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INSTITUT ZA NUKLEARNE NAUKE

„BORIS KIDRIČ“

401/18

KALORIMETRIJSKA MERENJA
APSORBOVANIH DOZA
U REAKTORU NA TEŠKU VODU
I OBOGAĆENI URAN

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NI URAN U VINČI

NOSILAC ZADATKA
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ŠEF ODELJENJA 22,
(Dr.Ivan Draganić)

Br.ugovora sa SKNE

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KALORIMETRIJSKA MERENJA APSORBOVANIH DOZA
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Primenu kalorimetrijske metode nametnula je potreba za poznavanjem topografije apsorbovanih doza u eksperimentalnim kanalima reaktora. Ostale metode (jonizacione, hemijske) su manje pouzdane jer se u reaktoru radi o smeši zračenja.

Rad se razvijao u dve faze i to:

I.- Kalorimetrijska merenja na nižim snagama reaktora (13-80 kW)

- Izotermski kalorimetar

II.- Konstrukcija kalorimetra za rad na višim snagama reaktora (do 1 MW)

- Diferencijalni kalorimetar.

I.- Kalorimetrija na nižim snagama

Za ova merenja konstruisan je izotermski kalorimetar sa termistorima. Konstrukcija ovog uređaja opisana je u prilogu (1). Opseg primenljivosti ove konstrukcije je 10^4 do 6×10^5 rad/h što odgovara snagama reaktora "RA" nižim od 100 kW. Preciznost merenja 2-5%. Prema konsultovanoj literaturi, ovo je prvi uređaj za kalorimetriju reaktora koji koristi termistorske termometre i primenjuje t.zv. "kinetičku" metodu određivanja ravnotežne temperaturske razlike.

Merenja na reaktoru "RA", vršena uglavnom na snazi od 20 kW, pokazala su da se krive visinske raspodele apsorbiranih doza poklapaju sa krivama fluksa termalnih neutrona iz perioda nulte snage. Određeni su takodje i doprinosi gama zraka i brzih neutrona u apsorbiranoj dozi. Rezultati ovih merenja i razmatranja problema dozimetrije reaktora dati su opširnije u prilogima (2) i (3).

II.- Kalorimetar za merenja na višim snagama reaktora

Da bi se mogle direktno meriti apsorbirane doze na višim snagama reaktora ostvarena je nova konstrukcija kalorimetra. Ovo je učinjeno da bi se izbegla ekstrapolacija vrednosti sa nižih snaga. Osim toga postojala je potreba za kalorimetrom koji će odjednom u nekoliko tela meriti apsorbiranu dozu. Jedan od direktnih razloga bio je razlika rezultata hemijske dozimetrije (radjeno na višim snagama) sa kalorimetrijom (radjeno na nižim snagama) u izvesnim tačkama.

Razradjen je novi tip diferencijalnog kalorimetra sa termoelementima. Glavne odlike nove konstrukcije su:

- koristi princip da ravnotežna temperatura toplotno aktivnog tela ne zavisi od toplotnog kapaciteta
- transportna sredina nije vazduh nego polistirolska pena
- radi sa velikim temperaturnim razlikama (do 50°C) koje nisu uobičajene u kalorimetriji.

Merenja na reaktoru pokazala su da se sa novom konstrukcijom može ići do snage od oko 1 MW. Rezultati za grafit veoma se dobro slažu sa vrednostima očekivanim na osnovu ranijih merenja sa izotermnim kalorimetrom (3). Opširnije o novom kalorimetru i merenju dato je u prilogu (4).

Z a k l j u č a k

S obzirom da je radom na ovom zadatku:

- konstruisan izotermiski kalorimetar sa termistorima;
 - izvršena topografska odredjivanja apsorbovanih doza u eksperimentalnim kanalima reaktora "RA";
 - odredjen doprinos brzih neutrona i gama zraka u apsorbovanoj dozi;
 - ostvarena i isprobana nova konstrukcija kalorimetra za rad na višim snagama reaktora;
- smatramo da je zadatak po ovom ugovoru izvršen.

ŠEF ODELJENJA 22,

Ivan Draganić
(Dr. Ivan Draganić)

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(†) Odobreno za objavljivanje u inostranstvu.

^{*})

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PRILOG I

ISOTHERMAL CALORIMETRY FOR REACTOR RADIATION DOSEMETRY

by

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Chemistry

An isothermal calorimeter with thermistors for measuring absorbed dose rates from 10^4 - $5 \cdot 10^5$ rad/h in reactor experimental holes has been designed.

A kinetic method for determining the equilibrium temperature difference has been developed, and its application in isothermal calorimetry proved.

The expected accuracy in measurements within $\pm 2-5\%$ has been proved by measurements carried out in the reactor.

Some data obtained by measurements in the reactor SA are presented.

1. Introduction

After the publication of the papers presented by D. M. Richardson et al. [1], and A. S. Anderson et al. [2], calorimetric dosimetry has become a method very much required in the technique of reactor exploitation and operation, and in radiation chemistry.

We, also, have designed a calorimeter and developed a method of measurement different from the ones published so far [1,2,3 and 4]. The difference consists in the application of the "kinetic method" for the determination of the equilibrium temperature difference, and in the use of thermistors for its measurement.

In the beginning, the calorimeter was designed for reactor operation at low power levels, and the expected absorbed dose rates ranged between 10^4 and 10^6 rad/h.

We have preferred the principle of the isothermal to that of the adiabatic calorimeter because of the lower limit of the dose rate to be measured (10^4 rad/h). Calculations for the adiabatic calorimeter have shown that this absorbed dose rate in a water calorimetric body would produce the heating rate of $2.5 \cdot 10^{-2}$ °C/h. If copper-constantan thermocouple was used, we could observe changes of only about 1 microvolt/h, this being very inconvenient for manipulation. Thermistors could not be used in adiabatic calorimetry, because it is very hard to provide two identical thermistors. That is why it is more convenient to apply the method of determining the equilibrium temperature difference between the calorimetric body and its jacket (maintained at a constant temperature) - the principle of isothermal calorimetry. Rough calculations have shown that by applying thermistors with $R_{25} \approx 5000$ ohms, one could expect the equilibrium resistance difference to be, for 10^4 rad/h, about 3 to 5 ohms which could be easily measured with good accuracy.

II. Method of measurement: "kinetic" method; calibration during irradiation

In long process isothermal calorimetry, measurements are usually made of the equilibrium temperature difference established after rather a long time. In order to determine the equilibrium temperature before it has been established, thus reducing the time required for measurement, an equation of the heating of the thermally active body has been checked⁽⁺⁾.

The thermally active body is heated due to the internal process of energy development (the power w =constant), and is cooled (or heated) simultaneously owing to the exchange of heat with its jacket. The change of temperature with time will then be defined [6] by:

$$\frac{dT}{dt} = \frac{w}{mc} - K (T - T_0) \dots\dots\dots (1)$$

where:

- T - body temperature
- T_0 - temperature of the jacket (= constant)
- t - time
- w - heating power of the internal process
(=constant)
- K - cooling constant
- mc - heat capacity of the calorimetric body

Integration of equation (1) yields:

$$T = T_0 + \frac{w}{Kmc} + C \cdot e^{-Kt} \dots\dots\dots (2)$$

⁺According to Swietoslawski [5] there is an internal process of energy development in the thermally active body, as distinct from the thermally inert body cooled or heated only due to the exchange of heat with surrounding media.

where G is the integration constant defined by the initial conditions $t=0$ and $T=T'$:

$$G = T' - T_0 - \frac{W}{Kmc} \dots\dots\dots (3)$$

Equation (2) represents the general time function of the thermally active body temperature. It is obvious that, after a sufficiently long time, the equilibrium body temperature (T_p) is established, provided the jacket temperature (T_0) is constant. At this temperature the heating power is equalized to the heat losses. Under these conditions one obtains from equation (2):

$$T_p - T_0 = \frac{W}{Kmc} \dots\dots\dots (4)$$

provided $t = \infty$, i.e. the relation usually used in isothermal calorimetry, and according to which the equilibrium temperature difference is linearly proportional to the heating power of the internal process. When using equation (4) for determining the energy development (w), one of the problems encountered in practice is that too much time is often required for reaching equilibrium. This is particularly expressedⁱⁿ constructions with high sensitivity and very high inertia.

The application of equation (2) makes possible the determination of (T_p) even before it really has been established. It is sufficient to measure several temperature (T) values in the corresponding times (t). If the measured values of (T) are plotted in the function of corresponding e^{-Kt} values, one obtains a straight line (Fig.1). Extrapolation to $e^{-Kt} = 0$, i.e. for $t = \infty$, will give the value (T_p).

To perform such a measurement, one must know beforehand the "cooling constant" (K) for a given system.

Fig. 1. - Kinetic method shown graphically

Such mode of determining the equilibrium temperature is called the "kinetic method". The "static method" means direct measurement in the very equilibrium. The applicability of the kinetic method has been verified by measuring the (T_r) values both by the kinetic and the static method.

The linearity of equation (4) permits calibration in the course of irradiation (similarly to the method of "standard addition", often used in polarography). This method is illustrated in Fig.2.

Fig. 2. - Method of isothermal measurement shown graphically

Heating of the body due to the unknown process to be measured is observed first. Since (T_0) is known, (T_{rx}) or (ΔT_x) is determined by the "kinetic" or the "static" method. Then, without interrupting the unknown process (in our case irradiation), the calorimetric body is heated by means of a built-in heater with a known power input (w_k). A new equilibrium temperature (T_{rk}) or difference (ΔT_k) is thus reached, for the (T_{rx}) is known from the previous determination. The value (w_x), the only unknown quantity, is then estimated from:

$$\Delta T_x : \Delta T_k = w_x : w_k \dots\dots\dots (5)$$

Such mode of calibration is more direct than the comparison with the calibration performed in the laboratory, and it is of particular interest because the behaviour of thermistors can be checked in the reactor radiation field (and compared with their response without radiation).

III. Description of the calorimeter and measuring devices

The main structure material was an aluminum-silicone alloy of nuclear purity grade "SAV"-21" (USSR) and plexiglass. The electrical leads were of copper; constantan wire with enamel and silk insulation was used for the calibration and jacket heater. For better insulation use was made of capacitor paper and polystyrene film.

The calorimeter (fig.3) consisting of the calorimetric body (1) and the jacket (2) was positioned on the plexiglass spikes in the protective can (3). In the jacket there was a constantan wire heater for thermostating and 4 thermistors (two parallel pairs connected in series) as a control thermometer. Part of the jacket (isothermal unit) composed of two disks connected with 4 thin columns supported the calorimetric body.

Fig.3.- The scheme of calorimeter

The body was suspended and centered by means of thin nylon threads. Electrical connections are drawn out through tephlon cylinders in the upper disk. The body was a thin-walled vessel of plexiglass containing heavy water and light water (or some water solution).

The calibration heater was wound on the thin wall of a little tube immersed into the liquid. The vessel was hermetically closed. On the same tube there was a thermistor as well, insulated electrically from the liquid. The graphite body was the same in size and shape and was composed of several parts packed closely together forming a compact unit.

All the electrical leads were gathered in a long cable fastened mechanically to the lid of the protective can. The cable was protected electromag-

netically as well.

The thermistors used were "Phillips", Bead-type NTC Resistors with nominal resistance of 4700 ohms at 25°C. The measuring devices are given in Fig.4. The thermistor resistances were measured by a Wheatstone bridge with two arms R_1 and R_2 of 5000 ohms (constantan wire).

Fig.4. - Scheme of the calorimeter and the measuring system (P-commutator; K -calorimetric body; O-jacket; T -thermistors (T_1 - jacket; T_2 -body); K_g -calibration heater; G_o -jacket heater; Z-protective can; G-electronic galvanometer "KINTEL" model 204A)

All parts of the bridge except the 5-decade resistance box (R_d) (manganin 0.02% grade) and the galvanometer (G) were in an iron box. With this bridge, resistances from 3000 to 5000 ohms could be measured with an accuracy of ± 0.1 ohm, or a resistance difference of 20 ohms with maximum error of $\pm 1\%$. By means of a commutator, the thermistor of the jacket (T_1) and the thermistor in the body (T_2) were switched on alternatively in one arm of the bridge. Thus, the same bridge served for the measurement of the calorimetric body temperature variations by the thermistor (T_2) and for the temperature control in the jacket by the total resistance of 4 thermistors (T_1).

The heating current in the jacket heater was adjusted manually with a variable resistance (R_3), and the temperature maintained at a constant value ($\pm 0.005^\circ\text{C}$) of a few degrees above the ambient temperature.

The resistances of the calibration heaters (200-400 ohms) were measured by a specially constructed Wheatstone bridge with symmetrical arms and

checked by comparison with the standard resistances of the 0.02% grade (Rühstrat - Göttingen). The current in the calibration circuit was measured with a precise milliammeter of the 0.5% grade (Iskra - Kranj).

IV. Results

The purpose of laboratory measurements quoted in IV.1, IV.2, and IV.3 was to examine the applicability of the constructed apparatus and the measuring method. The results quoted in IV.4 justify the use of the apparatus for measurements in the field of reactor radiation. Further details on these measurements are given in another paper [7].

IV.1. The stability of ^{THERMISTORS} measurements was of special importance. The question was whether the thermistor resistance for a given temperature changes with time. We used thermistors previously "aged" for about 4000 h at 105°C. Then we followed the change of resistance with time for a fixed resistance (R_1) of the thermistor set in the jacket, and we obtained the following satisfactory values:

Table 1

day	R_0 (ohms)
1	3663.1
2	3663.0
3	3663.1
4	3663.2
5	3663.7
6	3663.2

IV.2. The applicability of the "kinetic" method was checked by heating the body by means of a calibration heater with a known and constant power input, and by following the heating curve. The kinetic method was used, and the value(R_x) was determined graphically. Heating with the same power

input was continued for a few hours until the temperature equilibrium reached the corresponding value of (R_p). In fact, equilibrium temperature differences for different power inputs were determined. The results obtained are given in Table 2.

Table 2

w (watt) 10^{-2}	0.544	0.966	1.51	2.17
ΔR (kinetic)	41.6	74.3	113.6	163.4
ΔR (static)	41.7	74.6	113.9	163.8
deviation %	-0.2	-0.4	-0.3	+0.2

Since satisfactory agreement was obtained, and as the time necessary for a measurement is 3-4 times less by the "kinetic" method than by the "static" method, we chose the former one. For example, 2-4 hours are necessary to reach equilibrium by the static method while the kinetic method requires 1 hour or less. The accuracy of the kinetic method was checked during reactor irradiation, as well as in the laboratory (6). The deviations never exceeded the limits of 2-3%.

Since the accuracy of such measurements depends on the cooling constant (K), we determined the latter for each calorimetric body by a great number of measurements. The uncertainty of its value never exceeded 5%. For the effects we measured it caused the error of only 0.1 - 1%.

IV.3. Linear dependence between the temperature change and the power input. According to equation (4), the equilibrium temperature difference is a linear function of the power input (w) in a calorimetric body. This dependence was examined for every sample separately. The values (ΔR_1) as the

function of (w_1) are plotted on the diagrams (Fig.5).

Fig.5. - Calibration diagram

We got a straight line for graphite, whereas in the case of liquids (H_2O and D_2O), deviation from linearity was obvious in the original construction. This was supposed to be due to the heater position which was in a very small volume above the thermistor. This caused convection in the upper part of the liquid, while the other part around the thermistor and in the bottom remained colder. Consequently, in reactor measurements with these bodies, a slightly changed method of calibration was applied.

This supposition was proved later when the heater was wound along the whole inner tube and the thermistor positioned in the middle of it. This was done with the samples filled with a water solution of oxalic acid (50 and 100 mM). A straight line was obtained with this construction (Fig.6).

Fig.6. - Calibration diagram for sample with oxalic acid

From the measurements illustrated in figures 5 and 6, it was possible to conclude that ^{DOSE} rates from 10^4 to $5-6 \cdot 10^5$ rad/h could be measured with an error not exceeding 2-5%.

These limits of dose rates correspond to low power levels of the reactor RA (below 100 kW).

IV.4. Results of measurements in the reactor experimental holes. Table 3 presents the results of measurements in the central vertical hole of the reactor RA (VK-5). These are only part of a series of calorimetric measurements carried out in the reactor RA [7]. The Reliability of the calorimetric results

for the total absorbed dose rates was about 2-5% as expected. Good agreement (about 10%) with the results of chemical dosimetry[8] and with some epithermal flux measurements proved the reality of the calorimetric results.

Table 3

Material	Total absorbed dose rate	γ -contribution	n -contribution	Relative contribution	
		10^6 rad/MWh		$\gamma\%$	$n\%$
H ₂ O	25.8	20.4	5.42	79	21
D ₂ O	20.8	18.4	2.39	88.5	11.5
C	18.9	18.4	0.53	97	3

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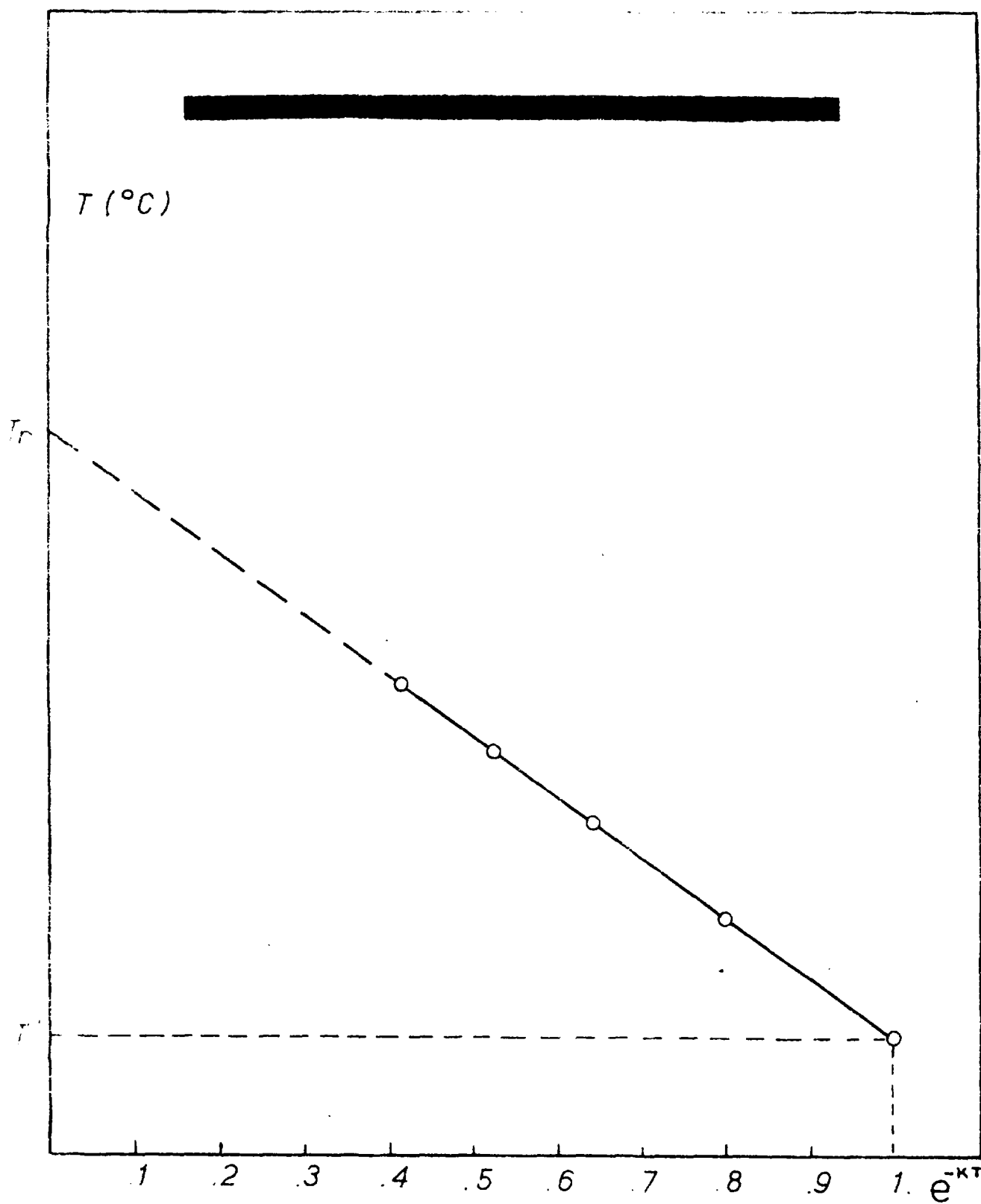
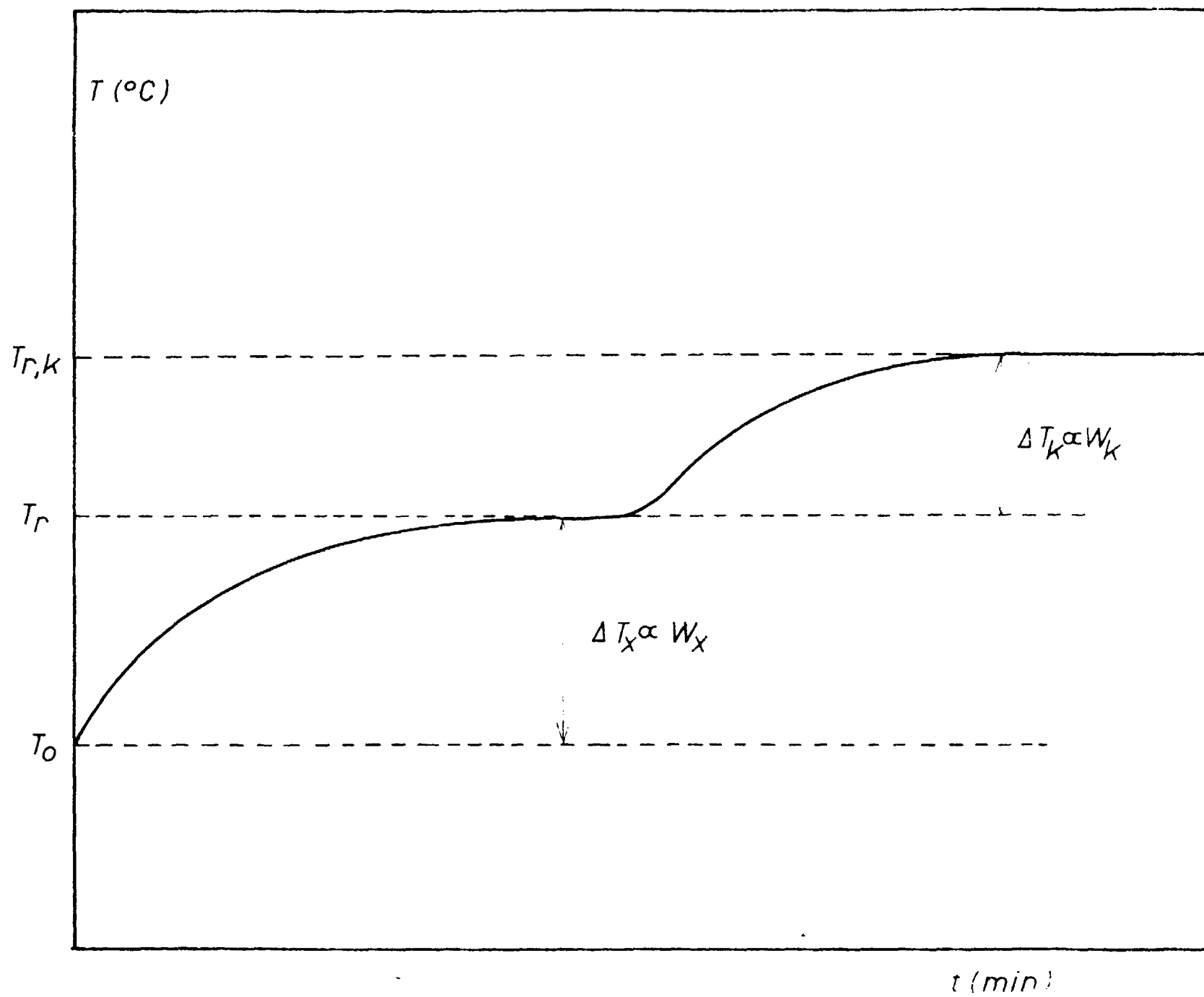


Fig.1.

Fig. 2.



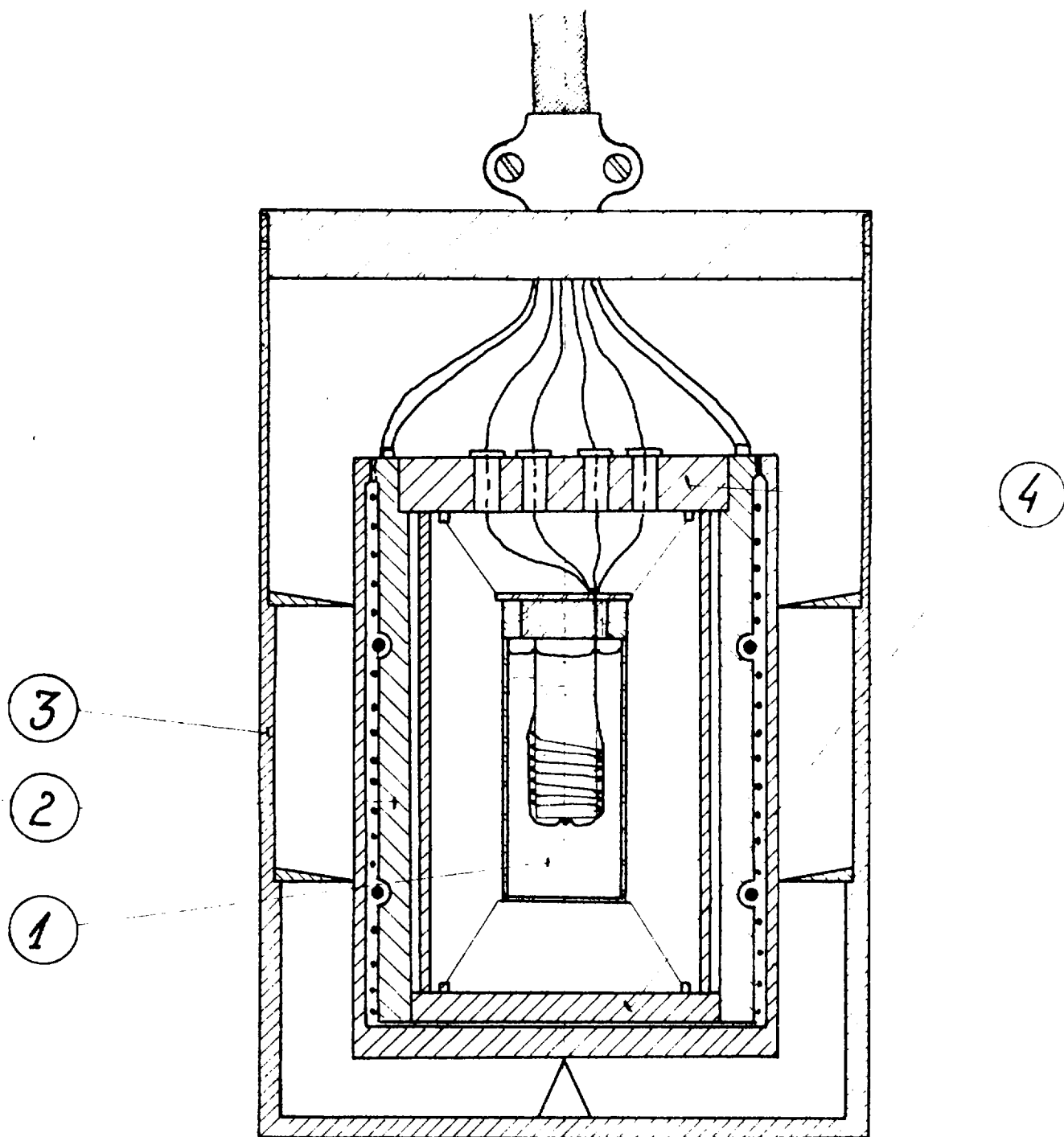


Fig.3.

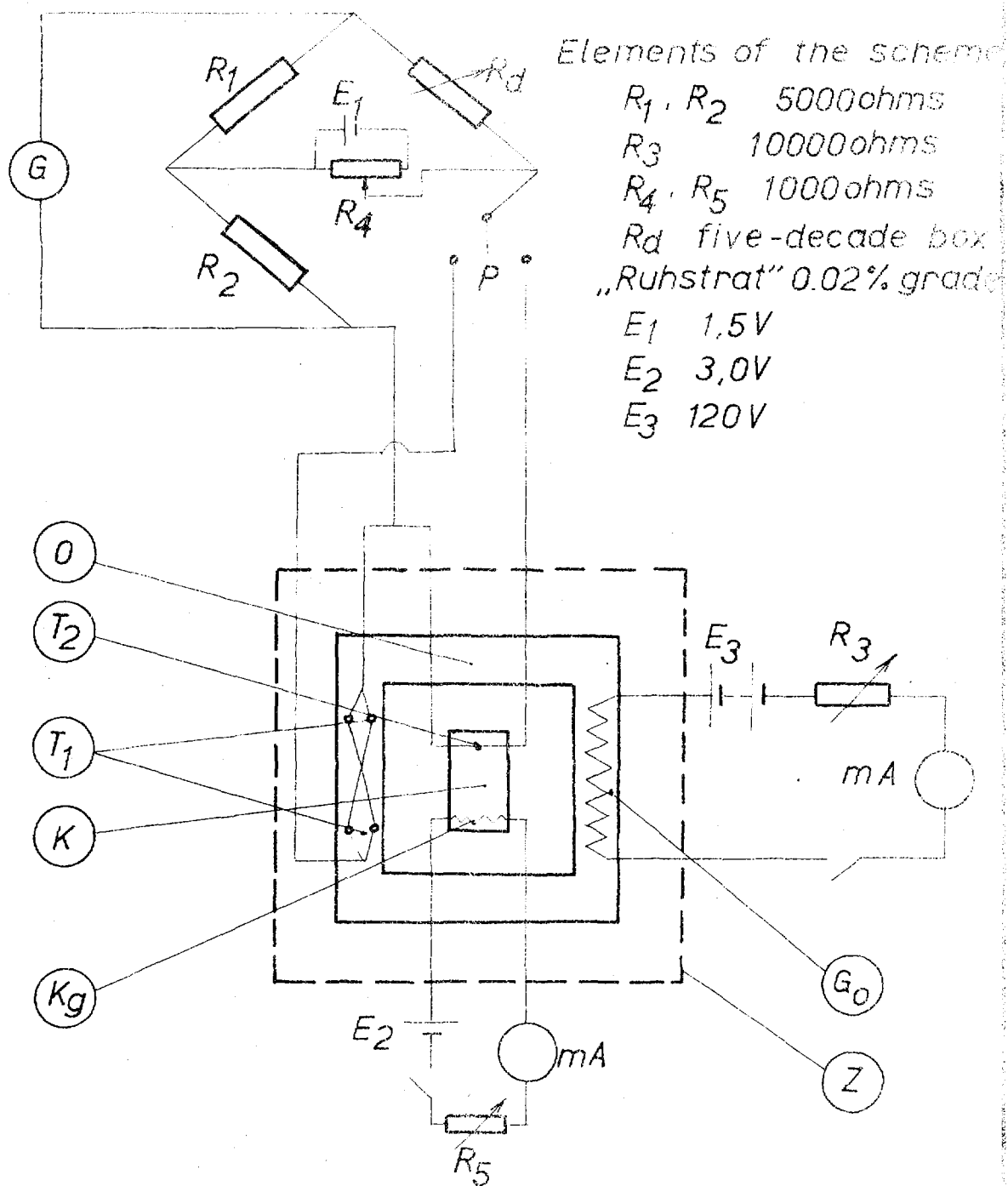
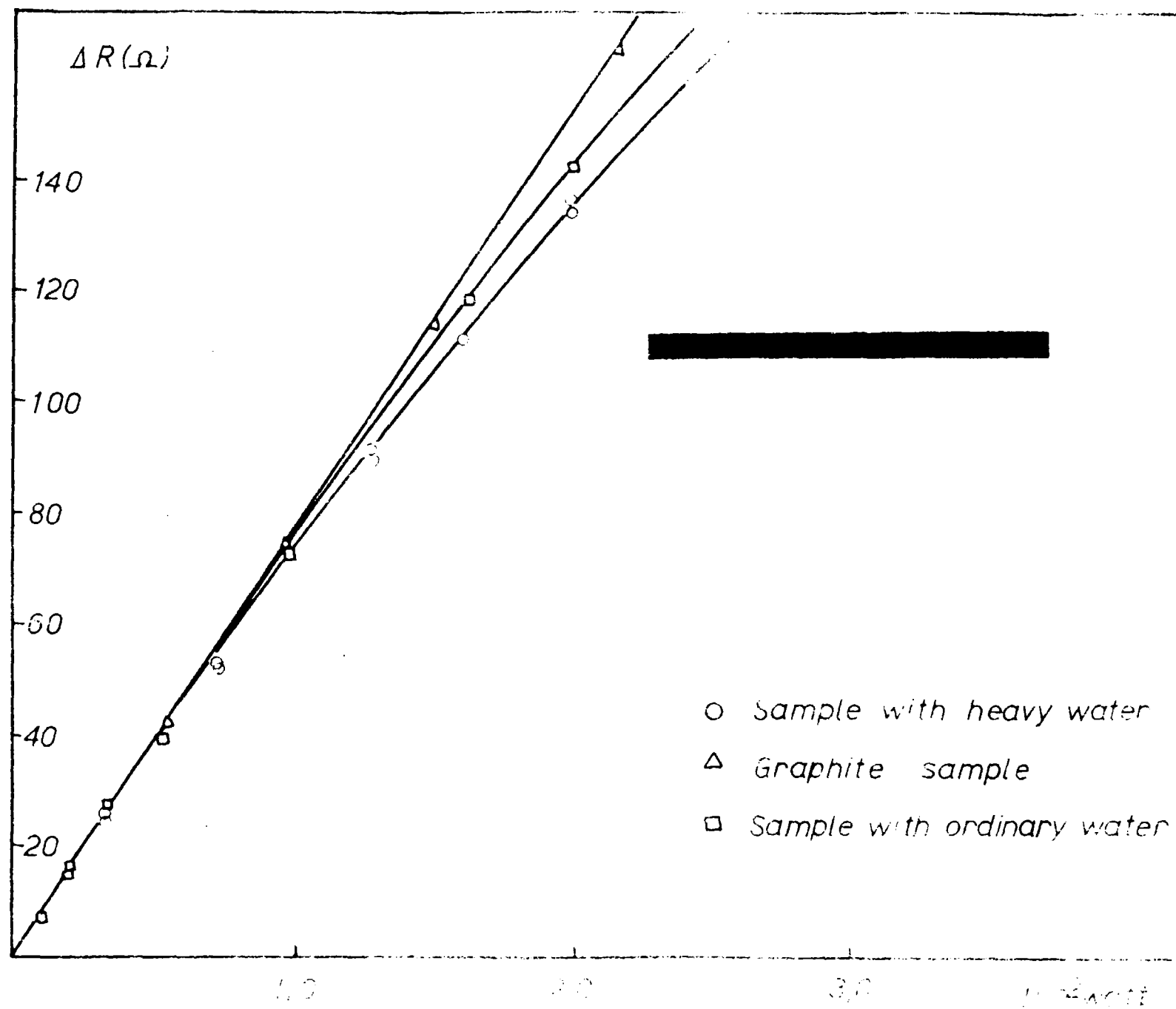
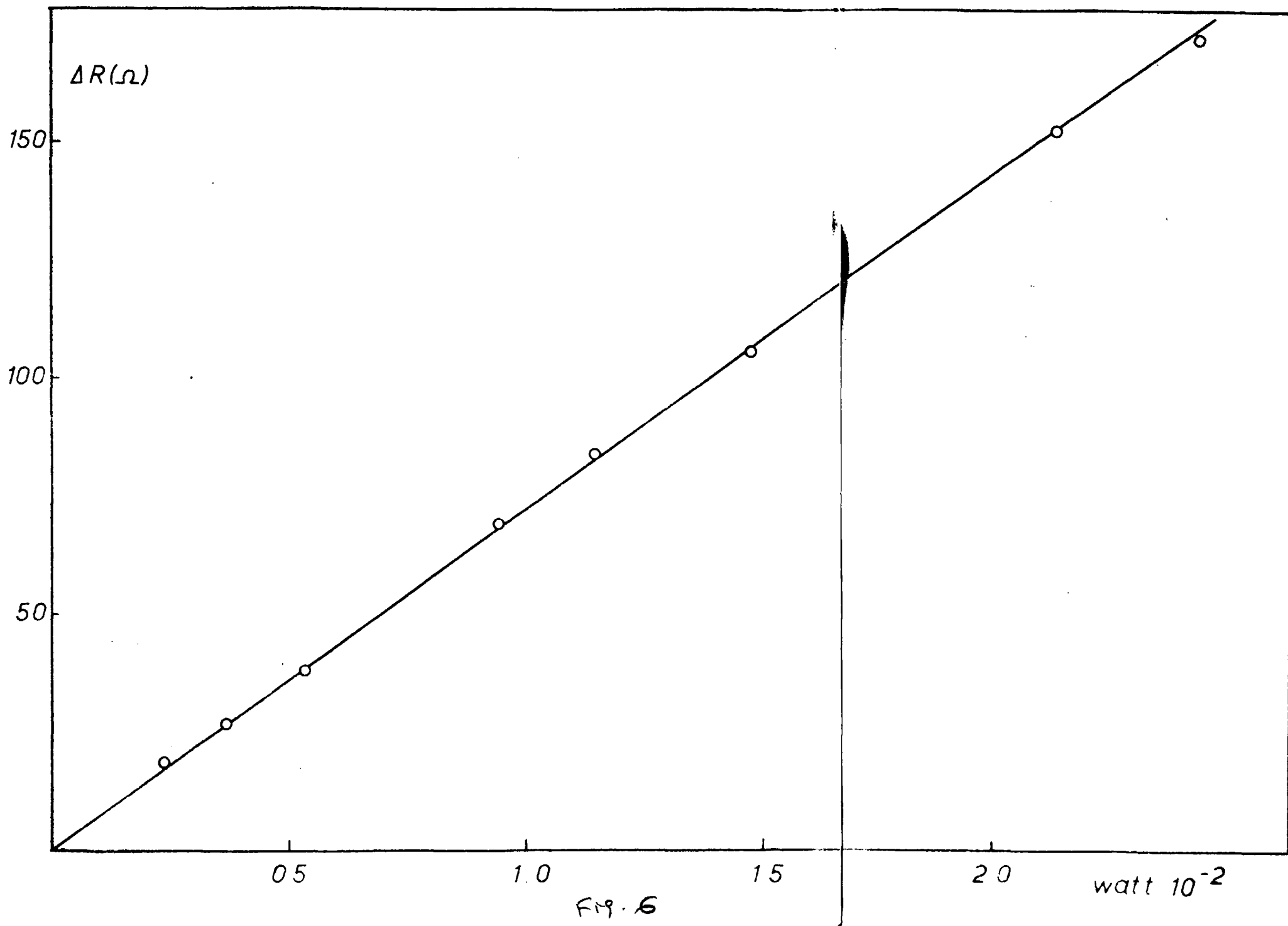
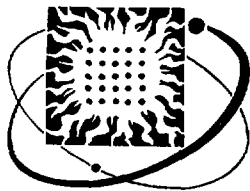


Fig.4.

Fig. 5.







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SIMPOZIUM

O NUKLEARNOM GORIVU

RADOVLJICA, 20-25 APRIL 1961

INSTITUT ZA NUKLEARNE NAUKE
„BORIS KIDRIČ“ – Vinča

KALORIMETRISKA DOZIMetriJA REAKTOR-
SKOG ZRACENJA

B. Radak, V. Marković, I. Draganić

KALORIMETRIJSKA DOZIMETRIJA REAKTORSKOG ZRAČENJA

- B. Radak, V. Marković i I. Draganić -

Kalorimetrijska dozimetrija reaktorskog zračenja je relativno nova metoda dozimetrije reaktora i broj do sada objavljenih radova je vrlo skroman.

S obzirom na složenu prirodu zračenja postoje neke teškoće pri radu sa standardnim metodama (hemijski dozimetri, jonizacione komore). U principu, upotreba kalorimetra za merenje apsorbovanih doza je najegzaktnija. Osim toga, uz pogodni izbor kalorimetrijskih tela postoji mogućnost za određivanje doprinosa pojedinih komponenti smeše zračenja u totalnoj apsorbovanoj dozi.

U tekstu je dat kratak pregled osnovnih metoda kalorimetrije i neki rezultati merenja sa izotermnim kalorimetrom na reaktoru "RA" u Vinči.

I. OPŠTE NAPOMENE

Reaktor kao izvor mešovitog zračenja i problem dozimetrije

Reaktor je snažan izvor mešovitog zračenja raznolikog po svojoj prirodi i po energijama pojedinih vrsta. Dozimetrija, koja se svodi na merenje apsorbovanih energija u raznim materijalima, ovde je stoga veoma složena i skopčana sa znatnim teškoćama. Nešto jednostavniju situaciju imamo ako se ograničimo samo na unutrašnjost eksperimentalnih kanala. Ovde su, pored gama zraka složenog spektra, prisutni jedino neutroni različitih energija - termalni i brzi.

Termalni neutroni ne predaju neposredno energiju sredini kroz koju prolaze, nego u izvesnim materijalima izazivaju nuklearne reakcije. Energija oslobođena u ovim reakcijama apsorbuje se u uzorku delimično ili potpuno i kod većine dozimetrijskih merenja predstavlja neželjeni efekat. Zbog toga se nastoji da se pogodnim izborom materijala ovaj efekat ukloni. Problem se onda svodi na merenje oslobođene energije, koja potiče jedino od apsorpcije gama zraka i usporavanja brzih neutrona.

Mora se odmah reći da se dozimetrija u reaktoru ni jednom drugom metodom ne rešava u osnovi tako čisto i jasno kao kalorimetrijom.

Hemijskim dozimetrima, na primer, merila bi se hemijska promena koju izazivaju brzi neutroni i gama zraci preko sekundarnih jonizujućih čestica. Međutim, prinosi radijaciono hemijskih reakcija^{*)} zavise od prirode i sastava zračenja, tj. od odnosa gama zračenja prema brzim neutronima. Ako taj odnos ne poznajemo, ne možemo ni apsorbovanu energiju izračunati sa dovoljno pouzdanosti.

Primena jonizacionih komora je moguća, ali ima sličnu nepouzdanost kao i hemijski dozimetar. Nedostatak ove metode je nedovoljno poznavanje prosečne energije (w^-) potrebne za stvaranje jednog jonskog para u gasu kojim je ispunjena šupljina komore. Naime, i ta veličina zavisi od sastava smeše zračenja.

Zbog svega toga, veliki deo radova sa reaktorom kao izvorom zračenja zasniva se više na relativnom merenju radijacionih promena u funkciji raznih parametara i ima dosta ograničen karakter.

*) G-vrednost ili prinos radijacionohemijske reakcije označava broj hemijskih promena koje se odigravaju na svakih apsorbiranih 100 eV.

Princip kalorimetrijske dozimetrije

Energija koju zračenje predaje nekoj sredini oslobadja se većim delom kao toplota i održava se u povišenju temperature. Samo jedan mali deo (nekoliko procenata ili manje) od ukupno apsorbovane energije troši se na unutrašnje promene sistema kao što su: hemijske promene, promene kristalne strukture itd.

Merenjem oslobodjene količine toplote u kalorimetarskom telu, koje se nalazi u polju zračenja, direktno određujemo apsorbovanu energiju. Prednost kalorimetrijskih metoda nad ostalim metodama dozimetrije je baš ta neposrednost merenja. Razlozi zbog kojih ove metode i pored toga relativno retko koriste su u većini slučajeva tehničke prirode.

Samo određivanje svodi se na primenu kalorimetrijskih metoda merenja dugotrajnih procesa, koje se mogu podeliti na dve osnovne: izotermску i adijabatsku metodu.

Izotermска metoda, ili tačnije metoda merenja temperaturske razlike, sastoji se ukratko u sledećem: kalorimetarsko telo, koje se zagreva apsorbujući energiju zračenja, nalazi se u okolini čija se temperatura ne menja u toku merenja. Nakon izvesnog vremena uspostavlja se ravnoteža u kojoj se snaga zagrevanja izjednačuje sa snagom gubitaka usled toplotnog zračenja i konvekcije. Razlika temperature tela i okoline proporcionalna je snazi zagrevanja, odnosno brzini kojom telo apsorbuje energiju zračenja:

$$\Delta T = T_r - T_o = \frac{W}{Kmc} \quad \dots (1)$$

gde su:

T_r - ravnotežna temperatura tela ($^{\circ}\text{C}$)
 T_o - temperatura okoline, konstantna ($^{\circ}\text{C}$)
 W - snaga zagrevanja, konstantna (watt)
 mc - toplotni kapacitet tela (joule/ $^{\circ}\text{C}$)
 K - konstanta definisana Njutnovim zakonom
hladjenja.

Faktor proporcionalnosti ($1/Kmc$) odredjuje se električnim putem preko kalibracionog grejača ugradjenog u telu.

Izotermska metoda je do sada često primenjivana. Izmedju ostalog i prva kalorimetrijska merenja na grafitnom reaktoru u Oak Ridgeu izvedena su izotermским kalorimetrom (1).

Za dozimetriju reaktora "RA" u Vinči, u probnom periodu njegovog rada, konstruisan je u Odeljenju za radijacionu hemiju kalorimetar sa termistorima, takodje izotermски, sa kojim je izvršen niz merenja. O rezultatima tih merenja biće reči kasnije.

Druga metoda koja se takodje koristi za kalorimetrijska merenja na reaktoru je adijabatska metoda. Ovde se okolina kalorimetarskog tela zagreva istom brzinom kao i telo koje apsorbuje energiju zračenja. U kalorimetarskom sistemu nema razmene toplote. Meri se brzina zagrevanja tela koja je proporcionalna brzini kojom telo apsorbuje energiju zračenja:

$$\frac{dt}{dt} = \frac{W}{mc} \quad \dots\dots (2)$$

Faktor proporcionalnosti ($1/mc$) i ovde se odredjuje električnim putem preko kalibracionog grejača.

Sa takvim tipom kalorimetra je takodje do sada radjeno, a najpoznatiji je svakako Andersonov i Waiteov rad na reaktoru BEPO u Engleskoj (2), (3).

Obe ove metode, izotermska i adijabatska, imaju svoje prednosti i nedostataka, a upotreba jedne ili druge zavisi od specifičnosti namene kalorimetra, flukseva na kojima se radi itd.

Tako je izotermski kalorimetar veoma pogodan instrumentat za kontinualno praćenje snage reaktora, kao i za merenje manjih temperaturskih efekata (do oko 10°C).

Nedostatak ove metode je relativno dugo vreme potrebno da se uspostavi ravnoteža (ponekad i oko 3,4 časa), što sama merenja čini prilično sporim.

Adijabatska metoda, nasuprot tome, mnogo je brža i omogućava dobijanje gotovih rezultata za veoma kratko vreme (10-20 min). Medjutim, brzine zagrevanja moraju biti veće od neke minimalne vrednosti da bi se mogle meriti, odnosno pratiti. Ova donja granica uslovljena je, naravno, osetljivošću kalorimetra ili osetljivošću elemenata sa kojima merimo temperaturu.

Odredjivanje pojedinih komponenti u smeši zračenja

Složenost reaktorskog zračenja nije prepreka za primenu kalorimetra kao instrumenta za odredjivanje apsorbovanih energija, pošto se one njime direktno mere. I još više od toga, pogodnim izborom kalorimetarskih tela moguće je odrediti pojedine komponente u smeši zračenja, tj. procentne iznose njihovog doprinosa u totalnoj apsorbovanoj dozi. Udeo termalnih neutrona se eliminiše izborom materijala sa zanemarljivo malim efikasnim presekom ili izračunavanjem njihovog udela u totalnoj apsorbovanoj dozi (4). Tada je izmerena brzina apsorbovane doze u materijalu (M) zbir dveju komponentata koje potiču od gama zračenja i brzih neutrona tj.:

$$w_M^{Tot} = w_M^{\gamma} + w_M^n \quad \dots\dots (3)$$

gde su:

- w_M^{Tot} - totalna brzina apsorbovane doze u materijalu (M)
- w_M^{γ} - doprinos gama zraka
- w_M^n - doprinos brzih neutrona

a u nekom drugom materijalu (M_1):

$$w_{M_1}^{Tot} = a \cdot w_M^{\gamma} + b \cdot w_M^n \quad \dots\dots (4)$$

gde je:

- $w_{M_1}^{Tot}$ - brzina apsorbovane doze u materijalu (M_1)

Koeficijent (2) definisan je ovde odnosom masenih apsorpcionih koeficijenata za ova dva materijala. Pošto je srednja energija gama zračenja u reaktoru oko 2 MeV:

$$a = \frac{\mu_{M_1}}{\mu_M} \left(\frac{M_1}{M} \right)^2 \text{ MeV} \quad \dots\dots (5a)$$

Koeficijent (b) dat je odnosom izraza oblika:

$$\frac{1}{(A + 1)^2} \cdot \int_{th}^{\infty} \sigma_s \cdot dE \quad \dots\dots (5b)$$

i predstavlja "moć usporavanja" brzih neutrona elastičnim rasejanjem. Njegova vrednost se odredjuje grafički. Ovde su (A) atomske težine materijala, a (σ_s) efikasni preseki za elastično rasejanje brzih neutrona.

Izmerene vrednosti apsorpcije energije u dva ili više različita materijala daju nam tako niz simultanih jednačina. Rešavanjem metodom najmanjih kvadrata dobijamo parcijalne apsorbovane doze od gama zraka i brzih neutrona u referentnom materijalu (M). Odavde se posle mogu izračunati preko koeficijenata (a) i (b) odgovarajuće vrednosti za ostale materijale prostog ili složenog sastava.

II. REZULTATI MERENJA U KANALIMA REAKTORA "RA" U VINČI

Dozimetrijska merenja sa izotermnim kalorimetrom vršena su na reaktoru "RA" u Vinči, u probnom periodu njegovog rada. Merenja su izvedena u vertikalnim eksperimentalnim kanalima VK-5 i VK-9 (vidi na slici 1). Raspodela brzine apsorbovane doze po visini svakog kanala određena je merenjima na najmanje tri različite visine u aktivnoj zoni.

Radjeno je sa tri kalorimetarska tela: običnom vodom, teškom vodom i grafitom.

Sva merenja izvedena su na 20 kW a dobivene vrednosti obračunate na snagu od 1 MW.

Skica kalorimetra zajedno sa šemom merenja i kontrole data je na slici 2. Termostatiranje okoline vršeno je ručno preko promenljivog otpora i u toku merenja temperatura je održavana konstantnom u granicama $\pm 0,005^{\circ}\text{C}$. Za kontrolisanje i merenje temperature upotrebljeni su termistori ("Philips - Bead type NTC Resistors"), čiji je otpor meren Wheatstoneovim mostom. Mereni efekti bili su između $0,2$ i 2°C , što odgovara promeni otpora termistora za oko 20-200 oma. Ove razlike merene su sa maksimalnom greškom $\pm 0,2$ oma (0,1 - 1%).

Promene na termistorima koje bi uticale na pouzdanost rezultata nisu zapažene pri radu. Kalibraciona zagrevanja poznatim snagama, izvedena u polju reaktorskog zračenja, izazivala su onolike promene otpora termistora ($\Delta R \propto \Delta T$) kolike su dobijane i prilikom laboratorijskih kalibracija bez zračenja. Saglasnost je bila u okviru 1-2%. Izvršeno je i jedno merenje na 80 kW. Njegovo zadovoljavajuće slaganje sa rezultatima dobivenim na 20 kW dokazuje da su merenja sa termistorima pouzdana i na nešto višim snagama reaktora.

Brzine apsorbovanih doza u vodi, teškoj vodi i grafitu

U tablici 1 date su vrednosti maksimalne brzine apsorbovane doze u jedinicama 10^6 rad/MWh. U prvoj koloni su vrednosti za ukupno apsorbovane doze, korigovane za apsorpciju indukovanog zračenja iz kalorimetarske okoline (aluminijum) i za apsorpciju energije u sudovima od pleksi stakla za tela sa vodom i teškom vodom.

Iz tih vrednosti izračunati su energetske doprinosi gama zračenja i brzih neutrona.

Na dijagramima 1, 2 i 3 prikazana je verovatna vimska raspodela brzine apsorbovane doze u kanalima VK-5 i VK-9, na kojima su unete i izmerene eksperimentalne vrednosti. Izvučene krive predstavljaju relativnu raspodelu termalnog fluksa, normiranog za svaki kanal posebno prema maksimalnoj vrednosti apsorbovane doze. Kao što se vidi postoji vrlo dobra saglasnost u odnosima apsorbovane doze i termalnih flukseva duž jednog kanala. Međutim, treba uočiti da takva saglasnost ne postoji za dva različita kanala. Tako, na primer, odnos maksimalnih apsorbovanih doza u VK-5 i VK-9 iznosi 1,95, dok odnos maksimalnih termalnih flukseva iznosi 1,66. To dolazi verovatno otuda što se zbog nepotpunog broja gorivnih elemenata kanal VK-9 praktično već nalazi u reflektoru (D_2O).

Greška sa kojom su date vrednosti za maksimalnu apsorpciju u oba kanala procenjena je u grafitu na $\pm 2,5\%$, a u vodi i teškoj vodi na $\pm 5\%$ od izmerene vrednosti.

Poredjenje rezultata sa vrednostima dobivenim hemijskim oksalatnim dozimetrom

Vrednosti za brzine apsorbovanih doza, izmerene kalorimetrijski uglavnom se dobro slažu sa vrednostima dobijenim ozračivanjem vodenog rastvora oksalne kiseline. Na mestima maksimuma termalnog fluksa u oba kanala slaganje je bolje od 10%. Sa obe vrste dozimetara dobija se slična kriva visinske distribucije apsorbovane doze duž kanala. Odstupanje između kalorimetrije i hemijske dozimetrije je najveće na mestima koja odgovaraju gornjem kraju aktivne zone. Predpostavljamo da to dolazi usled različite geometrije ozračivanja hemijskih i kalorimetrijskih uzoraka.

Poredjenje sa nekim rezultatima merenja epitermalnog fluksa

Apsorbovana energija usled usporavanja brzih neutrona u materijalu atomske težine (A) može se izračunati ako poznajemo vrednosti termalnog i epitermalnog fluksa na odredjenom mestu eksperimentalnog kanala. Predpostavićemo da se svi energetski neutroni nalaze u "1/E" oblasti spektra, da je ova oblast oštro odsečena na granicama 1 eV i 2 MeV (srednja energija fisionih neutrona) i da neutroni gube energiju elastičnim sudarima. Brzina apsorbovane doze se onda izračunava iz izraza:

$$w_A = \frac{N}{A} \cdot \frac{2 A}{(A+1)^2} \int_{1 \text{ eV}}^{2 \text{ MeV}} \frac{k(nv)_{th}}{E} \cdot \phi_s \cdot E \cdot dE (\text{eV/gr/sec})$$

..... (6)

gde su: N - Avogadrov broj
 $(nv)_{th}$ - fluks termalnih neutrona ($n/cm^2/sec$)
6 σ_s - "scattering" efikasni presek (cm^2)
 E - energija neutrona (eV)
 k - reaktorska konstanta koja zavisi od
 odnosa epitermalnog i termalnog fluksa
 i određuje se merenjem kadmijumskog
 odnosa.

Za eksperimentalne kanale VK-5 i VK-9 dobiveno je (5):

U VK-5 $k = 0,035$

U VK-9 $k = 0,025$

Na osnovu poznatih flukseva termalnih neutrona u oba kanala i ovih vrednosti izračunata je snaga zagrevanja od brzih neutrona, za maksimalnu apsorpciju u vodi, teškoj vodi i grafitu. Tako dobivene vrednosti uporedjene su sa onima koje su izvedene iz kalorimetrijskih merenja. Slaganje je uglavnom zadovoljavajuće.

Korišćenje dobivenih podataka za proračun apsorbovanih doza u raznim materijalima

Kao što smo već videli, izmerene vrednosti za parcijalne apsorpcije gama zračenja i brzih neutrona u jednom materijalu daju nam mogućnost proračuna apsorbovane doze sa dovoljnom preciznošću ($\pm 10\%$) i u mnogim drugim materijalima. Za ovo je potrebno poznavati samo relativne odnose masenih apsorpcionih koeficijenata za gama od 2 MeV (5a) i odnose izraza (5b). Kod složenih jedinjenja računa se posebno doprinos svakog elementa, a totalna apsorbovana energija dobija preko njihovog procentnog iznosa u ukupnoj masi.

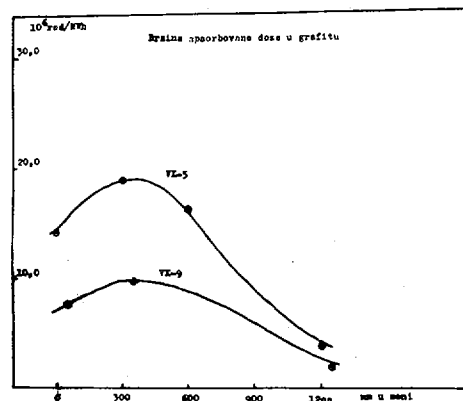
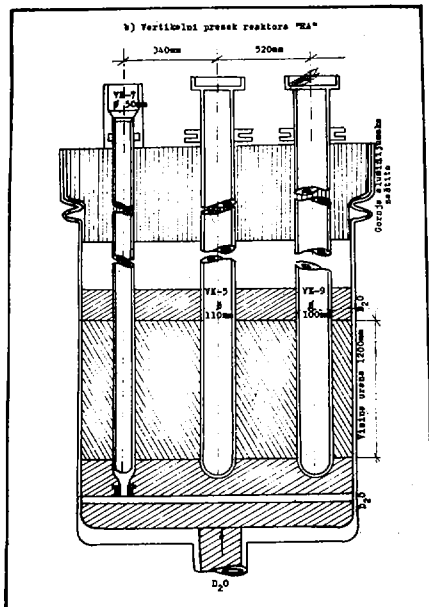
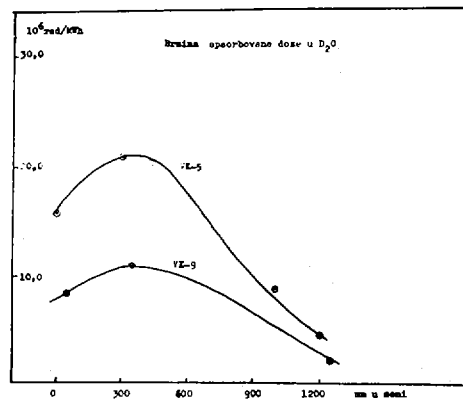
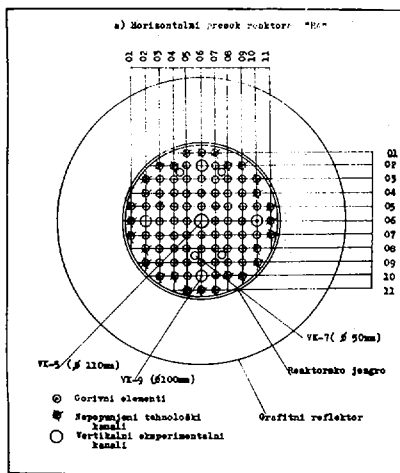
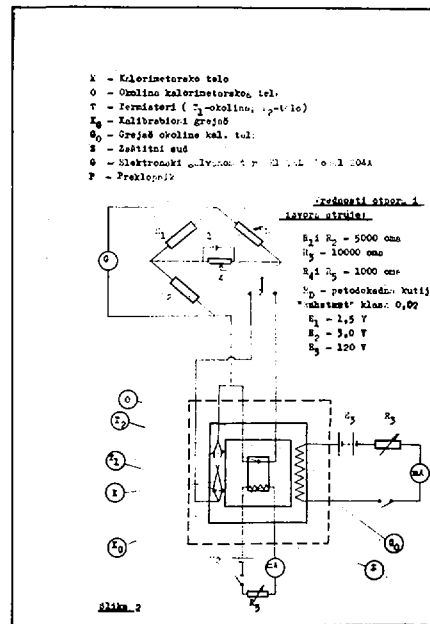
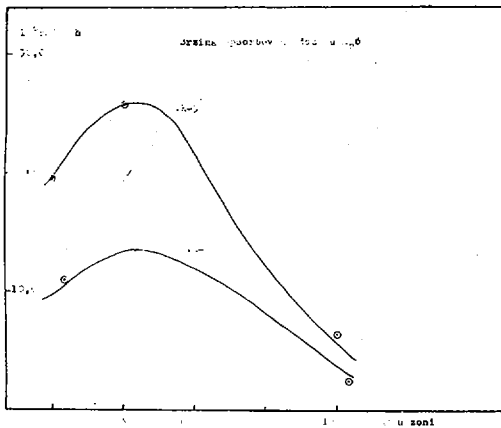
Tablica 1

Maksimalne apsorbovane doze

Kanal	Mate- rijal	tot.brz. aps.doze	udeo γ	udeo brz.n.	relativni deo	
		10^6	rad/MWh	γ	zraci %	brzi n %
VK-5	H ₂ O	25,8	20,4	5,42	79	21
	D ₂ O	20,8	18,4	2,39	88,5	11,5
	C	18,9	18,4	0,53	97	3
VK-9	H ₂ O	13,4	10,5	2,90	78	22
	D ₂ O	10,7	9,41	1,28	88	12
	C	9,70	9,41	0,28	97	3

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RADIATION DOSIMETRY OF THE REACTOR RA AT VINČA

MEASUREMENTS BY ISOTHERMAL CALORIMETER

by

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1. — In this work we have made attempts to:
 - analyze the problems of reactor radiation dosimetry;
 - describe the solution of this problem by the calorimetric method;
 - present our results of measurements on the reactor RA at Vinča, and to describe the method, apparatus and measuring equipment used.
2. — Use was made of the isothermal calorimeter with thermistors which measured the absorbed dose rates within the range 10^4 — 10^6 rad/h, with an accuracy of 2—5%. It was shown that the reactor radiation in which the thermal neutron flux is up to the order of magnitude 10^{12} n/cm²/sec, and the integral thermal neutron flux up to about 10^{16} n/cm² exerts no significant influence upon the working characteristics of the thermistors used.
3. — Determination was made of the absorbed dose distribution into the gamma-ray and the neutron contribution. For this purpose we used 3 materials: ordinary water, heavy water and graphite.
4. — Measurements were carried out in two vertical experimental holes „VK -5“ and „VK -9“ of the reactor RA at several heights. It has been shown that the absorbed dose height distribution agrees well with the thermal flux distribution curve, although the relations of the absorbed doses of the two holes are not in accordance with the corresponding thermal flux relations.

I. — INTRODUCTION

I. 1. NOTES

Calorimetric radiation dosimetry, the subject of this paper, was one of the various measurements carried out in the experimental reactor RA at Vinča during its test operation.

The aim of these experiments was to determine the absorbed dose rates by various materials placed at different positions in some experimental

holes, as well as to determine approximately the contribution of various components of reactor radiation to the total absorbed doses.

Measurements were carried out in a heavy water — enriched uranium (2% ^{235}U) reactor. The nominal power is 6.5 MW, but during the test operation period our measurements were made at powers lower than 100 kW*.

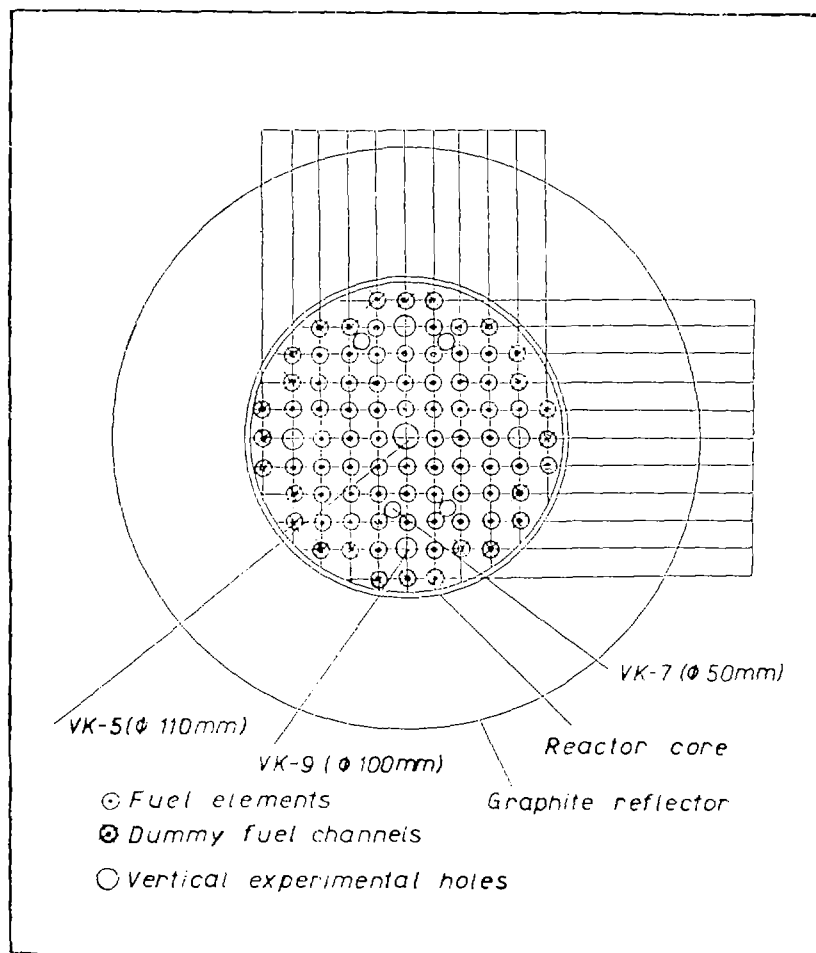


Fig. 1a. — Horizontal cross section of the reactor RA

The reactor and the geometrical conditions of measurements (see II. 4.) are shown schematically in Fig. 1. a) and b).

* Reports on some of the results were submitted at the Symposium on Nuclear Fuel held at Radovljica, Yugoslavia, in April 1961.

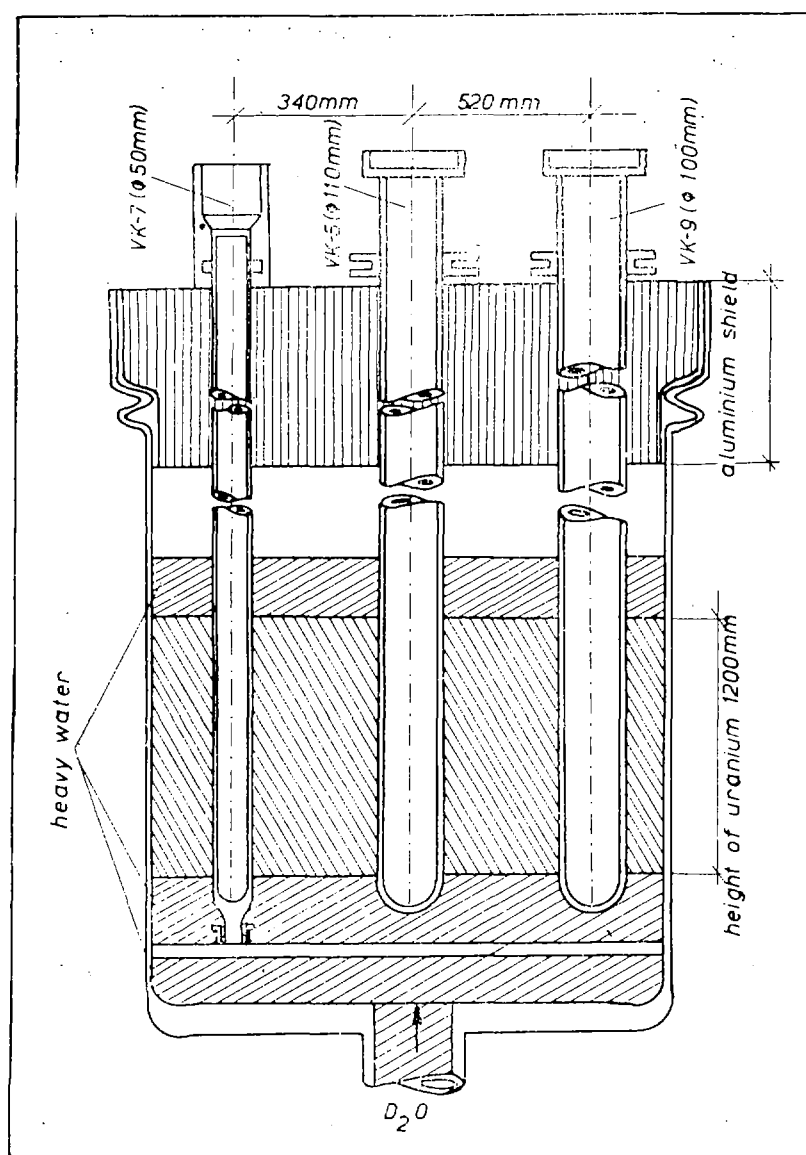


Fig. 1b. — Vertical cross section of the reactor RA

I. 2. REACTOR RADIATION AND ITS DOSIMETRY

The nuclear reactor is a source of mixed radiation ranging from slightly penetrating fission fragments, alpha and beta particles, to more penetrating gamma rays and fast neutrons. However, for irradiation in reactor experimental holes the most interesting types of radiation are gamma rays and neutrons of various energies.

1. 2. 1. REACTOR AS A GAMMA RADIATION SOURCE

Gamma rays in a reactor are produced by the following processes:

- by fission of ^{235}U
- by radioactive decay of fission products
- by thermal neutron capture reactions (n, γ) with the most important reactor materials such as: ^{238}U , aluminium, graphite and iron
- by fast neutron inelastic scattering
- by decay of radioactive isotopes produced by various nuclear reactions during the operation of the reactor.

Due to the great variety of sources, as well as to the scattering and absorption in the reactor materials, there is a very complex spectrum of radiation in the experimental holes. The average energy of gamma photons, however, is probably about 2 MeV for many reactors.

The absorption process is very complex and it depends on the energy of the photon and the nature of the absorbing material. Thus,

- in the interaction of low energy photons with heavy elements there is a *photoelectric effect*, a process in which the photon disappears ejecting an electron;
- in the interaction of photons of moderate energies with light elements there is a *Compton effect*, a process in which the photon ejects an electron transferring to it only part of its energy;
- in the interaction of photons of high energies (over 1.02 MeV) with heavy elements, a pair *production* also takes place — the photon disappears producing one electron and one positron.

1. 2. 2. REACTOR AS A NEUTRON SOURCE

Neutrons in a reactor are produced by the following processes:

- by fission of ^{235}U , where 2.5 neutrons per fission are released in average. The energies of these neutrons range from 0.5 to 15 MeV, the most probable energy being approximately 0.7 MeV, and the average energy about 2 MeV;
- by photonuclear reaction which is of particular interest when heavy water is used as moderator;
- by fission of ^{238}U with fast neutrons;
- by nuclear reactions of the type ($n, 2n$), ($n, 3n$), etc.

Referring to their history, the neutrons have various energies upon which the absorption process depends.

Fast neutrons (in this paper referred to as all neutrons with energies above the cadmium cut-off) lose their energy mainly by elastic scattering. The mean energy transferred in an elastic collision decreases with the increase of the mass number of ambient nuclei in which scattering or slowing down takes place.

Thermal neutrons, i.e. neutrons which have the same kinetic energy as the ambient atoms and molecules (0.025 eV at 20° C), do not transfer their energy directly. However, thermal neutron reactions such as (n , gamma), (n , alpha) etc., are the source of energy received by the ambient in the interaction with thermal neutrons.

1. 2. 3. PROBLEMS OF REACTOR RADIATION DOSIMETRY

The difficulties encountered in reactor radiation dosimetry can be either:

- basic, due to the great variety of the type and energy of radiation, or
- experimental, due to relatively high dose rates, inconvenient operation with measuring devices, their activation during the measurement, limited volumes, etc.

Thus, in ionization measurements, apart from experimental difficulties, high dose rates and activation, estimation of the absorbed doses is unreliable due to complex corrections for geometry, and inaccurate knowledge of the w values, i.e. the average energies required to produce an ion pair.

Chemical changes induced by radiation can serve as a measure for the absorbed dose. The experimental difficulties in chemical methods are less than those in physical methods, while the basic difficulties are similar in both cases. Chemical changes depend more or less on the type and the energy of radiation. Hence, a chemical system used as a dosimeter in a reactor must be calibrated for the given conditions, i.e. the radiation-chemical yield for the reactor mixed radiation in which routine measurements are to be carried out, must be determined.

In respect to the difficulties encountered in experimental determination of the absorbed doses, the irradiation data in literature are given sometimes as a function of the integrated thermal neutron dose (nvt), assuming that the dose rate is proportional to the thermal neutron flux, i.e. that the total absorbed energy is proportional to the integrated thermal neutron dose. Hence, the (nvt) values are considered the relative measure of the absorbed doses.

One can see at once that such a way of representing the absorbed energies renders impossible the comparison of values obtained in various reactors, since the penetrating radiation which follows the thermal neutrons

depends, inter alia, on the age of the fuel, the kind of reactor materials, etc. The works of A. R. Anderson (2) and D. M. Richardson (1) have shown that in the reactor core with a graphite moderator, and for a given material, the energy absorbed in different places is proportional to the integrated thermal neutron dose and could be expressed conveniently in ergs per gram for n/cm^2 . Other measurements (3) have shown, however, that for a heavy water moderated reactor, the energy deposition for n/cm^2 is not constant even for the same material; it depends on the irradiation place. Hence, such kind of interpretation has only a relative and extremely limited character. The measurement of the released amount of heat into which the radiation energy is converted in a medium, can serve as a measure for the energy absorbed. This is the principle of calorimetric dosimetry. Since the total absorbed energy is practically converted into heat under the given conditions*, this kind of measurement makes possible its exact and quantitative determination. By appropriate choice of the absorbing media it is possible to determine the contribution of each radiation component to the total energy absorbed. The basic limitations encountered in chemical dosimetry or ionization methods are considerably smaller in calorimetric dosimetry, and that is why it may be considered to be the method most reliable and perspective for energy absorption measurements.

1. 3. ISOTHERMAL CALORIMETER WITH THERMISTORS

1. 3. 1. ISOTHERMAL CALORIMETRY

With regard to the temperature of the calorimeter jacket during operation, calorimetric measurements can be carried out in two ways. The adiabatic method, often used, consists in heating the jacket electrically at the same rate as the calorimetric body absorbs the radiation energy. Thus, the absorbed dose rate is determined from the heating rate.

In isothermal calorimetry used in our case, the jacket temperature is kept constant during the measurement. Since the calorimetric body is heated by the radiation energy absorption, the absorbed dose rate is measured from the difference between the temperature of the body and the jacket. Measurements are carried out in the steady state in which the heating power in the body is equalized with the heat losses caused by radiation, conductivity and convection.

The isothermal method (or more exact the temperature difference method) can be represented by the following expression:

$$T_r - T_o = \frac{W}{Kmc} \quad [1]$$

* Usually only a negligible part, 1—2% (rarely 5—10%), is spent on the change in the internal energy in the system (chemical effects, change in crystal structure, etc.).

where:

T_o — jacket temperature, constant $^{\circ}\text{C}$

T_r — body temperature in steady state $^{\circ}\text{C}$

W — heating power, constant (watt)

K — constant, defined by Newton's cooling law (sec^{-1})

mc — heat capacity of the body (joule/ $^{\circ}\text{C}$)

Calibration of the calorimeter is carried out by heating the calorimetric body at an exactly defined and well known power (w_k) by means of a built-in calibration heater. Now a new steady state temperature difference is determined, thus eliminating the constant characteristic for the measuring system (Kmc). The disadvantage of this static method is the considerable time lag for reaching the steady state (several hours for inert systems).

That is why the kinetic method is more efficient for determining the steady state temperature before real equilibrium has been established (4). This method is based upon the fact that the temperature change in the calorimetric body in the course of heating is an exponential function of time (5) and can be expressed as follows:

$$T = T_r + G \cdot e^{-Kt} \quad [2]$$

where:

T — temperature of the calorimetric body at the time (t)

T_r — equilibrium temperature of the calorimetric body (i.e. $T = T_r$ for $t = \infty$)

K — cooling constant, a value characteristic for the measuring system, and:

$$G = (T' - T_o) - \frac{W}{Kmc} \quad [3]$$

where:

T' — temperature of the body at the time $t = 0$

By using the equation [2] the kinetic method is reduced to the analysis of the heating curve. The results obtained by temperature measurement in the function of time are plotted as usual. The only difference is that the abscissa is the time axis in an implicit form, i.e. e^{-Kt} . The straight line shown in Fig. 2 begins at the moment $t = 0$, where the temperature of the body is (T'), and the abscissa is $e^{-Kt} = 1$. On the basis of several points, one obtains the value of the equilibrium temperature (T_r) by extrapolation up to the intersection with the ordinate axis ($t = \infty$).

By this method measurements in one system may be carried out several times faster than by the static method.

The reliability of this method in determining the equilibrium temperature depends on the stability of the constant (K), and the accuracy of knowing it.

The calorimeter for absorbed dose measurement was anticipated in our case for work at powers less than 100 kW, at which the dose rates could

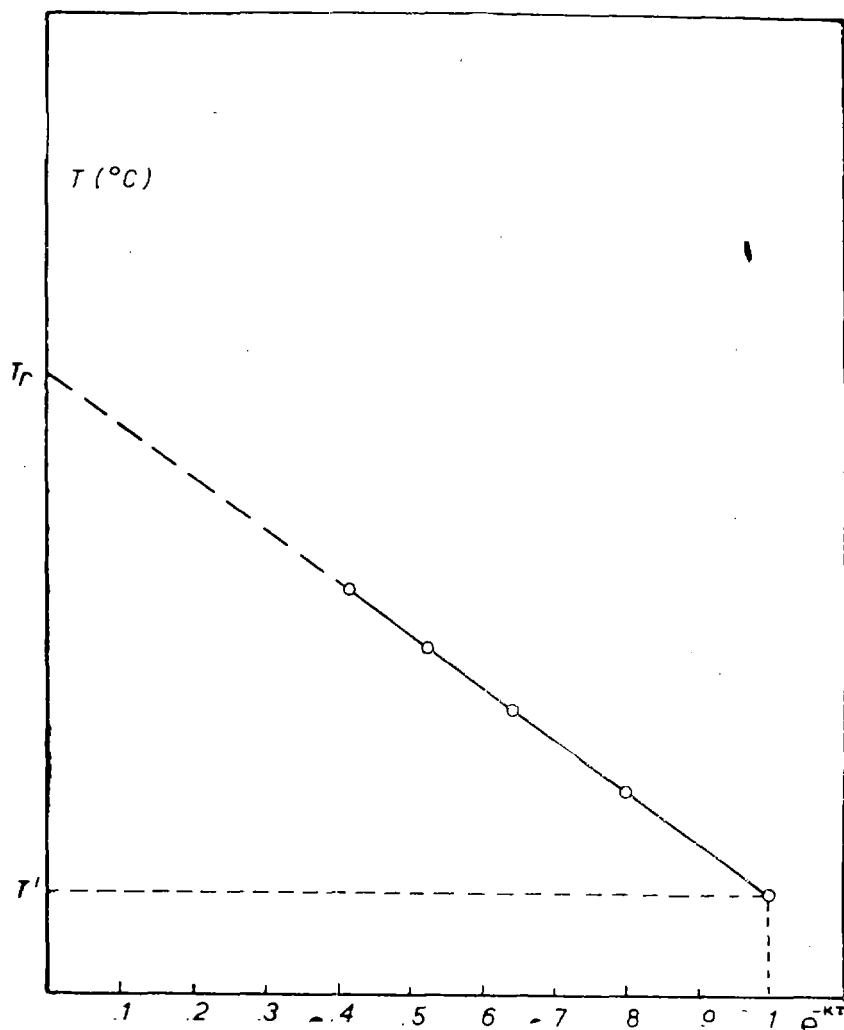


Fig. 2. — Kinetic method shown graphically

be expected to be between 10^4 and 10^6 rad/h in water. That is why a calorimeter with relatively good heat isolation was constructed, and the corresponding sensitivity achieved. On the other hand, this conditioned higher thermal inertia of the whole system. It would be very difficult to maintain adiabatic control under such conditions, and the rate of temperature rise at these powers would be very low and hard to measure. That is why use was made of the isothermal method with constant temperature of the jacket. The kinetic method for equilibrium temperature determination has shortened the time required for measurements to a considerable extent.

I. 3. 2. TEMPERATURE MEASUREMENT BY THERMISTORS

The temperature effects of microcalorimetric measurements are usually of the order of magnitude of several hundredths of a centigrade or less. The measurement of such small differences with adequate accuracy is carried out mainly by the use of

- thermocouples or
- resistant thermometers.

The choice of one of these two depends on the kind of processes to be measured and the sensitivity required.

Thermistors, which according to their electrical properties are semi-conductors, belong to the second group of these thermometers. According to their composition they are nickel, manganese and cobalt oxides, and their form and size vary. A great number of various properties make the thermistors very suitable for the measurement of small temperature variations. Those are:

- an extremely high temperature resistance coefficient. It is about 3—4% per °C (copper 0.4% per °C). This means that with a thermistor whose resistance is several thousands of ohms, one can carry out very easily the measurement of temperature variations of several thousandths of degrees.
- small volume and mass, and
- quick establishment of resistance for a fixed temperature.

The resistance of a thermistor is an exponential function of temperature. In small temperature intervals (a few °C), however, this dependence can be considered linear. Thermistors which have not been used long enough have an unstable resistance and, therefore, they are unreliable for absolute measurements of the temperature. This does not mean that they are less applicable in the temperature measurement variation where the absolute values of temperature are not of interest. This disadvantage of thermistors is usually eliminated by artificial „aging“ obtained by heating the thermistors for 3—4 thousands of hours at a temperature above 100°C.

Thermistors used for a longer time are stable enough and usually give very reproducible results.

Owing to their good properties we used thermistors in our calorimeter for reactor measurements too, although there was fear regarding their behaviour in the neutron flux. One of the reasons for which thermistors were used is the rather simple technique of measurement.

The results and data obtained during our work (see II. 2) have justified the use of thermistors for these purposes.

I. 3. 3. PRINCIPLE OF THE METHOD. SELECTION OF CALORIMETRIC BODIES

The absorbed energy of radiation is measured by a calorimeter directly from the temperature rise in the calorimetric body. When we are interested only in the doses absorbed in various materials, we make calorimetric bodies from these materials and measure the energy absorbed by irradiating each body separately. The heating power is the absorbed dose rate in the given material.

If we are interested in the contribution of each type of radiation to the absorbed energy, the interpretation of the results is then somewhat more complicated. First of all by selecting the material for the calorimetric bodies, we can avoid the energies of nuclear transmutations caused by thermal neutrons. Thus, the problem is reduced only to the determination of the contribution of gamma rays and fast neutrons. Therefore, in a material (M) the energy absorbed will be the sum of two components (1, 2):

$$(w)_M = (w)_M^{\gamma} + (w)_M^n \quad [4]$$

where:

$(w)_M$ — total absorbed dose rate

$(w)_M^{\gamma}$ — contribution of gamma rays

$(w)_M^n$ — contribution of fast neutrons

If the absorbed energy is measured in two different materials, one obtains two equations:

$$(w)_1 = (w)_1^{\gamma} + (w)_1^n \quad [5a]$$

$$(w)_2 = (w)_2^{\gamma} + (w)_2^n \quad [5a]$$

or

$$(w)_1 = (w)_1^{\gamma} + (w)_1^n \quad [5b]$$

$$(w)_2 = a \cdot (w)_1^{\gamma} + b \cdot (w)_1^n \quad [5b]$$

where:

$$a = \left(\frac{\mu_2}{\mu_1} \right)_{2 \text{ MeV}} \quad [6a]$$

$$b = \frac{\left[\frac{1}{(A+1)^2} \cdot \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE \right]_2}{\left[\frac{1}{(A+1)^2} \cdot \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE \right]_1} \quad [6b]$$

where:

μ — mass absorption coefficient

A — mass number of the material

σ_s — fast neutron scattering cross section

The value of the top integral limit in expression [6b] does not exert great influence on the calculated relations. Some authors (6) take the average fission neutron energy (2 MeV) to be the upper limit. Anderson (2)

takes it to be 1.8 MeV. Richardson (1) calculated the expression [6] within the interval from thermal energies to ∞ . Although in all these cases the

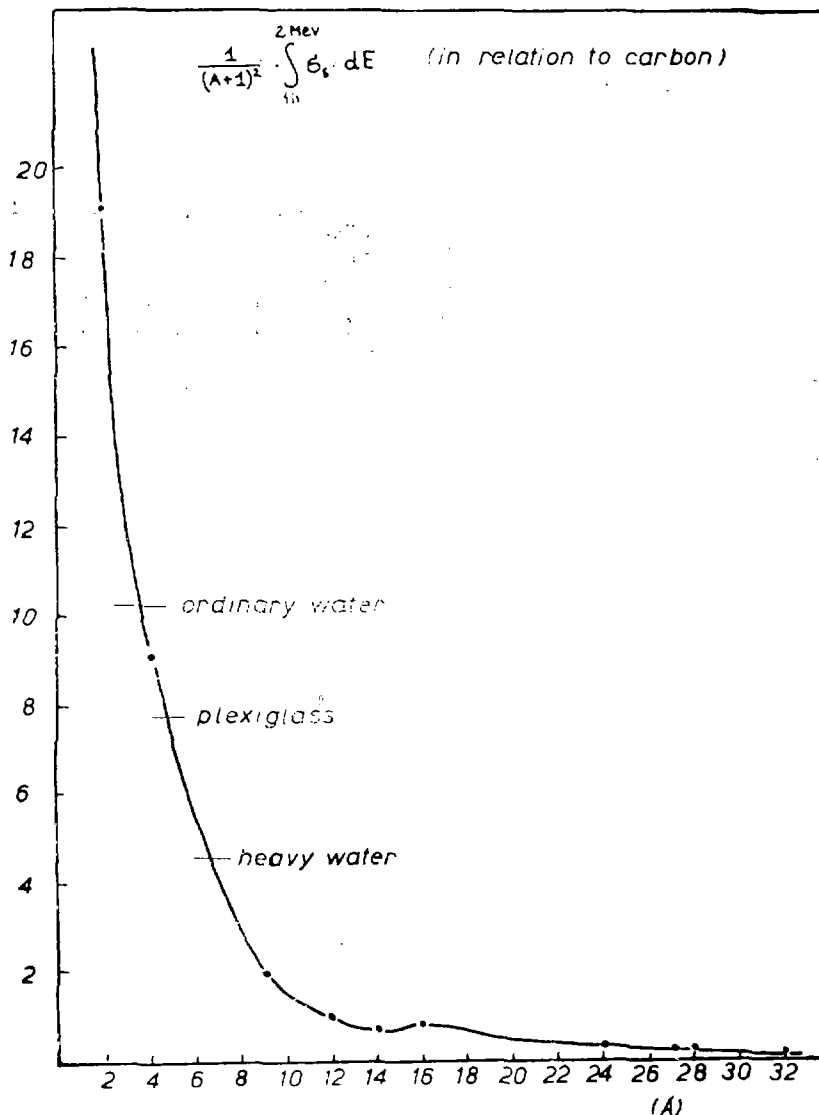


Fig. 3. — Relative values of fast neutron energy deposition

absolute integral values vary considerably, their relations remain, in fact, almost constant.

For the measurement of the distribution of the absorbed energy into fast neutron and gamma ray contribution, it is necessary to measure the

absorbed energy in at least two materials for which the mass absorption gamma coefficients, and the so-called „scattering“ integrals, are known. There is a great number of materials for which these values are known quite precisely.

Instead of two bodies, three or more bodies are used in practice. One of them (usually graphite) is taken as the reference ($a=b=1$), thus obta-

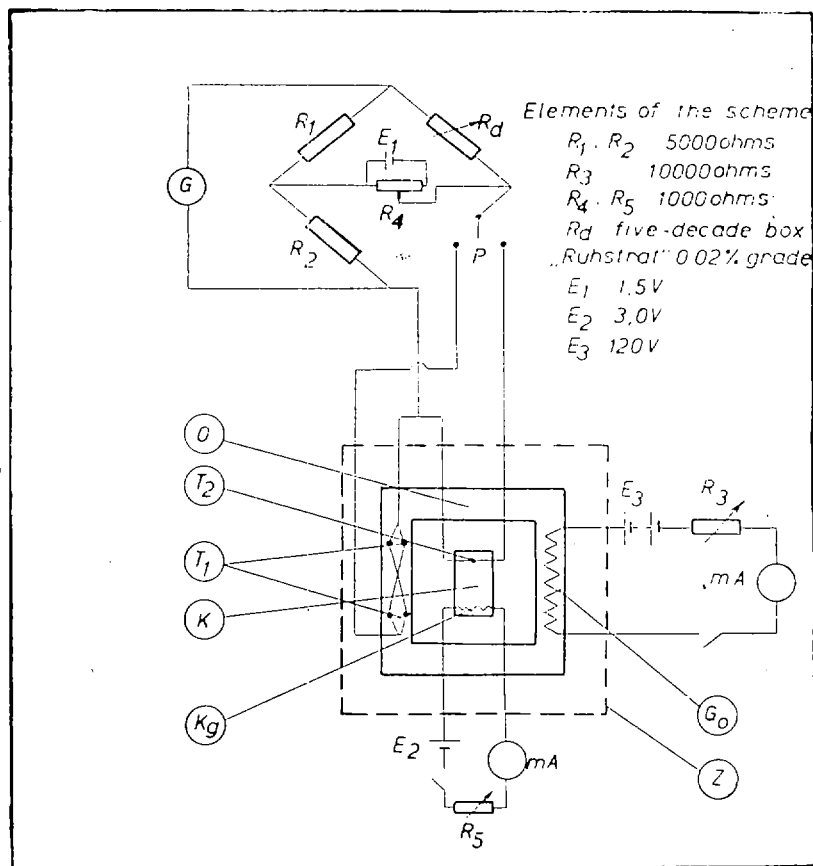


Fig. 4. — Scheme of the calorimeter and the measuring system (P — commutator; K — calorimetric body; O — jacket; T — thermistors (T_1 — jacket; T_2 — body); K_g — calibration heater; G_0 — jacket heater; Z — protective can; G — electronic galvanometer „KINTEL“ model 204A)

ining a series of simultaneous equations from which the values $(w)_C^Y$ and $(w)_C^Z$ are calculated by the least square method. On the basis of these values one can easily calculate, by means of the coefficients (a) and (b), the values of partial and total doses absorbed in any other materials.

In our measurements we used three calorimetric bodies: ordinary water, heavy water and graphite. The two liquids were put in vessels of

plexiglass. All these materials have negligible cross sections for thermal neutrons, so corrections for the energy of the induced nuclear reactions are not necessary. Mass absorption coefficients for gamma rays of 2 MeV are very close one to another. Apart from this, the ratios between these coefficients (which, in fact, is of interest) are constant in a very wide range of energy. The most important fact is, however, that the „stopping power“ for the fast neutrons in carbon, heavy and ordinary water differs quite a lot. Their ratio is 1 : 4.52 : 10.2. This is shown in Fig. 3. (The Figure also shows that the „stopping power“ and consequently the energy absorbed from fast neutrons is negligible for the elements with $A > 30$).

II. DETAILS ON THE MEASUREMENT AND IRRADIATION TECHNIQUE

II. 1. DESCRIPTION OF THE CALORIMETER

II. 1. 1. MECHANICAL PART

A draft of the calorimeter together with the scheme of measurement and control is shown in Fig. 4. The calorimetric body (K) for liquids is made of plexiglass. Another body with the same dimensions (height 50 mm, diameter 20 mm) is made of graphite. All these bodies are shown in Fig. 5.

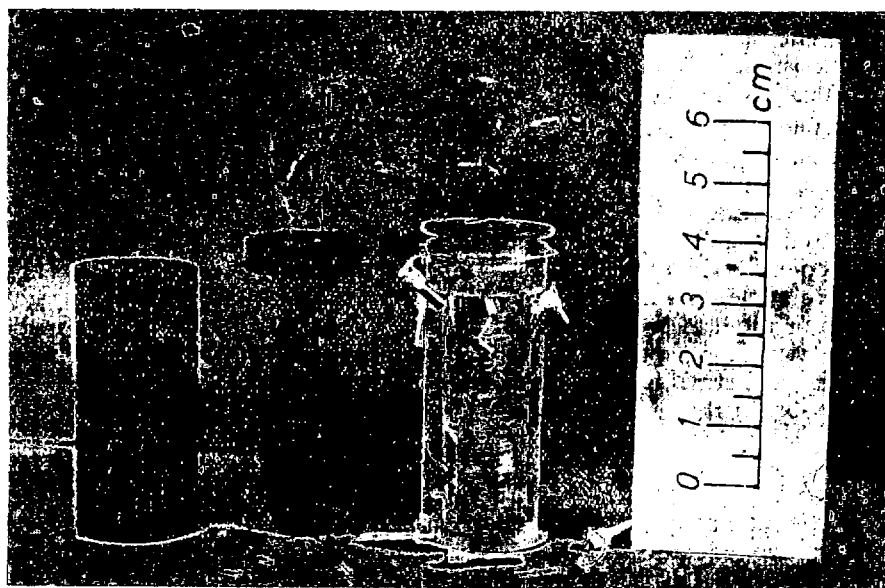


Fig. 5. — Calorimetric bodies

For heat isolation the calorimetric bodies are centered in the jacket by nylon thread. The ambient of the calorimeter (O) is a polished aluminium cylinder, 50 mm in diameter, consisting of two parts. A heater of constantan wire

(0.1 mm) is wound on the surface of the inner part. Thermistors („Philips“ Bead type NTC Resistor“) with nominal resistance of about 5000 Ω at 20° C, for the measurement of the jacket temperature are fastened to it. For mechanical protection and better heat isolation from the ambient in which it is placed, the complete calorimeter is put in a protective aluminium can (Z) 98 mm in outer diameter.

II. 1. 2. ELECTRICAL MEASUREMENTS

The resistances of the thermistors are measured by a Wheatstone bridge with two arms R_1 and R_2 of 5000 ohms (constantan 0.06 mm). All parts of the bridge, except the decade box (R_d) and the galvanometer (G), are placed in a closed iron box. With this bridge, measurements of the resistances of 3000—5000 ohms could be made with an accuracy of ± 0.1 ohms, or measurements of the resistance difference of 20 ohms with a maximum error of $\pm 2\%$.

By means of a commutator (P), the thermistors of the jacket (T_1) and the thermistors in the body (T_2) are switched on alternatively in one arm of the bridge. Thus, the same bridge served for the measurement of the calorimetric body temperature variations by the thermistor (T_2), and for the temperature control in the jacket by a total resistance of 4 thermistors (T_1) (two parallel pairs connected in series).

The heating current in the jacket was adjusted manually with a variable resistance (R_3), and the temperature maintained at a constant value ($\pm 0.005^\circ$ C) of a few degrees above the ambient temperature.

The resistances of the calibration heaters (200—400 ohms) were measured on a specially constructed Wheatstone bridge with symmetrical arms, and checked by comparison with the standard resistances of the 0.02% grade „Göttingen-Ruhrstrat“. The current in the calibration circuit was measured by a precise milliamperimeter of the 0.5% grade („Iskra-Kranj“). Correction for the resistance change in the calibration heater due to heating was negligible, and has not been taken into account.

For the lead and connection isolation in the calorimeter, use was made of the capacitor paper and a polystyrene film. For our working conditions (maximum thermal neutron flux about $2 \cdot 10^{11}$ n/cm²/sec and temperature about 30° C) this was quite satisfactory.

II. 2. STABILITY OF THERMISTORS

Measurement with thermistors in the calorimeter consists in determining two equilibrium values of the resistance. The first value (R_o), corresponds to the jacket temperature (T_o), and the second value (R_r) corresponds to the equilibrium temperature (T_r), when the body is heated by the constant power (W). Similarly to the expression [1], the equilibrium difference of the resistance is proportional to the heating power, i.e.

$$-\Delta R = R_r - R_o = \frac{W}{KmcA} \quad [7]$$

where (A) is the conversion factor for ohms into degrees centigrade and it depends on the characteristics of the thermistor used. The thermistors have a negative temperature coefficient so that $R_0 > R_T$ when $T_0 < T_T$. An indispensable condition for obtaining reliable and reproducible results when working with thermistors is the stability of their resistance for a given temperature.

II. 2. 1. WITHOUT RADIATION

In order to distinguish irregularity in the behaviour of the thermistors caused by radiation, it was necessary to examine primarily their behaviour without radiation.

The value of the thermistor resistance for a given jacket temperature can be changed : first, due to the change of characteristics of the thermistor itself (change in structure by „aging“), and second, due to insufficient heat isolation, i.e. the temperature variation of the ambient in which there are the calorimeter and its jacket.

The variation of the resistance due to the „aging“ of the thermistor is a very slow process, and it cannot exert any considerable influence on the temperature difference measurement. This has been proved by our observations of the value (R_0) for a constant jacket temperature during a longer period of time (7—10 days). For the sample with water we obtained e.g.

days	$R_0(\text{ohms})$
1	3663.1
2	3663.0
3	3663.1
4	3663.2
5	3663.7
6	3663.2

The influence of the ambient temperature variations could cause greater error; that is why the temperature of the heavy water in the core during work in the reactor is kept constant within $\pm 1^\circ \text{C}$. Under these conditions the error in the measured difference of resistance ($R_T - R_0$) was not larger than 0.6—0.8 ohms. According to the results obtained by laboratory measurements, the change in the ambient temperature caused changes in the value R_0 by about 0.3 to 0.4 ohms/ $^\circ \text{C}$. Since the effects measured in the reactor were between 50 and 200 ohms (about 0.5—2.0 $^\circ \text{C}$) the maximum possible error in the measured values was about 1%, while the error was probably smaller since the reactor was thermostated even better than $\pm 1^\circ \text{C}$.

II. 2. 2. DURING IRRADIATION

In the gamma radiation field thermistors have been used up to the present with satisfactory results. In the reactor, however, under the influence of the neutron flux, the recoil nuclei would be a great danger, because they could cause considerable excessive conductance and structural changes in the thermistor material. However, according to the relatively low values of the neutron flux and the short time of irradiation (a few hours), it was

normal to expect that the thermistor stability in the reactor would be sufficient for obtaining reproducible results. A series of data obtained during the work have proved this assumption.

Thus, for instance, the values of the resistance (R_0) determined at the same place before and after irradiation with an integrated thermal neutron dose of about 10^{16} n/cm², were obtained with a negligible difference of 0.2—0.4 ohms. Likewise, the deviation in the average value of two subsequent determinations of the absorbed dose rate was not higher than ± 2 —3%. The difference was not higher even after a longer period of time (3 months) between two irradiations, and the measured values agreed within the limits of the experimental error.

On the other hand, calibration of the calorimeter with a graphite sample was carried out during irradiation with a constant and known heating power. From a series of determinations we obtained the mean value of the resistance difference:

$$\Delta R_k = 41.0 \pm 0.9 \text{ ohms}$$

The values obtained in the laboratory before irradiation were within the same limits.

All this proved to be the reason for the use of thermistors in the measurements in a reactor with low power (20—100 kW), and with maximum fluxes of about 9.8×10^{11} n/cm²/sec.

II. 3. CALIBRATION DIAGRAMS FOR VARIOUS CALORIMETRIC BODIES

According to equation [7] there is a linear relation between the heating power and the equilibrium resistance difference $R_0 - R_r = \Delta R$. This relation has been checked by heating the samples with known power inputs, measuring the current through the calibration heater of the known resistance. The measured thermistor resistance for all the three calorimetric bodies in the heating power are plotted on the diagram (Fig. 6).

We have noticed that for the bodies containing H_2O and D_2O , the linearity defined by the equation [7] is valid only at the beginning of the obtained curve. Therefore, with these samples calibration could not be carried out electrically by a „standard addition“ of the known power during heating with an unknown power as in the case of the graphite body.

This disagreement could occur either due to convection in the calorimetric system, or due to inhomogeneous heating of the body by the calibration heater. In the first case there would be no reason that the calorimeter with the graphite body does not show a similar deviation too.

Assuming that the inhomogeneous heating was the only reason for the curving of the calibration curve towards the abscissa axis, measurements with these bodies were carried out in the following way: the resistance change was measured for the unknown heating power, and then the unknown power was determined graphically from the rectilinearly extrapolated initial part of the calibration diagram. This we were able to do also because the correction for deviation from linearity was of the order of 10—15%.

The justification of the foregoing assumption was proved by inter-comparison of the measured absorption values for all the three bodies. Thus,

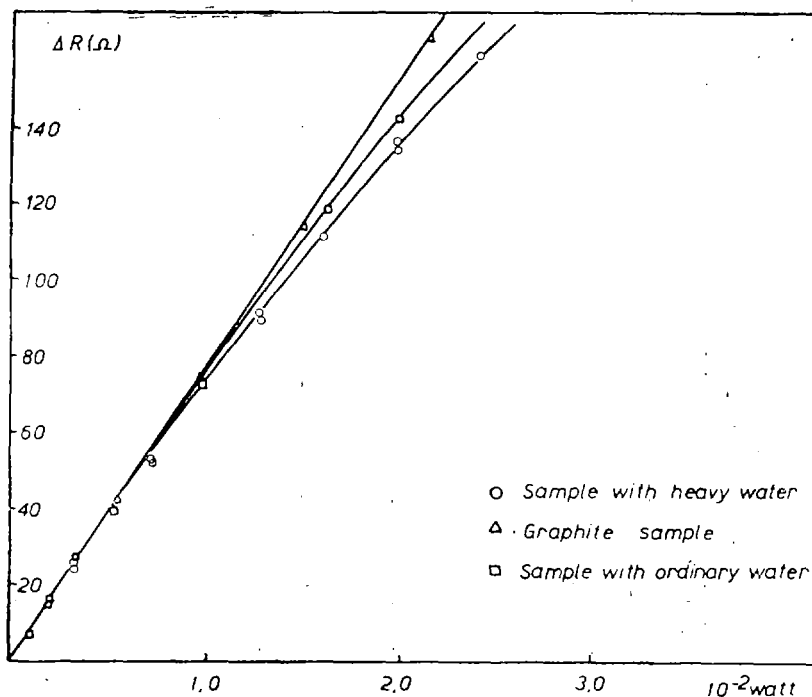


Fig. 6. — Calibration diagram

measurement of the absorbed dose rate at one irradiation place in two bodies, for instance in H_2O and graphite, was carried out in two different ways (with and without linear extrapolation). At the same place and in the same way as in ordinary water, the absorbed dose rate was measured in heavy water. The first two values, for graphite and ordinary water, make it possible for us to measure and to anticipate the absorbed dose rate in heavy water. The results of such calculation compared with the measured values are shown in Table I. Very good agreement of the calculated and the measured

Table I
Comparison of the calculated values for the heating power
in D_2O with the measured ones (at 20 kW)

	Calcul.	Measur.	Difference %
	10 ⁻⁵ w/gr		
VK-5 (300 mm)	119.8	119.9	— 0.1
VK-9 (305 mm)	61.7	61.4	+ 0.5

Table II

Heating powers in ordinary water, heavy water and graphite, at 20 KW, with corrections for the induced activity in the aluminium jacket and the heating power in plexiglass vessels

Hole	Height mm	Measured			Correction for the induced activity									Corrected			with correction for plexiglass	
					H_2O			D_2O			C							
		H_2O	D_2O	C	γ	β	tot	γ	β	tot	γ	β	tot	H_2O	D_2O	C	H_2O	D_2O
		10^{-5} watt/gr																
VK-5	0	114.3	96.9	85.7	6.0	1.9	7.9	5.4	1.8	7.2	5.6	1.1	6.7	106.4	89.7	79.0	108.5	87.0
	300	151.5	129.5	114.2	8.0	2.6	10.6	7.2	2.4	9.6	7.4	1.5	8.9	140.9	119.9	105.3	143.7	115.5
	600	—	—	96.7	—	—	—	—	—	—	6.1	1.3	7.4	—	—	89.3	—	—
				99.7												92.3		
	1000	—	53.7	—	—	—	—	2.7	0.9	3.6	—	—	—	—	50.1	—	—	48.6
	1200	37.9	27.9	23.9	1.7	0.6	2.3	1.6	0.5	2.1	1.6	0.3	1.9	35.6	25.8	22.0	36.3	25.0
VK-9	5	65.1	50.8	46.7	3.8	1.2	5.0	3.4	1.1	4.5	3.5	0.7	4.2	60.1	46.3	42.5	61.3	44.9
	305	79.1	67.1	59.4	4.8	1.5	6.3	4.3	1.4	5.7	4.5	0.9	5.4	72.8	61.4	54.0	74.2	59.4
	1205	15.3	14.0	12.5	1.1	0.4	1.5	1.0	0.3	1.3	1.1	0.2	1.3	13.8	12.7	11.2	14.2	12.3

values, even with many different corrections (for the induced activity in the aluminium jacket, for the energy absorption in plexiglass vessels, etc) proved the foregoing assumptions and justified the measurements with ordinary and heavy water in the way described above. Likewise, it has been shown (4) that by a more convenient positioning of the calibration heater, thus providing homogeneous heating, one obtains straight lines on the calibration diagram.

The same calculation was carried out also for the values calculated according to the obtained calibration diagrams (without linear extrapolation). The error in calculating the absorbed dose rate in heavy water is much greater than in the previous case and it amounts to about — 10% of the calculated value.

II. 4. IRRADIATION TECHNIQUE IN THE REACTOR

The absorbed dose rate was measured in the vertical experimental holes VK-5 and VK-9. In each hole values were measured for at least three different points, at the upper and bottom end of the active zone (0 and 1200 mm), and at 300 mm in the zone, where there is a maximum thermal neutron flux. The insertion of the calorimeter into the experimental holes and the variation of the height was carried out manually from the platform of the reactor by means of a cable with leads for electric measurements.

Since the bottom of the vertical hole is below the bottom of the active zone, it was necessary to insert the calorimeter right to the bottom of the hole which is semicircular, and then raise it up to a fixed height. That is why the real position of the calorimetric body is uncertain within ± 2 —3 cm of the assumed height. The error in the relative heights was not more than ± 1 cm.

All the measurements were carried out at 20 kW and the obtained results were corrected to the power of 1 MW.

III. RESULTS

The results of measurements in the reactor at 20 kW are presented in Table II together with the correction for the induced activity in the aluminium jacket, and with the corrected values. The values of the absorbed dose rates in ordinary and heavy water are corrected also for the energy absorption in vessels of plexiglass. This correction is +2% in H_2O and —3% in D_2O (see Appendix).

The obtained results were compared with the relative values of the thermal flux measured by the activation of the foils of gold and indium (7). The maximum absorbed dose rate in both holes (300 mm in the zone) is considered most reliable, since the probable error in the position of the calorimetric body of ± 2 cm in these places does not exert more influence than 1% on the measured values. From these experimental points and from the shape of the thermal flux distribution curve in the holes, we drew the height distribution of the absorbed dose rate in units of 10^6 rad/MWh for all three materials (Figures 7, 8 and 9).

As it can be seen there exists good agreement between the energy absorption and the thermal neutron flux. It should be pointed out, however,

that such agreement does not exist between these relations for two different holes. Thus, the relation between the maximum energy absorption in VK-5 and VK-9 is 1.95, whereas the same relation between the maximum thermal neutron flux is 1.65.

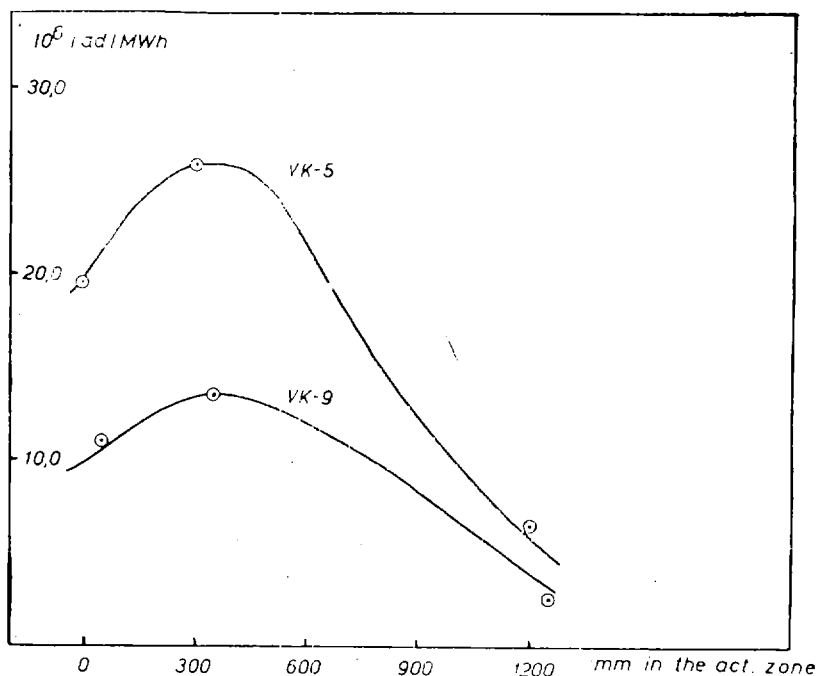


Fig. 7. -- The absorbed dose rate in water

The maximum deviations of the measured values from the accepted distribution (for graphite $\pm 5\%$, for H_2O and D_2O $\pm 10\%$) are within the limits of the error of experimental measurements and the unreliability of the geometric position of the calorimetric body in the hole.

Estimation was made of the error for the maximum energy absorption and it was found to be for graphite $\pm 2.5\%$ and for samples with H_2O and D_2O about $\pm 5\%$.

The relatively great deviations at the height of 1205 mm in VK-9 are probably due to the fact that the calorimetric body is 5 cm above the top of the uranium rods, practically almost in the reflector. For all three materials the measured value is 12 to 20% lower than that expected from the relative value of the thermal flux compared to the maximum. In addition, the error in the position of the calorimetric body of ± 1 cm leads to deviation of the measured value by about $\pm 5\%$ in this place.

One measurement with D_2O in VK-9 (0 mm in the zone) was carried out at 80 kW. The absorbed dose rate corrected to 1 MW was

$$w_x = 7.15 \times 10^6 \text{ rad/MWh}$$

The deviation from the distribution curve is — 8.7%, i.e. it is still within the maximum deviation of the measured values at 20 kW, in the same place.

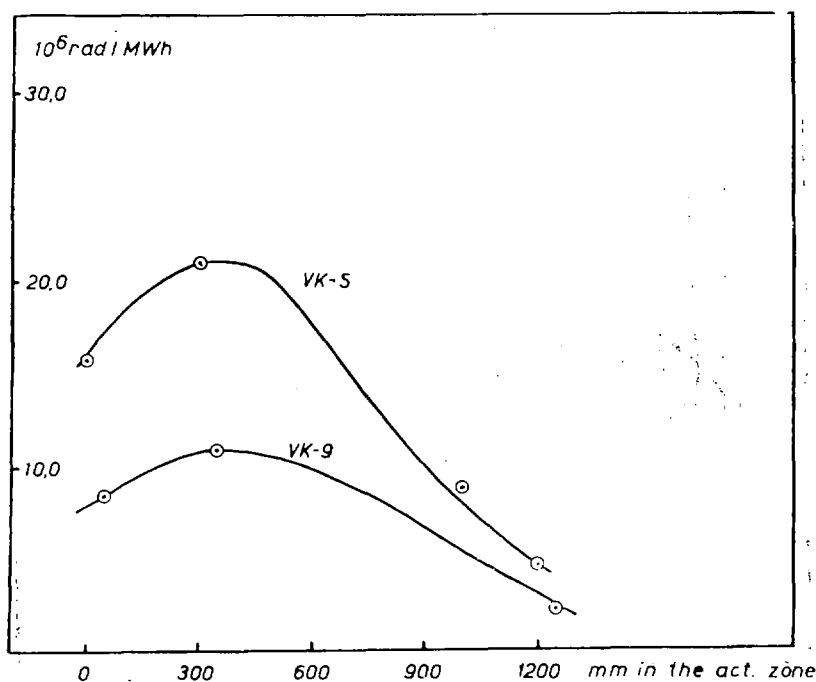


Fig. 8. — The absorbed dose rate in heavy water

IV. DISCUSSION

IV. 1. CONTRIBUTION OF GAMMA RADIATION AND FAST NEUTRONS TO THE TOTAL ABSORBED DOSE RATE

The values corrected for the induced activity in the aluminium jacket for maximum absorptions in the holes VK-5 and VK-9 are as follows:

VK-5	H_2O	$(25.4 \pm 1.3) \times 10^6 \text{ rad/MWh}$
	D_2O	$(21.6 \pm 1.1) \times 10^6 \text{ rad/MWh}$
	graphite	$(18.9 \pm 0.5) \times 10^6 \text{ rad/MWh}$
VK-9	H_2O	$(13.1 \pm 0.6) \times 10^6 \text{ rad/MWh}$
	D_2O	$(11.1 \pm 0.5) \times 10^6 \text{ rad/MWh}$
	graphite	$(9.72 \pm 0.24) \times 10^6 \text{ rad/MWh}$

The following system of equations for calculating the contribution of gamma radiation and fast neutrons to the total absorbed dose rate (see. I. 3. 3) was set for VK-5:

$$H_2O: 25.4 = A \cdot 1.11 (w)_C^Y + B \cdot 10.2 \cdot (w)_C^Z$$

$$D_2O: 21.6 = A_1 \cdot 1.0 (w)_C^Y + B_1 \cdot 4.52 \cdot (w)_C^Z$$

$$C: 18.9 = (w)_C^Y + (w)_C^Z$$

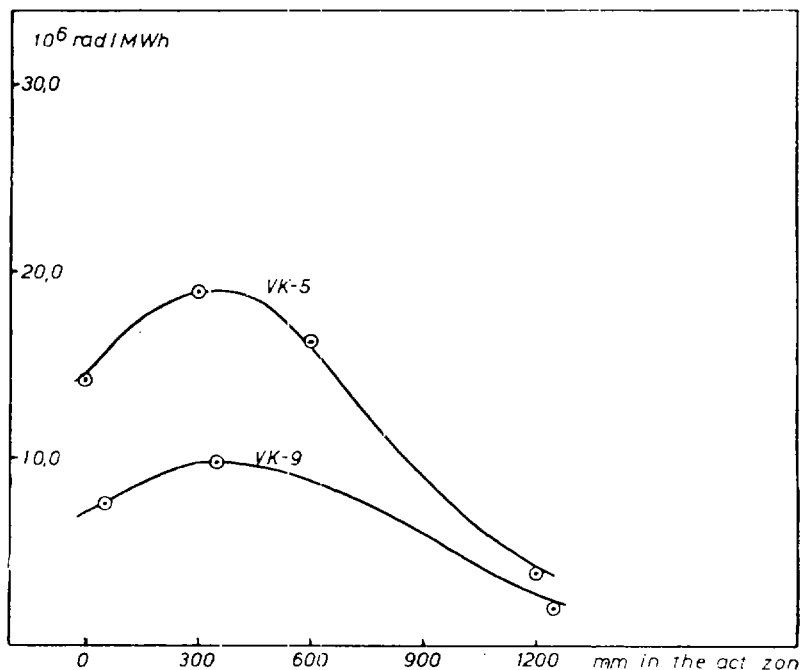


Fig. 9. — The absorbed dose rate in graphite

where (A) and (B) are the correction factors for energy absorption in plexi-glass vessels. These factors are (see Appendix):

$$A = 0.993$$

$$A_1 = 1.02$$

$$B = 0.932$$

$$B_1 = 1.17$$

A similar system of equations is set also for VK-9.

The solution by the least square method yielded the data given in Table III.

From these results one can calculate the absorbed dose rate with an error less than $\pm 10\%$ in any material whether simple or complex composition. For this calculation it is necessary to know only the relative values of the mass absorption coefficient for gamma rays of 2 MeV and the values

of the expression $1/(A+1)^2 \cdot \int_{E_0}^{2 \text{ MeV}} \sigma_s \cdot dE$ for any of the materials used.

Table III

Gamma radiation and fast neutron contribution to the total absorbed dose rate

Hole	Material	Measured absorbed dose-rate	Contri- bution γ	Contri- bution n	Calculated absorbed dose-rate	Relative* contribution	
						γ %	n %
10 ⁶ rad/MWh							
VK-5	H ₂ O	25.4	20.4	5.42	25.8	79	21
	D ₂ O	21.6	18.4	2.39	20.8	88.5	11.5
	C	18.9	18.4	0.53	18.9	97	3
VK-9	H ₂ O	13.1	10.5	2.90	13.4	78	22
	D ₂ O	11.1	9.41	1.28	10.7	88	12
	C	9.72	9.41	0.28	9.70	97	3

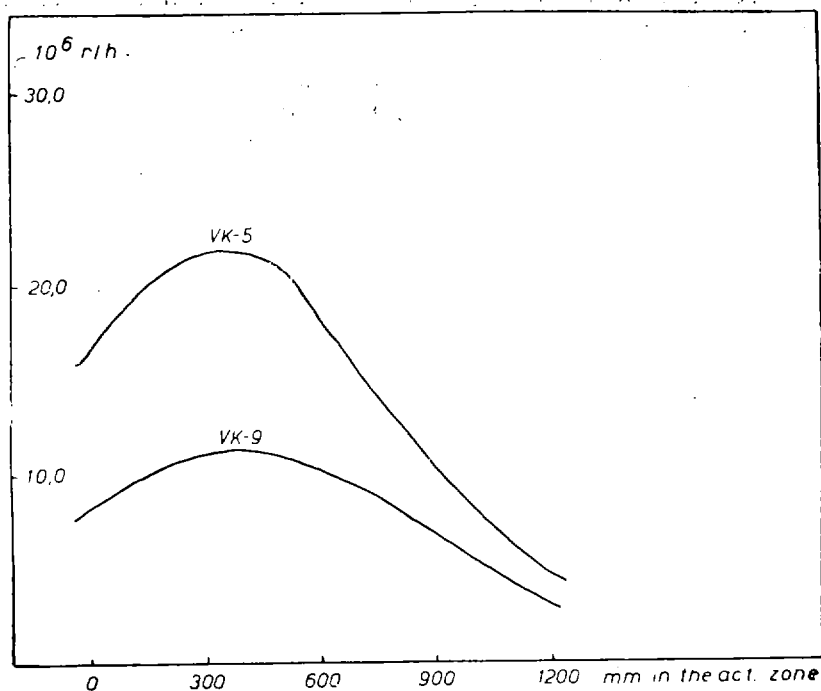


Fig. 10. — The gamma dose rate in holes VK-5 and VK-9 at 1 MW

* Because of a small number of measurements at one position in the experimental hole (one measurement with each sample) and the sensitivity of the system of equations to the error in the measured values, these data are not quite reliable. Some subsequent measurements carried out in the reactor have shown that the percentages of gamma rays in comparison with fast neutrons are probably somewhat changed — for instance in water from gamma 75%, from fast neutrons 25%. In graphite from gamma 96.5% and from fast neutrons 3.5%.

IV. 2. GAMMA RADIATION DOSE RATE IN EXPERIMENTAL HOLES

The gamma radiation dose of 1 röntgen transfers the energy of 94 erg/gr, i.e. 0.94 rads to the water. From this and from the values calculated for the absorption of the gamma radiation energy in water (Table III), calculation was made of the gamma radiation dose rate in the experimental holes VK-5 and VK-9. The maximums are:*

in VK-5	21.7×10^6 r/MWh
in VK-9	11.2×10^6 r/MWh

According to these values, the most probable distribution in both holes was drawn (Fig. 10).

IV. 3. COMPARISON WITH SOME RESULTS OF EPITHERMAL FLUX MEASUREMENTS

The values of the doses absorbed from fast neutrons, obtained by calorimetric measurements, were compared with the values calculated knowing the ratio of thermal and epithermal neutron flux (0.4 eV — 1.8 MeV). Calculation was carried out on the assumption that all the fast neutrons are in the „1/E“ region of the spectrum, that this region is cut off sharply at the limits of 0.4 eV and 1.8 MeV, and that these neutrons release energy by elastic collisions. The neutron absorbed dose rate in the material with the atomic weight (A) was calculated from the equation:

$$(W_{s/gr})_A = \frac{N}{A} \cdot \frac{2A}{(A+1)^2} \cdot \int_{0.4 \text{ eV}}^{1.8 \text{ MeV}} \frac{k(nv)_{th}}{E} \cdot \sigma_s \cdot E \cdot dE \quad (\text{ev/gr/sec}) \quad [8]$$

where:

- N — Avogadro's number
- $(nv)_{th}$ — thermal neutron flux (n/cm²/sec)
- σ_s — „scattering“ cross section (cm²)
- E — energy of neutrons (eV)
- k — reactor constant dependent on the ratio of the epithermal and thermal flux and determined by measuring the cadmium ratio.

For the experiment holes VK-5 and VK-9, the following values are determined for k (7):

in VK-5	$k = 0.035$
in VK-9	$k = 0.025$

From the known thermal neutron flux according to the expression [8], calculation was made of the dose rate absorbed from fast neutrons in H₂O, D₂O and graphite. The comparison of the results for maximums in both holes is shown in Table IV.

* These values due to partial gamma radiation absorption in the calorimeter aluminium jacket are somewhat lower (about 10%) than the true ones in experimental holes.

Table IV
Comparison of the calorimetric and calculated values for the maximum doses absorbed from fast neutrons.

Hole	Material	Calcul. from R_{Cd}	Measured by calor.	Calcul/Measured
		$\cdot 10^6$ rad MWh		
VK-5	H_2O	9.05	5.42	1.67
	D_2O	3.99	2.39	
	C	0.885	0.53	
VK-9	H_2O	3.72	2.90	1.28
	D_2O	1.64	1.28	
	C	0.363	0.28	

IV. 4. THE AVERAGE ENERGY OF FAST NEUTRONS

To calculate the G values* for various chemical systems in the reactor, it is necessary to know also the average energy of fast neutrons, apart from the percentage of the gamma ray and fast neutron contribution to the total absorbed dose.

The equation [8] for the calculation of the energy absorbed from fast neutrons in the material with the mass number (A) can be written in the following form:

$$(w)_A^n = \frac{N}{A} \cdot \bar{\sigma}_s \cdot \frac{2A}{(A+1)^2} \cdot \bar{E} \cdot \lambda \cdot (nv)_{th} \text{ (eV/gr/sec)} \quad [9]$$

where:

$\bar{E}$ — average energy of neutrons (eV)

$\bar{\sigma}_s$ — average value of the elastic scattering cross section within the given integration limits (determined graphically)

$(nv)_{th}$ — thermal neutron flux (n/cm²/sec)

λ — ratio between the thermal and epithermal flux

From the calorimetrically measured values for $(w)_C^n$ in eV/gr/sec and the known values for (λ) and $(nv)_{th}$, we can calculate roughly the average energy of fast neutrons ($\bar{E}$, for graphite in the given integration limits is about 2.8 barns). In our case somewhat less than 100 keV is obtained for the average energy of fast neutrons in experimental holes where our measurements were done.

IV. 5. COMPARISON WITH CALORIMETRIC MEASUREMENTS IN OTHER REACTORS

The measured values for the energy absorption in the reactor RA are compared with the results obtained by calorimetric measurements in other reactors. Data are taken for the reactors DIDO, NRX and BEPO. DIDO is a reactor with enriched fuel and heavy water as moderator. NRX also has heavy water as moderator, and it uses natural uranium. BEPO also uses

* Number of chemical acts for the absorbed 100 eV.

natural uranium, but has graphite as moderator. While in BEPO the absorbed energy is proportional to the integrated thermal neutron dose, and the factors of proportion are independent of the place of irradiation in the reactor DIDO(3) and the reactor RA, as shown by these measurements, these factors vary with the horizontal distance from the vertical axis of the reactor core. The absorbed energies per gram of material for n/cm^2 are compared for these three reactors (Table V). The values for DIDO and the reactor RA are

Table V
Comparison of results with other reactors

Material	BEPO	DIDO	RA
	10^{-8} erg/g for n/cm^2		
H_2O	7.50	8.17 [*]	7.32
D_2O	4.57	6.15 [*]	5.90
C	2.83	5.74	5.36

given only for the vertical axis of the reactor core. The data for NRX are not taken into account here because the measurements were carried out in the reflector outside the reactor tank, and the values are, therefore, much lower.

Since the measurements of the energy absorbed in the reactor RA were not carried out simultaneously with the measurements of the thermal neutron flux, the values shown in the Table are only approximate values with a possible error even over 20%.

Comparison of the percentage of the gamma ray and fast neutron contribution to the total absorbed energy are shown in Table VI.

Table VI

Comparison of the percentage of gamma rays and fast neutron contribution to the total absorbed dose in other reactors

Material	BEPO		Oak Ridge		NRX		DIDO		RA	
	γ	n	γ	n	γ	n	γ	n	γ	n
H_2O	35	65	34	66	52	48	68	32	79	21
D_2O	52	48	47	53	69	31	81	19	88	12
C	83	17	82	18	92	8	95	5	97	3

V. APPENDIX

V. 1. ACTIVATION OF THE ALUMINIUM JACKET AND ITS CONTRIBUTION TO THE MEASURED ENERGY ABSORPTION

During the reactor run the aluminium jacket becomes a source of radiation which transfers its energy to the sample, thus contributing to the rise of its temperature. Due to its good properties, aluminium is used for the construction of calorimeters for the reactor. The significant advantage

* Values calculated from the absorption measured in graphite

it has over other materials (*Ag*, *Cu*) used for the same purposes is in the fact that its thermal neutron absorption cross section is considerably smaller, and the half-life is very short.* Consequently, aluminium which is exposed to the thermal neutron flux, becomes saturated very quickly, the number of desintegrations in the unit of time being equal to the number of atoms newly activated. The jacket is then a constant source of radiation which does not change with time (provided the thermal neutron flux does not change). The energy which the jacket transfers to the calorimetric body can be calculated approximately.

The mode of calculation we have applied is described in the literature (2), and it consists, briefly, in the following:

The capture of the thermal neutrons in ^{27}Al produces gamma radiation with an energy of 7.5 MeV. The obtained product ^{28}Al emits beta particles with the mean energy of about 1 MeV, and gamma rays with an energy of 1.8 MeV.

The number of gamma quanta of 7.5 MeV is equal to the number of absorbed thermal neutrons, and that is also the number of desintegrations of ^{28}Al in a unit of time.

The number of events which take place in a gram of aluminium, in a unit of time is:

$$(A/\text{gr}) = \frac{N}{27} \cdot \sigma_{\text{Al}} \cdot (nv)_{th} \quad [10]$$

where:

N — Avogadro's number

σ_{Al} — thermal neutron capture cross section in aluminium

$(nv)_{th}$ — thermal neutron flux ($\text{n/cm}^2/\text{sec}$)

If the weight of the aluminium cylinder is (G) grams, the total number of events is

$$A = G \cdot \frac{N}{27} \cdot \sigma_{\text{Al}} \cdot (nv)_{th} \quad [11]$$

The calculation of the gamma intensity to which the calorimetric body is exposed depends strictly upon the geometric conditions and, consequently, the error can be about 30% of the calculated value and even higher. However, the contribution of the induced activity to the total absorbed dose rate is less than 10%, so the error is negligible.

By approximating the aluminium jacket with a thin sphere of equivalent value, one can calculate the gamma flux in the centre.

* ^{27}Al (100%)	= 0.2 barns	$T_{1/2} = 2.3 \text{ min}$
^{65}Cu (31%)	= 2 "	$T_{1/2} = 5.1 \text{ min}$
^{63}Cu (69%)	= 4 "	$T_{1/2} = 12.8 \text{ h}$
^{107}Ag (51%)	= 30 "	$T_{1/2} = 2.3 \text{ min}$
^{109}Ag (49%)	= 84 "	$T_{1/2} = 270 \text{ days}$

If (E) is the energy of the gamma photons in MeV, (A') is the surface activity, i.e.

$$A' = A/S \text{ (desint/cm}^2\text{/sec)}$$

where (S) is the surface of the cylinder expressed in cm^2 , the gamma intensity (I) is given with:

$$I_{(E)} = A' \cdot E \text{ (MeV/cm}^2\text{/sec)} \quad [12]$$

The absorbed energy in the calorimetric body is calculated from:

$$(w)\gamma = I_{(E)} \cdot \mu_{(E)} \cdot 1.6 \cdot 10^{-12} \text{ (erg/g/sec)} \quad [13]$$

where $\mu_{(E)}$ is the mass absorption coefficient for gamma with (E) — MeV, in the calorimetric body material.

For this kind of calculation use can be made of the equation [14] for the gamma radiation dose rate in the centre of the source which has the form of a hollow cylinder. Provided self-absorption in the walls is insignificant:

$$D = \frac{2A \cdot I_{\gamma} \cdot \text{arc tg } \frac{Z}{2R}}{R \cdot Z} (r/h) \quad [14]$$

where:

- A — total activity (mC)
- I_{γ} — ionization constant ($\text{r} \cdot \text{cm}^2/\text{h/mC}$)
- R — average radius of the cylinder (cm)
- Z — average height of the cylinder (cm)

For the maximum flux in VK-5 one obtains in this way about 9 r/sec along the vertical axis of the cylinder at the power of 20 kW. This corresponds to the absorbed dose rate in water of 1.53×10^6 rad/MWh, which is 5.6 per cent of the measured value. The same correction calculated previously in the same way is 1.44×10^6 rad/MWh or 5.3 per cent of the measured value.

Beta particles with the mean energy 1 MeV have a range of 0.15 cm in aluminium. The number of desintegrations occurring in this range is given with:

$$A_{(\beta)} = A' \cdot \frac{0.15}{d} \quad [15]$$

where (d) is the thickness of the aluminium cylinder in (cm), and (A') the surface activity, i.e. the number of desintegrations/ $\text{cm}^2\text{/sec}$. The fraction of the total energy coming from the inner surface is calculated from the formula given by Richards and Rubin (8) for the surface layer whose thickness is equal to the range of the particles. For energies 1 MeV this fraction amounts to 1/8 of the total energy. Therefore, the loss energy is:

$$E_{(\beta)} = A' \cdot \frac{0.15}{d} \cdot 1 \cdot 10^6 \cdot \frac{1}{8} \cdot 1.6 \cdot 10^{-12} = \frac{A'}{d} \cdot 3 \cdot 10^{-8} \text{ (erg/cm}^2\text{/sec)} \quad [16]$$

If (S) is the surface of the calorimetric body in (cm^2), and (m) its mass in grams, the dose rate absorbed from beta radiation of aluminium is calculated from:

$$(w)\beta = \frac{A'}{d} \cdot 3 \cdot 10^{-8} \cdot \frac{S}{m} \quad (\text{erg/gr/sec}) \quad [17]$$

The corrections for gamma and beta radiation of the jacket calculated in percentages of the measured values are given in Table VII.

Table VII

Corrections for the induced activity in the aluminium shield in percentages of the measured values

Hole	H_2O			D_2O			C		
	γ	β	Tot	γ	β	Tot	γ	β	Tot
VK-5	5.3	1.7	7.0	5.6	1.8	7.4	6.5	1.3	7.8
VK-9	6.0	1.9	7.9	6.4	2.1	8.5	7.5	1.5	9.0

V. 2. CORRECTION FOR THE ENERGY ABSORPTION IN PLEXIGLASS VESSELS

The heating power measured in samples with ordinary and heavy water comes partially from the absorption in plexiglass vessels. This fraction should be subtracted from the total measured values in order to obtain the heating power in H_2O or D_2O . In order to carry this out, it was necessary to determine the heating power in an empty vessel or a calorimetric body made of plexiglass; the heating power obtained per gram had to be multiplied by the mass of the calorimetric vessel and subtracted from the total heating power.

It is more simple, however, to calculate the correction for the error we take by assuming the total mass of the calorimetric body to be equal to the mass of the water, i.e. that the measured heating power divided by the mass of the body gives the absorbed dose rate in H_2O and D_2O .

The calculation is based upon the relative values of the absorbed energy in plexiglass, H_2O and D_2O . As we have already seen, the absorbed energies of the gamma radiation in two different materials are given by the ratio of mass absorption coefficients, or by the ratio of electron densities. Thus,

$$\frac{(w)_{H_2O}^{\gamma}}{(w)_{\text{plexi}}^{\gamma}} = 1.03; \quad \frac{(w)_{D_2O}^{\gamma}}{(w)_{\text{plexi}}^{\gamma}} = 0.923$$

The energies absorbed by elastic scattering of fast neutrons in two different materials are given by the ratio of the expression

$$\frac{1}{(A+1)^2} \cdot \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE$$

for each material.

Calculation of this value for plexiglass is made from the data for H , C and O (constituents of plexi) and their ratios in the total mass expressed in abundances. The following was found:

$$\frac{1}{(A+1)^2} \cdot \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE = 25.3 \times 10^4 \text{ barn eV}$$

Considering the values from Table IX we have:

$$\frac{(w)_{H_2O}^n}{(w)_{plexi}^n} = 1.33; \quad \frac{(w)_{D_2O}^n}{(w)_{plexi}^n} = 0.59$$

The correction for the energy absorption in plexiglass vessel is calculated in the following way:

In the body we have:

(y) grams of plexiglass

(x) grams of H_2O

By dividing the absorbed energy into water and plexi, and then into gamma and neutron absorption, we have (w_{Tot} is the absorbed energy per gram of the mass of the calorimetric body):

$$(x+y) \cdot w_{Tot} = (x \cdot w_{H_2O}^{\gamma} + y \cdot w_{plexi}^{\gamma}) + (x \cdot w_{H_2O}^n + y \cdot w_{plexi}^n)$$

Considering the ratios calculated above, all the members on the right-hand side of the equation can be expressed in relation to water. Thus,

$$(x+y) \cdot w_{Tot} = \left(x \cdot w_{H_2O}^{\gamma} + y \cdot \frac{w_{H_2O}^{\gamma}}{1.03} \right) + \left(x \cdot w_{H_2O}^n + y \cdot \frac{w_{H_2O}^n}{1.33} \right)$$

or:

$$(x+y) \cdot w_{Tot} = w_{H_2O}^{\gamma} \cdot \left(x + \frac{y}{1.03} \right) + w_{H_2O}^n \cdot \left(x + \frac{y}{1.33} \right)$$

By dividing the above equation by the total mass of the calorimetric body ($x+y$), one obtains:

$$w_{Tot} = A \cdot w_{H_2O}^{\gamma} + B \cdot w_{H_2O}^n$$

where:

$$A = \frac{1.03 \cdot x + y}{1.03(x+y)}$$

$$B = \frac{1.33 \cdot x + y}{1.33(x+y)}$$

The analogous expression is obtained for the body with D_2O where the constants (A) and (B) are given by the ratio:

$$A = \frac{0.923 \cdot x + y}{0.923(x + y)}$$

$$B = \frac{0.59 \cdot x + y}{0.59(x + y)}$$

here: (y) — number of grams of plexiglass

(x) — number of grams of D_2O

Therefore, the whole mass of the calorimetric body can be considered to be equal to the mass of ordinary water or D_2O , and it can be divided into gamma and neutron absorption which is multiplied by the factors (A) and (B), thus eliminating the influence of the plexiglass.

For two calorimetric bodies, the constants A and B were calculated and the following values obtained:

	A	B
H_2O	0.993	0.932
D_2O	1.02	1.17

Calculation was made also of the total correction (for gamma and neutrons) and it amounts in ordinary water to +2%, and in heavy water to —3% of the measured value.

V. 3. CALCULATION OF THE HEATING POWER (ABSORBED DOSE RATE) IN VARIOUS MATERIALS

The calculation of the heating power can be made from the measured values of the energy absorption in a given material, for instance in graphite. The total absorbed energy comes partially from the absorption of gamma radiation, from the slowing down of fast neutrons and from the energy of nuclear reactions which take place in the material itself. That is why the heating power is to be found first for each component separately, their sum giving the total heating power in a given sample.

For instance, we shall calculate the heating power per gram of aluminium in VK-5 for the position with the maximum thermal neutron flux (300 mm).

At the same place one obtains in graphite:

from gamma: $w_C^\gamma = 18.4 \times 10^6$ rad/MWh

from fast neutrons: $w_C^n = 0.53 \times 10^6$ rad/MWh

The absorbed energies in two different materials are in the ratio of the mass absorption coefficients for gamma of 2 MeV (the average energy of gamma photons in the reactor).

We have (Table VIII):

Table VIII
Mass absorption coefficients for gamma rays of 2 MeV

Material	μ (cm ² /gr)	value in relation to graphite
<i>H</i>	0.0469	1.98
<i>C</i>	0.0237	1.00
<i>O</i>	0.0238	1.00
<i>D</i>	0.0232	0.98
<i>Al</i>	0.0234	0.99
<i>H₂O</i>	0.0264	1.11
<i>D₂O</i>	0.0237	1.00

$$\left(\frac{\mu_{AL}}{\mu_C} \right)^{2 \text{ MeV}} = \frac{0.0234}{0.0237} = 0.99$$

The absorption energy from gamma radiation is then:

$$w_{Al}^{\gamma} = w_C^{\gamma} \cdot 0.99 = 18.4 \times 10^6 \times 0.99 = 18.2 \times 10^6 \text{ rad/MWh}$$

The ratios of the energies absorbed by the slowing down of fast neutrons depends on the value of the „scattering“ integrals in the region (0.025 eV — 2 MeV) and the atomic weight. In this case we have (Table IX):

Table IX

Values of the expression $\frac{1}{(A+1)^2} \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE$ for the materials used

Material	$\frac{1}{(A+1)^2} \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE$ (Barn · eV · 10 ⁴)	Value in relation to graphite
<i>H</i>	281.0	85.4
<i>C</i>	3.29	1.00
<i>O</i>	2.76	0.84
<i>D</i>	63.5	19.2
<i>Al</i>	0.95	0.28
<i>H₂O</i>	33.7	10.2
<i>D₂O</i>	14.9	4.52

$$\frac{w_{Al}^n}{w_C^n} = \frac{\left[\frac{1}{(A+1)^2} \cdot \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE \right]_{Al}}{\left[\frac{1}{(A+1)^2} \cdot \int_{th}^{2 \text{ MeV}} \sigma_s \cdot dE \right]_C} = 0.28$$

The contribution of fast neutrons to the heating of aluminium is:

$$w_{Al}^n = w_C^n \times 0.28 = 0.53 \times 10^6 \times 0.28 = 0.15 \times 10^6 \text{ rad/MWh}$$

In heavier elements, for $A > 30$ this fraction of the absorbed energy is less than 1% and can be neglected completely.

The heating of aluminium due to the induced activity is calculated independently of the calorimetric results and it depends on the size of the sample, its geometric form, etc.

Therefore, irrespective of the fraction of energy, which must be calculated for various forms of samples separately (9), the heating power per gram of aluminium is:

$$w_{Al}^{Tot} = (18.2 + 0.15) \times 10^6 = 18.4 \times 10^6 \text{ rad/MWh}$$

In complex compounds the heating power is calculated from the percentage ratios of all the elements from which it is composed.

In *polyethylene* $(CH_2)_n$ we have for instance: (molecule weight $M = n \cdot 14$).

The heating in carbon is:

$$w_C^Y = 18.4 \times 10^6 \text{ rad/MWh}$$

$$w_C^n = 0.53 \times 10^6 \text{ rad/MWh}$$

and in hydrogen:

$$w_H^n = 45.4 \times 10^6 \text{ rad/MWh}$$

$$w_H^Y = 36.4 \times 10^6 \text{ rad/MWh}$$

The contribution of carbon in the heating of polyethylene is:

$$\frac{12}{14} \cdot 18.9 \times 10^6 \text{ rad/MWh} = 16.2 \times 10^6 \text{ rad/MWh}$$

The contribution of hydrogen is:

$$\frac{2}{14} \cdot 81.8 \times 10^6 \text{ rad/MWh} = 11.7 \times 10^6 \text{ rad/MWh}$$

The total heating power in polyethylene is:

$$w_{(CH_2)_n}^{Tot} = 27.9 \times 10^6 \text{ rad/MWh} (\pm 5-10\%)$$

The contribution of neutrons is:

$$\text{from carbon: } \frac{12}{14} \times 0.53 \times 10^6 \text{ rad/MWh} = 0.46 \times 10^6 \text{ rad/MWh}$$

$$\text{from hydrogen: } \frac{2}{14} \times 45.4 \times 10^6 \text{ rad/MWh} = 6.5 \times 10^6 \text{ rad/MWh}$$

The total from fast neutrons is:

$$w_{(CH_2)_n}^n = 6.96 \times 10^6 \text{ rad/MWh}$$

which means 25% of the total power.

The contribution of gamma radiation is:

$$\text{from carbon: } \frac{12}{14} \times 18.4 \times 10^6 \text{ rad/MWh} = 15.8 \times 10^6 \text{ rad/MWh}$$

$$\text{from hydrogen: } \frac{2}{14} \times 36.4 \times 10^6 \text{ rad/MWh} = 5.2 \times 10^6 \text{ rad/MWh}$$

or the total from gamma radiation:

$$w_{(CH_2)_n}^{\gamma} = 21.0 \times 10^6 \text{ rad/MWh}$$

which means 75% of the total.

The heating powers in aluminium and polyethylene, calculated in watts per gram, for the maximum thermal neutron flux in VK-5 (at 1 MW) are:

$$w_{Al} = 5.14 \times 10^{-2} \text{ watt/gr}$$

$$w_{(CH_2)_n} = 7.76 \times 10^{-2} \text{ watt/gr}$$

R é s u m é

DOSIMETRIE DU RAYONNEMENT DE LA PILE RA DE VINČA

1. — Dans ce travail nous avons essayé:

— de présenter une analyse des problèmes concernant la dosimétrie du rayonnement de la pile;

— de présenter la solution de ce problème par la méthode calorimétrique;

— de donner les résultats des mesures faites dans la pile RA de Vinča et de décrire les méthodes, les appareils et les dispositifs de mesure dont nous nous sommes servis.

2. — Nous avons utilisé le calorimètre isothermique aux thermistors, par lequel nous avons mesuré la vitesse des doses absorbées dans les limites de 10^4 à 10^6 rads/h, avec la précision de 2 à 5%. Il a été constaté que l'irradiation de la pile, dont le flux des neutrons thermiques est de l'ordre de 10^{12} n/cm²/sec et le flux intégral des neutrons thermiques de l'ordre de 10^{16} n/cm², n'influence pas visiblement les caractéristiques du fonctionnement des thermistors utilisés.

3. — Nous avons déterminé la distribution de la dose absorbée et les contributions des rayons gamma et des neutrons. Dans ce but, nous avons fait les mesures dans trois différents matériaux: eau, eau lourde et graphite.

4. — Les mesures sont faites dans deux canaux verticaux de la pile RA: „VK-5“ et „VK-9“ à plusieurs niveaux. Il a été démontré que la distribution de la dose absorbée par hauteur est en bon accord avec la distribution du flux thermique pour chaque canal, bien que les rapports des doses absorbées dans deux canaux ne soient pas en accord parfait avec les rapports correspondants des flux thermiques.

Р е з ю м е

ДОЗИМЕТРИЯ ИЗЛУЧЕНИЯ РЕАКТОРА РА В ВИНЧЕ

1. В данной статье мы попытались:

— провести анализ проблем дозиметрии излучения в реакторе.
— описать способ решения этого проблема калориметрическим методом.

— дать результаты измерения на реакторе РА в Винче, описание метода, аппаратов и измерительных приборов которыми мы пользовались.

2. Применялся изотермический калориметр с термисторами с помощью которых проводились измерения мощности поглощенных доз в пределах от 10^4 — 10^6 рад/ч, с точностью от 2-5%. Показано, что излучение реактора в котором поток тепловых нейтронов примерно до порядка 10^{12} н/см² сек, а интегральный поток тепловых нейтронов не превышает 10^{16} н/см², не оказывает существенное влияние на рабочие характеристики использованных термисторов.

3. Определялось распределение поглощенной дозы. С той целью проведены измерения на 3 материалов: вода, тяжелая вода и графит.

4. Измерения проводились в двух вертикальных экспериментальных каналах реактора РА: и „ВК-5“ и „ВК-9“ на различных высотах. Обнаружено, что кривая распределения поглощенной дозы по высоте в достаточной мере совпадает с кривой распределения теплового потока, хотя отношения поглощенных доз в двух назначенных каналов не совпадают с соответствующими отношениями тепловых потоков.

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V.Marković i B.Radak:

DIFERENCIJALNI KALORIMETAR ZA DOZIMETRIJU
REAKTORSKOG ZRAČENJA

I. Uvod. Dozimetrija zračenja u vertikalnim eksperimentalnim kanalima reaktora RA izvedena je do sada hemijskim dozimetrima (ferosulfat i oksalna kiselina) (1) i izotermским kalorimetrom (2). Dobivena je slika raspodele apsorbovanih doza u jezgru reaktora i grafitnom reflektoru, a na osnovu kalorimetrijskih merenja i približna kontribucija brzih neutrona i gama zračenja u totalno apsorbovanim dozama. Na osnovu ovoga izračunate su G vrednosti za oksalnu kiselinu (3,98) i ferosulfatni dozimetar (13,6), a prva vrednost i eksperimentalno proverena (4,30).

Sa izotermским kalorimetrom merenja su izvedena na nižim snagama reaktora (20 kW), a dobivene vrednosti preračunate na snagu od 1 MW. Pretpostavka o proporcionalnosti brzine apsorbovane doze sa snagom reaktora proverena je jednim merenjem na 80 kW i dobivena je zadovoljavajuća saglasnost. Međutim hemijski eksperimenti (sa oksalnom kiselinom napr.) izvođe se na mnogo višim snagama reaktora (0,5-1 MW) pa je direktno merenje apsorbovanih doza i raspodele pod tim uslovima poželjnije nego bilo kakav proračun. Ovo je poželjno i zbog toga što je prema hemijskim merenjima kriva raspodele na višim snagama nešto drukčija, zbog pomeranja maksimuma neutronskog fluksa prema gornjem kraju aktivne zone.

Za ova merenja konstruisan je i ispitan diferencijalni kalorimetar sa opsegom merenja koji odgovara snagama reaktora od 0,5 do 1 MW (na mestu maksimalnog neutronskog fluksa).

II. Opis metode merenja.

II.1. Osetljivost kalorimetarskog sistema.

Ako temperatura okoline kalorimetarskog tela (T_0) ostaje nepromenjena u toku merenja a telo se zagreva konstantnom snagom (w), onda je ravnotežna razlika temperature tela i okoline $\Delta T = T - T_0$ proporcionalna snazi zagrevanja (w):

$$\Delta T = \alpha \cdot w \quad \dots\dots\dots (1)$$

gde je faktor proporcionalnosti (α) dat u $^{\circ}\text{C}/\text{watt}$ i predstavlja ustvari osetljivost datog sistema. Faktor (α) odredjen je odnosom:

$$\alpha = \frac{1}{Kmc} \quad \dots\dots\dots (2)$$

gde je (K) konstanta hlađenja, A (mc) toplotni kapacitet uzorka. Ili:

$$\alpha = \frac{1}{P \cdot \sum_i h_i} \quad \dots\dots\dots (3)$$

Gde je (P) površina tela u cm^2 , a $\sum_i h_i$ faktor koji zavisi od toplotne izolacije tela od njegove okoline.

Prema izrazu (3) osetljivost jednog kalorimetarskog sistema zavisi samo od odnosa površina tela i načina na koji je ono izolovano od svoje okoline. To praktično znači da uzorci od različitih materijala i sa različitim toplotnim kapacitetima mogu imati isti faktor proporcionalnosti između snage zagrevanja i ravnotežne temperaturske razlike (ΔT).

II.2. Metoda merenja. Uzećemo dva tela od različitih materijala ili dva tela od istog materijala a različite mase, naprimer šuplje telo od aluminijuma i drugo telo od punog aluminijuma. Snage zagrevanja po

gramu materijala pri radu reaktora na odredjenoj snazi jednake su za oba uzorka. Neka je m_1 masa praznog tela a m_2 masa punog tela. Snaga zagrevanja u praznom telu je $m_1 w$ a u punom telu $m_2 w$ (w =snaga zagrevanja u watt /gr aluminijuma). Odgovarajuće ravnotežne temperaturske razlike su:

$$\Delta T_1 = \alpha_1 (m_1 w)$$

$$\Delta T_2 = \alpha_2 (m_2 w) \dots\dots\dots (4)$$

Ako su oba tela jednakog oblika (iste površine) i termički izolovana na isti način onda je $\alpha_1 = \alpha_2 = \alpha$. Zatim, ako su okoline oba tela na istoj temperaturi, razlika temperature između ova dva tela je:

$$\Delta T_{1/2} = \alpha (m_2 w - m_1 w)$$

ili

$$\Delta T_{1/2} = \alpha (m_0 w) \dots\dots\dots (5)$$

gde je $m_0 = m_2 - m_1$

Razlika temperatura oba tela proporcionalna je snazi zagrevanja u masi m_0 . Pošto znamo faktor proporcionalnosti (α)- prethodno odredjen kalibracijom električnim putem- i pošto znamo razliku masa m_0 , pomoću izraza (5) možemo izračunati nepoznatu snagu zagrevanja po gramu aluminijuma (w). Slično imamo i kada je šupljina u aluminijumu ispunjena nekim drugim materijalom. Ovde je razlika temperature između punog i praznog tela:

$$\Delta T_{1/2} = \alpha [m_1 w_1 + m_0 w_0] - \alpha (m_1 w_1)$$

$$\Delta T_{1/2} = \alpha (m_0 w_0) \dots\dots\dots (6)$$

gde su m_0 - masa uzorka u aluminijumu
 w_0 - snaga zagrevanja po gramu materijala α
uzorka
 m_1 - masa praznog suda od aluminijuma
 w_1 - snaga zagrevanja po gramu aluminijuma.

Pod uslovom da su mase oba aluminijumska suda (puno - i prazno) jednake, snaga zagrevanja (w_0) izračunava se iz izraza (6).

III. Opis kalorimetra. Na slici 1. data je šema konstrukcije kalorimetra (horizontalni presek). Kalorimetarska tela (A) su: prazno telo od aluminijuma ($m_1=4,61$ gr), isto takvo telo od aluminijuma sa uzorkom od grafita ($m_0=3,42$ gr) i puno telo od aluminijuma ($m_2=10,23$ gr). Sa ovakvom kombinacijom merimo istovremeno snage zagrevanja (brzinu apsorbovane doze) u grafitu i aluminijumu. Ispunjavanjem šupljine u aluminijumu drugim uzorcima, možemo meriti snagu zagrevanja u bilo kom materijalu koji nas interesuje.

Sva tela su jednakih dimenzija: visina 50 mm i spoljašnji prečnik 10 mm. Na površini tela urezana su dva uzdužna kanala za smeštaj termoelemenata (bakar-konstantan). Položaj termoelemenata i kalibracionih grejača prikazani su na slici 2.

Težina kalibracionog grejača i termoelementa na telu iznosi oko 0,1 gr. Pošto se približno iste mase nalaze na svim telima ovo ne utiče na temperaturske razlike između pojedinih tela.

Kalorimetarska tela centrirana su u okolini od aluminijuma (2 mm) (B). Za toplotnu izolaciju i u isto vreme za centriranje upotrebljena je pena od polistirola (C) specifične težine oko 15 mg/cm^3 . Doprinos stiropora zagrevanju podjednak je za sva tela i nema uticaja na temperaturske razlike. Tri aluminijumska suda (B)-okoline kalorimetarskih tela- smeštena su u zaštitni sud (D) od tankog aluminijskog lima

(2 mm). Svi delovi se nalaze u tesnom medjusobnom kontaktu. Ceo kalorimetar je napravljen od nuklearno čistog materijala: grafit i aluminijum 99,99%.

Spoljašnji prečnik zaštitnog suda (D) podešen je tako da rastojanje izmedju površine suda i zidova eksperimentalnih kanala bude oko 1 mm i time odvoda toplote zbog velike površine i malog rastojanja spreči veliko zagrevanje aluminijuma.

Na slici 3. prikazan je vertikalni presek celog kalorimetra u eksperimentalnom kanalu reaktora.

IV. Ispitivanje konstrukcije.

IV.1. Termoelementi. Temperaturske razlike merili smo termoelementima bakar-konstantan (0,1 mm) sa $\Delta V \approx 40 \mu V/^{\circ}C$. Zbog velikog preseka za apsorpciju termalnih neutrona u boru standardni način zavarivanja bakra i konstantana u boraksu zamenjen je zavarivanjem u kalofonijumu. Ovako dobiveni termospoj je podjednako dobar kao i onaj dobiven sa boraksom što su pokazala i uporedna merenja sa oba termoelementa.

IV.2. Merenje EMS termoelemenata. Za merenje termoelektromotorne sile sastavljen je potencijometar sa opsegom merenja od 0-10 mV i greškom od $\pm 1 \mu V$ za relativna merenja. Potencijometar je šematski prikazan na slici 4. EMS termoelemenata kompenzuje se preko osetljivog galvanometra (G_1). Poznatim padom potencijala na standardnom promenljivom otporu (R_4). Pomoću promenljivog otpora (R_1), etalona (E_2)- Westonov element- i galvanometra (G_2) struja kroz otpornik (R_2) od 10 oma održava se stalno na 1 mA. Ovo na krajevima ovoga otpora stvara pad napona od 10 mV. Ako se promenljivi otpori (R_4) i (R_5) podešavaju tako da stalno bude $R_4 + R_5 = 10.000$ oma, na svakom omu otpora R_4 imamo pad napona od $1 \mu V$.

Svi otpori u potencionometru su klase 0,02. Tipične vrednosti otpora i EMS pokazane su na slici 4. U ovom slučaju na otporu R_4 imamo **pad napona 200 μ V.**

Medjutim i pored velike osetljivosti i opsega merenja ovaj potencionetar je nepraktičan za izvođenje više istovremenih merenja. Zato je kasnije za direktno merenje EMS termoelemenata upotrebljen višekanalni rekorder MECI sa opsegom od 2 mV na punoj skali.

IV.3. Kalibracioni dijagrami. Zavisnost definisana jednačinom (1) poverena je zagrevanjem kalorimetarskih tela sa nekoliko poznatih snaga zagrevanja (w). Ako se dobivene (ΔT) nanose na dijagram u funkciji snage zagrevanja (w), onda nagib krive prema apscisi određuje osetljivost sistema (α).

Prethodna ispitivanja u laboratoriji bila su usmerena na potvrđivanje pretpostavke u II.1. po kojoj osetljivost kalorimetarskog sistema ne zavisi od prirode i toplotnog kapaciteta kalorimetarskog tela. Stoga su određivane vrednosti (α) za sisteme sa raznim masama, dobre toplotne provodljivosti (tela od aluminijuma prazna i puna) i loše toplotne provodljivosti (tela od pleksi stakla prazna i napunjena vodom). Pravoliniska zavisnost prema jedan l. potvrđena je u svim slučajevima (do maksimalnog $\Delta T \approx 40^\circ \text{C}$). Na još većim temperaturnim razlikama ($40-50^\circ \text{C}$) primećeno je zakrivljenje prema apscisi, koje nigde ne prelazi 2-3% od srednjeg nagiba kalibracione krive. (jedan primer takvog dijagrama prikazan je na slici 17. u V.).

Medjutim pretpostavka iz II.1. potvrđena je samo kod kalorimetarskog tela od aluminijuma, dok u drugom slučaju (pleksi i H_2O) važi samo za jedan određen položaj termoelementa na površini tela.

Ovo se može objasniti postojanjem temperaturnog gradijenta u samom telu usled nejednakog odvo-

djenja toplote sa površine. Gradijent je znatnije izražen kod tela koja su loši provodnici toplote, a gotovo je neznatan kod tela koja su dobri provodnici toplote. (v.sledeći odeljak).

U Tabeli I. date su neke vrednosti (α) u $\mu\text{W}/\text{mWatt}$ za tela od aluminijuma i pleksi stakla. (Sve vrednosti odnose se na položaj termoelementa 2,5 cm od dna, na površini tela).

TABELA I.

	aluminijum	pleksi, gre- l mm od vert. ose tela	pleksi, gre- jač 4 mm od vert. ose tela
prazno	3,89	4,71	4,65
puno	3,88	4,66	4,38

IV.4. Temperaturski gradijenti u telu.

Temperaturski gradijenti u telu odredjeni su merenjem temperature za 4 različita položaja termoelementa na površini kalorimetarskog tela. Dobivene vrednosti za prazan aluminijum, pun aluminijum, prazan pleksi i pleksi napunjen vodom date su na dijagramima slika 5.

Sa dijagrama (b) vidimo da postavljanjem termoelemenata na oko 1 cm od gornjeg kraja osetljivost ostaje ista bilo da je telo puno ili prazno. Kod aluminijuma koji je dobar provodnik toplote temperaturski gradijent je mali i položaj termoelementa nema takvog značaja kao u prvom slučaju.

Problem kalibracionog grejača. Kao posledica svega ovoga postavlja se pitanje da li položaj kalibracionog grejača (4 mm od vertikalne ose kalorimetarskog tela) i ovakva kalibracija mogu da se upoređuju sa homogenim razvijanjem toplote kakvo imamo pri apsorpciji zračenja u reaktoru. Zato je sve ovo ponovljeno sa drugim telom od pleksi stakla u kome je grejač namotan na 1 mm od vertikalne ose. Temperaturni gradijenti u dva ovakva tela dati su na slici 6.

Kao što vidimo dobivena raspodela temperature je veoma slična onoj na slici 5. (dijagram b) samo što su obe krive (za puno i prazno telo) pomerene ulevo. U maksimumu krivih odstupanja je 2-6% a u tačkama preseka (3 cm od dna) 2-12%, što znači da nam bilo jedan bilo drugi položaj kalibracionog grejača omogućuje poređenje sa homogenim razvijanjem toplote, sa greškom koja nije veća od 10%. Međutim i pored toga očigledno je da su aluminijumska tela, kod kojih je sve to izraženo u mnogo manjoj meri, mnogo prikladnija za izradu kalorimetarskih tela.

IV.5. Zaključak o ispitivanju konstrukcije kalorimetra. Na osnovu prethodnih ispitivanja (IV.3 i IV.4. možemo zaključiti da se:

- metoda merenja opisana u II.2. može primeniti na konstrukciju kalorimetra (v.III)

- može podesiti da osetljivost dva razna kalorimetarska tela prazno i puno (bilo da su od aluminijuma ili nekog slabijeg provodnika toplote) mogu, podesnim položajem termoelemenata podesiti da budu jednake među sobom.

V. Merenje na reaktoru. Konstrukcija kalorimetra je isprobana na reaktoru i izmerene su snage zagrevanja u uzorcima od aluminijuma i grafita. Merenja su vršena na nekoliko raznih snaga reaktora od 400-800 kW, a dobivene vrednosti ekstrapolisane su na 1 MW i upoređene sa ranijim merenjima izotermnim kalorimetrom (2).

Na osnovu kalibracionog dijagrama (slika 7) određene su osetljivosti za sva tri kalorimetarska tela: prazan aluminijum $\alpha_1 = 4,00 \mu\text{V/mW}$, pun aluminijum $\alpha_2 = 3,87 \mu\text{V/mW}$ i aluminijum napunjen grafitom $\alpha_3 = 4,01 \mu\text{V/mW}$.

Razlika od 3% između α_1 i α_2 uslovljava u izmerenim vrednostima za snagu zagrevanja po gramu aluminijuma grešku

$$\delta = \frac{m_1}{m_0} \cdot \frac{(\alpha_2 - \alpha_1) \cdot 100}{\alpha_2}$$

gde se (m_1) masa praznog tela a (m_0) razlika u masama praznog i punog tela. Ova greška je zbog odnosa $m_1/m_0 < 1$, ~~#~~ manja od 3% i može se izvršiti korekcija.

Rezultati merenja na raznim snagama dati su na dijagramu (slika 8).

Srednje vrednosti rezultata ekstrapolisanih na 1MW su:

u aluminijumu $(65,7 \pm 0,9) \text{ mW/gr}$

u grafitu $(52,5 \pm 0,6) \text{ mW/gr}$

sa odstupanjem od srednje vrednosti $\pm 1,3\%$ za aluminijum i $1,1\%$ za grafit.

Korekcija za indukovanu aktivnost u okolini od aluminijuma iznosi približno 2% za oba uzorka, a korekcija za indukovanu aktivnost u uzorku od aluminijuma oko 14%. Sa oduzetim korekcijama totalne snage zagrevanja u oba uzorka su:

u aluminijumu: $55,2 \text{ mW/gr}$

u grafitu : $51,5 \text{ mW/gr}$

Na osnovu radijnih merenja u grafitu je dobiveno[†] $52,2 \text{ mW/gr}$ a u aluminijumu $51,5 \text{ mW/gr}$ pa je slaganje vrednosti izmerenih sa dva različita kalorimetra i na raznim snagama reaktora zadovoljavajuće.

[†]Sve vrednosti se odnose na položaj maksimalnog neutronskog fluksa u centralnom kanalu reaktora VK-5.

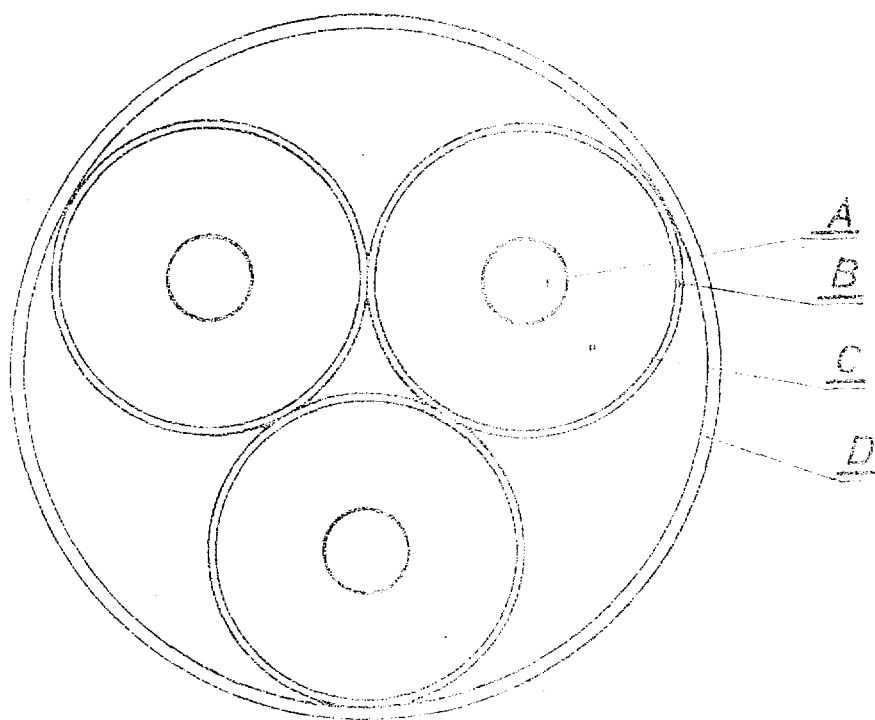
Ovo slaganje opravdava ekstrapolaciju sa nižih snaga koja je ranije izvedena (2), što uostalom potvrđuje i hemijska merenja na istom tom položaju u eksperimentalnom kanalu gde je konstrukcija isprobana: Ovo slaganje se moglo i očekivati pošto se položaj maksimuma veoma malo menja pri radu reaktora na raznim snagama.

Rezultati probnih merenja sa diferencijalnim kalorimetrom pokazuju da se on može upotrebiti za direktna merenja na visokim snagama reaktora, što je i bila svrha ovoga zadatka.

Reference:

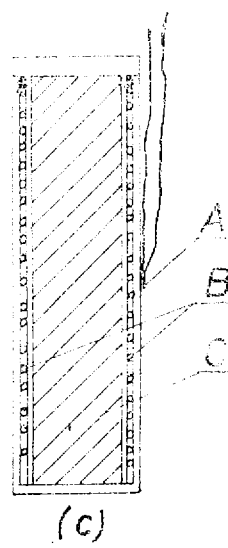
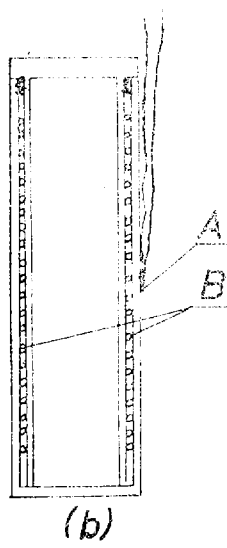
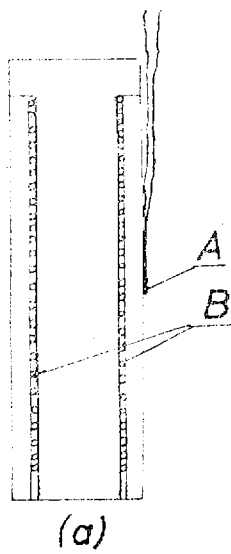
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"Boris Kidrič", Beograd (u štampi).
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Beograd, 12, 7, (1961).

Slika 1.
Šema konstrukcije kalorimetra
(horizontalni presek)



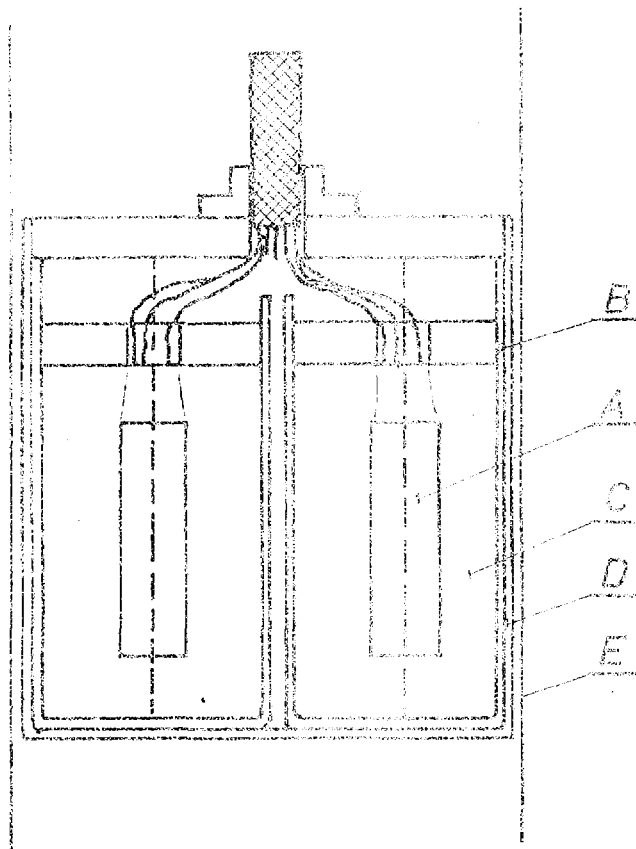
Slika 2.

Kalorimetarska tela: (a) - pun aluminijum, (b) - prazan aluminijum, (c) - aluminijum sa grafitom. (A-termoelementi, B-kalibracioni grejači, C-uzorak od grafita).

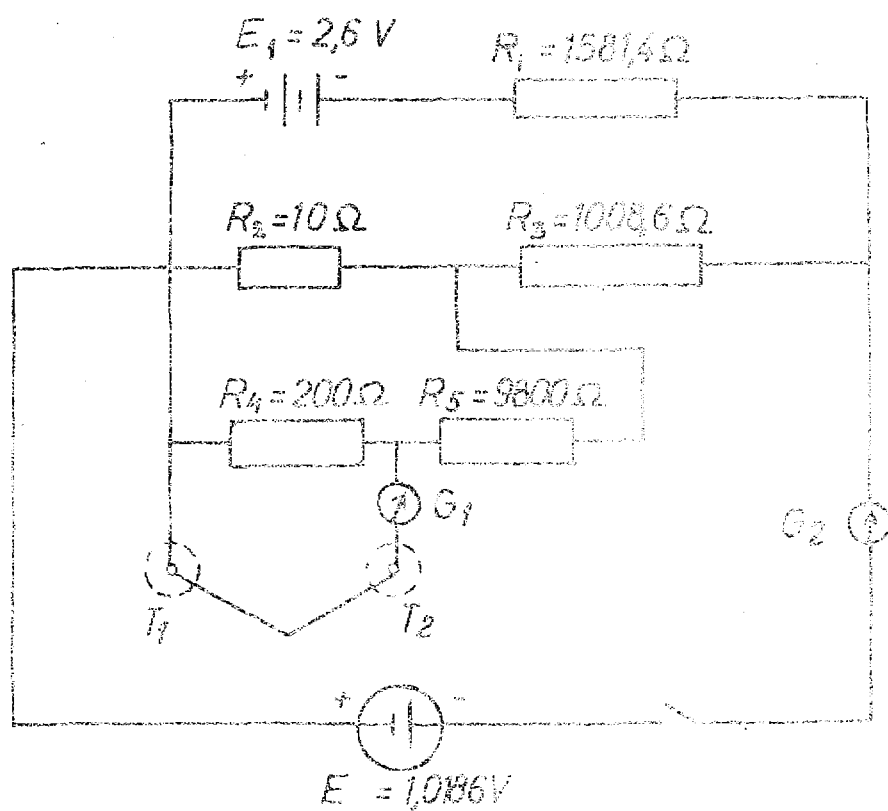


Slika 3.

Vertikalni presek kalorimetra (A-kalorimetarsko telo, B-okolina kalorimetarskog tela, C-stirpor, D-zaštitni sud, E-zid eksperimentalnog kanala).

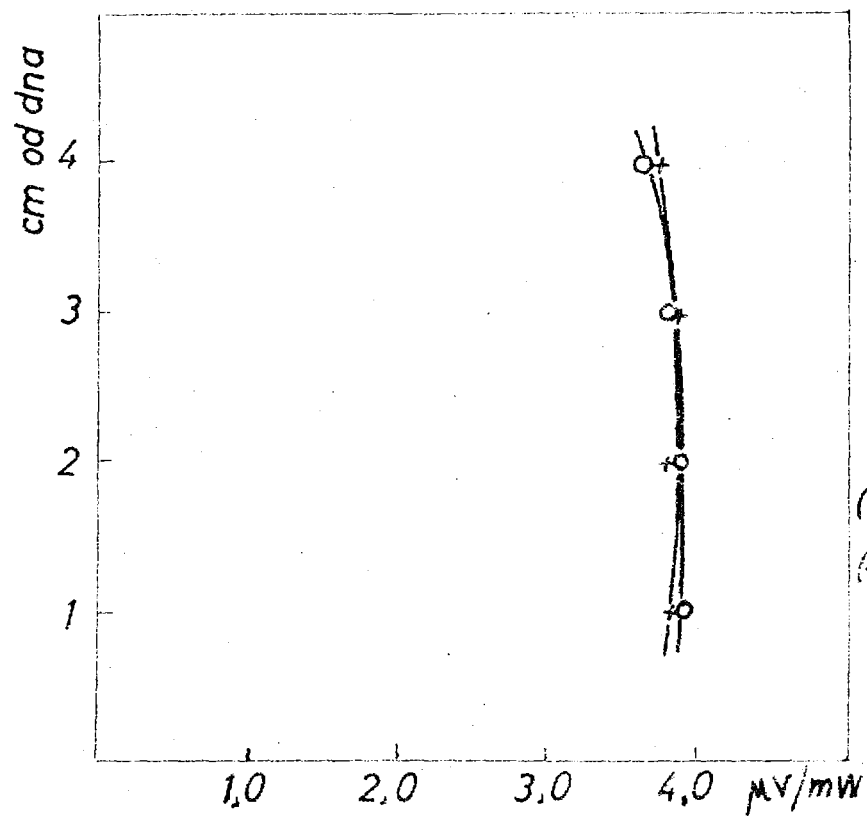


Slika 4.
Šema potenciometra.

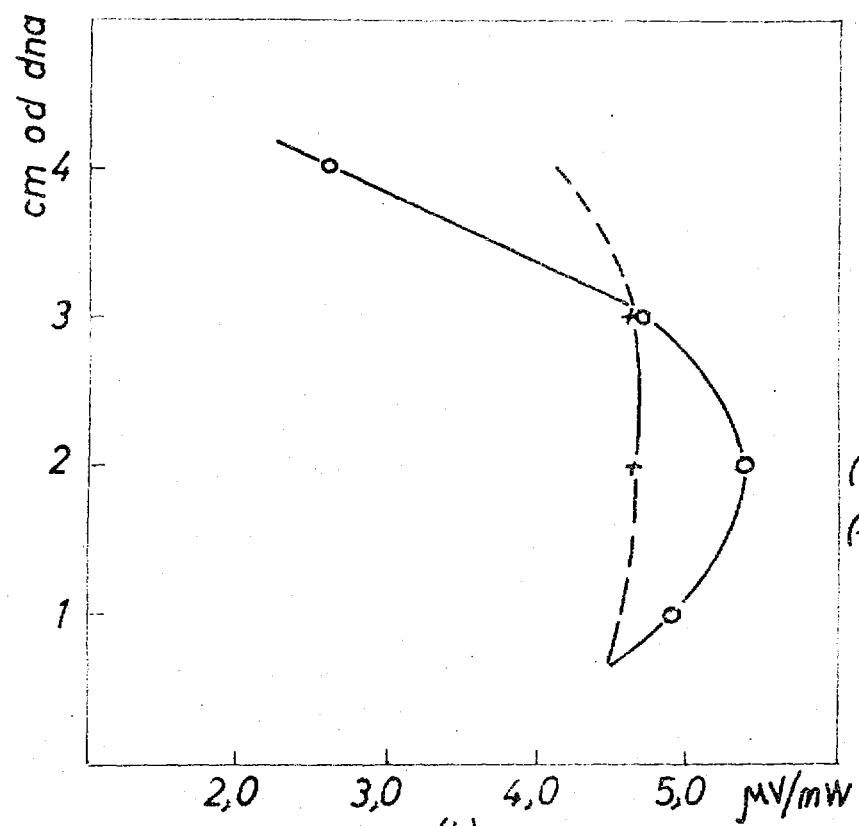


Slika 5.

Temperaturski gradijenti u telu:
(a) aluminijum, (b) pleksi staklo i voda.

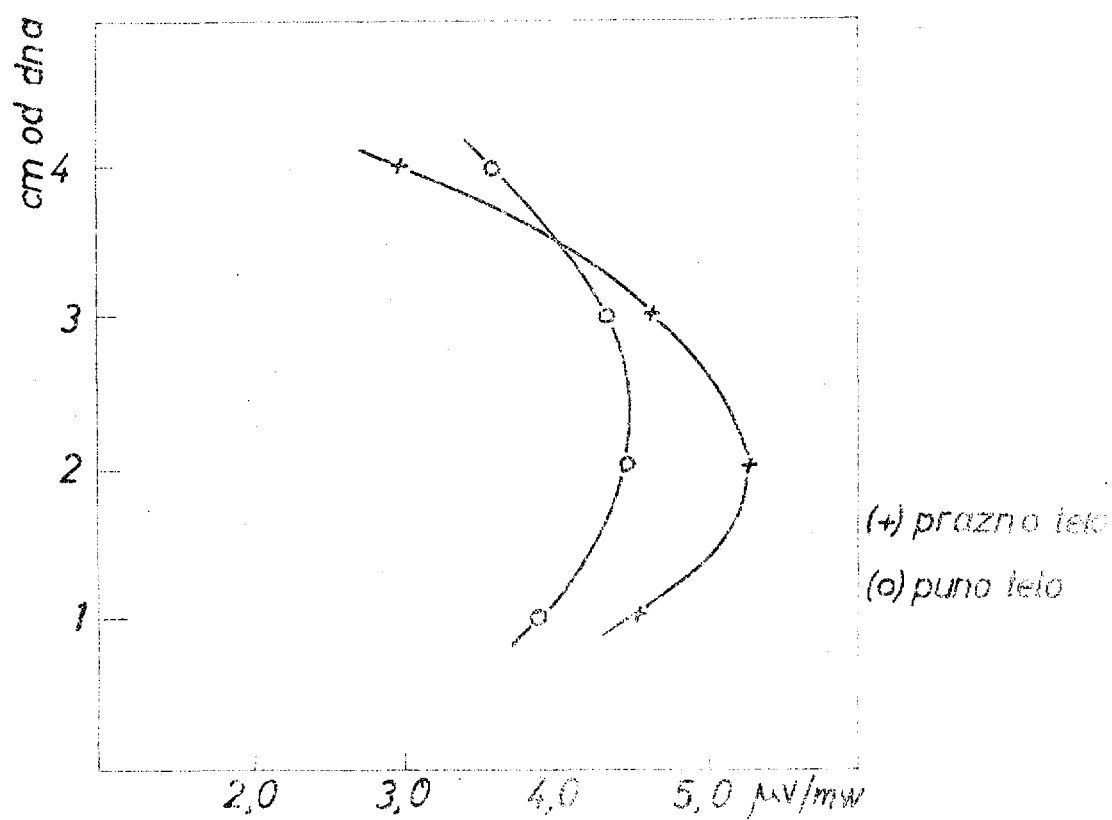
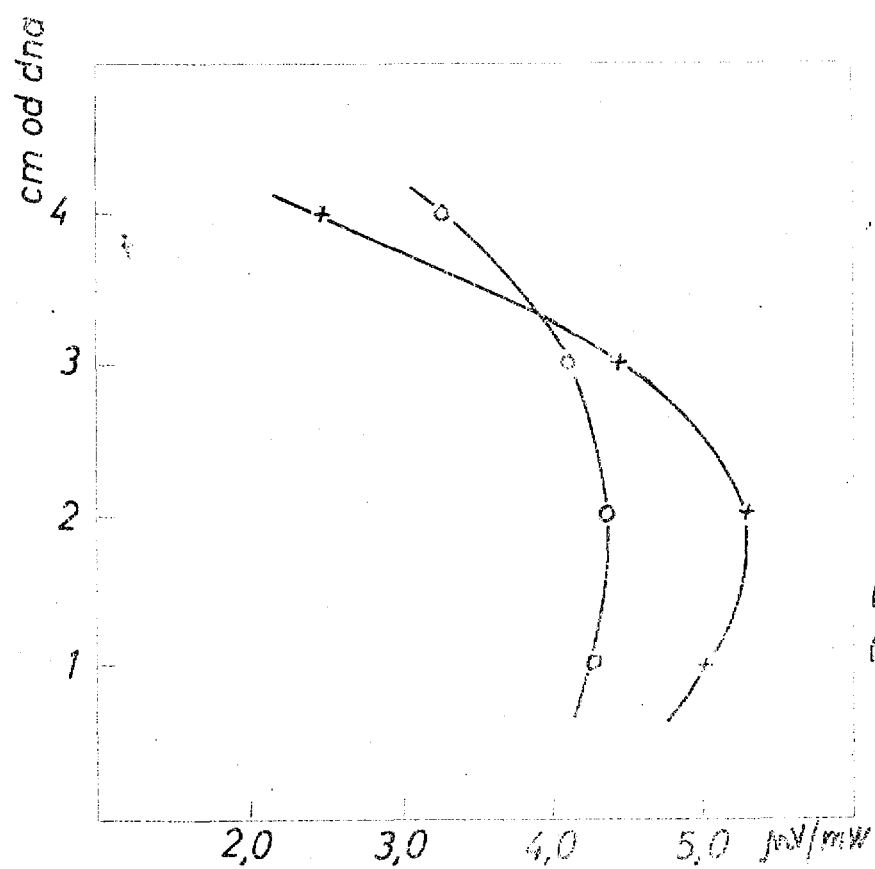


(a)

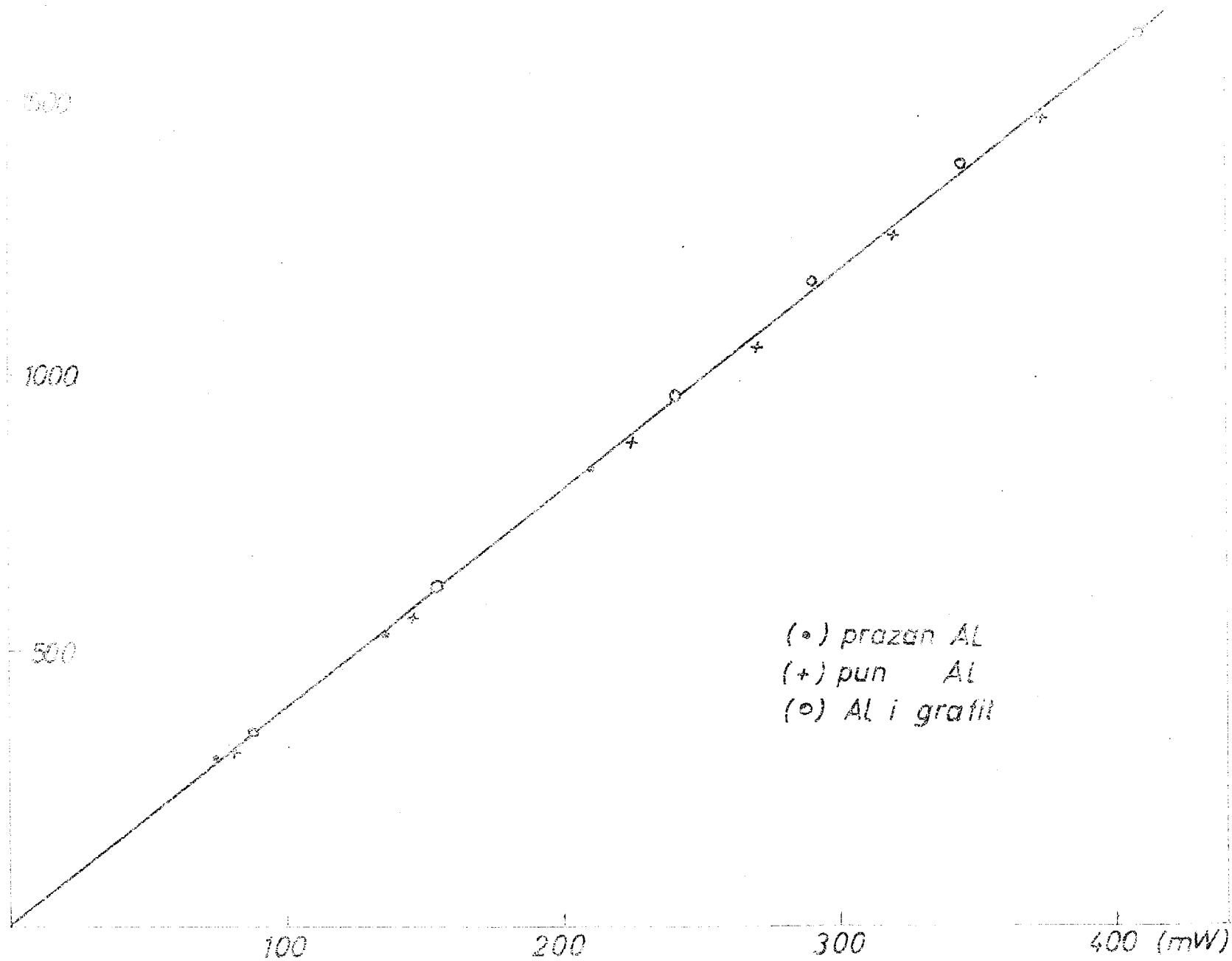


(b)

Slika 6.
Temperaturski gradijenti u telima od
pleksi stakla.



Slika 7.
Kalibracioni dijagram.



Slika 8.
Rezultati merenja na raznim snaga reaktora.

(MW/g)

80

70

60

50

40

30

20

10

⊙ ALUMINIUM

△ GRAFIT

