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EUROPEAN ATOMIC ENERGY COMMUNITY - EURATOM

A SIMPLIFIED METHOD FOR ORGANIC, HEAVY WATER LATTICE CALCULATIONS

by

G. CASINI, A. KIND, G. ROSSI

1963

ORGEL Program
Joint Nuclear Research Center
Ispra Establishment - Italy
Reactor Physics Department
Applied Mathematical Physics

Paper presented at the Panel on Heavy Water Lattices
Vienna, 18-22.2.1963

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For hot lattices rethermalization "spectral constants" obtained by Termidor are introduced as input data in Caroline I.

The long term reactivity effects are calculated by RLT 2, a code for IBM 650 and 7090. The point reactivity curve is determined by using mainly the AECL proposed data for the 2 200 m/sec nuclear cross-sections for U and Pu isotopes and fission products constants. The Westcott factors are adopted and the neutron temperature is calculated by Termidor. The method established for point reactivity calculations has been tested on the experimental Canadian results for rods irradiated in NRX and oscillated in GLEEP; a satisfactory agreement was found.

The variation of the reactivity balance following the fuel movement assumed in the power reactor design is also calculated by RLT 2. The method used is based on the perturbation theory. Steady state conditions are supposed. The following types of fuel movements have been considered up to now in the code : homogenized fuel model, single rod fuelling, 2 slug bi-directional fuelling, continuous bi-directional fuelling.

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FOR ORGANIC, HEAVY WATER LATTICE CALCULATIONS

SUMMARY

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1. Introduction

In this document, the main lines of the calculation method of organic liquid cooled, heavy water moderated lattices, within the framework of the ORGEL reactor studies, are described.

This method of calculation can be considered as divided, following the classical scheme, into a first part dealing with the unirradiated lattice conditions and a second part with the long term reactivity effects.

2. Unirradiated lattice calculations

The unirradiated lattice calculations are performed by Caroline I, an IBM 7090 code established at Euratom (Ref. 1).

a) Cold conditions

The calculation method for cold unirradiated conditions is based on the results of the French correlation for heavy water moderated and cooled lattices (Ref. 2).

This correlation, established by Mr. Naudet and his associates, was obtained as the result of a long series of cold lattice buckling measurements performed at Saclay on Aquilon, a heavy water, natural uranium, critical assembly.

The parameters adjusted in this correlation are :

- η (thermal fission factor)
- the constants A and B of the effective resonance integral.

We have assumed the fundamental hypothesis that these three constants remained unchanged for the ORGEL lattices.

The fact of having accepted these values required conformity with Naudet's calculation method as regards the quantities which, in the correlation, are assigned to the calculation, as well as with the values put forward by him for the nuclear constants which enter into the calculation.

In order to make allowance for the characteristics for which the studied lattices differ from those on which the French correlation was based, particularly the presence of organic liquid instead of heavy water in the fuel element, appropriate modifications to Naudet's calculation method have been introduced.

Thus, for example, the thermal flux distribution across the lattice cell has been calculated by using the Amouyal and Benoist method extended to the case of a cell containing any number of concentric media; the details of these calculations, as well as the criteria for the determination of the other lattice parameters, are described in Ref. 1.

b) Temperature effects

In an ORGEL type reactor the operating temperature of the organic liquid is much higher than the heavy water temperature. In order to take in a simple manner this effect into account in the hot lattice calculations, we made the hypothesis that the spectrum hardening due to the absorption in the fuel element and the heating effect due to the interaction of the neutrons with the coolant are, at least in a first approximation, independent from one another (Ref. 3).

In view of the fact that in the French correlation of the heavy water lattices we use the spectrum hardening due to absorption is not calculated theoretically but directly incorporated in the adjusted constants, we have only taken into account in the thermal utilization calculation the spectrum effects connected with the heating due to the organic liquid.

The method used to evaluate this effect is a modification of the two overlapping thermal group method originally proposed by Selengut (Ref. 4). As a matter of fact, if any spectral distortion due to the selective absorption of the fuel can be disregarded, it is possible to carry out the calculations in terms of two overlapping pure maxwellian distributions, at the physical temperatures of moderator and coolant.

On the other hand, a pure rethermalization effect not too close to the interface between the two media at different temperatures can be considered as fairly well described by a two thermal group approximation (Ref. 5).

This formalism has the advantage of exhibiting in a rather explicit manner the dependence of the results on the physical parameters, in particular on the transfer cross section between the thermal groups. Due to the use of the maxwellian distributions, the calculations are relatively easy : as a rule, they could be almost entirely carried out with desk computers. Nevertheless, to allow extensive design analysis, an IBM 7090 FORTRAN code (Termidor) (Ref. 6) was written at Ispra, which also includes the evaluation of the hardening effect (see below).

The Termidor output gives the averaged thermal cross sections of the cell different materials, which enter as input data in the Caroline I code. The details of this procedure are indicated in Ref. 1 and 6.

3. Long term reactivity effects

The long term reactivity effects are calculated by a method established at Euratom and codified on IBM 7090 (RLT 2 program) (Ref. 7).

The point reactivity curve is determined by a one-group model using the Westcott factors to describe the spectrum effects.

The input data for this calculation are given by Caroline I and Termidor.

In particular, due to the fact that in the Caroline I code the resonance effective integral is a pure adjustment parameter of the correlation, it is not possible to use this value to calculate the initial conversion factor. Therefore, the resonance absorption is evaluated by means of the formula suggested by Hellstrand for the effective resonance integral.

The neutron temperature in the fuel element is calculated according to the hypothesis of independence between the effects of rethermalization and selective hardening proviously indicated. This second effect is evaluated with a multigroup diffusion model (Ref. 8), by disregarding the neutron transfer between the groups due to the interaction with the nuclei of the hot coolant, which is already calculated in global way by the two overlapping thermal group formalism. A neutron temperature in the fuel element, which takes into account the hardening process and the rethermalization at the same time, is then given by Termidor for the two limit cases of "small" and "big" $a\Sigma_R$ values (a = radius of fuel element; Σ_R = rethermalization cross section).

The cross sections data of the fuel isotopes and fission products are mainly the AECL proposed data (Ref. 9 and 10). In particular, the fission cross section of Pu 239 is slightly different (1 %) from the value proposed in Ref. 9 in order to obtain a better agreement with the experimental Canadian results (see chapter 4.).

The variation of the neutron balance following the fuel movement assumed in the design is still calculated by the RLT 2 code.

The method used is the following (see Ref. 7) : for each type of fuel cycle considered, the spatial distribution of the irradiation τ corresponding to the steady state conditions is determines, assuming the unirradiated flux distribution of the core. The parameters of the lattice corresponding to this spatial distribution of the τ values are then evaluated by making the hypothesis, suggested by Kushneriuk, that the neutron in-current on each fuel bundly does not change during the burn-up (i.e. the neutron absorption of the fuel bundle is proportional to the blackness).

The k_{eff} of the reactor is finally determined by averaging the local values of the lattice parameters on the basis of the perturbation theory.

The following types of fuel movement have been considered up to now in the code :

- homogenized fuel model : the fuel from 0 to the maximum value of τ is supposed to be mixed and uniformly irradiated;
- single rod fuelling : the fuel of each reactor channel is removed when it reaches the maximum value of the irradiation. The irradiation changes in the radial direction to compensate the flux variation;
- two slug bi-directional fuelling : the fuel is divided, following the channel direction, into two elements. The position of each fuel element is reversed at the end of the first half of the irradiation. Also in this case the irradiation time changes in the radial direction;
- continuous bi-directional fuelling : the fuel is supposed to be continuously moving in the axial direction through the reactor. The movement is opposite in two adjacent channels. The speed of the transport changes in the radial direction.

4. Comparison with experimental results

The calculation method previously described has been compared with the experimental results now available.

a) Cold critical and exponential measurements for organic-heavy water lattices

A certain number of buckling experiments has been performed for cold organic-heavy water lattices. In all cases, the fuel was natural uranium either as metal or as oxyde.

- Oxyde fuel elements : two series of buckling results are available from experiments made by Euratom and AECL.

The first series of measurements was carried out on the Aquilon II pile of Saclay (France); the progressive replacement method was used to determine the bucklings of 9 natural uranium-heavy water-organic lattices. Three types of fuel elements, consisting in clusters of 19 uranium oxyde rods immersed in an organic liquid contained in a hexagonal aluminium tube, were tested (Ref. 11).

The second series of measurements was performed on the ZED II pile of Chalk River (Canada). The fuel elements were clusters of 7 aluminium-clad uranium oxyde rods immersed in an organic liquid contained in a circular aluminium tube (Ref. 12).

The results of the comparison with Caroline I, described in Ref. 1, are given in Fig. 1, 2, 3, 4. Generally the agreement is fairly satisfactory; the inaccuracy of the measurements was of about 0.15 m^{-2} in Euratom experiments and of 0.1 m^{-2} in the Canadian measurements.

A value of about 0.2 m^{-2} can therefore be assumed as representative of the accuracy of our cold lattice calculation method for uranium oxyde fuel elements.

- Uranium metal fuel elements : a set of buckling measurements has been done at the outset of the ORGEL project by Euratom in collaboration with the French C.E.A. at Saclay (France).

The fuel elements, tested by the progressive substitution method in the Aquilon I pile, were bundles of 6 or 7 plates immersed in organic liquid contained in a rectangular tube.

The results of these experiments have been presented at the 1960 Meeting of Palma de Mallorca (Ref. 13) together with a comparison with calculations. The general conclusion was that the agreement was fairly satisfactory if the relative density of hydrogen nuclei as compared with the uranium nuclei did not exceed 0.75 (which is certainly the case of the ORGEL power reactor).

The comparison of these experimental results with Caroline I method, which is slightly different from the method used at that time, has not yet been done because we are waiting for some small modifications of the reference buckling values used in the measurements. But we can say that the limitation, as far as the relative density of hydrogen is concerned, will remain unchanged.

A second set of experiments with natural uranium metal fuel elements has been performed at Risø (Denmark). Buckling exponential measurements have been done by using a 19 rod cluster immersed in an organic liquid contained in two aluminium tubes (Ref. 14).

The comparison with Caroline I showed the trend of the buckling curve as a function of the lattice pitch to be quite satisfactory. On the contrary, the absolute values were appreciably different (about 0.5 m^{-2}), i.e. the calculated curve was lower than the measured one.

Also in this case the relative density of hydrogen nuclei exceeded 0.75 (about 1.0); therefore, this seems to be a confirmation of the fact that our calculation method cannot be used when the organic contents per channel is too high.

The reasons of this difficulty must certainly be found in the hypothesis made about η , A and B in Caroline I method. This point is discussed in the document entitled "A development program for D_2O lattices" presented at this meeting (Ref. 15).

b) Hot coolant activation measurements

A series of hot loop experiments has been done at Chalk River (Ref. 16) : Pu_{239} - U_{235} fission rate and Lu_{176} - Mn_{55} absorption rate ratios inside a UO_2 rod were measured in different positions in a fuel element of the Candu type.

The measurements were repeated for different coolant temperatures, and a "coolant temperature coefficient" $\frac{\Delta Tn}{\Delta Tc}$ (variation of the mean neutron temperature in the fuel element Tn, following a unit variation of the coolant temperature Tc) was obtained. Our simplified model for the spectrum evaluation in a cluster-type fuel element allows the determination of the same quantity, which, in good approximation, is independent from the hardening of the spectrum.

Up to now, our calculations only concerned Pu_{239} - U_{235} fission rate ratios, owing to the unsatisfactory knowledge of Lu_{176} absorption cross section.

The calculated $\frac{\Delta Tn}{\Delta Tc}$ has been found to be in fairly good agreement with the experimental one :

$$\left[\frac{\Delta Tn}{\Delta Tc}\right]_{th} = 0.19 \qquad \left[\frac{\Delta Tn}{\Delta Tc}\right]_{exp} = 0.207 \pm 0.02$$

Also the hardening effect was taken into account in the framework of our model and the experimentally determined neutron temperature was in a general way found to be comprised between the two limit temperatures determined by the theoretical model (see fig. 5). Obviously, in the case of an ORGEL type lattice some caution will be justified, due to the less complete information on the scattering properties of the proton bounded in the organic molecule.

c) Irradiation measurements

The RLT 2 calculation method was checked on the results of Canadian experiments on long irradiation of natural uranium (Ref. 17 and 18).

In these experiments, the composition of uranium metal fuel samples irradiated in the NRX reactor was first measured by chemical and mass-spectrometric analyses.

Afterwards, oscillator measurements of the reactivity of these samples were done in the GLEEP pile.

The main data used in the RLT 2 code for the comparison were the following :

- initial conversion factor of the NRX lattice during irradiation : 0.76 (experimental value)
- neutron temperature in the fuel during the irradiation : 93°C; epithermal ratio (r factor in the Westcott model) : 0.07
- resonance cross section of Pu_{240} (for self-shielding calculation) : $1.734.10^5$ b
- neutron temperature in the fuel during oscillation in GLEEP : 88°C; epithermal ratio : 0.066.

The comparison between experimental and RLT 2 code results of the concentrations of the fuel isotopes is shown in Fig.6, 7, 8, 9, 10.

The agreement seems to be satisfactory, apart from Pu_{240} where the deviation is of 10 % for an irradiation of 1 n/kb.

The reactivity results from oscillation measurements are indicated in Fig. 11. The reactivity changes during irradiation are referred to the AERE standard boron and are then called "apparent cross section values" (Ref. 17).

By using the formula proposed in Ref. 17 to interpret the apparent cross section changes and the values as calculated by RLT 2 for concentrations and cross sections of fuel isotopes and fission products, curve 1 was obtained. Curve 2 was determined by reducing the Pu_{239} fission cross section by 1 %.

The first curve seems to be in better agreement with the measured values but the second one generally remains on the inside of the experimental errors.

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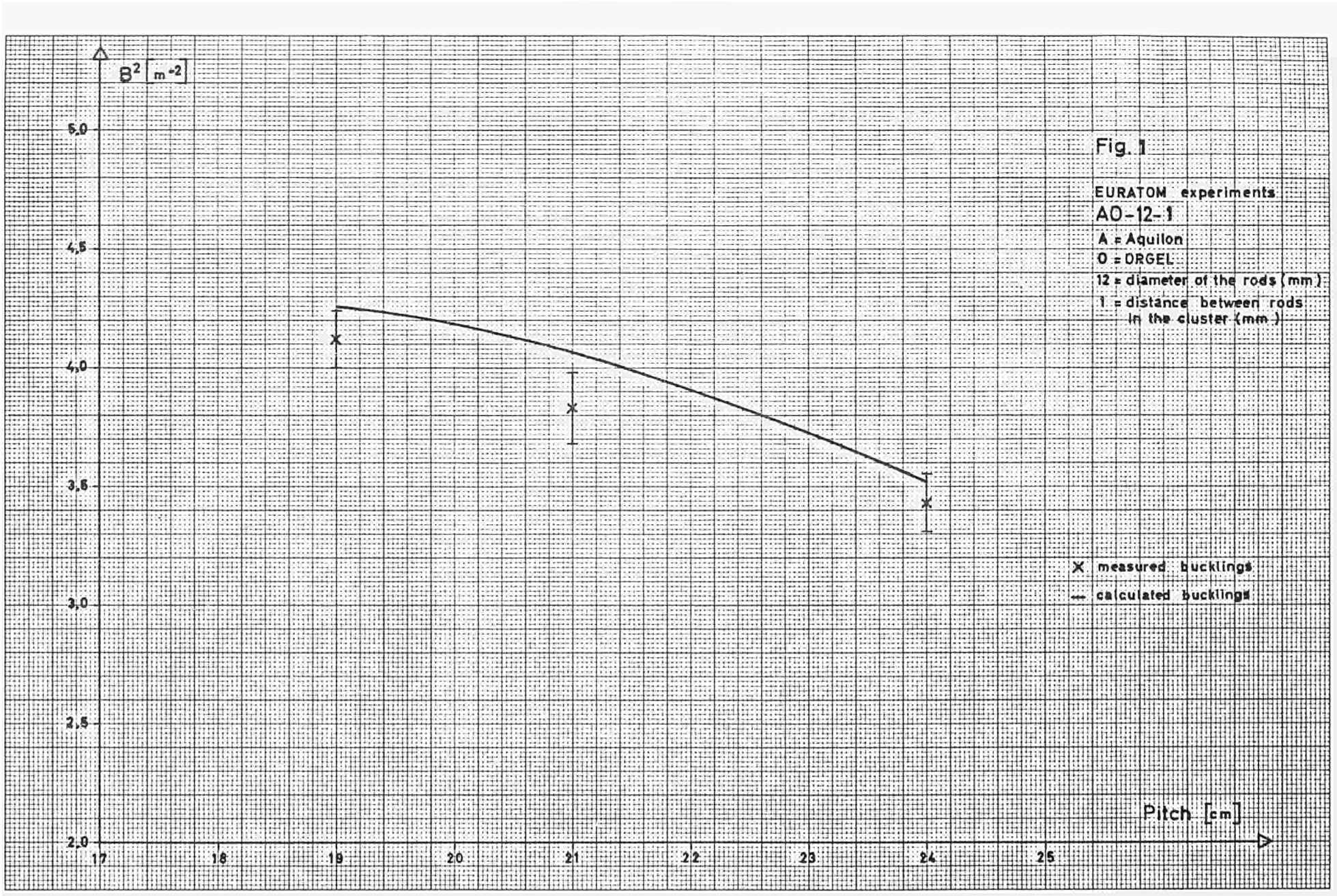
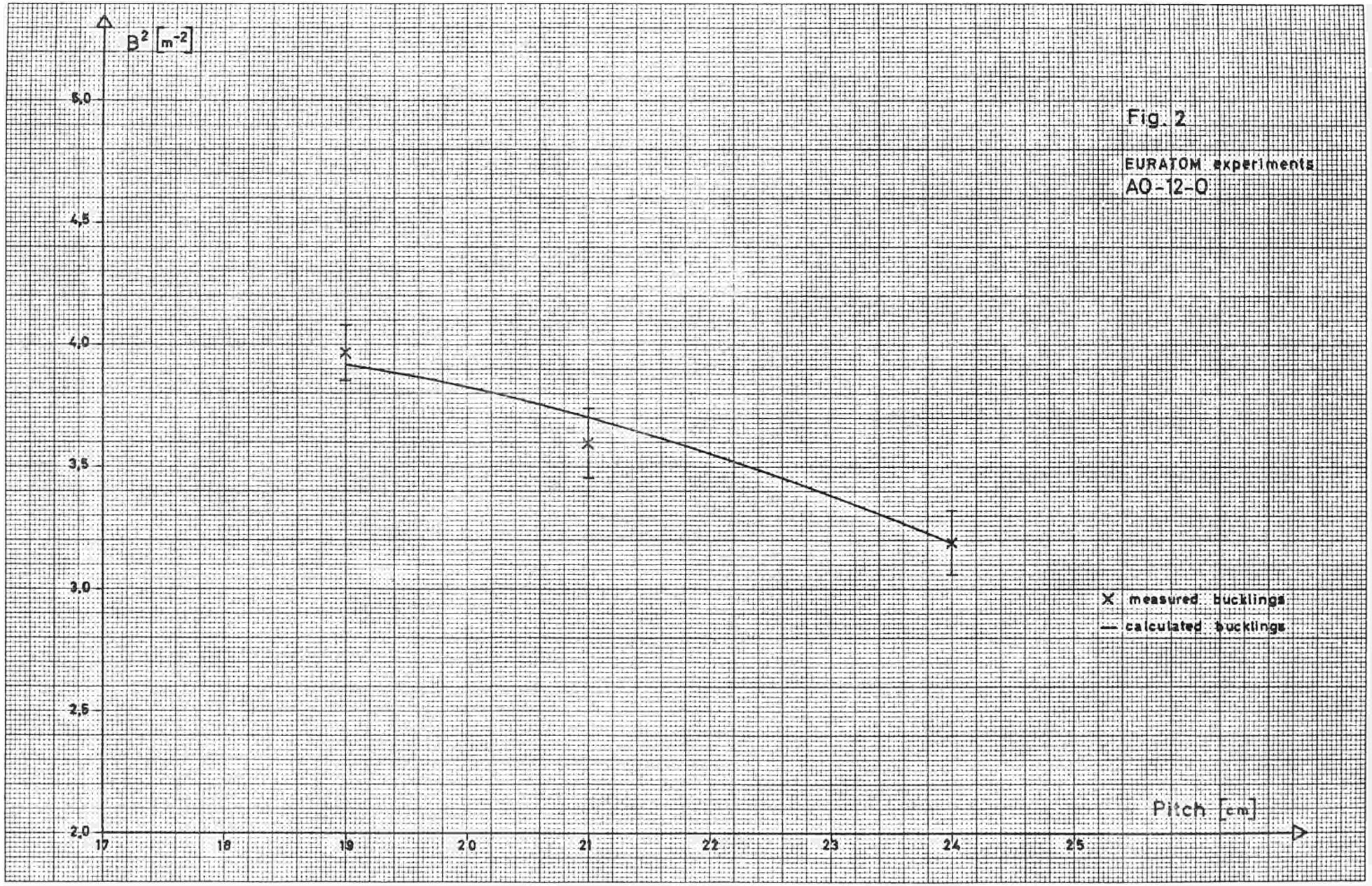

B^2 [m^{-2}]
5,0
4,5
4,0
3,5
3,0
2,5
2,0
17
18
19
20
21
22
23
24
25
Pitch [cm]
Fig. 1
EURATOM experiments
AO-12-1
A = Aquilon
O = ORGEL
12 = diameter of the rods (mm)
1 = distance between rods in the cluster (mm)
measured bucklings
calculated bucklings


B^2 [m^{-2}]
5,0
4,5
4,0
3,5
3,0
2,5
2,0
17
18
19
20
21
22
23
24
25
Pitch [cm]
Fig. 2
EURATOM experiments
A0-12-0
measured bucklings
calculated bucklings

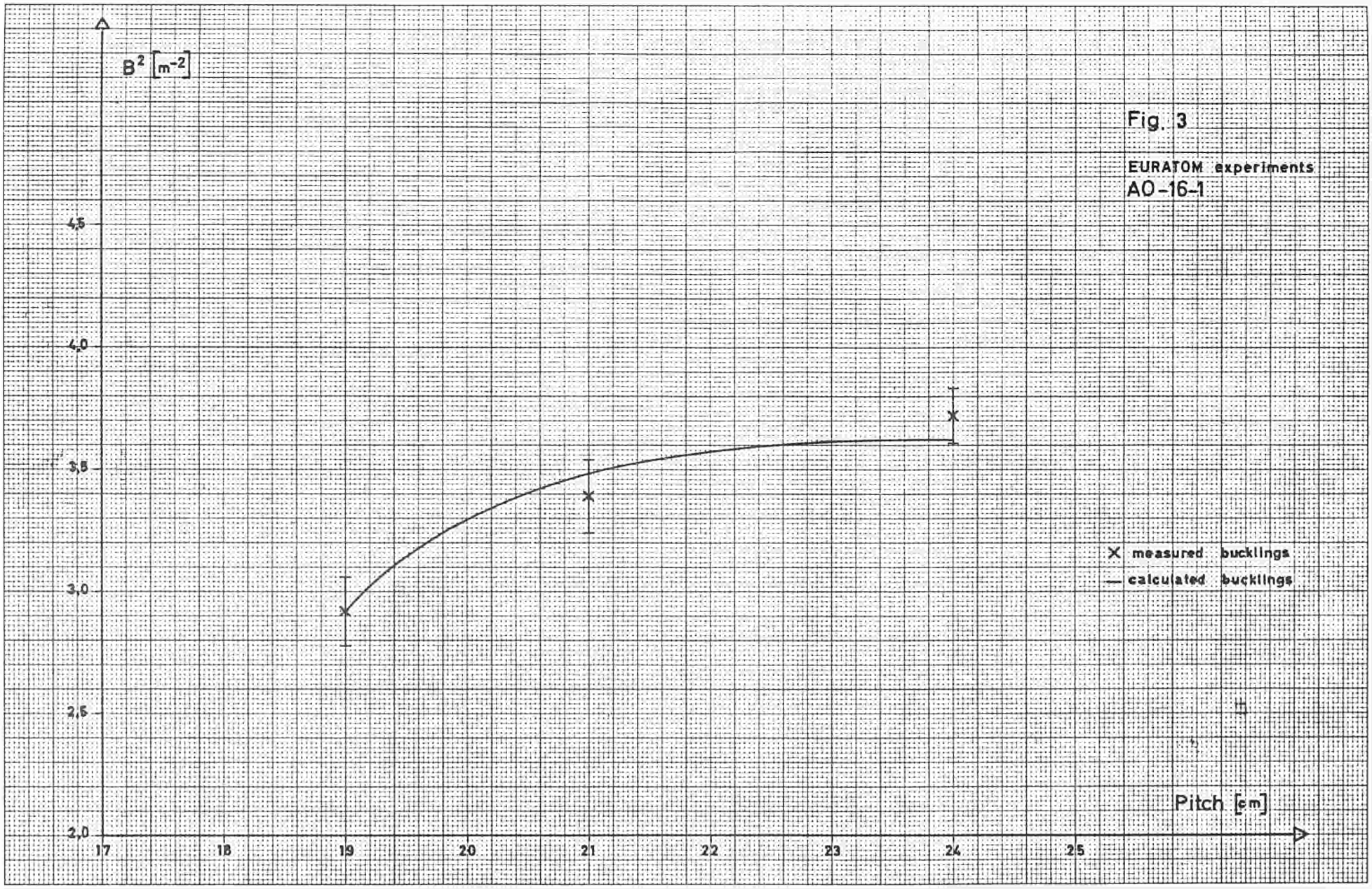
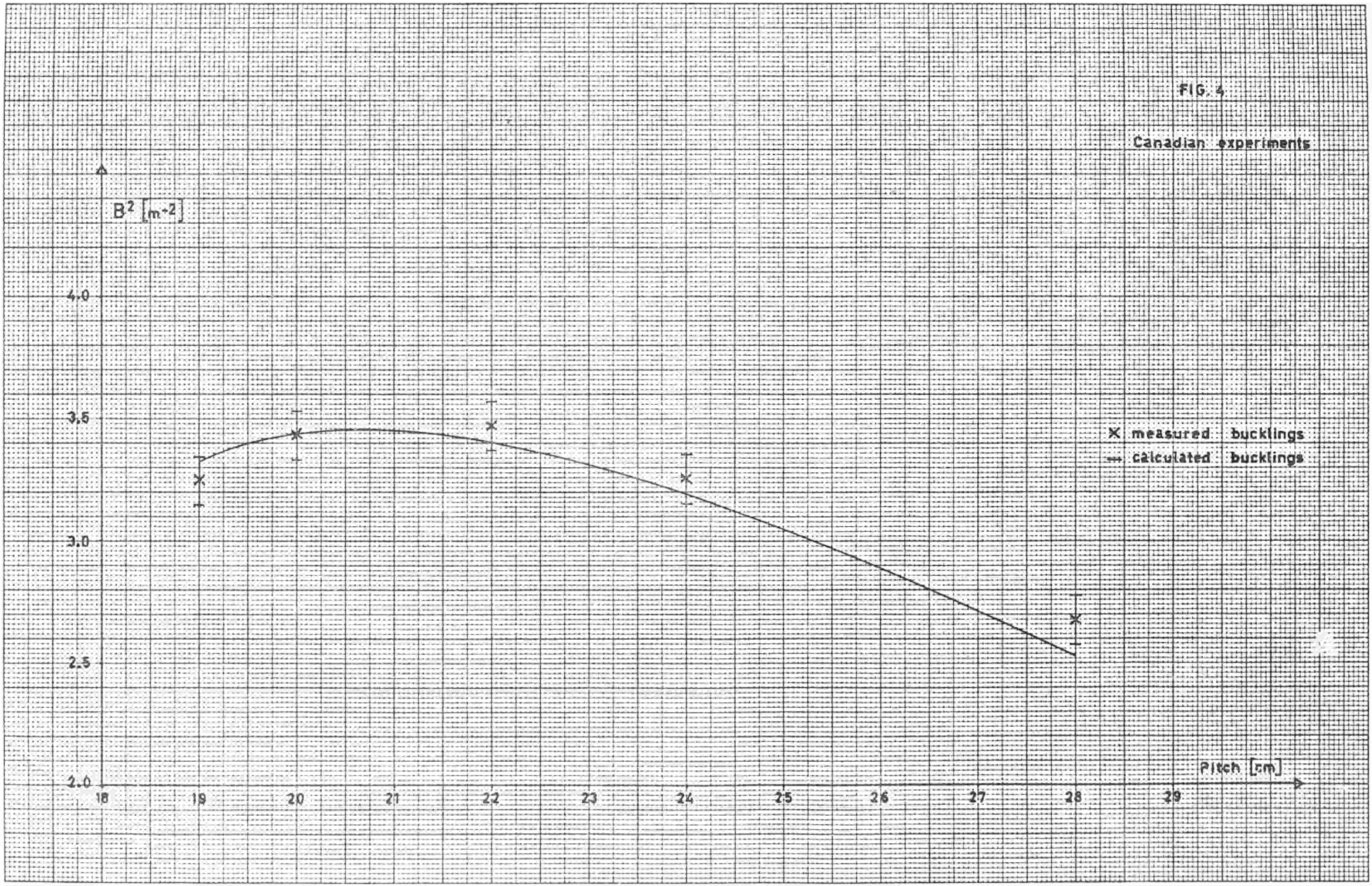


Fig. 3

EURATOM experiments
AO-16-1

FIG. 4

Canadian experiments



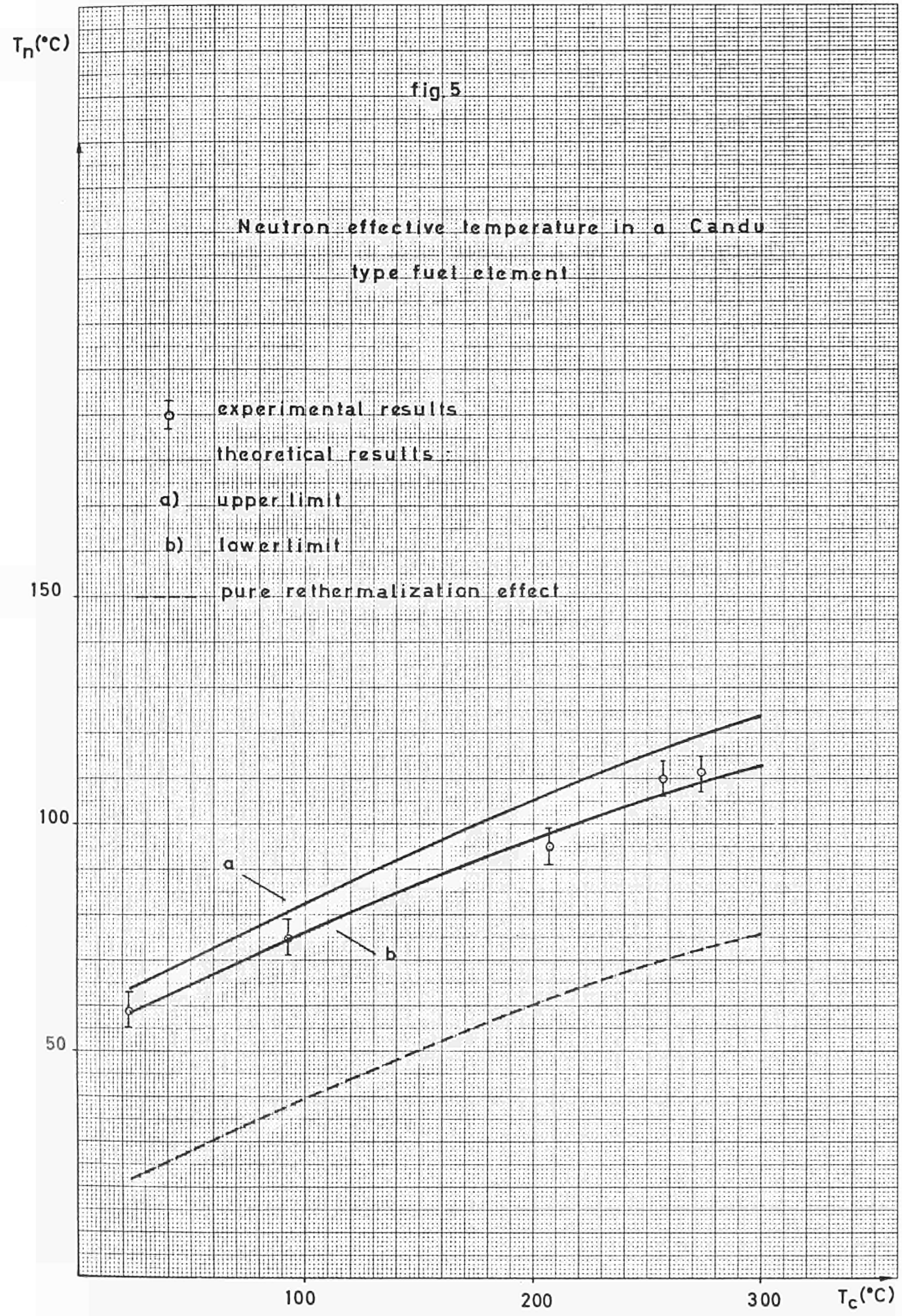


fig. 5
Neutron effective temperature in a Candu type fuel element
experimental results
theoretical results :
a) upper limit
b) lower limit
pure rethermalization effect
T_n(°C)
150
100
50
a
b
100
200
300
T_c(°C)

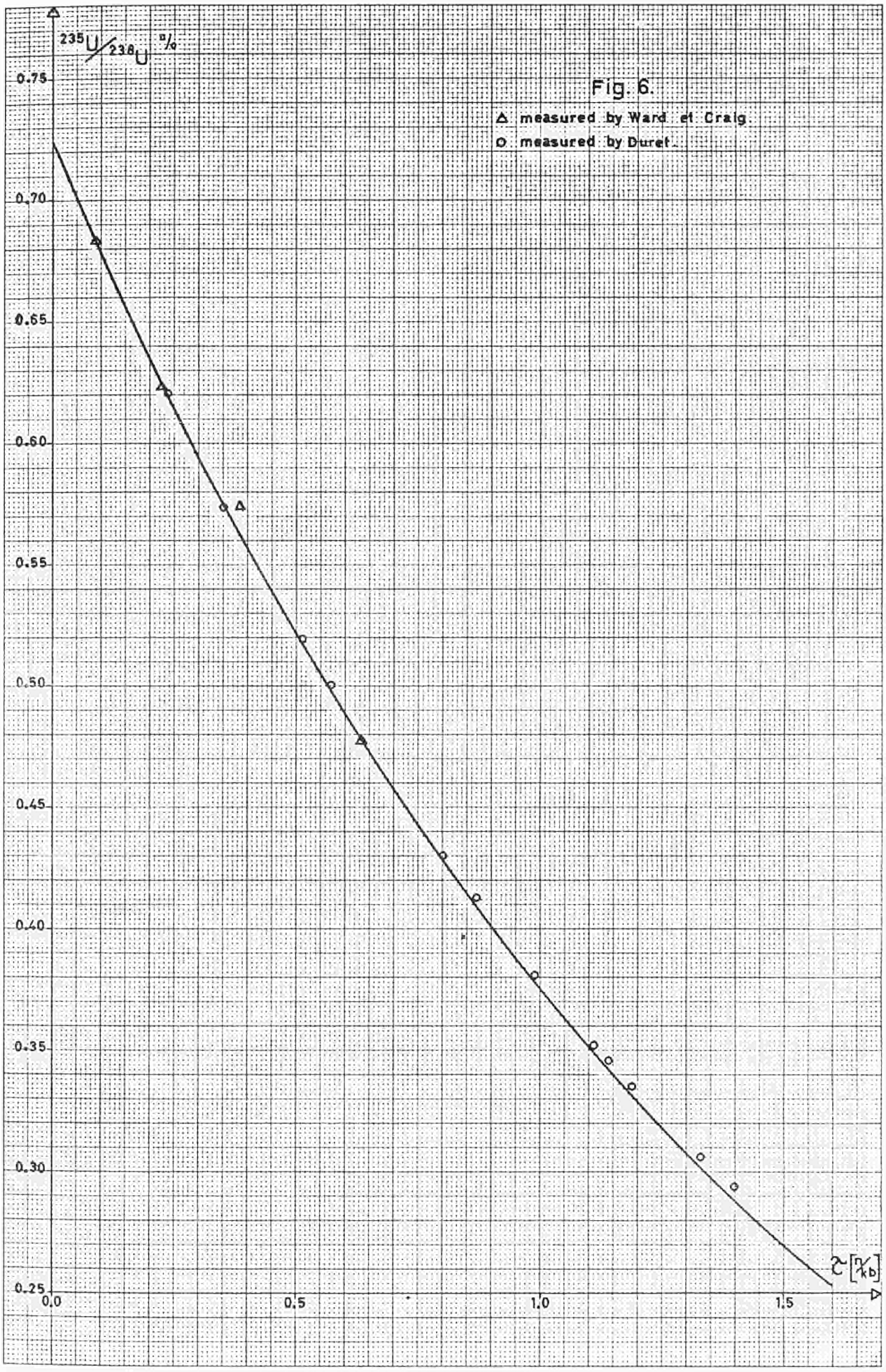


Fig. 6.
△ measured by Ward et Craig.
○ measured by Duret.
$^{235}U/^{238}U$ %
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.0
0.5
1.0
1.5
τ [n/kb]

Fig. 7.

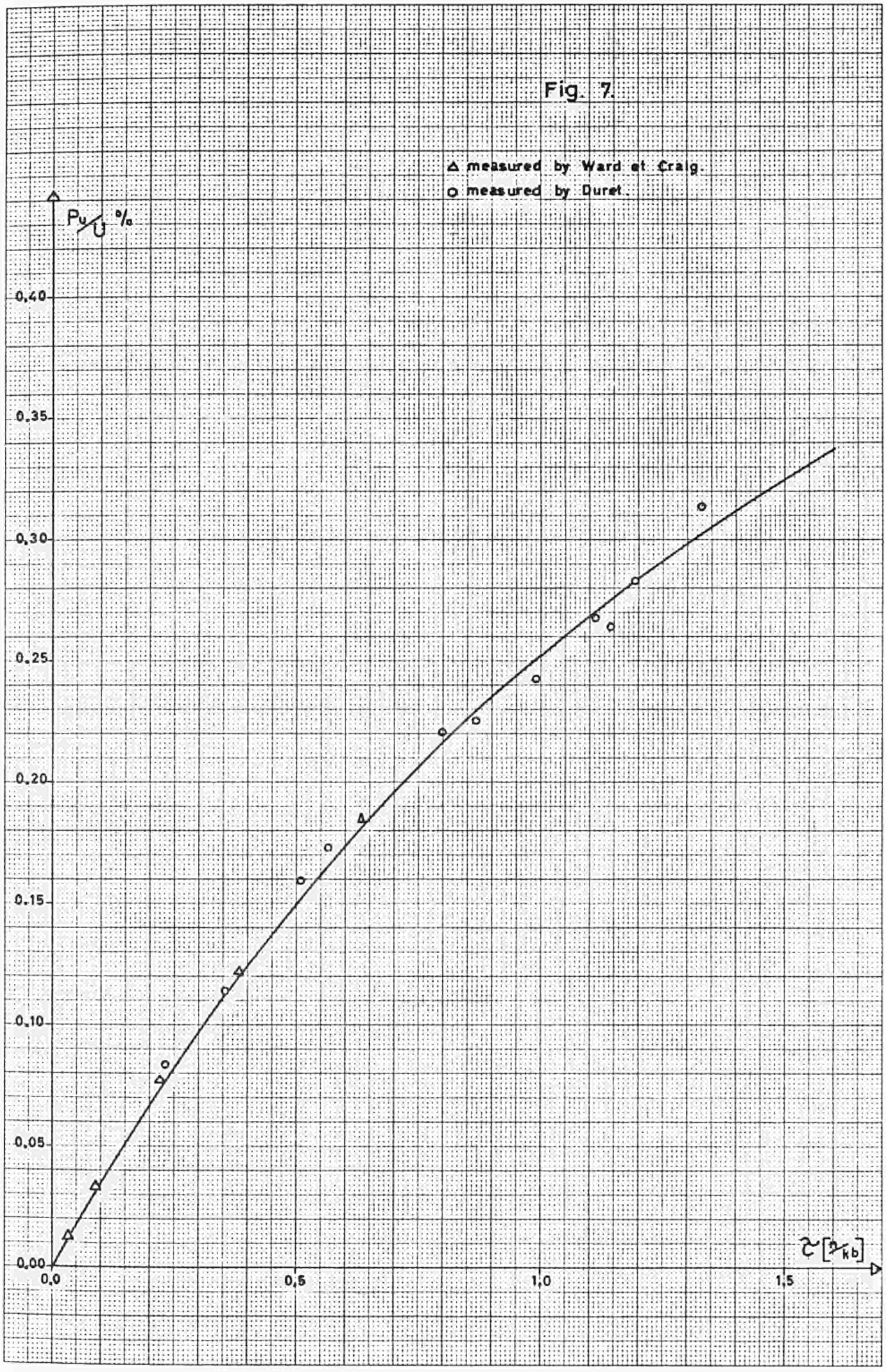

△ measured by Ward et Craig.
○ measured by Duret.
$P_u/_U$ %
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0,0
0,5
1,0
1,5
$\tau\,[kb]$

Fig. 8.

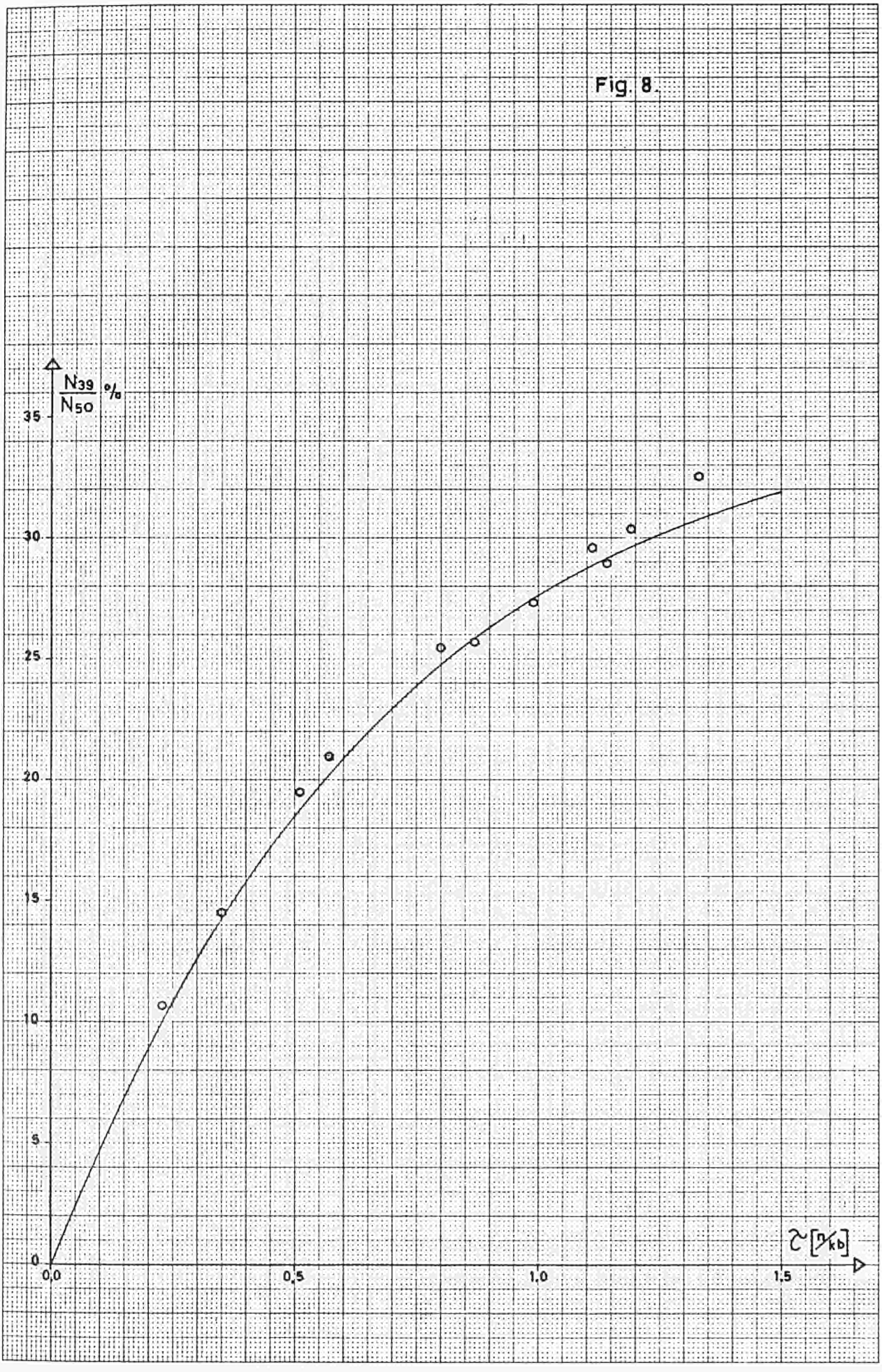


Fig. 9.

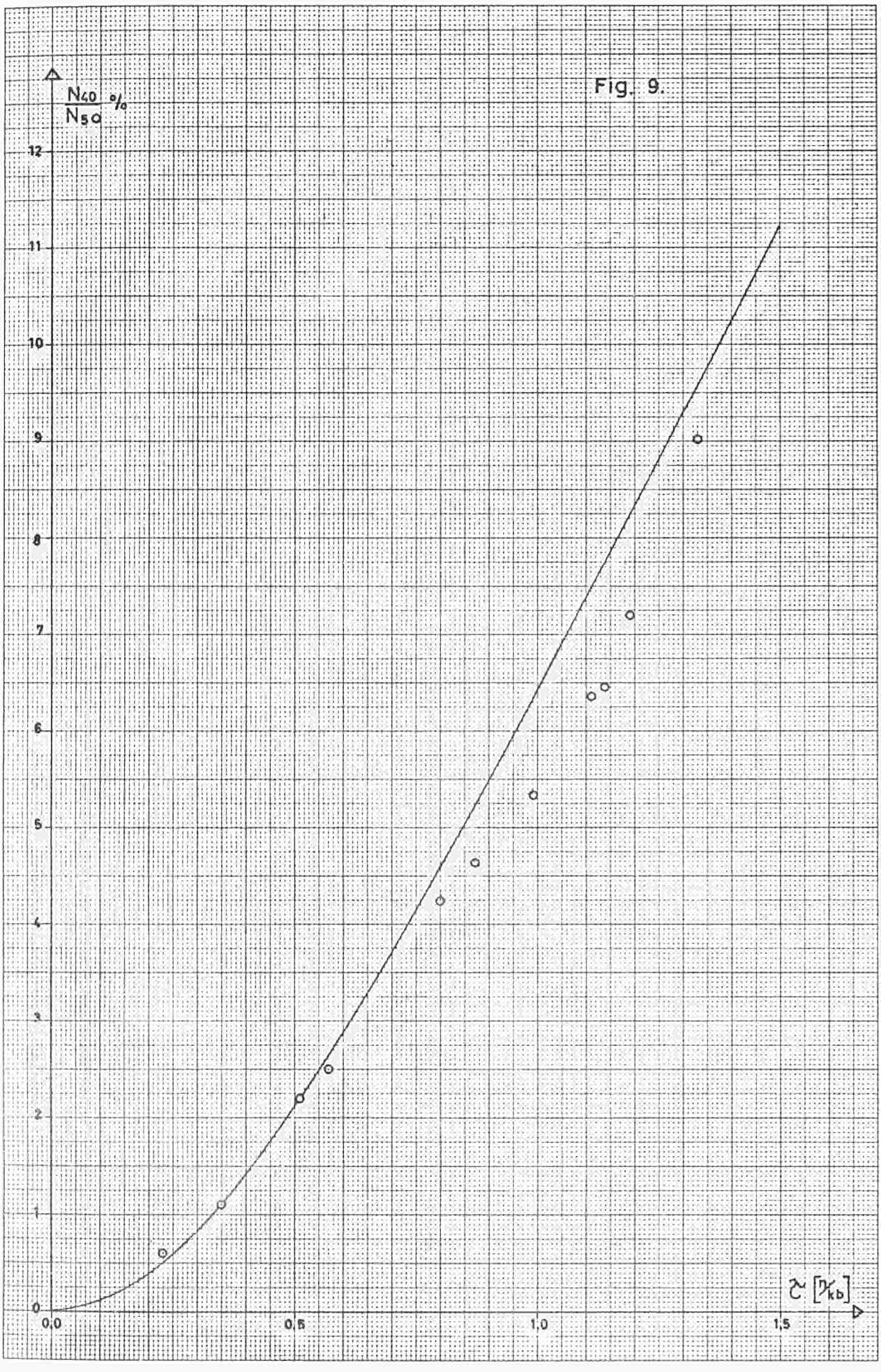
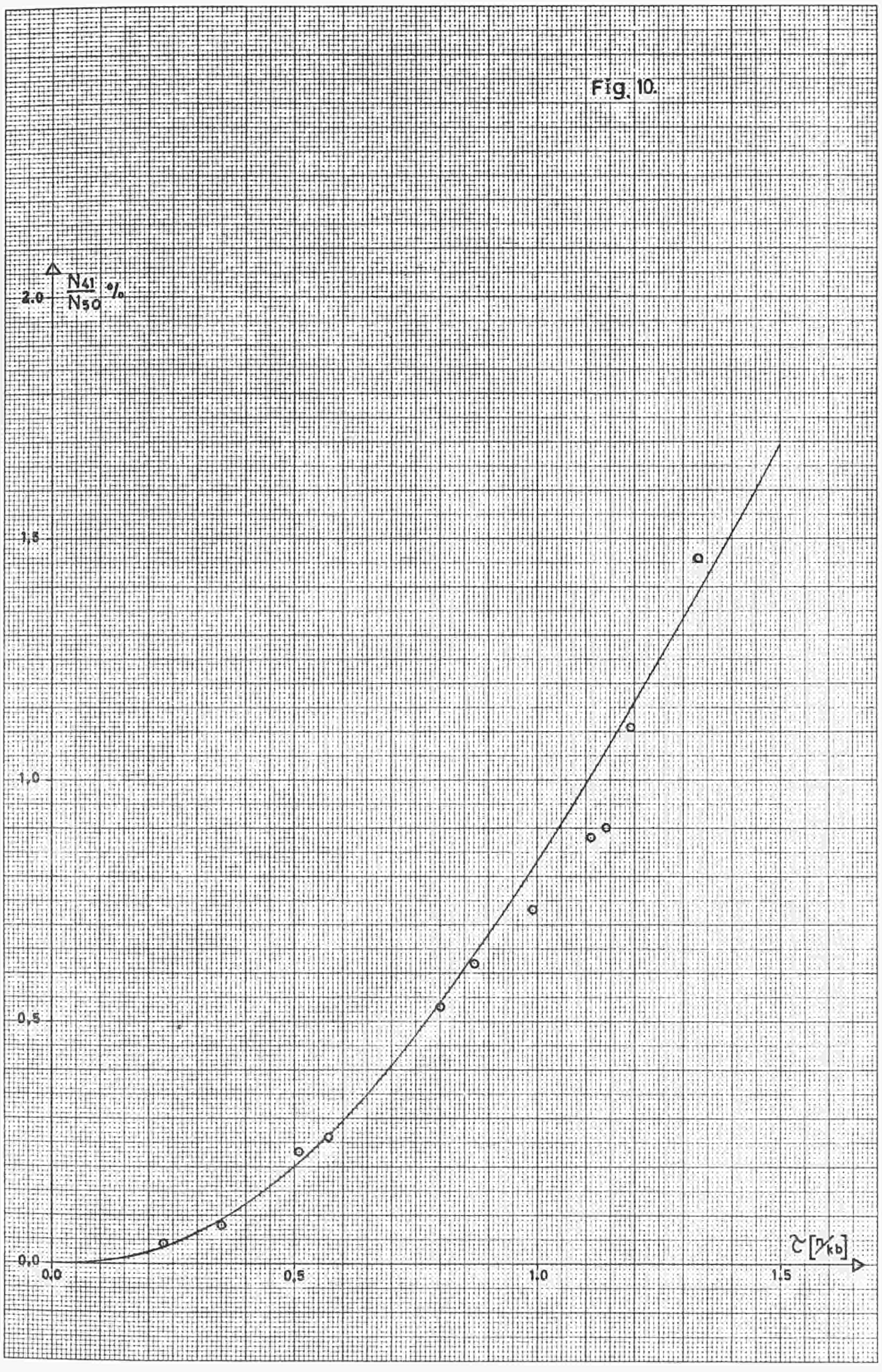


Fig. 10.



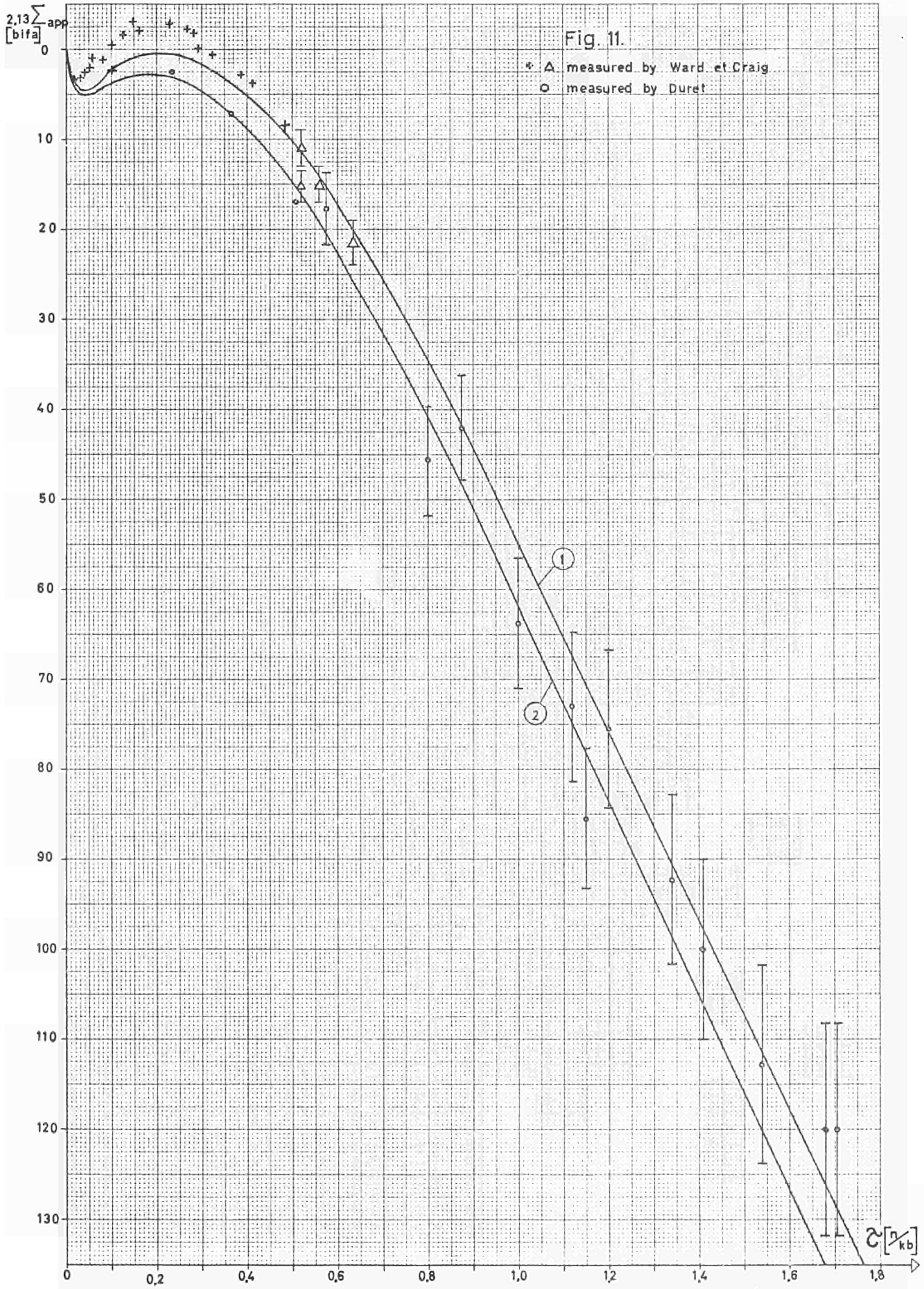


Fig. 11.
measured by Ward et Craig
measured by Duret
2,13 Σapp [bifa]
0
10
20
30
40
50
60
70
80
90
100
110
120
130
1
2
0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
1,8
τ [n/kb]

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