CNIC-0745
IAE-0118

镉比R_{Cd}和热中子通量测量数据处理的标准化基础

A BASE TO STANDARDIZE DATA PROCESS OF CADMIUM RATIO R_{Cd} AND THERMAL NEUTRON FLUX MEASUREMENTS ON REACTOR

原子能出版社

中国核情报中心
China Nuclear Information Centre

李兆桓：中国原子能科学研究院研究员。1955年毕业于上海交通大学机械制造系，1958年于莫斯科动力学院核电专业研究生毕业。

Li Zhaohuan: Professor of China Institute of Atomic Energy. Graduated from Department of Machine Building, Shanghai Jiaotong University in 1955 and graduated from Energy Institute of Moscow in Nuclear Power Plant as a postgraduate in 1958.

CNIC-00755
IAE-0118

镉比 R_{Cd}和热中子通量测量数据处理的标准化基础

李兆桓

（中国原子能科学研究院，北京）

摘　要

镉比 R_{Cd}和热中子通量是堆内常测的参数。但它们的数据处理却相当复杂，对同一测量数据采用现有不同的方法得的结果是不同的。为了建立 R_{Cd}和热中子通量测量的标准化基础，一个自然选择是在标准的平均热中子活化截面和共振积分的基础上导出 R_{Cd}公式和定义有关参数因子，作为实验室间测量的唯一比较基础。参数包括：在热能区的有 E_c，F_m、F'_m 和 G_{th}，它们是由 Maxwell 谱截去上端引起的；在中能区的有 E_{Cd}、F_{Cd}，G_r 和 S_r。它们都是多变量的函数。以金片为例，选择图表显示它们的特性，亦为手动处理提供实用数据。还讨论了称为适用区和最佳区问题，指出在常用的探测材料（如 An，In，Mn，W 和 Co 等）中，Co 和 Mn 片的适用区较宽。

ING

A BASE TO STANDARDIZE DATA PROCESS OF CADMIUM RATIO R_{Cd} AND THERMAL NEUTRON FLUX MEASUREMENTS ON REACTOR

Li Zhaohuan

(CHINA INSTITUTE OF ATOMIC ENERGY, BEIJING)

ABSTRACT

The cadmium ratio R_{Cd} and thermal neutron flux are usually measured in a reactor. But its data process is rather complex. The results from same measured data differ by different existing process methods. The purpose of this work is to standardize data process in R_{Cd} and thermal neutron flux measures. A natural choice for this purpose is to derive a R_{Cd} formula based on standard average thermal activation cross section and resonance integral and to define related parameters or factors that provide an unique base for comparison between different measures in laboratories. These parameters or factors include E_t, F_m, F_m' and G_{th}' in thermal energy region due to upper truncated Maxwellian distribution and E_{Cd}, F_{Cd}, G_r' and S_r in intermediate energy region. They are the function of muitiple variables. The Au foil is used as an example to demonstrate their behaviors by chosen figures and tables which provide for practical data process by hand. The work also discusses limitation of R_{Cd} measurement in terms of so called available and optimum region and notes that Co and Mn foils have a much wider available region among Au, In, Mn, W and Co, the commonly used detector foils.

INTRODUCTION

The cadmium ratio R_{Cd} measurement is one of the most common measurements in thermal neutron reactors. The main goal of R_{Cd} measurement is to determine the thermal neutron flux and the hardness of intermediate neutron flux spectrum. Sometimes the spectrum hardness is often expressed by the measured R_{Cd} itself. For low power and zero power reactors the power calibration also requires the measured R_{Cd} data.

The data process of R_{Cd} measurement for obtaining the thermal neutron flux and intermediate spectrum hardness is a rather complicated work. Until now many widely used methods (Refs. 1～5) are approximate. The results from same measured data differ by different existing process methods. The purpose of this work is to standardize data process of R_{Cd} and thermal neutron flux measures. A natural choice for this purpose is to derive a R_{Cd} formula based on standard average thermal activation cross section and resonance integral and to define clearly related parameters or factors that can obtain the exact result and provide an unique base for comparison between different measures by different laboratories. At same time it provides the necessary data for such process by hand. Besides the work also discusses limitation of R_{Cd} measurement in terms of so called available and optimum region and notes that Co and Mn foils have a wider available region among Au, In, Mn, W and Co, the detector foils used commonly. Beyond this region it is difficult to obtain the exact result.

It is well known that the thermal neutron spectrum in a thermal reactor is not a complete Maxwell distribution but a truncated one. It can be found in the classical description. In Weinberg-Wigner's textbook (Ref. 6) the upper energy of thermal neutron was defined as such energy above which neutron moderation obeys the standard moderation model. Galanin called it the joint energy E_r (Ref. 7). This means that thermal neutron spectrum in a thermal neutron reactor only extends to E_r, beyond this energy neutrons are intermediate neutrons. However, the thermal neutron flux and the average cross section are always based on the complete Maxwell spectrum (Refs. 8, 9). The parameters derived from the complete and the truncate spectrum are obviously different. It causes to introduce the correction factors of F_m, F_m' and G_{th}' in this work.

In the following the first section introduces a general neutron flux spectrum as the base of discussion. The second section derives a R_{Cd} formula and defines related parameters or factors. The third section estimates and demonstrates behaviors of these parameters or factors by the selected curves and tables which are also provided for practical data process by hand. The fourth section discusses the available region of R_{Cd} measurement.

1 The General Expression of Neutron Flux Spectrum

In a thermal neutron reactor the neutron flux spectrum is generally expressed in the following

$$\phi(E)dE = \phi_{th}(E)dE + \phi_{int}(E)dE + \phi_{f}(E)dE \tag{1}$$

where th, int and f denote thermal, intermediate and fast neutron, respectively. Commonly, the thermal neutron flux is expressed by the complete and normalized Maxwellian spectrum.

$$\Phi_{th} = \int_0^\infty \phi_{th}(E)dE = \Phi_{th}\int_0^\infty \left(\frac{E}{(kT_n)^2}\exp\left(-\frac{E}{kT_n}\right)dE\right) \tag{2}$$

where k is the Boltzmann constant, T_n is the neutron temperature. The integral on right side is normalized. In fact, the thermal neutron flux in a reactor is an upper truncated Maxwellian distribution. The truncated energy is E_c, the joint energy between thermal and intermediate neutron fluxes. It is determined by the equation

$$\frac{E_c}{(kT_n)^2}exp\left(-\frac{E_c}{kT_n}\right) = \beta\delta(E_c)\frac{1}{E_c^{1+\alpha}} \tag{3}$$

Symbols introduced in above equation will be explained later. Let us first introduce the truncated Maxwellian flux correction factor F_m' which is defined as

$$F_m' = \int_0^{E_c} \phi_{th}(E)dE \Big/ \int_0^\infty \phi_{th}(E)dE \tag{4}$$

Similarly, the truncated Maxwell spectrum activation rate correction factor F_m is defined as

$$F_m = \int_0^{E_c} \sigma_{act}(E)\phi_{th}(E)dE \Big/ \int_0^\infty \sigma_{act}(E)\phi_{th}(E)dE \tag{5}$$

For commonly used detectors the activation cross section in the thermal energy region obeys the $1/v$-law well. The above equation can be approximated by the thermal neutron density n_{th} as

$$F_m = \int_0^{E_c} n_{th}(E)dE \Big/ \int_0^\infty n_{th}(E)dE \tag{5a}$$

The intermediate neutron flux spectrum is described by Fermi spectrum. For the experiment Fermi spectrum is usually modified by

$$\phi_{epi}(E)\mathrm{d}E=\frac{\theta\delta(E)\mathrm{d}E}{E^{1+\alpha}} \tag{6}$$

Where the α is the correction index of derivation from Fermi spectrum, the θ is intermediate neutron flux in unit lethargy, $\delta(E)$ is the joint function of intermediate flux. A typical expression of which (Ref. 10) is

$$\delta(E)=\begin{cases}0 & \text{when } E<E_c, \\ 1+1.6(\frac{E}{kT_n}-5.0)\exp(-\frac{E}{3.05kT_n}) & \text{when } E\geqslant E_c\end{cases} \tag{7}$$

The fast neutron flux plays a small role in R_{Cd} measurement, it can expressed by a form of fission spectrum, for example the fission spectrum described in Ref. 11.

Thus the general expression of neutron flux spectrum in a thermal neutron reactor is

$$\phi(E)\mathrm{d}E=\Phi_{th}[\frac{E}{(kT_n)^2}\exp(-\frac{E}{kT_n})+\beta\frac{\delta(E)}{E^{1+\alpha}}+f_f(E)]\mathrm{d}E \tag{8}$$

Where the β is the hardness of intermediate neutron flux spectrum.

2 R_{Cd} FORMULA AND RELATED PARAMETERS

The procedure of R_{Cd} measurement is often processed by use of same detector foil irradiated in bare and in cadmium cover respectively, and then to measure its reaction ratio. Assume that detector foil thickness is t, the cadmium cover thickness is t_{Cd}, the cadmium ratio is defined as follows

$$R_{Cd}=\frac{\text{bare foil reaction rate}}{\text{cadmium covered foil reaction rate}}=\frac{\int_0^\infty G(t)\sigma_{act}(E)\phi(E)\mathrm{d}E}{\int_0^\infty G(t,t_{Cd})\sigma_{act}(E)\phi(E)\mathrm{d}E} \tag{9}$$

If the foil is irradiated in an empty, then $G(t)$ and $G(t,t_{Cd})$ are the neutron flux self-shielding factors of bare foil and Cd covered foil, respectively. The neutron scattering effect including the resonance scattering should be considered during the calculation of self-shielding factors (Ref. 12).

Usually, the definition of cadmium cut-off energy E_{Cd} is that the reaction rate of cadmium covered foil equals to the reaction rate of bare foil induced by those neutrons, the energy of that is above E_{Cd}. That is

$$\int_{0}^{\infty} G(t,t_{Cd})\sigma_{act}(E)\phi(E)\mathrm{d}E = \int_{E_{Cd}}^{\infty} G(t)\sigma_{act}(t)\phi(E)\mathrm{d}E \tag{10}$$

The reasonableness of this idea will be discussed later. The equation (9) can be rewritten in the following form

$$R_{Cd} = \frac{\int_{0}^{E_c} G(t)\sigma_{act}(E)\phi_{th}(E)dE + \int_{E_c}^{\infty} G(t)\sigma_{act}(E)\phi_{int,f}(E)dE}{\int_{E_{Cd}}^{\infty} G(t)\sigma_{act}(E)\phi_{int,f}(E)dE} \tag{11}$$

Where the $\phi_{int,f}(E)$ is a written form of a combination of the intermediate and fast neutron flux. The difference between the second term in the numerator and denominator in equation (11) is only the low limit of integral. Let us define

$$F_{Cd} = \frac{\int_{E_c}^{\infty} G(t)\sigma_{act}(E)\phi_{int,f}(E)\mathrm{d}E}{\int_{E_{Cd}}^{\infty} G(t)\sigma_{act}(E)\phi_{int,f}(E)\mathrm{d}E} \tag{12}$$

The physical meanings of $F_{Cd} - 1$ is a ratio of reaction rate in neutron energy interval from E_c to E_{Cd} to the Cd covered foil reaction rate.

The base for standardization of data process of R_{Cd} and thermal neutron flux measures is to derive R_{Cd} formula on standard resonance integral and complete Maxwellian spectrum average activation cross section which are always given in literatures (for example, Refs. 8, 9). The standard resonance integral is defined (Ref. 9) on the standard Fermi spectrum and with a definitive initial energy (0.5 eV or 0.55 eV, here the 0.55 eV is used) as

$$I_s = \int_{0.55\,\mathrm{eV}}^{\infty} \sigma_{act}(E)\frac{\mathrm{d}E}{E} \tag{13}$$

In order to make R_{Cd} formula based on these standard cross sections let us introduce the following definitions. In the thermal energy region let us define

$$G_{th}{}' = \int_{0}^{E_c} G(t)\sigma_{act}(E)\phi_{th}(E)\mathrm{d}E \Big/ \int_{0}^{E_c} \sigma_{act}(E)\phi_{th}(E)\mathrm{d}E \tag{14}$$

The $G_{th}{}'$ differs from self-shielding factor G_{th} normally used in literatures which is defined by

$$G_{th} = \int_{0}^{\infty} G(t)\sigma_{act}(E)\phi_{th}(E)\mathrm{d}E \Big/ \int_{0}^{\infty} \sigma_{act}(E)\phi_{th}(E)\mathrm{d}E \tag{14a}$$

From equations (5) and (14) the first term in numerator of equation (11) is $G_{th}'F_m\bar{\sigma}_{act}\Phi_{th}$. In intermediate energy region G_r' and S_r are defined in the following, respectively. The super cadmium self-shielding factor G_r' is

$$G_r'=\int_{E_{Cd}}^{\infty}G(t)\sigma_{act}(E)\phi_{epi}\cdot f(E)\mathrm{d}E\Big/\int_{E_{Cd}}^{\infty}\sigma_{act}(E)\phi_{epi}\cdot f(E)\mathrm{d}E \qquad (15)$$

The induced spectrum factor S_r is

$$S_r=\int_{E_{Cd}}^{\infty}\sigma_{act}(E)\phi_{epi}\cdot f(E)\mathrm{d}E/\theta I_r \qquad (16)$$

From equations (8), (13), (15) and (16) the denominator of equation (11) is $G_r'S_r\theta I_r$. Thus the equation (11) can be re-written in the following form,

$$R_{Cd}=\frac{G_{th}'F_m\bar{\sigma}_{act}\Phi_{th}}{G_r'S_r\theta I_r}+F_{Cd} \qquad (17)$$

If the fast neutron flux is neglected, then equations (12), (15) and (16) can be written in the following

$$F_{Cd}=1-\int_{E_r}^{E_{Cd}}G(t)\sigma_{act}(E)\frac{\partial(E)\mathrm{d}E}{E^{1+\alpha}}\Big/\int_{E_{Cd}}^{\infty}G(t)\sigma_{act}(E)\frac{\partial(E)\mathrm{d}E}{E^{1+\alpha}} \qquad (12a)$$

$$G_r'=\int_{E_{Cd}}^{\infty}G(t)\sigma_{act}(E)\frac{\partial(E)\mathrm{d}E}{E^{1+\alpha}}\Big/\int_{E_{Cd}}^{\infty}\sigma_{act}(E)\frac{\partial(E)\mathrm{d}E}{E^{1+\alpha}} \qquad (15a)$$

and

$$S_r=\int_{E_{Cd}}^{\infty}\sigma_{act}(E)\frac{\partial(E)\mathrm{d}E}{E^{1+\alpha}}/I_r \qquad (16a)$$

The hardness of intermediate neutron flux spectrum β and the thermal neutron flux expressed in R_{Cd} are in the following, respectively,

$$\beta=\frac{1}{R_{Cd}-F_{Cd}}\times\frac{G_{th}'F_m\sigma_{act}}{G_r'S_rI_r} \qquad (18)$$

and

$$\Phi_{th}=(1-F_{Cd}/R_{Cd})A_{bare}/G_{th}'F_m\bar{\sigma}_{act} \qquad (19)$$

or

$$\Phi_{th}=A_{Cd}(R_{Cd}-F_{Cd})/G_{th}'F_m\sigma_{act} \qquad (19a)$$

Where A_{bare} and A_{Cd} are the single nucleus reaction rate of bare and Cd covered foil, respectively.

When using equation (10) to derive equation (11) the cadmium cut-off energy is assumed. This means that thermal neutrons transmitted through the cadmium cover are treated as intermediate neutrons i. e. the thermal and intermediate neutrons are confused. If the fraction of reaction rate contributed by transmission thermal neutrons in the cadmium covered foil

$$R_{\rm tsb}=\int_0^{E_c} G(t)\sigma_{\rm act}(E)\phi_{\rm th}(E){\rm d}E\Big/\int_0^{\infty} G(t,t_{\rm Cd})\sigma_{\rm act}(E)\phi(E){\rm d}E \qquad (20)$$

is very small, then the derivation of equation (11) from equation (10) is reasonable. Otherwise, it should be to create other $R_{\rm Cd}$ model. In order to check the role of fast neutron flux the ratio of fast neutron reaction rate to Cd covered reaction rate R_f is introduced.

$$R_f=\frac{\text{Fast neutron reaction rate}}{\text{Cd covered reaction rate}}=\frac{\Phi_{\rm th}\int_{E_f}^{\infty}\sigma_{\rm act}(E)\phi f(E){\rm d}E}{\int_0^{\infty}G(t,t_{\rm Cd})\sigma_{\rm act}(E)\phi(E){\rm d}E} \qquad (21)$$

Where E_f is the initial energy of fast neutrons. For fast neutron flux the self-shielding factor disappears.

3 BEHAVIORS OF PARAMETERS AND AVAILABLE DATA FOR HAND PROCESS

In this section we demonstrate behaviors of parameters or factors related to the $R_{\rm Cd}$ and thermal neutron flux measurement by selected curves and tables which also provide the available data for data process by hand. Cross sections used for parameter or factor calculation are based on references 13～15.

The data process of the $R_{\rm Cd}$ and thermal neutron flux measurement involves parameters in thermal energy region, namely E_c, F_m, F_m' and $G_{\rm th}'$, and parameters in intermediate energy region, namely $E_{\rm Cd}$, $F_{\rm Cd}$, G_r' and S_r. Each of them is the function of a part or all variables including T_n, β, α, t, $t_{\rm Cd}$, medium temperature T_m during the irradiation, geometry configuration of detector foil and cadmium cover and cross sections of detector material. It is very complex.

We take Au detector foil as an example to demonstrate their beings in the following, since Au foil is a very common activation detector. Thus the geometry configuration and cross sections of material are fixed. Remainder variables are neutron flux spectrum parameters T_n, β, α and measurement parameters t, $t_{\rm Cd}$ and T_m.

For common detector material as Au, In, Mn, W and Co, the Doppler broadening effect is small. So the T_m is not discussed as an independent variable. But the Doppler broadening effect of main resonance peak due to the environment temperature T_m during irradiation is considered in the calculation of these parameters or factors. For cadmium covered foil irradiation the maximum temperature T_m is limited in about 300℃. Considering the physical performance of thermal neutron reactors and measure technique, the ranges of variables in the calculation are selected in the following. T_n: 293.3～700 K, β: 0.001～0.25, α: -0.09～0.09, t: 0～0.003 cm (for Au foil, for other foil 0～0.03 cm), t_{Cd}: 0.05～0.1 cm. These ranges can cover the general measurement of R_{Cd} and thermal neutron flux.

The joint energy E_c is a boundary energy between thermal and intermediate neutrons. It is a function of T_n, β and α. When β is 0.001 i.e. the neutron flux spectrum approximates to pure Maxwellian, E_c is about 0.37 eV. When $\beta > 0.1$, the $E_c \sim \beta$ curve approaches to even as shown in the figure 1. The E_c depends slightly on α. The figure 2 of $E_c \sim T_n$ curves shows that E_c strongly depends on T_n and β. In above selected T_n range the E_c varies from 0.11－0.75eV. For small β the E_c is large. It means the thermal neutron spectrum approaches to the complete Maxwellian. For large β the E_c is small. It means the thermal neutron spectrum be more freencated. The change of E_c causes the change of F_m, F_m', F_{Cd} and G_{th}.

The correction factor of F_m determines the reaction rae correction due to the truncated Maxwell spectrum. It is proportional to ratio of truncated Maxwellian neutron density distribution to its complete Maxwellian one for $1/v$ detector as mentioned previously. The dependence of F_m on β is strong, but on α and T_n is slight as shown in the figure 3. For such cases that the measured hardness of intermediate neutron flux is smaller than about 0.02 the correction of F_m can be neglected.

The correction factor of F_m' is ratio of a truncated Maxwell neutron flux spectrum to its complete Maxwellian distribution. The F_m' is used only for the expression of thermal neutron flux. The means of F_m' differs from F_m which appears in equations (17), (18) and (19). The value of F_m' is about two times larger than the value of F_m. The dependence of F_m' on β is strong, but on α and T_n is slight as shown in the figure 4.

The behavior of the self shielding factor of a truncated Maxwell neutron flux spectrum G_{th}' is shown in the figure 5. It is expected that the G_{th}' is mainly dependent on the foil thickness. The value of G_{th}' is approximate to G_{th}.

The cadmium cut-off energy E_{Cd} varied from variables causes the change of values of parameters or factors in the intermediate energy region. Dependences of E_{Cd} on t , α and t_{Cd} are shown in the figure 6. When t is small the E_{Cd} is strongly depending on t. When t is large the E_{Cd} is almost even. Dependence of E_{Cd} on β and α as well as T_n(not shown) are light as shown in the figure 7.

F_{Cd}-1 is the fraction of intermediate reaction rate of bare foil induced by neutrons in energy range from E_r to E_{Cd}. It plays an important role in data process of R_{Cd} measures. The value of F_{Cd} is in the interval of 0. 8~1. 16. F_{Cd} depends on each of variables as shown in the figure 8 and tables 1 and 2.

The definition of G_r' is similar to the resonance self-shielding. They have a strong dependence on t and also detector foil material especially for having large resonance peak. Besides, it depends on β, α and t_{Cd}. The behavior of G_r' is shown in the figure 9.

The factor S_r is introduced for the use of standard resonance integral. The behavior of S_r is shown in the figure 10 and table 3. When t is small, the S_r depends strongly on β . When t is large, it becomes even. It almost is independent on T_n.

The dependence of R_{Cd} on variables is shown in figures 11 and 12. As expected that R_{Cd} depends on T_n and t strongly, shown in the figure 11. The figure 12 shows that R_{Cd} varies from β and α and t_{Cd} as well.

From previous analysis it is seen that behaviors of parameters or factors relative to cadmium ratio measurement are rather complex. Thus its data process by hand is a time consuming. A PC Code RCDTH (Ref. 16) is specially prepared for that.

Besides, the R_{sub} and R_f defined by equations (20) and (21),respectively, are also calculated for checking. The maximum values of R_{sub} must be happened in the case when the t_{Cd} is thin and T_n is high as well as β is small. The calculated result of R_{sub} listed in the table 4 shows that in this extreme case R_{sub} is not small i. e. for small β and high T_n the above R_{Cd} model is not good. But in other cases R_{sub} is negligible. This characterizes that the previous derivation of formula R_{Cd} based on the idea of E_{Cd} assumption is reasonable. The calculated result of R_f listed in the table 5 shows that the contribution of fast reaction rate to R_{Cd} measurement is very small.

4 AVAILABLE REGION OF R_{Cd} MEASUREMENT

The criterion which judges a measure technique available or not for the given object is the sensitivity of direct measured quantity to the objective quantity of measurement. The main object of R_{Cd} measure is to determine the hardness of the intermediate neutron flux spectrum β. Consequently, the sensitivity of R_{Cd} to β is an unique criterion to judge its availability.

The slop of curves shown in the figure 12 decreases fastly and monotonously when the β increases. When the β is larger than about 0. 1 curves become approximately even. independent on T_n, α, t and t_{Cd}. It means that the available sensitivity of the cadmium ratio measurement to the hardness of spectrum is limited. The region where the slop of curves is large i. e. the β is below about the mentioned value can be called as the available region. Within it the region where the β is smaller than about 0. 05 i. e. the slop is rather large is called as the optimum region. Outside the available region where the slop is very small is a defective region. Because in this region even the statistical error of measurement can cause a large uncertainty of processed β result. Although the figure 12 is for fixed T_n and t, but this phenomenon is valid for all calculated intervals.

The above conclusion is derived from Au detector foil. For commonly used detector foil material they also have this behavior. The available region of In and W is approximately same with Au. The Co detector foil has a large available region as shown in the figure 13. The slop of Co foil curves decreases much slower than for the Au. Consequently, for such neutron field where a more harder neutron flux spectrum is existed and the Co foil is more suitable for such measurement. The Mn foil nearly has the same behavior as Co foil.

5 A BRIEF SUMMARY

From the previous analysis we can briefly summarize in the following.

1. A base to standardize data process of R_{Cd} and thermal neutron flux measures is to derive a R_{Cd} formula based on standard average thermal activation cross section and resonance integral and to define related parameters or factors that provide an unique base for comparison between different measures in laboratories. These parameters or factors are also used to obtain exact result.
2. In the R_{Cd} measurement parameters or factors necessary for the data process are

always the function of objective quantity. Thus the multiple approach is required.

3. The commonly used detector foil material has an available region for the R_{Cd} measurement. For Au, In and W the available region is about $\beta < 0.1$. For Co and Mn detector foils this region are much wider. For very small β and high T_n the above R_{Cd} model will be meaningess.

4. Very rich curves and tables have been given above. They provide not only for the estimation by hand, but also for understanding of essential features of data process in the R_{Cd} measurement, one of the most commonly used measurements.

5. Due to the complexity of data process by hand in cadmium ratio measurement a special code, like the Code RCDTH, for such process is absolutely necessary.

REFERENCES

[1] C. H. Westcott and et. al, Effective Cross Section and Cadmium Ratio for the Neutron Spectra and Thermal Reactors. Int. Conf. Peaceful Uses Atomic Energy (Proc. Conf. Geneva, 1958) 16, UN. New York (1958) 70

[2] W. H. Walker, C. H. Westcott and T. K. Alexander, Measurement of radoactive capture resonance integrals in a thermal reactor spectrum and thermal cross section of Pu-240, Canadian Journal of Physics, vol 38, No 1, p57—77 (1960)

[3] K. H. Beckurts and K. Wirtz, Neutron Physics, (1964)

[4] W. L. Zijp, Review of Activation Methods for the Determination of Intermediate Neutron Spectra, RCN Report 40, (Oct. 1965)

[5] Neutron Fluence Measurements, Technical Reports series No 107, IAEA (1970)

[6] A. M. Weinberg and E. P. Wigner, The Physical Theory of Neutron Chain Reactor, (1958)

[7] A. G. Galanin, Theory of Thermal Neutron Reactors, (1959) (Russian)

[8] Reactor Physics Constants, ANL-5800, (1958) and (1963)

[9] H. Albinsson, Handbook on Neutron Activation Cross Section, Technical Reports series No 156, IAEA, Vienna (1974)

[10] Li Zhaohuan and et. al. , The Measurement of Thermal Neutron Flux in lattices of The Swimming Pool Reactor by Activation Foil Method, Atomic Energy Science and Technology, vol. 3, p309 — 315 (1980)(Chinese)

[11] J. A. Grundle and C. M. Eesenhues, Fission Spectrum Neutron for Cross Section Validation Neutron Flux Transfer, Conference on Cross Section and Technology, Washington D. C. ,(1975)

[12] Li Zhaohuan, Gao Jikin and Wang Yunqing, The calculation of Self-shielding Factors of Cadmium Covered Foil with Consideration of Neutron Scattering, Institute of Atomic Energy, Annual Report, p177, (1979) (Chinese)

[13] ENDF/B-V, National Nuclear Data Center, BNL (1988)

[14] Li Zhaohuan, Gao Jikin and Wang Yunqing, 640 Group Cross Section for Neutron Dosimetry, IAE, Annual Report, p145, (1981) (Chinese)

[15] JENDL Dosimetry File, Japan Atomic Energy Research Institute, (1992)

[16] Li Zhaohuan, User Manual of Code RCDTH —— A Code for Data Process of Cadmium Ratio Measurement, CIAE, (1992)(Chinese)

Table 1 Dependence F_{Cd} of Au Foil on β and T_n during $a = 0.0$

T_n K	293.3	340.0	420.0	500.0	580.0	700.0
β	Cd Cover Thickness t_{Cd} = 0.05 cm					
0.001	1.01073	1.00700	0.98756	0.96010	0.89373	0.75889
0.010	1.04457	1.03893	1.03103	1.02421	1.01598	0.99016
0.050	1.06095	1.05426	1.04521	1.03782	1.03181	1.02382
0.100	1.06870	1.06148	1.05176	1.04396	1.03762	1.02983
0.150	1.07301	1.06554	1.05547	1.04742	1.04089	1.03296
0.200	1.07585	1.06820	1.05788	1.04965	1.04295	1.03496
β	Cd Cover Thickness t_{Cd} = 0.08 cm					
0.001	1.04369	1.03858	1.02953	1.01501	0.97315	0.87315
0.010	1.05771	1.05192	1.04384	1.03726	1.03019	1.01741
0.050	1.07246	1.06577	1.05671	1.04934	1.04328	1.03512
0.100	1.08006	1.07285	1.06314	1.05559	1.04895	1.04060
0.150	1.08434	1.07688	1.06683	1.05883	1.05221	1.04365
0.200	1.08716	1.07953	1.06923	1.06106	1.05432	1.04563
β	Cd Cover Thickness t_{Cd} = 0.10 cm					
0.001	1.05058	1.04549	1.03760	1.02569	1.00192	0.91345
0.010	1.06428	1.05850	1.05045	1.04398	1.03785	1.02651
0.050	1.07909	1.07240	1.06336	1.05601	1.04997	1.04240
0.100	1.08673	1.07951	1.06983	1.06209	1.05567	1.04779
0.150	1.09103	1.08357	1.07354	1.06555	1.05895	1.05085
0.200	1.09387	1.08623	1.07595	1.06780	1.06107	1.05284

Table 2 Dependence of F_{Cd} of Au Foil on t during $T_n = 340$ K

β	0.010			0.100			0.250		
a	−0.09	0.00	0.09	−0.09	0.00	0.09	−0.09	0.00	0.09
t (mμ)	Cd Cover Thickness t_{Cd} = 0.05(cm)								
0.0	1.03315	1.03720	1.04230	1.04388	1.05190	1.06253	1.04800	1.05745	1.06990
6.0	1.03251	1.03893	1.04696	1.04884	1.06148	1.07862	1.05512	1.07002	1.09001
10.0	1.03598	1.04363	1.05314	1.05502	1.07009	1.09037	1.06236	1.08010	1.10374
16.0	1.04028	1.04902	1.06091	1.06273	1.08084	1.10457	1.07136	1.09267	1.12042
20.0	1.04295	1.05260	1.06570	1.06734	1.08727	1.11332	1.07673	1.10018	1.13064
30.0	1.04802	1.06012	1.07570	1.07707	1.10034	1.13203	1.08805	1.11552	1.15246
t (mμ)	Cd Cover Thickness t_{Cd} = 0.08(cm)								
0.0	1.04923	1.05324	1.05832	1.05901	1.06687	1.07740	1.06311	1.07240	1.08477
6.0	1.04503	1.05192	1.06090	1.05991	1.07285	1.09035	1.06615	1.08135	1.10171
10.0	1.04880	1.05694	1.06822	1.06618	1.08147	1.10282	1.07346	1.09143	1.11616
16.0	1.05416	1.06405	1.07720	1.07463	1.09309	1.11826	1.08320	1.10487	1.13409
20.0	1.05669	1.06794	1.08281	1.07897	1.09963	1.12768	1.08830	1.11248	1.14497
30.0	1.06398	1.07755	1.09544	1.09008	1.11489	1.14848	1.10099	1.13001	1.16891
t (mμ)	Cd Cover Thickness t_{Cd} = 0.10(cm)								
0.0	1.05877	1.06255	1.06808	1.06859	1.07626	1.08729	1.07271	1.08184	1.09471
6.0	1.05103	1.05850	1.06792	1.06597	1.07951	1.09751	1.07224	1.08806	1.10893
10.0	1.05545	1.06396	1.07575	1.07290	1.08860	1.11052	1.08022	1.09862	1.12395
16.0	1.06070	1.07162	1.08496	1.08126	1.10080	1.12625	1.08988	1.11266	1.14218
20.0	1.06415	1.07622	1.09098	1.08653	1.10807	1.13612	1.09591	1.12101	1.15353
30.0	1.07212	1.08589	1.10409	1.09834	1.12343	1.15748	1.10933	1.13867	1.17806

Table 3 Dependence Sr of Au Foil on t and β during $T_n = 340$ K, $\alpha = 0.0$

β	0.001	0.010	0.030	0.050	0.080	0.100	0.150	0.200	0.250
t (cm)	Thickness of Cd cover t_{Cd} 0.05 (cm)								
0.0000	0.99499	0.98252	0.98161	0.98143	0.98133	0.98130	0.98126	0.98123	0.98122
0.0006	1.00650	0.99399	0.99310	0.99290	0.99280	0.99277	0.99272	0.99270	0.99269
0.0010	1.00765	0.99514	0.99423	0.99406	0.99396	0.99393	0.99388	0.99386	0.99385
0.0016	1.00872	0.99616	0.99525	0.99507	0.99497	0.99494	0.99490	0.99487	0.99486
0.0020	1.00908	0.99657	0.99567	0.99547	0.99537	0.99533	0.99529	0.99527	0.99526
0.0030	1.00978	0.99726	0.99635	0.99616	0.99606	0.99602	0.99598	0.99596	0.99594
t (cm)	Thickness of Cd cover t_{Cd} 0.08 (cm)								
0.0000	0.96923	0.96892	0.96890	0.96890	0.96890	0.96889	0.96889	0.96889	0.96889
0.0006	0.98653	0.98621	0.98620	0.98619	0.98619	0.98619	0.98619	0.98619	0.98619
0.0010	0.98843	0.98811	0.98809	0.98809	0.98809	0.98808	0.98808	0.98808	0.98808
0.0016	0.99006	0.98973	0.98972	0.98971	0.98971	0.98971	0.98971	0.98971	0.98971
0.0020	0.99073	0.99044	0.99043	0.99042	0.99042	0.99042	0.99042	0.99042	0.99042
0.0030	0.99170	0.99138	0.99136	0.99136	0.99135	0.99135	0.99135	0.99135	0.99135
t (cm)	Thickness of Cd cover t_{Cd} 0.10 (cm)								
0.0000	0.96190	0.96185	0.96185	0.96185	0.96185	0.96185	0.96185	0.96185	0.96185
0.0006	0.98250	0.98243	0.98243	0.98243	0.98243	0.98243	0.98243	0.98243	0.98243
0.0010	0.98480	0.98473	0.98473	0.98473	0.98473	0.98473	0.98473	0.98473	0.98473
0.0016	0.98679	0.98671	0.98671	0.98671	0.98671	0.98671	0.98671	0.98671	0.98671
0.0020	0.98761	0.98754	0.98754	0.98754	0.98754	0.98754	0.98754	0.98754	0.98754
0.0030	0.98878	0.98871	0.98871	0.98871	0.98871	0.98871	0.98871	0.98871	0.98871

Table 4 R_{sub} of Au Foil during $T_n = 700$ K $\alpha = 0.0$

$\beta =$	0.001			0.050			0.250		
t_{Cd}(cm)	0.05	0.08	0.10	0.05	0.08	0.10	0.05	0.08	0.10
t (mμ)									
0.0	1.42E-1	8.20E-2	6.21E-2	1.67E-3	5.56E-4	3.05E-4	3.46E-5	7.95E-7	7.39E-8
6.0	2.00E-1	1.19E-1	9.07E-2	2.52E-3	8.37E-4	4.58E-4	5.22E-5	1.20E-6	1.11E-7
10.0	2.27E-1	1.36E-1	1.05E-1	2.95E-3	9.77E-4	5.35E-4	6.09E-5	1.40E-6	1.30E-7
20.0	2.76E-1	1.70E-1	1.32E-1	3.80E-3	1.26E-3	6.93E-4	7.85E-5	1.80E-6	1.68E-7
30.0	3.11E-1	1.96E-1	1.53E-1	4.49E-3	1.50E-3	8.21E-4	9.28E-5	2.14E-6	1.98E-7

Table 5 Ratio of Fast Reaction Rate to Cd Covered R_f of Au Foil

T_n°K	293.3			340.0		
α	−0.09	0.00	0.09	−0.09	0.00	0.09
β						
0.001	2.64064E-03	1.01824E-03	3.85762E-04	2.64013E-03	1.01799E-03	3.85647E-04
0.010	2.64064E-03	1.01824E-03	3.85762E-04	2.64013E-03	1.01799E-03	3.85646E-04
0.100	2.64064E-03	1.01824E-03	3.85762E-04	2.64013E-03	1.01799E-03	3.85647E-04
0.150	2.64064E-03	1.01824E-03	3.85761E-04	2.64013E-03	1.01799E-03	3.85646E-04
0.200	2.64064E-03	1.01824E-03	3.85762E-04	2.64013E-03	1.01799E-03	3.85647E-04
0.250	2.64064E-03	1.01824E-03	3.85762E-04	2.64013E-03	1.01799E-03	3.85646E-04

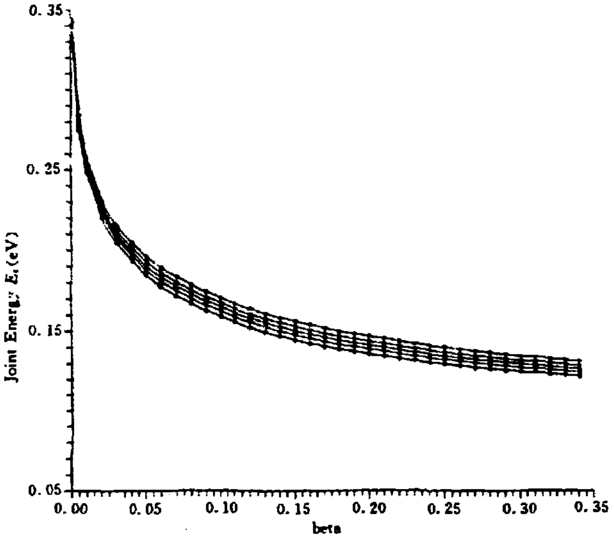

Fig. 1 Dependence of E_t on beta, during T_n=340°K, aplha= : (from top to bottom) −0.09, −0.04, 0.0, 0.04, 0.09

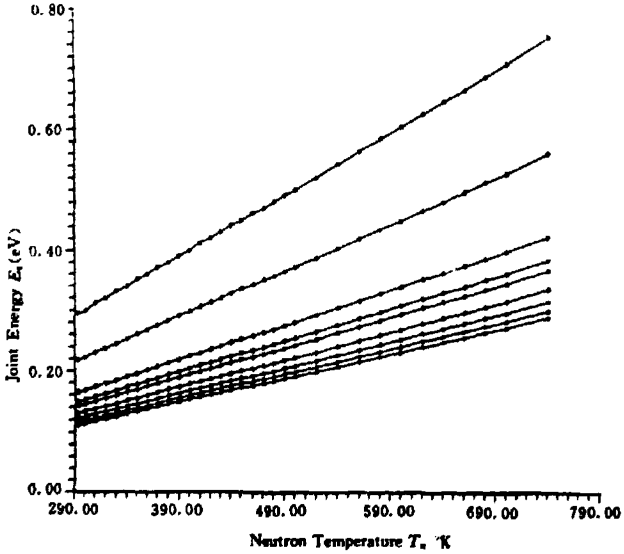

Fig. 2 Dependence of joint energy E_t on T_n(°K) during alpha=0.0, beta= : (from top to bottom) 0.001, 0.01, 0.05, 0.08, 0.1, 0.15, 0.20, 0.25 and 0.30

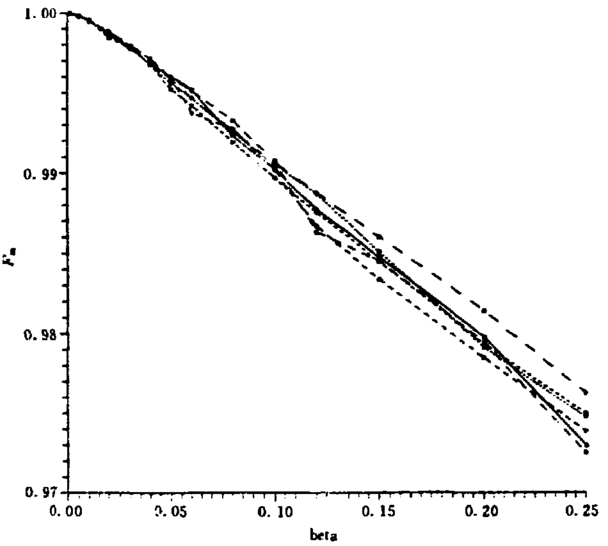

Fig. 3 Dependence of correction factor of truncated Maxwell spectrum F_m on beta during fixed T_n= 293.3 (solid), 340, 420, 500, 580 and 700°K (dashed from short to long), alpha=0.0

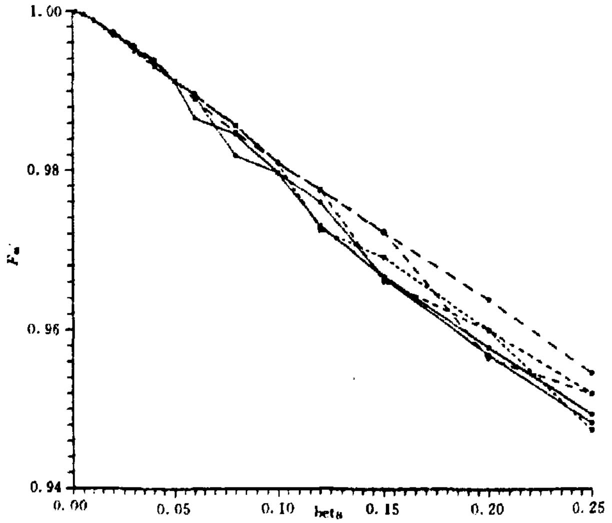

Fig. 4 Dependence of correction factor of truncated Maxwell flux spectrum F_m on beta during fixed T_n= 293.3 (solid), 340, 420, 500, 580 and 700°K (dushed from short to long), alpha=0.0

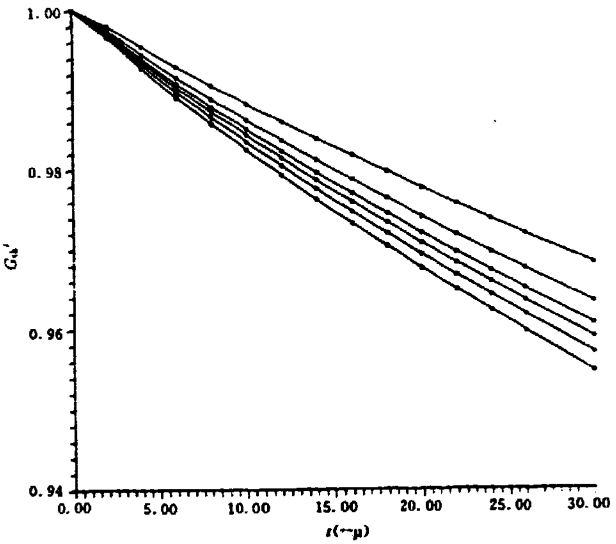

Fig. 5 Dependence of thermal neutron flux self-shielding factor G'_{th} of Au foil on t (mμ) during fixed T_n = : (from bottom to top) 293.3, 340, 380, 420, 500 and 700°K, alpha=0.0

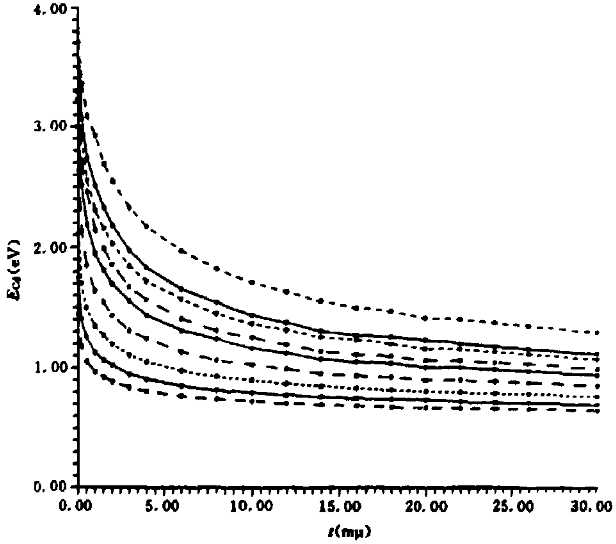

Fig. 6 Dependence of cadmium cut-off energy of Au foil on t during fixed T_n=340°K, beta=0.05, t_{Cd}= : (from bottom to top) 0.5, 0.8 and 1.0 mm, alpha= : −0.09 (short dushed), 0.0 (solid) and 0.09 (long dashed)

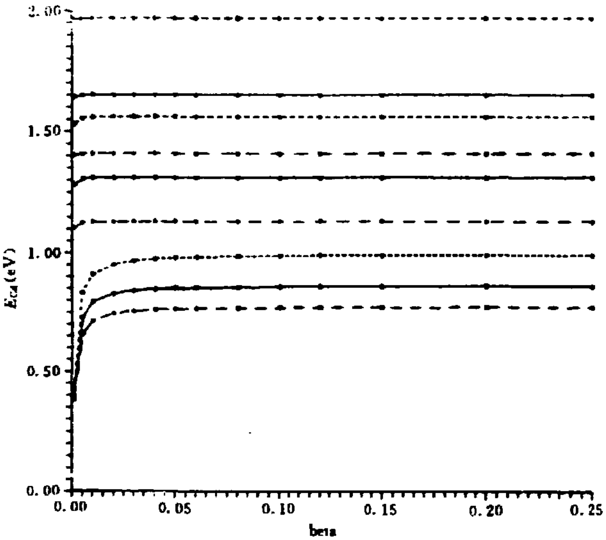

Fig. 7 Dependence of cadmium cut-off energy of Au foil on beta during fixed T_n=340°K, t= 0.006 mm, t_{Cd}= : (from bottom to top) 0.5, 0.8 and 1.0 mm, alpha= : −0.09 (short dashed), 0.0 (solid) and 0.09 (long dashed)

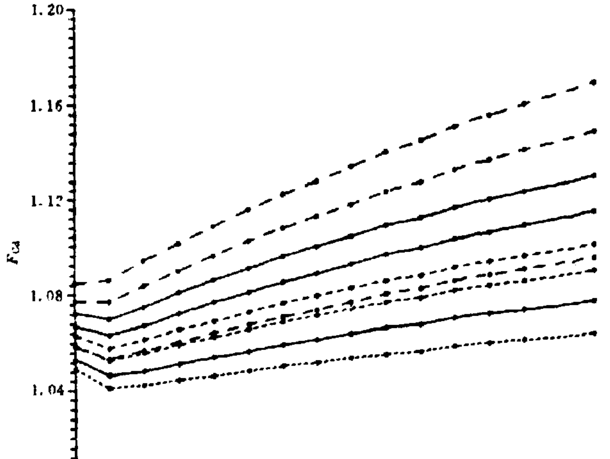

Fig. 8 Dependence of F_{Cd} of Au foil on t during T_n=340°K and t_{Cd}=0.8mm, beta= : (from bottom to top) 0.01, 0.10 and 0.25, alpha= : 0.09 (short dashed), 0.0 (solid) and 0.09 (long dashed)

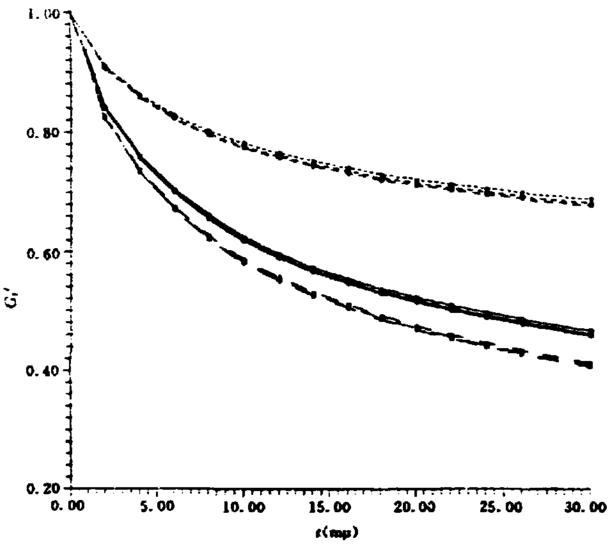

Fig. 9 Dependence of super Cd self-shielding factor G_t of Au foil on t during fixed alphu=0, T_n=340°K, t_{Cd}=(from top to bottom) 0.5, 0.8 and 1.0 mm, beta=0.01 (short dashed), 0.05 (solid) and 0.1 (long dashed)

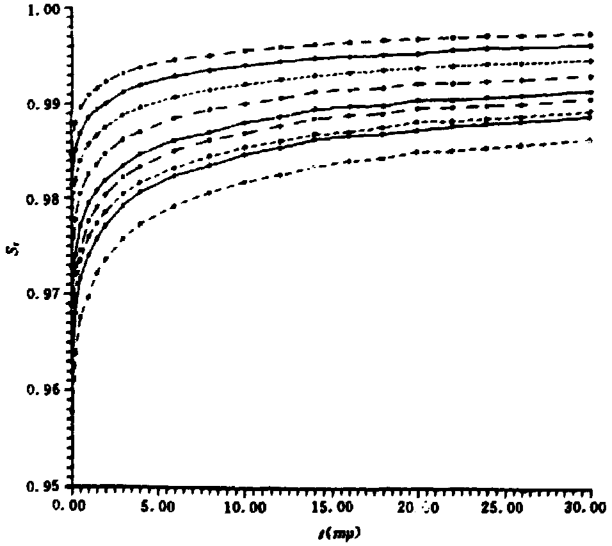

Fig. 10 Dependence of spectrum induced factor S_t of Au foil on t during fixed T_n=340°K, beta=0.05, t_{Cd}= : (from top to bottom) 0.5, 0.8 and 1.0 mm, alpha= : −0.09 (short dashed), 0.0 (solid) and 0.09 (long dashed)

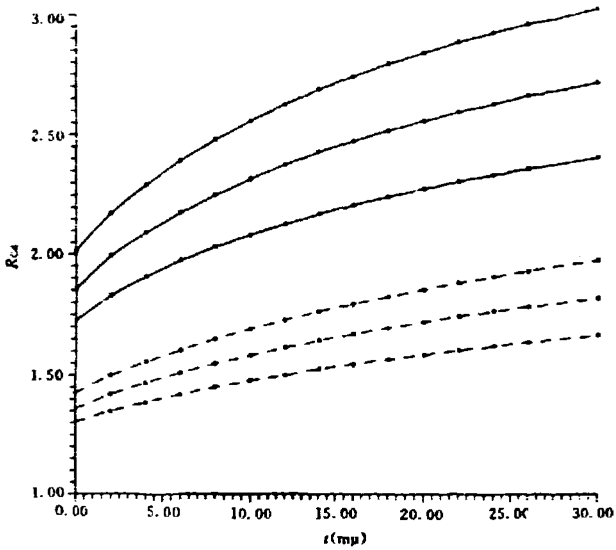

Fig. 11 Dependence of R_{cd} of Au foil on t (mμ) during alpha = 0, t_{cd} = 0.8mm, beta = 0.05 (solid) and 0.15 (dashed), T_n = : (from top to bottom) 293.3, 420 and 700°K

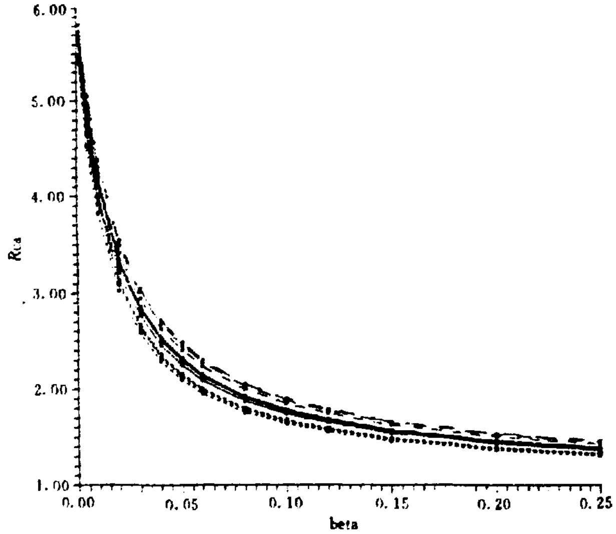

Fig. 12 Dependence of R_{cd} of Au foil on beta during fixed T_n = 340°K, t = 0.006mm, alpha = : −0.09 (short dashed), 0.0 (solid) and 0.09 (long dashed), t_{cd} = : (from bottom to top) 0.5, 0.8 and 1.0 mm

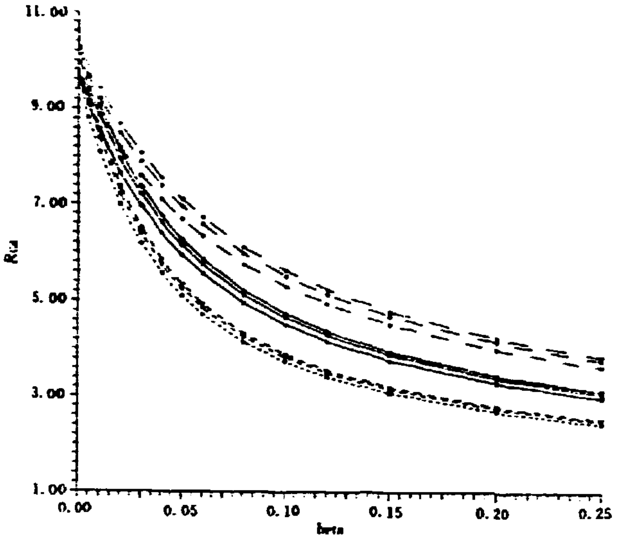

Fig. 13 Dependence of R_{Cd} of Co foil on beta during fixed $T_a = 340°K$, $t = 0.06mm$, alpha = : −0.09 (short dashed), 0 (solid) and 0.09 (long dashed), t_{Cd} = : (from bottom to top) 0.5, 0.8 and 1.0 mm

镉比 R_{Cd} 和热中子通量

测量数据处理的标准化基础

原子能出版社出版

（北京 2108 信箱）

中国核科技报告编辑部排版

核科学技术情报研究所印刷

☆

开本 787×1092 1/16 · 印张 1/2 · 字数 11 千字

1993 年 8 月北京第一版 · 1993 年 8 月北京第一次印刷

ISBN 7-5022-0931-X

TL · 587

CHINA NUCLEAR SCIENCE & TECHNOLOGY REPORT

P.O.Box 2103
Beijing, China

ISBN 7-5022-0931-X
TL·587

China Nuclear Information Centre