturers should deliver the SD with I^2t withstand not lower than the values specified by standard for given rated currents.

To reach this state it is necessary to complete the existing standards with corresponding requirements.

REFERENCES

1. Rauch W.: 'Strombegrenzung bei der Abschaltung von Wechselstrom - Kurzschlüssen durch Sicherung'. ETZ-A. 1958. H.16. S.543-547

2. Lipski T.: 'A graphical method of cut-off current estimation of the fuses' (in polish). Przegląd Elektrotechniczny 1963. No.3. p.101-106

3. Wilkins R., Mc Ewan P.M.: 'A.c. short-circuit performance of notched fuse elements'. Proc.IEE No.3 March 1975 p. 289-292

4. Hibner J.: 'A resistance gradient method for calculation of arc overvoltage peak values generated by current limiting fuses' (in polish). Ph.D. Dissertation. T.U. Gdańsk 1973

5. 'Low-voltage fuses. Part 1: General requirement'. IEC Publication 269-1.1968

6. Ky Hong: 'I^3t of fuses and semiconductors' IEEE Trans. on Ind.Electr. a. Control Instr. No.2. May 1971. p.29

7. Czucha J.: 'The desirable short-circuit parameters of semiconductor fuses' Int.Conf. on Electric Fuses a. their Applications. Liverpool. 7 - 9 April 1976.

8. Vermij L., Raelofs : 'The Joule integral of the protective fuses for semi-conductor devices'. CIRED-Conference. 1975. A.I.M. Liége. Reports No.48

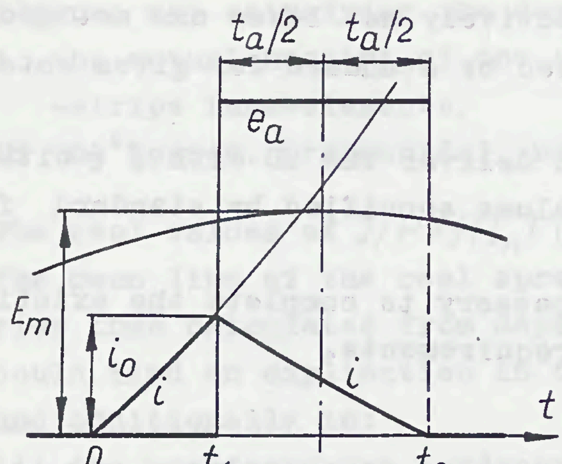

Fig.1 Simplified short--circuit breaking oscillogram of SF

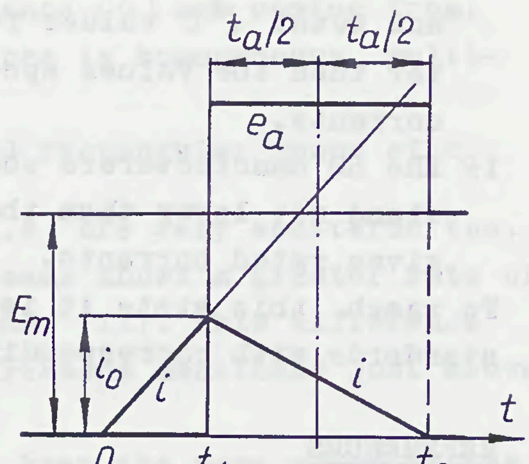

Fig.2 Mode of operation of an ideal SF in the case of worst circuit conditions

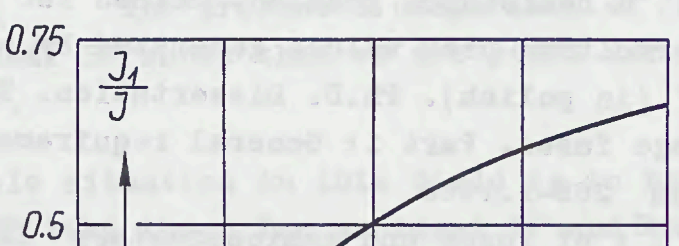

Fig.3 J_1/J ratio versus n of an ideal SF

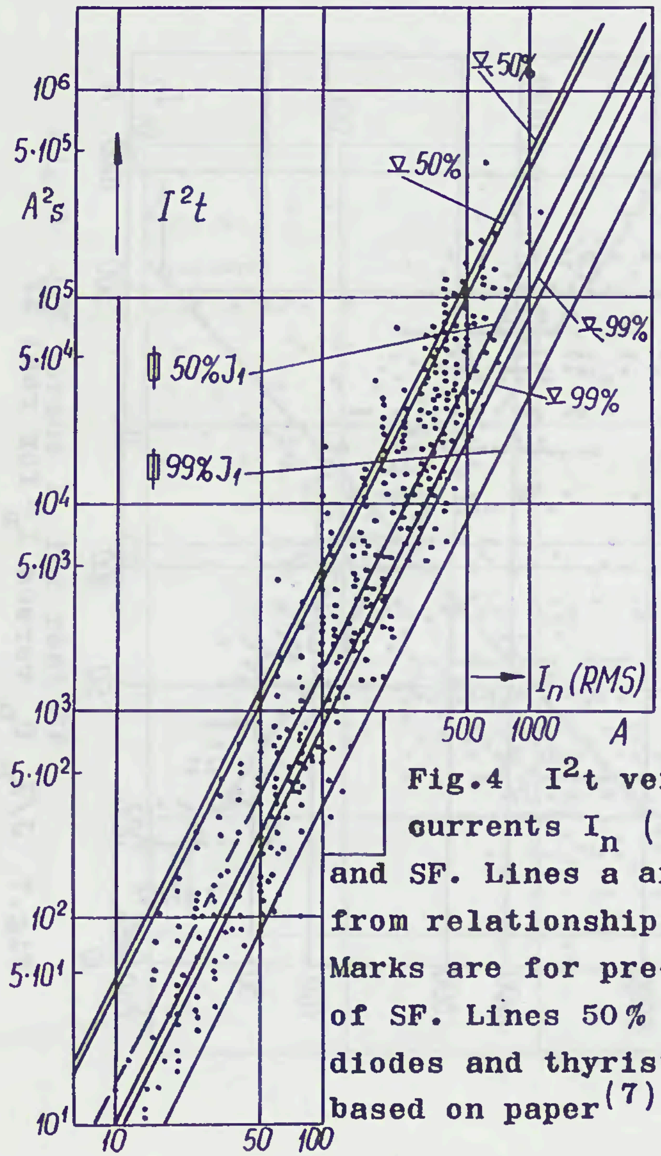

Fig.4 I^2t versus rated currents I_n (in RMS) of SD and SF. Lines a and b calculated from relationship (3) for SF. Marks are for pre-arcing I^2t of SF. Lines 50 % and 99% for diodes and thyristors are based on paper(7)

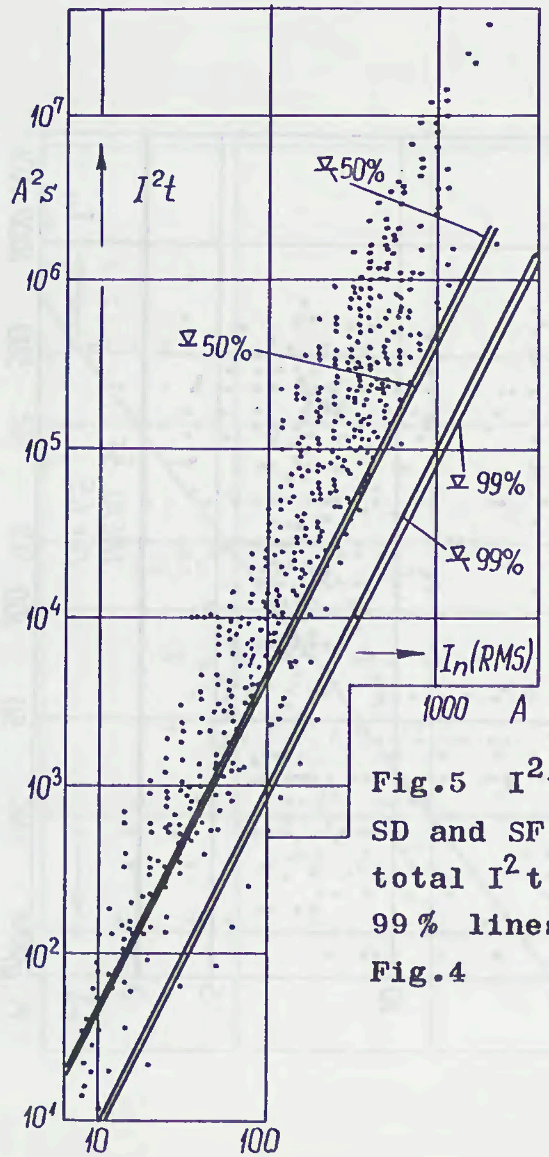

Fig.5 I^2t versus I_n of SD and SF. Marks are for total I^2t of SF. 50 % and 99 % lines are as in Fig.4

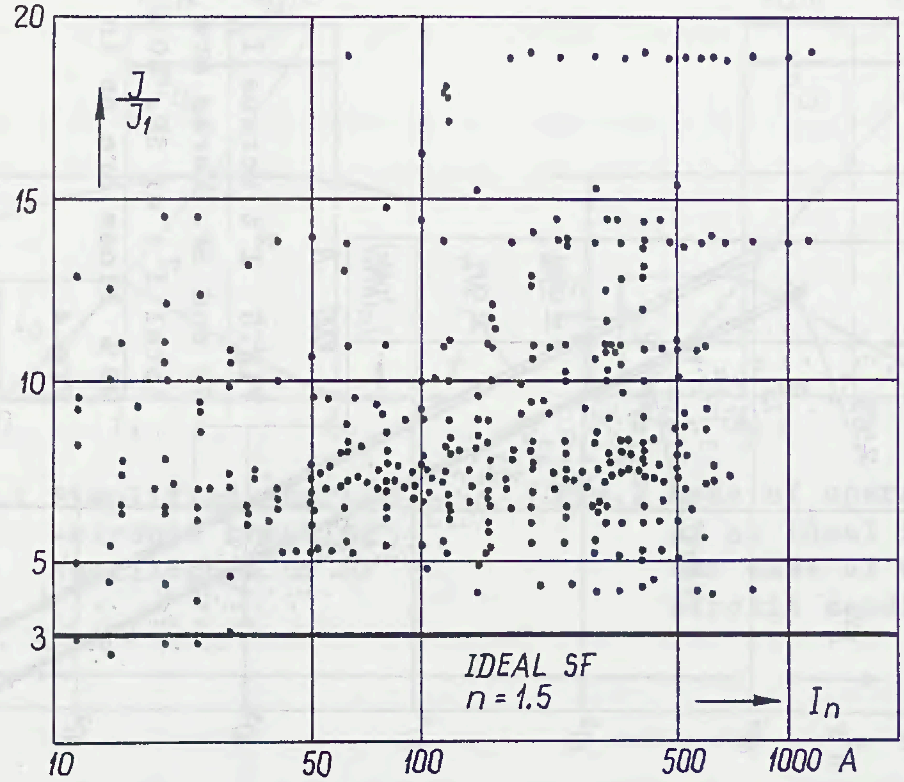

Fig.6 J/J_1 versus I_n for real SF

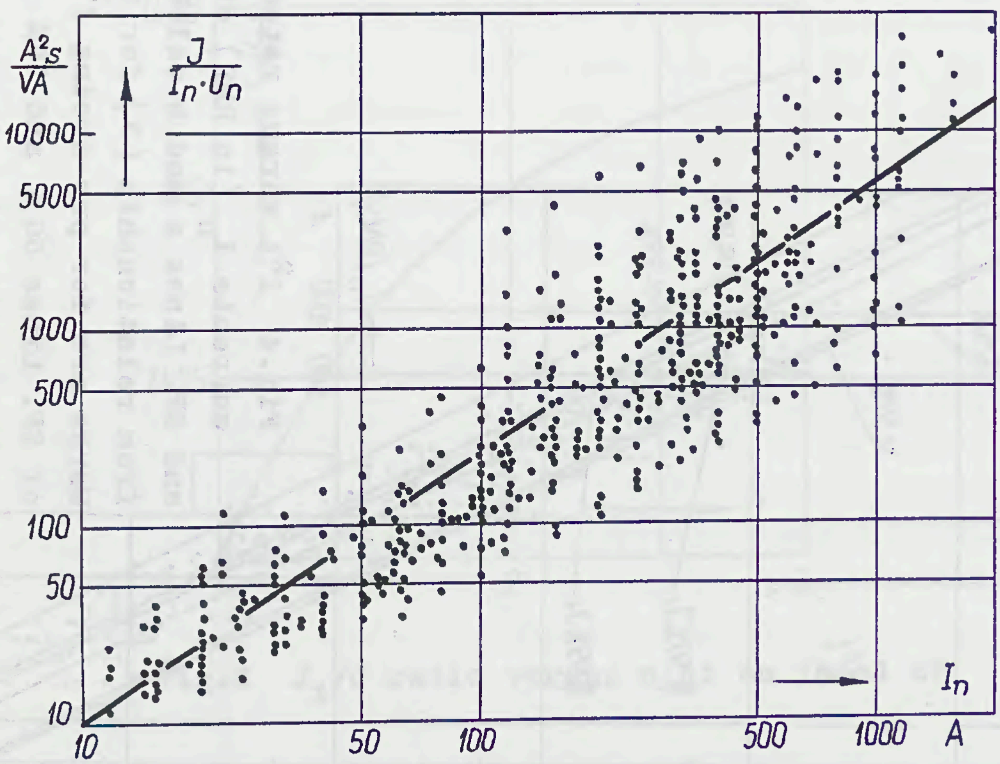

Fig.7 $J/I_n\ U_n$ versus I_n for real SF

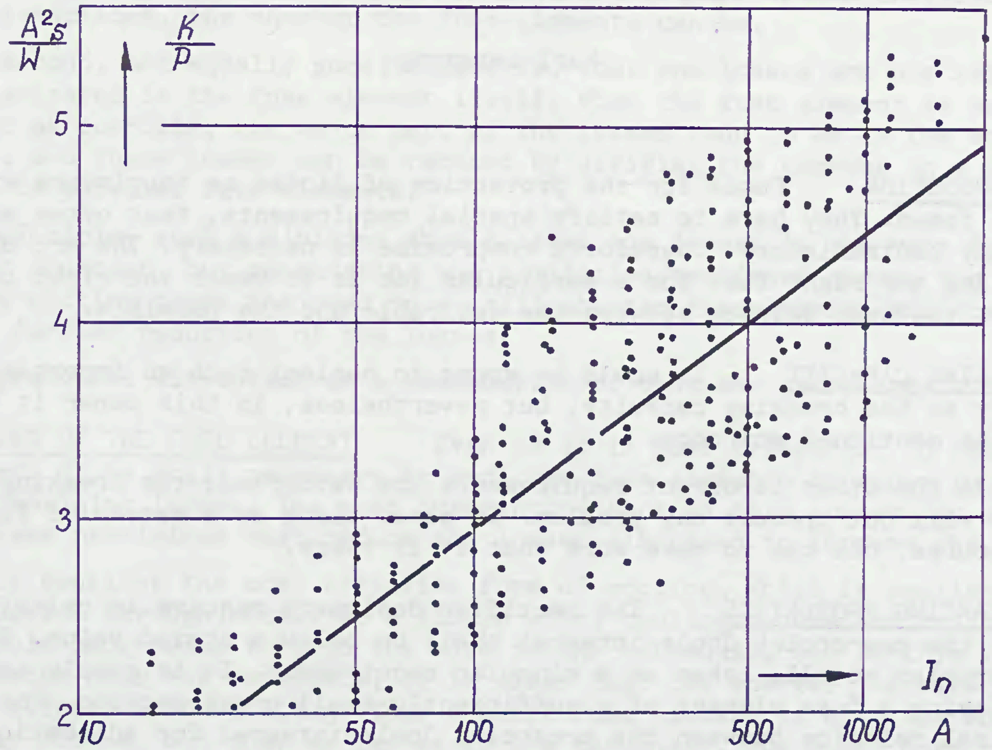

Fig.8 J/P versus I_n for real SF

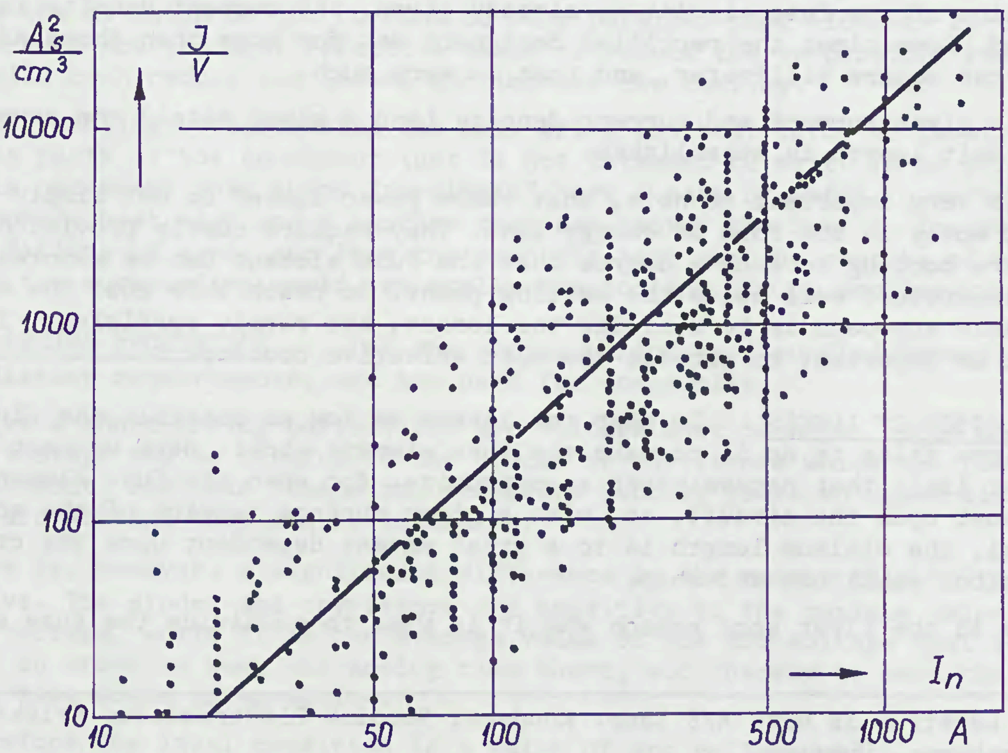

Fig.9 J/V versus I_n for real SF