EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

HS-RP/052/CF 14 August 1980

DEFINITION OF RADIATION QUALITY BY INITIAL RECOMBINATION OF IONS

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ABSTRACT

Initial recombination of ions in a gas or liquid is a phenomenon dependent on the distance between the ions formed along the tracks of charged particles and hence on rate of energy deposition. Radiation quality as applied to radiobiological effects and radiation protection is also dependent on the rate of energy loss along the track of charged particles. Therefore the parameters involved in recombination could possibly be used as the basis of a practical definition of radiation quality and provide a means of physically comparing different radiations.

A quantity called Recombination Index of Radiation Quality (RIQ) is defined which is effectively a measure of the difference in recombination occurring at two different operating voltages in a suitable ionization chamber. The values of the voltages at these two operating points determine the dependence of RIQ on ionization density or LET. For example, if these two points are chosen such that there is 4% and 0.1% recombination with Co-60 gamma rays, then it is shown that RIQ will depend on LET in about the same manner as does Quality Factor (QF). The dependence of RIQ on LET can be made to match that of biological effectiveness by suitably selecting the operating points. The results of measurements of RIQ for radiations ranging from gamma rays to alpha particles are presented and it is shown that operating points can be selected such that the measured RIQ's correspond with the QF of these radiations.

To be presented at
Seventh Symposium on Microdosimetry
Oxford, 8-12 September 1980

1. INTRODUCTION

The effect of ionizing radiation on material through which it passes may depend on the microdistribution of the energy deposition along the tracks of charged particles. This is particularly so in the case of the biological effects of radiation and gives rise to the dependence of radiobiological effectiveness (RBE) on the linear energy transfer (LET) of charged particles. This dependence of effect on ionization distribution gives rise to the notion of the quality of radiation with respect to its ability to cause biological effects. Radiation quality has not been rigorously defined, and it is of interest to investigate physical radiation processes that also depend on ionization density distribution in order to try to define a scale of radiation quality in terms of physically measurable quantities. The initial recombination of ions in a gas is such a process and from which a Recombination Index of Radiation Quality (RIQ) can be defined. Moreover, the dependence of initial recombination on ionization density is well established theoretically and experimentally [1,2] and its relation with radiation quality has previously been demonstrated[3,4,5,6].

2. THE RECOMBINATION INDEX OF RADIATION QUALITY (RIQ)

The dependence of initial recombination on radiations of different ionization density and hence of different quality is demonstrated in Fig. 1, which shows saturation curves of ion collection efficiency versus applied polarizing voltage in a suitable ionization chamber when irradiated by gamma rays, neutrons and alpha particles. From these curves it can be seen that a unique parameter attributable to radiation quality could be determined from the difference in collection efficiency at two fixed voltages. Hence a recombination index of radiation quality can be based on measuring the difference in collection efficieny at the two defined voltages U_R and U_S as shown in Fig. 1 and normalizing so that the index will be unity for gamma rays. The definition of RIQ is therefore :

$$RIQ = \frac{(f_S - f_R)_{\text{radiation}}}{(f_S - f_R)_{\text{gamma}}} \tag{1}$$

where f_S and f_R are the measured collection efficiencies.

The RIQ defined in this way can be shown to be single valued in the case of mixed radiation.

Supposing that a RIQ of Q is measured for an absorbed dose D of mixed radiation, then it can be shown that

$$DQ = \Sigma D_j Q_j \tag{2}$$

where D_j and Q_j are the absorbed dose and RIQ of the j'th component of the mixed field. In a suitable recombination chamber the saturation current i_o will be proportional to absorbed dose, hence if the currents measured at the voltages R and S were i_R and i_S , then

$$DQ = k\, i_o \frac{(i_R - i_S)}{i_o} \tag{3}$$

where k is a constant.

The summed dose times RIQ of the components will be given by :

$$\sum D_j Q_j = k \sum i_{o_j} \frac{(i_{R_j} - i_{S_j})}{i_{o_j}} \tag{4}$$

$$= k \left[\sum i_{R_j} - \sum i_{S_j} \right] = k\, i_o \frac{(i_R - i_S)}{i_o} \tag{5}$$

$$= DQ \tag{6}$$

Hence the recombination index has the necessary property of being the dose average of the components that make up the radiation field.

3. DEPENDENCE OF RIQ ON LOCAL ION DENSITY

The dependence of RIQ on local ion density is determined by the choice of the operating voltages U_R and U_S for a given ionization chamber and gas filling. To achieve a definition independent of the experimental equipment, the operating voltages are redefined as those voltages which give a specified fraction of recombination with Co-60 gamma rays. The two operating points can then be defined as R and S , where R and S are the recombined fraction of ions occurring with gamma rays at the voltages that should be used.

For radiation with a single-valued ion density the ion collection efficiency can be expressed as[5] :

$$f = \frac{1}{1 + m\mu} \tag{7}$$

where m depends on the ionization chamber parameters such as voltage, gas pressure, etc., and μ is the ion density. This ion density is associated with a sensitive volume of diameter of the order of 0.07 μ of water[5]. For the purposes of comparison, μ is considered proportional to LET and is arbitrarily assigned a value of 1 for Co-60 gamma rays. Using eq. (7) and expressing m in terms of R and S, the dependence of the RIQ ($Q_{R/S}$) on ion density μ and measuring conditions becomes

$$Q_{R/S} = \frac{1}{R - S}\left[\frac{1 - S}{1 + S(\mu - 1)} - \frac{1 - R}{1 + R(\mu - 1)}\right] \tag{8}$$

Such a function has a maximum value for $Q_{R/S}$ when

$$\mu = \sqrt{\frac{(1 - R)(1 - S)}{RS}} \tag{9}$$

Of particular interest is the case when $S = 0$; this condition is obtained when the recombination chamber is fully saturated at the upper voltage used. In this case the dependence of RIQ ($Q_{S=0}$) on ionization density reduces to :

$$Q_{S=0} = \frac{\mu}{1 + R(\mu - 1)} \tag{10}$$

Assuming the LET of gamma rays to be 3.5 keV/μ and that LET is proportional to ionization density, then $Q_{S=0}$ can be determined as a function of μ and of LET. The family of curves obtained with different values of R are shown in Fig. 2. As can be seen with R = 0.03 or 3%, the form of the RIQ dependence on LET matches that required by the recommended QF dependence of LET[7] up to a QF of 20 at 176 keV/μ. The RIQ with $S = 0$ will always increase with increasing LET. However, biological sensitivity to radiation tends to show a maximum RBE at some optimum LET. The RIQ dependence on LET can be made to simulate this form of response by giving a finite value to S. Curves based on eq. (8) with selected values for S are shown in Fig. 3 as $Q_{R/S}$ as a function of ion density and LET. Curve (a) is with R = 3.5% and S = 0.1% and is shown to follow closely the QF/LET relation over its entire range. The curve (b) with R = 15% and S = 0.1% roughly simulates the observed dependence of RBE on LET for biological systems such as human kidney cell survival[7], whereas the curve (c) with R = 15% and S = 5% is the nearest match to the variation of the RBE with LET for DNA transformation[7]. The relation between RIQ and RBE as demonstrated above is uncertain in as far as the relation between LET and ion density is defined on the basis of the effective LET of gamma rays being 3.5 keV/μ. This is not necessarily true and the curves presented merely indicate the feasibility of matching RIQ to biological response. In practice the RIQ of the radiations used for radiobiology should be measured directly; when a more realistic response curve could be determined and from which the biological effectiveness of any other radiation could then be predicted from a measurement of RIQ.

4. THE DESIGN OF THE RECOMBINATION CHAMBER

The chamber to be used for RIQ measurements has to be tissue equivalent to ensure that ionization from uncharged radiation is proportional to absorbed dose. In addition the electric field should be uniform over the ionization cavity making it desirable to have a parallel-plate electrode construction. Many factors may influence the ionization measurements and modify the shape of the saturation curve. In particular field strengths should be high enough that the volume recombination is not a problem. On the other hand gas multiplication that may occur at very high fields has to be avoided. Care is also necessary in the design to ensure that sensitive volume of the chamber is not dependent on electric field strength. In addition the radiosensitivity of connectors, cables, etc., has also to be kept to a minimum.

The practical range of chamber parameters that are possible are gas pressure in a range of 0.1 to 1 MPa (low pressure is possible if gas of high molecular weight is used). The electrode spacing can be in the range 1 to 10 mm. The degree of saturation with gamma rays necessary for RIQ measurements is with R in a range from 0.03 to 0.3 (i.e. between 3 and 30% from saturation) and the difference in collection efficiency, S - R, in a range 0.02-0.2. Chambers of different construction within the above range of parameters have been used to measure RIQ. Minor variations depending on the construction have been noted, and some standardization of recombination chambers for RIQ measurements may be necessary.

5. THE METHOD OF MEASUREMENT

To measure RIQ according to its definition requires the measurement of ionization currents at 3 voltages, U_R, U_S and U_{max}, where U_{max} is the maximum that can be applied and at which the ion collection efficiency is near to 100% for all radiations to be considered. From the measured currents i_R, i_S and i_0 the RIQ can be estimated from :

$$RIQ = \frac{(i_R/i_o) - (i_S/i_o)}{R - S} \qquad (11)$$

Alternatively to determining i_o using a very high voltage in the recombination chamber, an additional low-pressure chamber may be used which will be fully saturated and from which the required saturation current can be inferred. For many applications i_S will be practically equal to i_o, in which case only two ionization current measurements are required to determine RIQ.

6. EXPERIMENTAL MEASUREMENTS

Measurements of RIQ have been made using various chambers. Some results are presented in Fig. 4 where the RIQ for different radiations has been plotted as a function of R. Curve (a) is for alpha particles from ^{222}Rn and was obtained with a chamber in which the radon was incorporated with a CO_2 gas filling at 300 MPa. Similar curves for other external radiations were made with a chamber filled to 110 kP of butadien (C_4H_6). In this chamber the plate spacing was 1.5 mm and the sensitive volume 5 cm^3. The chamber was placed in a water phantom and the depth adjusted for maximum dose rate in different radiation fields. The external radiations that have been measured include neutrons from a PuBe source (curve b) in which gamma rays contribute about 12% to the absorbed dose. Curve (e) is for negative pions where about 30% of the dose was from muons and electrons[8]. Curve (d) is for high-energy neutron beam $\overline{E}$ = 250 MeV where gamma radiation was negligible. The values of RIQ for these radiations with R = 4% correspond closely with the quality factors determined on the basis of dose distribution versus LET.

Measurements of RIQ have also been made as a function of the attenuation of radiation from a PuBe neutron source. Bismuth absorbers were added and the RIQ is observed to increase with increasing thickness of bismuth as the gamma rays from the source are attenuated and hence the radiation quality increases. The results of these measurements are shown in Fig. 5.

7. CONCLUSIONS

Initial recombinations of ions in a gas can be used to determine a quantity that depends on radiation quality in a way similar to biological effectiveness and quality factor. This quantity, the Recombination Index of Radiation Quality (RIQ) is measurable using a suitable ionization chamber. Actual measurements of the RIQ of radiations ranging from gamma rays to alpha particles confirm that it is possible to adjust the parameters involved such that RIQ is proportional to quality factor over its entire LET range. Other response curves, such as that of the dependence of RBE on LET can also be matched by selecting suitable operating voltages. This ability to control the parameters influencing initial recombination of ionization in gases make it possible to use the phenomenon as a basis for a practical definition of radiation quality.

REFERENCES

1. G. Jaffé, Ann. der Physik, 42, 317 (1913).
2. D.E. Lea, Proc. Camb. Phil. Soc., 30, 80 (1933).
3. M. Zielczynski, Proc. Conf. Neutron Dosimetry II, IAEA, Vienna (1963).
4. A.H. Sullivan and J. Baarli, CERN report 63-17 (1963).
5. A.H. Sullivan, CERN report 69-1 (1969).
6. M. Zielczynski and K. Zarnowieski, Proc. Conf. Neutron Monitoring, IAEA, Vienna (1967).
7. ICRU Report 16 (1970).
8. V.M. Abazov et al., JINR Report 8079 (1974).

FIGURE CAPTIONS

Fig. 1. Saturation curves of ionization collection efficiency versus log of collecting voltage U for radiations of different quality -- gamma rays, neutrons and alpha particles. The curves D_1 and D_2 are those obtained with low and high dose rates.

Fig. 2. The recombination index of radiation quality Q_R as a function of ion density and LET when Q_R is determined between a saturation voltage (S = 0) and a voltage which gives a recombination of R% for gamma rays. Also shown is the ICRP-recommended relation between QF and LET, for comparison.

Fig. 3. The recombination index of radiation quality as a function of LET determined between different operating points compared to ICRP-recommended QF-LET relations (curve a) and with experimental RBE/LET data for human kidney cell survival (curve b) and DNA transformation (curve c).

Fig. 4. Experimental values of recombination index of radiation quality Q_R versus the operating point R for
a) alpha particles from ^{222}Rn,
b) radiation from a PuBe neutron source,
c) negative pion beam at JINR,
d) neutron beam of mean energy 250 MeV, and
e) ^{60}Co gamma radiation.

Fig. 5. RIQ for radiation from a PuBe neutron source as a function of bismuth filter thickness.

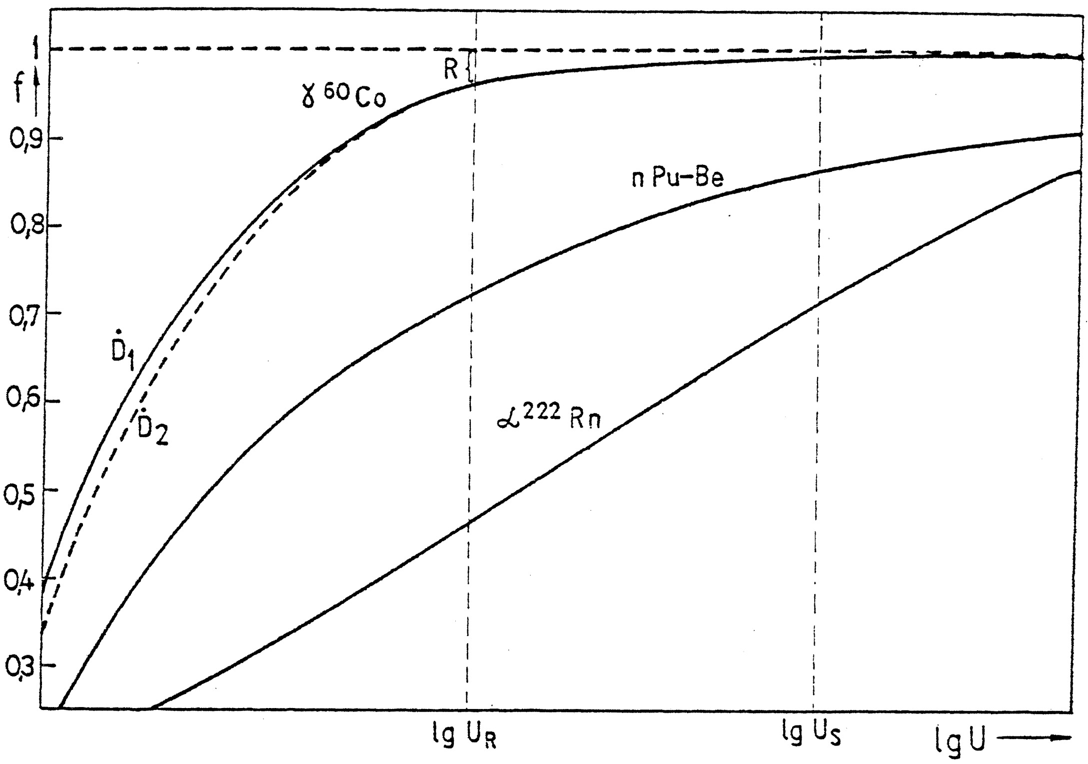
f
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
R
γ 60 Co
n Pu-Be
α 222 Rn
Ḋ1
Ḋ2
lg U_R
lg U_S
lg U

Fig. 1

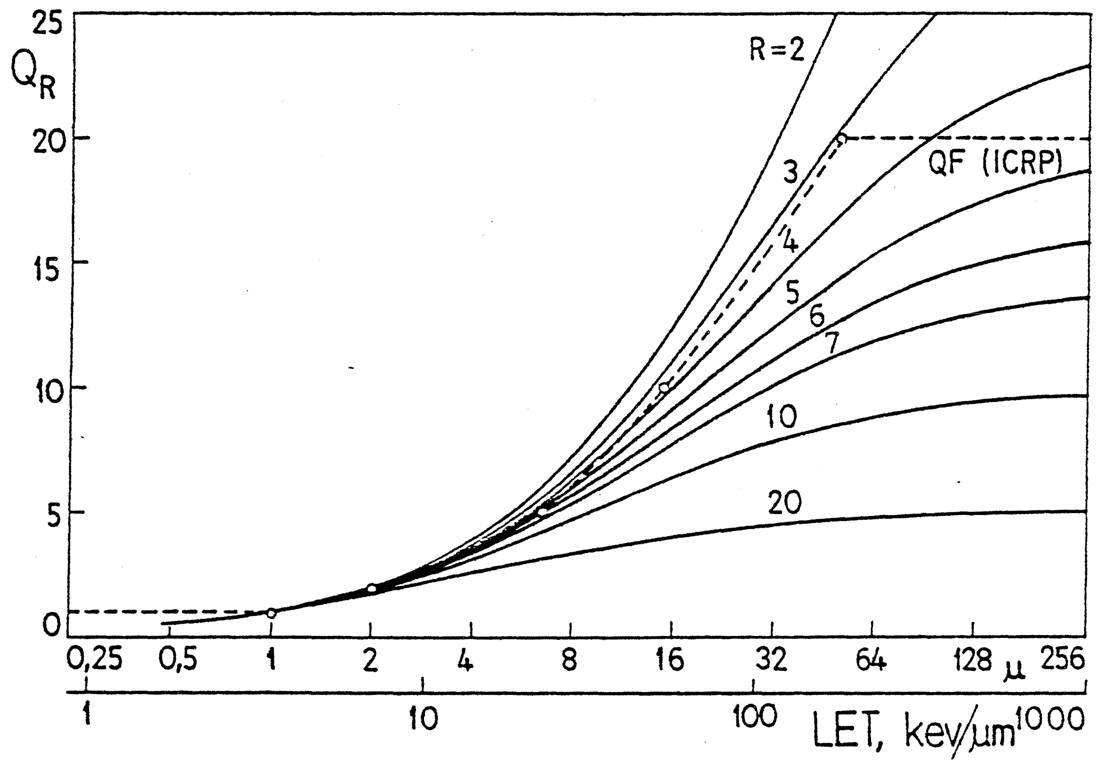
Q_R
25
20
15
10
5
0
R=2
3
4
5
6
7
10
20
QF (ICRP)
0,25 0,5 1 2 4 8 16 32 64 128 μ 256
1 10 100 1000
LET, kev/μm

Fig. 2

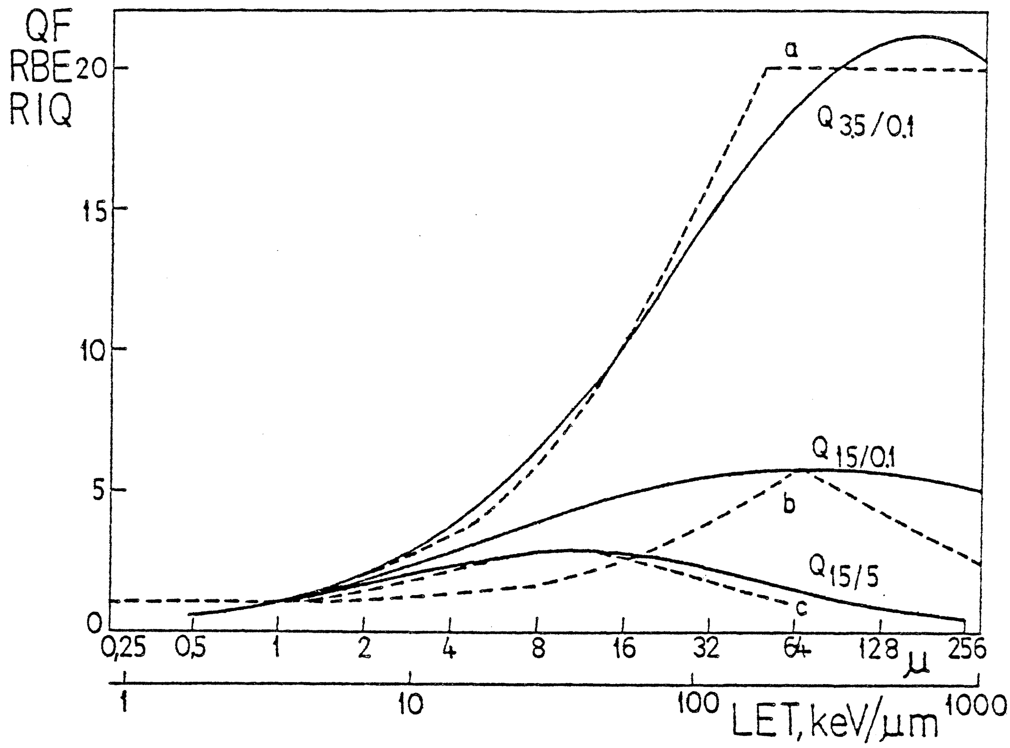
QF
RBE
RIQ
0
5
10
15
20
a
$Q_{3.5/0.1}$
$Q_{15/0.1}$
b
$Q_{15/5}$
c
0,25
0,5
1
2
4
8
16
32
64
128
256
μ
1
10
100
1000
LET, keV/μm

Fig. 3

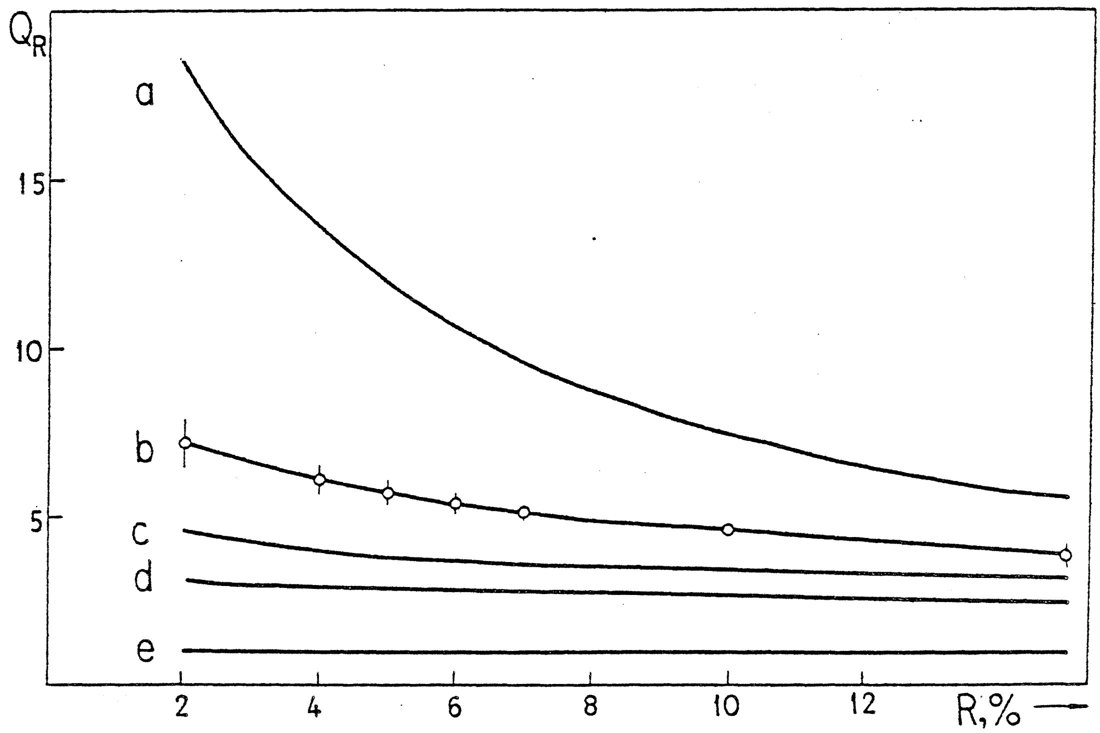
Q_R
15
10
5
a
b
c
d
e
2
4
6
8
10
12
R,%

Fig. 4

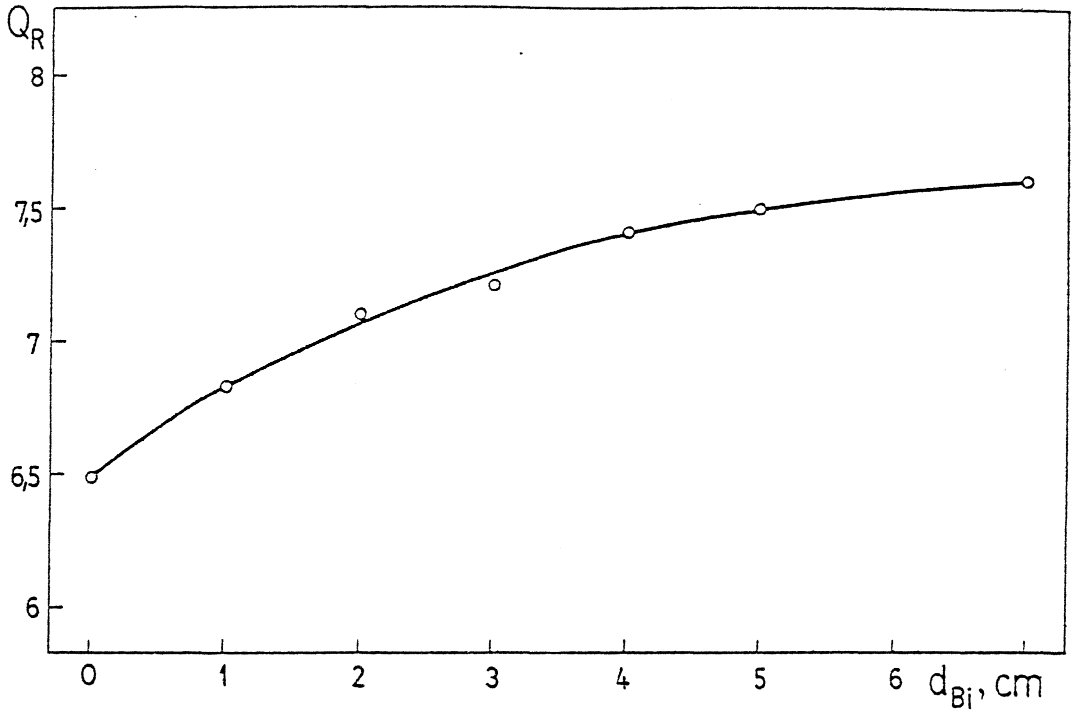

Fig. 5