COLLECTRONS,
SELF-POWERED NEUTRON FLUX DETECTORS

Part I : Theoretical considerations

by

M. GRIN

1972

Joint Nuclear Research Centre
Ispra Establishment - Italy
Materials Division
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Collections are self-powered neutron flux detectors based on the direct collection of electric charges emitted from a short lived $\beta$ emitter activated by neutron flux.

After a short description of components and measuring circuits, this report deals mainly with the theoretical sensitivity of the collectrons. An evaluation of self-shielding and flux depression factor and of self-absorption factor leads to the formulation of the theoretical sensitivity of the collectrons in normal working conditions. The cases of rhodium, silver and vanadium have been considered.
The second part of this report which will follow will essentially consider in-pile behaviour of collectrons with a chapter specially devoted to a confrontation between theoretical sensitivity and experimental calibration.
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ABSTRACT

Collectrons are self-powered neutron flux detectors based on the direct collection of electric charges emitted from a short lived $\beta$ emitter activated by neutron flux.

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KEYWORDS

NEUTRON DETECTION  SENSITIVITY
NEUTRON FLUX  SELF-SHIELDING
ELECTRIC CHARGES  RHODIUM
EMISSION  SILVER
BETA PARTICLES  VANADIUM
1. **INTRODUCTION**)  

Neutron flux measurements during irradiation tests are normally performed by activation methods using wires or foils of suitable materials like Co, Ag, Ni, Au, In, Cu ... The amount of radioactivity induced during a controlled exposure is a measure of the neutron flux intensity: after exposure the activities measured are those of the emitted $\beta$ or $\gamma$ rays. The method is simple, rather accurate but gives only a mean value of the neutron flux during the whole exposure.

A direct measurement of the neutron flux is possible with fission chambers but they require a complex electronic associated equipment and are generally of notable dimensions; however a dealer proposes a sub-miniature fission chamber of 1 mm O.d. and 10 mm long [1].

After the theoretical and experimental works of MITELHAN [2], CESARELLI [3] and HILBORN [4], a new type of instantaneous flux detector was developed, the "collectron" or continuous neutron flux detector which is self powered, gives a signal directly proportional to the neutron flux and can be easily miniaturized.

*) Manuscript received on January 5, 1972
2. DESCRIPTION AND WORKING PRINCIPLE OF THE COLLECTRON

2.1. Principle [2, 3, 4, 5, 6]

The detector consists of two coaxial electrodes: the inner electrode which is a $\beta$ emitter is isolated from the outer electrode or collector (Fig. 1). When a neutron flux impinges on the device, the inner electrode is activated and the emitted $\beta$ particles are collected by the outer electrode: it is sufficient to close the circuit on a suitable measuring device to measure an electric current which, at saturation, is directly proportional to the neutron flux.

2.2. Realization and component materials

Geometrically, the detector is composed of a $\beta$ emitter wire, a solid dielectric material (usually high purity $\text{Al}_2\text{O}_3$) and a sheath. The detector is then joined to a coaxial connecting cable (Fig. 1 and 2). The measured current is the resultant of $\beta$ emission from the emitter and from some impurities always present in the sheath and in the connecting wires.

2.2.1. The emitter

The emitter must present a high cross-section to give a good sensitivity but not too much in order to limit the loss of sensitivity due to burn out. The radioactive half life for decay in the material should be of the order of 4 to 5 minutes for normal in-reactor applications. If other neutron absorbing isotopes are present in addition to the principal $\beta$ emitter they must not produce long-lived $\beta$ emitter that could cause slow variation of the measured current.
Fig. 1. **PRINCIPLE OF A COLLECTRON**

- Alumina
- Stainless Steel or Inconel
- Collector
- Coaxial connecting cable

Detector

- Mono wire connecting cable.

**Fig. 2. MEASURING CIRCUITS**

- **a** - normal wiring
- **b** - background compensation circuit

\[ R_{L1} = R_{L2} \]
<table>
<thead>
<tr>
<th>Emitter</th>
<th>Abundance %</th>
<th>Cross sections</th>
<th>Westcott factors</th>
<th>Capture-product half life</th>
<th>Spectrum max. energy (Mev)</th>
<th>1st resonance peak (ev)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>at 2,200 m/s (barns)</td>
<td>at 20°C (brew)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>abs</td>
<td>act</td>
<td>g</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>V\textsuperscript{51}</td>
<td>99.76</td>
<td>4.5±0.9</td>
<td>1.00</td>
<td>0.0</td>
<td>3.76 m</td>
<td>2.6</td>
</tr>
<tr>
<td>Rh\textsuperscript{103}</td>
<td>100</td>
<td>156±7</td>
<td>12 ± 2</td>
<td>1.023</td>
<td>7.255***</td>
<td>4.4 m</td>
</tr>
<tr>
<td>Ag\textsuperscript{107}</td>
<td>51.35</td>
<td>140 ± 30</td>
<td>45 ± 4</td>
<td>1.0044</td>
<td>14.12</td>
<td>2.3 m</td>
</tr>
<tr>
<td>Ag\textsuperscript{109}</td>
<td>48.65</td>
<td>87±7</td>
<td>3.2±0.4</td>
<td>113 ± 13</td>
<td></td>
<td>270 j***</td>
</tr>
</tbody>
</table>

* Westcott (AECL) counsels the normalized value of 150.19

** negligible, 1% of signal after 1 year in a flux of 10\textsuperscript{13} n.cm\textsuperscript{-2} s\textsuperscript{-1}

*** S 4

TABLE I - Neutronic characteristics of β emitters employed for the realization of collectrons
The maximum energy of $\beta$ spectrum must be high to allow the $\beta$ to escape from the insulant and from the emitter wire itself.

All these conditions limit normally the choice of emitter to Rhodium, Vanadium or Silver whose main characteristics are summarized in Table 1.

2.2.2. The sheath or collector

Normally chosen with regard to applicability (weldability, compatibility in normal working conditions) the collector is usually (as the sheath of the connecting cable) a tube of stainless steel or inconel with a thickness sufficient to stop $\beta$ particles emitted from the central wire.

2.2.3. Connecting cable

It is a miniature sheathed cable of the type normally employed for temperature measurements: the sheath is in stainless steel or inconel, the wires (or the wire) are in Ni, the insulant is usually MgO. This connecting cable can be the origin of spurious currents and (or) electric leakage. Theoretically a compensating wiring (see § 2.3.) can eliminate spurious currents from the connecting cable.

2.3. Measuring circuit

It is possible to measure either directly the current, or, more simply, the tension at the terminals of a load resistance according to Fig. 2 a. It is obvious that the cable leakage resistance $R_l$ must be large compared to the load resistance $R_L$. 
Or, if $R_1$ is very high under the laboratory conditions at the moment of the fabrication of the detector ($R_1 \gg 10^4 \text{ M} \Omega$) it falls drastically in normal working conditions (influence of temperature and irradiation on the insulant, see § 3.6). The connecting cable, which is always partially submitted to neutron flux can be the origin of spurious currents: in fact either the sheath or the connecting wires contain traces of $\beta$ emitters and it is possible to obtain a secondary current coming from the connecting cable in addition to the main signal of the detector. Theoretically, a compensating wiring, as indicated in Fig. 2 b allows to eliminate this parasitic effect.

3. THEORETICAL SENSITIVITY OF THE COLLECTRONS

In the simplest case, when activation is due to a single emitter nuclide, the output current, as a function of time after exposure to the neutron flux, is given by:

$$I_T = K N. \phi . e \cdot \hat{\sigma} \int T - \exp(0.693 t/T_{1/2}) \gamma (1)$$

$N =$ number of atoms with $T_{1/2}$
$\phi =$ Westcott flux $\phi = n v_o$
$\hat{\sigma} =$ Westcott activation cross-section
$\hat{\sigma} = \sigma_o (g + rs)$
$e =$ electronic charge $1.602 \times 10^{-19}$ coulomb
$T_{1/2} =$ half-life of the emitter
$K =$ constant depending on geometry, beta self-absorption and neutron flux depression in the detector.
The response time $T_R$, which is the time requested to obtain 63% of the saturation signal corresponding to an instantaneous neutron flux variation, is defined as:

$$T_R = 1.44 \cdot T_{1/2}$$

The equilibrium output, or saturation signal, reached after some $T_{1/2}$ is thus:

$$I_s = K \cdot N \cdot \phi \cdot e^{\sigma t} \quad (2)$$

All neutron detectors gradually lose sensitivity, due to burn out of the neutron sensing $\beta$ emitter. If $N$ is the number of stable isotopes at instant 0 (beginning of irradiation), after the time $t$, it remains:

$$N = N_0 \cdot e^{\sigma t}$$

and the equilibrium output becomes:

$$I_s = K_1 \cdot N_0 \cdot \phi \cdot e^{\sigma t} \cdot e^{\sigma \cdot \phi \cdot t}$$

3.1. Evaluation of the correcting factor $K$

In first approximation $K$ may be considered as the product of two factors:

$$K = K_1 \cdot K_2$$

where:

$K_1$ = neutron self-shielding and flux depression factor
$K_2$ = self-absorption factor of $\beta$ particles in the emitter (and in the insulant)

$K_1$ and $K_2$ must evidently take into account the geometrical configuration of the device.
3.1.1. **Self-shielding and flux depression factor** $K_1$

Generally speaking, the presence of an absorber of macroscopic size in a neutron flux modifies the flux: it cannot be assumed that the flux in the absorber position is the same as that which would exist in that position if the absorber were absent. In general, the absorber will depress the flux in its vicinity.

KUSHNERIUK \(^{9}\) has shown that the ratio of mean flux to surface flux in an infinite long cylindrical absorber surrounded by an infinite predominantly scattering medium sustaining a thermal neutron flux, is adequately represented by the following formula:

$$\frac{\bar{\phi}}{\phi_0} = \frac{1}{a.\Sigma_a} \cdot \frac{\beta}{2 - \beta}$$

where

- $a = \text{radius of the cylinder}$
- $\Sigma_a = \text{macroscopic absorption cross section}$
- $\beta = \text{Probability that a neutron falling in the surface of the rod will be absorbed within it.}$

If $\Sigma_s$ is the macroscopic scattering cross-section and $\Sigma_t$ the macroscopic total cross-section, $\beta$ can be represented by the following expression valid for $a.\Sigma_t < 2.5$

$$\beta = \frac{a.\Sigma_a.\Sigma_1 (a.\Sigma_a + a.\Sigma_s)}{a.\Sigma_a + a.\Sigma_s.\Sigma_{ES}(a.\Sigma_a + a.\Sigma_s)}$$
where

\[ P_1 (a\Sigma_t) = \text{probability that a neutron, thrown into the absorber from a constant and isotropic source density in an infinite medium surrounding the absorber, undergoes collision within the cylindrical absorber.} \]

\[ P_{ES} (a\Sigma_t) = \text{collision escape probability for an isotropic source distribution within the cylindrical absorber.} \]

In these conditions:

\[ K_1 = \frac{\bar{\Phi}}{\Phi_0} = \frac{P_1 (a\Sigma_t)}{a \Sigma_a \cdot (2-P_1(a\Sigma_t))^2 + 2a \Sigma_s P_{ES}(a\Sigma_t)} \quad (3) \]

\[ a\Sigma_t = a\Sigma_a + a\Sigma_s \]

\[ P_1 \text{ and } P_{ES} \text{ are given for varying } (a\Sigma_t) \text{ in Fig. 3.} \]

Moreover Mc GILL and al. \cite{10} have made experimental measurements whose results are in good agreement with the KUSHNERIUK's computation.

For values of \( a\Sigma_a \) up to \( \approx 0.8 \) they propose the empirical correlation:

\[ K_1 = \frac{2}{K_a} \cdot \frac{I_1(Ka)}{I_0(Ka)} \quad (4) \]

with \( K = C \frac{(\Sigma_a)^{1/2}}{a} \]

\[ C = 0.183 \pm 0.13 \]

\( I_o \) and \( I_1 \) are Bessel's functions.
Fig. 3. $P_\alpha(\alpha \Sigma_k)$ AND $P_{ES}(\alpha \Sigma_k)$ VERSUS $(\alpha \Sigma_k)$. FROM Ref. 9
The experimental and calculated values are in good agreement with the computation made according to the Kushneriuk's formula. The % error between the two methods (5 to 10 %) is of the same order of magnitude as the experimental measurements.

Values of $K_1$ obtained by the two methods are compiled in Table 2.

<table>
<thead>
<tr>
<th>Emitter</th>
<th>$a$(cm)</th>
<th>macroscopic cross section $\Sigma_a$ (cm$^{-1}$)</th>
<th>$a \cdot \Sigma_a$</th>
<th>$K_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanadium</td>
<td>0.05</td>
<td>0.352</td>
<td>0.352</td>
<td>0.704</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>0.0088</td>
<td>=</td>
<td>0.99</td>
</tr>
<tr>
<td>Rhodium</td>
<td>0.05</td>
<td>10.9</td>
<td>0.366</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>0.272</td>
<td>0.91</td>
<td>0.90</td>
</tr>
<tr>
<td>Silver</td>
<td>0.05</td>
<td>3.69</td>
<td>0.352</td>
<td>4.04</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>0.092</td>
<td>0.92</td>
<td>0.96</td>
</tr>
</tbody>
</table>

**TABLE 2 : Flux depression factor $K_1$**

* from ANL 2nd edition

** non calculated because of the magnitude of errors due to $P_1$ and $P_{ES}$ for values of $a \Sigma_a$ close to zero.

Values of $K_1$ have been calculated for neutrons at 2,200 m/s; they must be corrected for the Westcott flux and the neutron temperature.
Preceding methods do not allow to take into account the effects due to sheath and insulant. In fact some elaborated nuclear codes exist which are able to take into account all the constitutive elements of a collectron.

The use of a WDSN code leads to the results of Table 3. The computation was made, considering on one hand, the shielding effect due to the single emitter and, on the other hand, the global effect due to the whole detector according to the geometrical conditions of Fig.4, in which are also indicated the nuclear data adopted.

<table>
<thead>
<tr>
<th>Emitter</th>
<th>Radius cm</th>
<th>due to the single emitter</th>
<th>due to the whole detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>0.05</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Rh</td>
<td>0.05</td>
<td>0.71</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>0.86</td>
<td>0.75</td>
</tr>
<tr>
<td>Ag</td>
<td>0.05</td>
<td>0.90</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>0.95</td>
<td>0.90</td>
</tr>
</tbody>
</table>

TABLE 3 - Computation of $K_1$ according to a nuclear code.

With respect to the preceding results the only sensible difference regards the rhodium. The additional effect of sheath and insulant is in the range of 10%.
Fig. 4 - COMPUTATION OF K1 FROM A NUCLEAR CODE

CONSIDEREDGEOMETRIES

ALLDIMENSIONSIN mm.

<table>
<thead>
<tr>
<th></th>
<th>Symbol</th>
<th>$\sum_a$</th>
<th>$\sum_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rh</td>
<td>9.657</td>
<td>0.366</td>
</tr>
<tr>
<td>2</td>
<td>Ag</td>
<td>3.269</td>
<td>0.352</td>
</tr>
<tr>
<td>3</td>
<td>V</td>
<td>0.288</td>
<td>0.325</td>
</tr>
<tr>
<td>4</td>
<td>Al$_2$O$_3$</td>
<td>0.00883</td>
<td>0.318</td>
</tr>
<tr>
<td>5</td>
<td>Void</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Stainless Steel</td>
<td>0.218</td>
<td>0.869</td>
</tr>
<tr>
<td>7</td>
<td>D$_2$O</td>
<td>$3.3 \times 10^{-5}$</td>
<td>0.449</td>
</tr>
</tbody>
</table>

NUCLEAR DATA ADOPTED
3.1.2. **Self-absorption factor \( K_2 \)**

To each monoenergetic \( \beta \) particle is associated a maximum range \( \lambda \) (which is normally expressed in the form of \( \lambda \cdot \rho \) in mg/cm\(^2\) of aluminium).

The probability for a \( \beta \) particle emitted from a point of a cylindrical source of radius \( a \) to escape from the cylinder is a function of \( a \) and \( \lambda \). For example, a \( \beta \) particle formed in the center of a rod, with a range less than the radius of the rod, would not escape.

The same \( \beta \) particle might escape if it were formed near the edge of the rod, depending on the direction of travel. If a sphere, with a radius equal to the range \( \lambda \) of the considered particle is placed with its center coincident with the origin of the \( \beta \) particle, the escape probability is the ratio of the area of the sphere that is outside of the rod divided by the total area of the sphere. It is possible to make a complete computation from this model [12], but it is easier to use the following formula, valid for a cylindrical emitter the diameter of which is low with respect to the length.

\[
K_2 = \frac{\lambda}{a} \left[ 1 - F_2 \left( \frac{a}{\lambda} \right) \right]
\]

\( \lambda = \) range of the particle in cm.

\( a = \) radius of cylinder in cm.

\( F_2 \left( \frac{a}{\lambda} \right) \) integral function defined by :

\[
F_2 (q) = \int_{-\infty}^{\infty} e^{-p} \frac{q^2}{p^3} \cdot dp
\]

with \( E_3 (q) = \int_{q}^{\infty} e^{-p} \frac{q^2}{p^3} \cdot dp \)
Values of $E_n(q)$ and $F_2(q)$ are tabulated in Annex I or in Ref. [14].

The range $\lambda$ must be calculated from empirical formulas like:

\[ \lambda \cdot \rho = 0.543 E - 0.16 \] \(\text{valid for aluminium between 0.8 and 3 Mev but extrapolable to other materials,}\)

\[ \lambda \cdot \rho = 0.142 E^{1.265} - 0.0954 \log E \] \(\text{valid for } 0.01 < E < 2.5 \text{ Mev}\)

\[ \lambda \cdot \rho = 0.53 E - 0.106 \] \(\text{valid for } E > 2.5 \text{ Mev}\)

where $\rho$ is the density of the considered material.

The computation of $K_2$ is complicated by the fact that $\beta$ particles are emitted with a continuous energy spectrum with energies varying from 0 to a maximum value which is considered as characteristic of the $\beta$ emitter considered. A general shape of a $\beta$ spectrum of energies is given by Fig. 5.

To each number $N_i$ of $\beta$ particles of a given energy must be associated a range $\lambda_i$ which allows to calculate a corresponding value $K_i$ of the self absorption factor. The value of $K_2$, for the considered reaction, is the integral of these elementary $K_i$ values. An approximate value of the solution can be obtained in assimilating the $\beta$ energy spectrum to a sum of rectangles to each of which is associated a mean number $N_i$ and a mean energy $E_i$. 
Fig. 5 β ENERGY SPECTRUM

$E_{\text{max}}$ - Kinetic energy $E$ (MeV)

$\beta$ emitted per unit energy $N(E)$
For each elementary rectangle it is possible to compute a mean absorption factor \( K_1 \); approached value of \( K_2 \) is then given by the sum:

\[
K_2 = \frac{\sum N_i K_i}{\sum N_i}
\]

The only difficulty consists in determining the \( \beta \) energy spectrum of the considered reaction.

In the litterature it is possible to find values of maximum energy \( E_{\text{max}} \) which are normally used in radiation protection; the few experimental \( \beta \) spectra existing are related to elements with a rather long half-life which is evidently not the case of Rh, Ag, V. The only alternative consists in calculating, for each considered element, the theoretical corresponding \( \beta \) spectrum, or to use an empirical formula giving, for the whole spectrum, a mean energy value.

a) determination of \( K_2 \) from a theoretical \( \beta \) energy spectrum.

The computation, detailed in Annex 2, has been made in the case of Rh\(^{104}\). The corresponding value of \( K_2 \) is 0.41.

b) determination of \( K_2 \) from a mean energy value.

A mean energy value (at \( \pm 5\% \)) of a \( \beta \) spectrum can be derived from the following formula:

\[
\bar{E} = 0.33 \, E \left(1 - \frac{Z^{1/2}}{50}\right) \left(1 + \frac{E^{1/2}}{4}\right) \sum_{15}
\]

where: \( E = \) maximum energy in Mev

\( Z = \) atomic number of the stable isotope.
Always in the case of Rh\textsuperscript{104} where \( E_{\text{max.}} = 2 \) and \( Z = 45 \) this formula gives \( \bar{E} = 0.967 \) which leads to a value of 0.43 for \( K_2 \).

This value is a justification of the validity of this determination and the results obtained, according to the application of this formula, are summarized in Table 4 for Rh, Ag and V in 0.5 mm diameter.

<table>
<thead>
<tr>
<th>Emitter</th>
<th>Isotopic abundance</th>
<th>Energy (Mev)</th>
<th>( K_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Rh}^{104} )</td>
<td>100</td>
<td>2.44</td>
<td>0.97</td>
</tr>
<tr>
<td>( \text{Ag}^{108} )</td>
<td>51.35</td>
<td>1.56</td>
<td>0.59</td>
</tr>
<tr>
<td>( \text{Ag}^{110} )</td>
<td>48.65</td>
<td>2.87</td>
<td>1.16</td>
</tr>
<tr>
<td>( \text{V}^{52} )</td>
<td>100</td>
<td>2.60</td>
<td>1.08</td>
</tr>
</tbody>
</table>

TABLE 4 - Values of \( K_2 \) computed from mean energy values.
3.2. Sensitivity of the collectrons

With the values of $K_1$ and $K_2$ it is now possible to calculate the theoretical sensitivity of the different $\beta$ emitters according to formula (1). For thermal neutrons at 2,200 m/s and neglecting the possible effects of resonance phenomena in the epithermal region, the theoretical values of the saturation current are given in Table 5 for the different emitters considered.

<table>
<thead>
<tr>
<th>Emitter</th>
<th>$\sigma_{20}$ barn</th>
<th>$K = K_1 K_2$</th>
<th>$I_s$ corrected A per neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma^{52}$</td>
<td>4.5</td>
<td>0.61</td>
<td>0.066 $\cdot 10^{-21}$</td>
</tr>
<tr>
<td>Rh$^{104}$</td>
<td>150.19</td>
<td>0.39</td>
<td>1.34 $\cdot 10^{-21}$</td>
</tr>
<tr>
<td>Ag$^{108}$</td>
<td>60</td>
<td>0.27</td>
<td>0.416 $\cdot 10^{-21}$</td>
</tr>
<tr>
<td>Ag$^{110}$</td>
<td>60</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5 – Theoretical values of the saturation current for various emitters of $\varnothing 0.5$ mm and 10 mm long.

As neither the silver nor the rodium follow a $\frac{1}{y}$ law, it is necessary for these elements to correct the values obtained for the Westcott cross section which depends on the condition of irradiation. Moreover all values must be corrected for the neutron temperature.
4. **LOSS OF SENSITIVITY OF THE VARIOUS $\beta$ EMITTERS AS A FUNCTION OF NEUTRON DOSE**

Due to irradiation the number of stable isotopes diminishes with increasing neutron exposure and consequently the sensitivity of the detector diminishes with neutron exposure. In Table 6 is indicated the loss of sensitivity (in % with respect to initial sensitivity) in function of the integrated flux for various emitters.

<table>
<thead>
<tr>
<th>Emitter</th>
<th>Integrated flux (n. cm$^{-2}$.S$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{20}$</td>
</tr>
<tr>
<td>V</td>
<td>0.045</td>
</tr>
<tr>
<td>Ag</td>
<td>0.44</td>
</tr>
<tr>
<td>Rh</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**TABLE 6** - Loss of sensitivity versus integrated neutron flux.
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Numerical values of the functions:

\[ E_3 (q) \equiv \int_{q}^{\infty} \frac{e^{-p}}{p^3} \cdot dp \]

\[ F_2 (q) \equiv q^2, \quad E_3 (q) \]

Values of \( E_3 \) have been computed in CETIS (C.C.R.ISPRA) in assimilating the integral to a sum of trapezia: thus the tabulated values are slightly higher than the theoretical ones.
$$q \quad E_3(q) \quad F_2(q)$$

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216 LINES OUTPUT THIS JOB.
ANNEX 2

Evaluation of the self-absorption factor of Rh$^{104}$

from the corresponding theoretical $\beta$ energy spectrum
A.2.1. Determination of the theoretical β energy spectrum

(A 1 and A 2.1)

For an allowed transition, the repartition of the energies of a β spectrum can be derived from the law:

\[ N(p) \, dp = K \cdot G(\pm Z, \Sigma) \, p \cdot \Sigma (\Sigma_0 - \Sigma)^2 \, dp \]

where:

\[ p \quad \text{= particle momentum} \]
\[ \Sigma \quad \text{= energy of the } \beta \text{ particle expressed in relativistic units} \]
\[ \Sigma_0 \quad \text{= maximum energy of the spectrum} \]
\[ Z \quad \text{= atomic number of the daughter} \]
\[ G(\pm Z, \Sigma) \quad \text{= Fermi function} \]
\[ p = (\Sigma^2 - 1)^{1/2} \]
\[ \Sigma = \frac{E}{0.512} + 1 \]

\[ G(\pm Z, \Sigma) \] is tabulated in function of \( \frac{p}{Z} \)

K is a complex factor whose absolute value is not necessary for the specific case considered where the only important term is the statistic factor \( \Sigma (\Sigma_0 - \Sigma)^2 \) which is representative of the shape of the spectrum.
After integration it follows:

\[ N = K' \cdot G(\pm z, \Sigma) \cdot p \cdot \Sigma (\Sigma_0 - \Sigma)^2 \]

In the specific case of rhodium we have:

\[ E_{\text{max.}} = 2.44 \text{ MeV} \]

\[ Z \text{ of the daughter} = 46 \]

\[ \Sigma_0 = \frac{E}{0.512} + 1 = 5.765 \]

It is possible to plot a theoretical spectrum, similar to the true spectrum except for the \( K' \) coefficient. The calculated values are tabulated in Table I and the corresponding spectrum has been plotted in Fig. I.

### A.2.2. Evaluation of the self-absorption factor by energy groups

From the preceding values it becomes possible to calculate a self-absorption factor in assimilating the spectrum to a sum of rectangles each of which corresponding to a mean energy value and a mean number of particles (proportional to the true number by \( K' \)).

By successive applications of the formula:

\[ f = \frac{\lambda}{a} \left(0.5 - \int_2 \left( \frac{a}{\lambda} \right) \right) \]

a good approximation of \( K_2 \), extended to the whole spectrum, can be obtained.

For a spectrum assimilated to a sum of 10 rectangles where the mean data are those of Table I the calculation, indicated in Table II, leads to:

\[ K_2 = \frac{10}{\sum N_f} = 0.41 \]
TABLE I - Determination of the theoretical β spectrum of Rhodium 104.
Fig. I - Rh$^{104}$ THEORETICAL $\beta$ ENERGY SPECTRUM

E (MeV)
### TABLE II - Computation of the self-absorption factor from the $\beta$ spectrum

\[
K_2 = \frac{\sum_{N_f} N_f}{\sum_{N} N} = \frac{6.658}{16.302} = 0.41
\]

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BIBLIOGRAPHY


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