AEC
RESEARCH
and
DEVELOPMENT
REPORT

BNWL-395
4-

**¹¹B BETA CURRENT THERMAL
NEUTRON FLUX DETECTOR**

C. N. JACKSON, JR.

APRIL, 1967

TO	FROM	DATE	REMARKS

BATTELLE-NORTHWEST

BATTELLE MEMORIAL INSTITUTE / PACIFIC NORTHWEST LABORATORY

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PACIFIC NORTHWEST LABORATORY

RICHLAND, WASHINGTON

operated by

BATTELLE MEMORIAL INSTITUTE

for the

UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

PRINTED BY/FOR THE U. S. ATOMIC ENERGY COMMISSION

ERRATA

PAGES 7 AND 8

The "Captions" on Figures 3 and 4 are reversed.

PAGE 4

The "Caption" for Figure 1 should read:

Photograph of ^{11}B Detector and Component Parts (The ^{11}B is contained in a quartz tube, which in turn is contained in the iron tube holder.)

PAGE 16

Item (A) in Figure should read:

Al_2O_3 Insulation

3 3679 00060 5610

BNWL-395
UC-37, Instruments

^{11}B BETA CURRENT THERMAL NEUTRON FLUX DETECTOR

By

C. N. Jackson, Jr.

Instrumentation Section
Applied Physics and Electronics Department

April, 1967

FIRST UNRESTRICTED
DISTRIBUTION MADE

MAY 22 '67

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON

Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

^{11}B BETA CURRENT THERMAL NEUTRON FLUX DETECTOR

C. N. Jackson, Jr.

ABSTRACT

The design and performance of a ^{11}B beta current, self-powered, in-core neutron flux detector was investigated during this thermal neutron detector development program. Experimental results, beta current calculations and some results obtained with a ^{103}Rh self-powered detector are given. Test instrumentation and in-core capsule design are described.

TABLE OF CONTENTS

LIST OF FIGURES	v
INTRODUCTION.	1
SUMMARY AND CONCLUSIONS	2
DISCUSSION.	4
Detector Design	4
Detector Geometry and Configuration.	6
Beta Current	6
Test Capsule.	8
Detector Gamma Tests.	9
In-Core Performance	10
Small Signal Mode.	10
Large Signal Mode.	11
Transient Response	13
ACKNOWLEDGEMENT	15
REFERENCES.	15
APPENDIX A: Rhodium Detector Tests	16
APPENDIX B: Test Circuits for I-V Measurement.	18
APPENDIX C: Analysis of Beta Detector Signals.	20
DISTRIBUTION.	25

LIST OF FIGURES

1	Photograph of ^{11}B Detector and Component Parts	4
2	Design Details of ^{11}B Detector	5
3	Instrumented Test Capsule	7
4	Simplified Electrical Circuit of ^{11}B Detector	8
5	Boron and Carbon Chamber I-V Curves	9
6	Boron and Carbon Chamber I-V Curves for High Neutron Flux In-Core Irradiation	12
7	Typical Large Signal Response of ^{11}B Chamber	14
8	Transient Response of ^{11}B Chamber	15
9	Commercial Rhodium Neutron Detector	16
10	Gamma Response of Rhodium Detector and Cable with Lead Foil Shielding	17
11	Functional Schematic and Equivalent Circuit of I-V Test Circuit	19
12	I-V Test Battery Box	20

^{11}B BETA CURRENT THERMAL NEUTRON FLUX DETECTOR

C. N. Jackson, Jr.

INTRODUCTION

Neutron flux density in a nuclear reactor core is directly related to heat generation or power level. Thus, the continuous measurement of flux density at many points throughout the reactor core contributes significantly to the efficient and safe control of the reactor. Nuclear detectors usually provide greater response speed and increased dynamic range than temperature sensors. This report describes a self-powered ^{11}B beta current detector, investigated in an effort to develop a useful, reliable, long-lived, in-core nuclear detector. Design concepts, test techniques, and experimental performance characteristics are described and analyzed.

In the ^{11}B detector, ⁽¹⁾ the sensitive detecting material captures neutrons to yield ^{12}B that decays, with a 20 msec half life, to ^{12}C yielding a beta particle with a maximum energy of 13.4 MeV in the process. The resultant electron flow from ground through the signal leads to the boron electrode neutralizes the positive charge left by the emitted betas. Thus, the electron flow should result in a measurable signal current proportional to neutron flux level. Earlier in-core investigations have shown, however, that the gamma sensitivity of the chamber and both positive and negative background currents generated in the detector signal cables were large enough to significantly reduce the accuracy of the readings from the detector.⁽²⁾ A gamma compensating chamber containing ^{12}C and a twin-wire cable were incorporated in the design of the detector in an attempt to obtain an optimum neutron to background signal ratio.

The ^{11}B was initially selected⁽²⁾ in preference to several other isotopes as the beta generating material because it seemed to offer the best compromise of several significant parameters: short half life, emitted high beta energy and low burnup associated with the small thermal neutron cross section. Until very recently, there have been conflicting values reported in the literature for the neutron cross section; however, it appears, as reported by another investigator,⁽⁴⁾ that 5 mb seems to be the more likely value as compared to 50 mb originally anticipated.

In addition to the ^{11}B detectors, two ^{103}Rh detectors were investigated to obtain information regarding their performance characteristics. The results of this work appear in Appendix A. The ^{11}B and ^{103}Rh neutron detectors were tested in both gamma and neutron irradiation facilities. The neutron in-core irradiation facilities are located in a Hanford production reactor operated by Douglas United Nuclear, Inc.

SUMMARY AND CONCLUSIONS

A self-powered ^{11}B thermal neutron flux detector was developed and thoroughly tested to establish performance characteristics of the device for possible use in thermal neutron flux reactors. The detector featured an integral twin-chamber, twin-lead design using a ^{11}B chamber for neutron detection and a carbon chamber for gamma compensation. The boron chamber contained 0.88 g of ^{11}B sensitive emitter material, and the gamma compensating chamber contained 0.72 g of carbon. The chamber housing provided a workable, reliable, test vehicle for conducting experiments both in reactor and gamma irradiation facilities. This housing featured an iron shield to reduce background effects from surrounding material and provided ample room for the relatively large amounts of sensitive detecting material.

The performance demonstrated by the ^{11}B detector was not satisfactory for thermal neutron flux measurement. The principal deficiencies of the ^{11}B concept are: (1) a very small neutron response signal current, and (2) a signal to background ratio of less than one. Unfortunately, the parameter limiting the signal level is the small thermal neutron cross section of ^{11}B , which in recent publications^(3,4) has been 5 mb.

Another problem is a large spurious current signal mode ($\sim 4 \mu\text{A}$) that provided an imprecise neutron flux measurement with large overshoot and a transient response time of about 30 sec. With additional work, the large signal mode reaction could probably be controlled. It might be possible to improve the ion pair recombination--the postulated cause of the large signal mode of operation--by mixing a conducting material with the ^{11}B sensitive material to reduce its resistivity.

Improvements achieved through additional effort appear to be insufficient to warrant further effort with the ^{11}B concept. However, similar approaches using other materials offer exciting promise. Development of an improved beta current detector could possibly be achieved by the use of ^7Li as the sensitive emitter material for thermal neutron detection.

Important performance characteristics were established for a commercial self-powered rhodium detector. Tests were conducted both at gamma and neutron irradiation facilities. When irradiated in gamma flux, the rhodium chamber exhibited a positive response, while the cable alone generated a negative signal. The rhodium detector provided a relatively large and continuous signal output current throughout a neutron exposure of 3×10^{21} nvt. Data taken after a reactor scram showed that the detector signal reversed polarity and attained a maximum negative signal of about -3nA .

DISCUSSION

DETECTOR DESIGN

The twin-chamber, twin-lead detector assembly proved excellent for obtaining the desired experimental performance data. Both the design and geometry of the detector are shown in Figures 1 and 2. The detector housing was designed to provide sufficient beta shielding and ample space in the chambers for nearly 1 gram of ^{11}B or ^{12}C .

FIGURE 1. Photograph of ^{11}B Detector and Component Parts (The ^{11}B is contained in the quartz tubes, which in turn is contained in the iron tube holder.)

Weights:

Boron, 0.88 g
Carbon, 0.72 g
Iron case, 250 g
Quartz tube, 3 g

- (A) Iron case 0.89 in. diam
(B) SS wire 0.005 in. diam
(C) Quartz tube 0.250 in. diam
0.040 in. wall thickness
nickel coating (outer surface)

Two wire cable

- (A) Sheath 304 SS
0.125 in. diam
0.030 in. wall
(B) Wire 0.005 in. diam SS
(C) Insulation MgO

FIGURE 2. Design Detail of ^{11}B Detector

Detector Geometry and Configuration

The ^{11}B chamber was filled with 0.88 g of boron powder to a theoretical density of 0.9 g/cm^3 , or about 38% of its normal density as a metal. The carbon chamber was filled with 0.72 g of carbon powder. These precise values were calculated as the necessary amounts of each material to obtain matched gamma signals from each chamber, based on experimental measurements made with a similar assembly. The quartz plugs minimized voids within the detector chambers. The quartz felt provided a mechanical support for anchoring the center electrode at the bottom end of the quartz tube. It also prevented the loss of material from the quartz tube chamber.

The detector could be evacuated or backfilled with a gas as desired through the evacuation tube. This feature allowed adjustment of the detector internal gas pressure during in-core reactor tests. Variations of gas pressure provided a valuable experimental procedure for determining both the gas and electrical conditions within the detector.

In the assembly, the two chambers were located side by side in a housing fabricated from high purity iron, a relatively low level beta emitting material. The relatively thick iron (1/8 in. minimum shield absorbs most beta particles originating outside the detector while generating a relatively low beta background itself.

Beta Current

Beta particle emission from radioactive ^{12}B is defined as positive current, and it should generate a positive potential at the signal lead. A large fraction of the energetic beta particles (13.4 MeV maximum) penetrates the quartz wall and is absorbed in the iron sheath, thus generating the "beta current" of the self-powered unit.

The convention adopted for defining positive and negative currents is described schematically in Figure 3. Compton scattered betas plus betas emitted from surrounding material contribute to the negative background current generated. Algebraic summing of the two chamber signals to achieve gamma cancellation is illustrated in principle by the following equations:

$$i_n = i_{(n + \gamma)} - i_{(\gamma)} \quad (1)$$

where

i_n = net neutron-caused signal

$i_{(n + \gamma)}$ = boron chamber output signal

$i_{(\gamma)}$ = carbon chamber output signal.

FIGURE 3. Simplified Electrical Circuit of ^{11}B Detector

The application of this principle of cancellation in earlier work reduced the background signal from the two wires of the twin-wire cable by a factor of six during reactor experiments. In total this detector assembly provided a reliable vehicle for investigating beta current effects.

TEST CAPSULE

For in-core reactor testing, the assembled chamber was placed into a long magnesium tube that constituted a simple but carefully engineered test capsule. Details of the capsule, as inserted in the reactor core, are shown in Figure 4. Magnesium, which contributes only low beta background, was selected in preference to aluminum for the capsule tube material. Efficient insertion and repositioning of the detector capsule in the reactor core (translation or rotation) was readily achieved as needed during the experiments. The outside of the capsule was water cooled, and an iron-constantan thermocouple was installed against the top of the chamber to monitor the temperature.

Positive current, primarily from neutron caused beta emission, is defined as transfer of negative charge (electrons) from central wire to sheath (ground).

Negative current defined as transfer of negative charge (electrons) from sheath (ground) to central wire.

Electrons can be ejected with sufficient energy to effect a charge transfer by photons (Compton scattering) or by neutrons (activating to beta decaying isotope).

FIGURE 4. *Instrumented Test Capsule (The test capsule is shown inserted into a water cooled channel in the reactor core.)*

DETECTOR GAMMA TESTS

The assembled chambers were carefully conditioned and tested prior to the reactor in-core experiments. They were subjected to an evacuated bake until the insulation resistance of each chamber exceeded one teraohm. The gamma sensitivity was then measured in an irradiation field of about 1×10^7 R/hr at a ^{60}Co irradiation facility. This gamma test also served as a final check of the detector and test instrumentation prior to the in-core experimentation.

Beyond measuring the gamma-caused currents, an I-V curve was obtained for each chamber. Potentials up to ± 100 V were applied in series with each chamber to obtain the complete set of data shown in Figure 5. Details of the I-V curve instrumentation are described in Appendix B. For practical purposes, the gamma sensitivities of both chambers were identical, with a value of $\sim 9 \times 10^{-17}$ A/R hr. In Figure 5 the "X" axis crossing indicates that +25 V is required to completely compensate the negative signal caused by gammas. The "Y" crossing corresponds to the magnitude of the gamma-induced beta current, which is about -9 nA.

FIGURE 5. Boron and Carbon Chamber I-V Curves (Boron and carbon I-V curves obtained during a gamma irradiation of about 1×10^7 R/hr. The boron curve is superimposed on the carbon curve indicating the excellent match achieved in balancing the gamma sensitivity. The self powered zero crossing output is 0.9 nanoamps for both chambers.)

Gamma irradiation reduces the electrical resistance of a chamber by inducing ionization in the insulators; the slope of the curve yields the equivalent resistance of the chamber; in this case 4×10^{10} ohms. These I-V curves were also useful in determining the self-powered sensitivity and for providing information on the resistance level and resistance linearity.

IN-CORE PERFORMANCE

High level, thermal neutron flux, in-core tests were conducted to define the principal operational characteristics of the detector. These tests were performed in two experimental assemblies in a facility at a Hanford production reactor. In separate tests, the boron chambers of both assemblies performed in an unexpected manner, exhibiting two distinct modes of operation. For one to several hours at the start of an irradiation, the self-powered current of the boron chambers was small and relatively stable. Then a period of steady signal increase occurred until restabilization was reached at a much higher level. The initial small stable current is identified as the "small signal mode," and the increasing high level current is identified as the "large signal mode." In the same tests, the companion carbon chamber performed as expected, generating a steady, continuous negative current output.

SMALL SIGNAL MODE

The current of the small signal mode was about -3 nA. Apparently the positive current, produced by the action of the neutron flux, was less than the opposing negative current, attributed mainly to gamma flux. This weak neutron flux signal correlates with a 5 mb thermal neutron cross section for ^{11}B . In general this small mode current does not provide a desirable signal strength; the signal to background ratio is less than one.

LARGE SIGNAL MODE

The in-core thermal neutron flux triggers some reaction that results in the second, large signal performance mode. This trigger action is manifested by a sudden increase in the signal current that starts in the low nA range and builds up to about 4 μ A. The buildup is smooth with a doubling time of about 2 min. The matched carbon chamber, subjected to the same environment and located less than 0.5 in. away, was not affected. It generated a prompt and steady output of about 20 nA. The carbon chamber signal seems well behaved, and the level is approximately proportional to the gamma flux level. As the two chambers are essentially identical in construction and have essentially the same test environment, the only significant variation is in the type of sensitive material.

With the information available, the mechanism causing the large signal current cannot be positively identified. However, discussion of possible factors contributing to the effect is illuminating. Since boron is a semiconductor material, the electrical resistance within the sensitive material of the boron chamber is much higher than resistance in the sensitive material of the carbon chamber. Comparative resistivities of boron and carbon are 1.8×10^{12} and $1.375 \times 10^3 \mu\Omega\text{-cm}$, respectively. The high resistance of the ^{11}B could lead to poor ion-pair recombination and hence, to availability of electrons for diffusion through the sensitive material. Competing cross sections resulting in reactions such as (n, α) especially with ^{10}B impurities could cause formation of many ion-pairs. Thus, it is postulated that electron diffusion resulting from poor ion-pair recombination is probably the source of the large current. Considering this possible mechanism, the I-V characteristics of the chamber and the transient characteristics of the large signal deserve discussion.

During large signal mode operation, unusual plateau and response time characteristics were exhibited by the boron chamber. Perhaps the most revealing are the changes that occurred in the I-V characteristics shown in Figure 6. The

FIGURE 6. Boron and Carbon Chamber I-V Curves for High Neutron Flux Incore Irradiation (The incore irradiation has radically altered the shape of the boron chamber I-V curve. The ordinate scale is increased by a factor of 1000 in order to accomodate the boron curve. The self powered output of the boron chamber is minus two microamps, that of the carbon chamber is minus twenty eight nanoamps.)

boron chamber exhibited a pronounced nonlinearity, described as "reverse diode effect." The current flows much more readily in the negative direction, increasing rapidly with voltage to reach a saturation level of about 1.9 μ A. Under these conditions, the general level of the boron signal was greatly increased (factor of 1000). During this large signal mode, both chambers were back-filled with air (atmospheric pressure) to observe the effect on the signal current. The boron current dropped sharply to about 5 nA, while the corresponding carbon signal was relatively unaffected. Application of chamber gas pressure up to 15 psig did not significantly affect the signal output of either chamber.

Although it cannot be fully explained at this time, the high current output, the "reverse diode effect," and the effect of back-filling the detector with air may eventually be instrumental in identifying the phenomena taking place during large signal mode operation.

TRANSIENT RESPONSE

Transient responses of both chamber signals to changes in thermal neutron flux level were observed, and a sample of this performance is shown in Figure 7. Compared with carbon, the boron signal exhibited spurious and poor time-response, resulting in imprecise indication of neutron flux level. The time lag in the signal was relatively long--in the order of minutes. This lag is far too long to result only from chamber resistance and capacitance effects. The RC time delay is small, significantly less than the 0.020 sec delay introduced by the ^{12}B beta decay half life.

A boron chamber time response of about 3 min was noted in a separate test, as shown in Figure 8. The response is

not a simple curve, but exhibits a complex nature with both buildup and decay. To achieve such a complex response, the operating mechanism may very well involve several competing nuclear reactions.

FIGURE 7. Typical Large Signal Response of Boron Chamber (As shown the boron signal yields an imprecise indication of neutron flux. During this test changes were made in neutron flux as shown by the carbon signal.)

FIGURE 8. *Transient Response of Boron Chamber (The signal current output is that obtained after a positive 30 volts has been placed on the signal collection wire while the detector was incore in a high neutron flux.)*

ACKNOWLEDGEMENT

The contributions of co-workers L. D. Philipp, W. L. Bunch, M. R. Wood and J. I. Forsberg during the various phases of the described work are gratefully acknowledged.

REFERENCES

1. W. L. Bunch and G. F. Garlick. Boron-12 Beta Decay Neutron Generator. U. S. Patent No. 3,259,745, granted July 5, 1966.
2. W. L. Bunch and M. R. Wood. Boron-11 Neutron Flux Monitors Interim Report, BNWL-64 Battelle-Northwest, Richland, Washington. April, 1965.
3. W. L. Imhof, R. G. Johnson, F. J. Vaughn and M. Walt. "Cross Sections for the $^{11}\text{B} (n, \gamma) ^{12}\text{B}$ Reaction," Physical Review, vol. 125, no. 4, pp. 1334-1336. February, 15, 1962.
4. D. T. Goldman. Chart of the Nuclides, APH 66H, Educational Relations. General Electric Co., Schenectady, New York 12305. July, 1965.

APPENDIX A
RHODIUM DETECTOR TESTS

APPENDIX A

RHODIUM DETECTOR TESTS

To augment available performance data, two rhodium self-powered devices were irradiated to 3×10^{21} nvt in a production reactor at Hanford. One device was a typical commercial rhodium detector with a 5 cm emitter wire, as shown in Figure 9. In order to obtain information on the extent of cable background signal, a second device (a cable only assembly) without the emitter wire was also tested. Both assemblies were placed in stainless steel capsules and inserted into a water-cooled test facility in the reactor core.

(A)	Al ₂ O ₃ Insulation	0.009 in. Wall
(B)	Rhodium Emitter wire	0.020 in. diam by 5.0 cm long
(C)	Collector Cap	0.010 in. Wall
(D)	Cable Wire	0.010 in. diam Inconel
(E)	MgO Insulation	0.009 in. diam
(F)	Cable sheath	0.006 in. Wall Inconel
	Sensitivity	6×10^{-19} amps/nv
	Detector size	1/16 in. diam x 5.0 cm in length

FIGURE 9. *Commercial Rhodium Neutron Detector (Small, self powered, in core neutron detector that uses a ^{103}Rh beta current emitter)*

GAMMA TESTS

Prior to reactor testing, the gamma sensitivity and the effect of various thicknesses of Pb foil wrapped around the

detector were measured in an irradiation field of 1×10^7 R/hr. The effect of foil wrappings (bare condition to 0.025 in. wrap) on the signal current is shown in Figure 10. Note that nearly the full gamma effect (Compton beta and other mechanisms) is reached in the first 0.005 in. of wrap.

FIGURE 10. *Gamma Response of Rhodium Detector and Cable with Lead Foil Shielding (This test was conducted in an irradiation field of 1×10^7 R/hr at a ^{60}Co gamma facility.)*

When the detector was inserted into the gamma irradiation facility, a maximum net positive current of 0.06 nA was observed. The rhodium tip of the detector was nearer the ^{60}Co gamma field than the cable. The gamma characteristic of a rhodium detector depends on the amount of cable exposed to the field. In a reactor installation where a significant length of cable is in-core, the gamma response current will probably be negative in polarity.

IN-CORE TEST

The same two units (a detector plus integral cable and a cable-only assembly) were irradiated in-core in a stainless steel, water-cooled capsule. The signal from the cable-only assembly was erratic and the unit failed shortly after installation in the reactor. The quality of this signal did not lend itself to quantitative measurement. However, the signal current polarity was consistently negative. The detector plus integral cable assembly generated a continuous output signal throughout the investigation. However, during this time, the signal amplitude varied as much as +30% to -10% from its initial value. This magnitude of signal variation precluded the possibility of performing burnup calculations. It should be recognized that most, if not all, of these variations in signal strength could have been caused by perturbations in the neutron flux level.

After a reactor scram shutdown, the signal current reversed polarity and reached a maximum negative output of -3 nA. Time constants of 42 sec and 4.4 min were observed during transient shutdown conditions. These time delays correspond with the half life decay of ^{104}Rh (the beta emitter) and indicate that the signal current is a function of the $^{103}\text{Rh} (n, \gamma) ^{104}\text{Rh}$ neutron reaction.

APPENDIX B

TEST CIRCUITS FOR I-V MEASUREMENTS

APPENDIX B

TEST CIRCUITS FOR I-V MEASUREMENTS

The test circuit used to obtain data for the I-V curve is shown in Figure 11. Accurate measurement of reactor in-core chamber performance can be obtained by uncorrected ammeter readings when the leakage current is smaller (by a factor of 100) than the chamber currents. An isolation leakage resistance greater than one terraohm was obtained; thus, the insulators in the battery box were in good condition. The battery box both supplies and measures polarization potentials up to ± 100 V. This voltage is conveniently adjusted as shown in the schematic of Figure 12.

Functional Schematic

R_C = Chamber resistance

Equivalent Circuit

FIGURE 11. Functional Schematic and Equivalent Circuit of I-V Test Circuit

APPENDIX C
ANALYSIS OF BETA CURRENT DETECTOR SIGNALS

APPENDIX C

ANALYSIS OF BETA CURRENT DETECTOR SIGNALS

A comprehensive formula relating all of the various parameters in terms of the output signal is useful in designing a beta current detector. A rather lengthy general expression, shown below, brings into perspective the many factors contributing to this current. Significant groups of these parameters, amenable to direct analysis, are calculated for typical emitter materials. Beta particle escape factors do not lend themselves to simple analysis, but some interesting beta escape efficiencies are calculated for limited special conditions.

The output signal of a beta current detector is characterized by the following general expression.

$$i_{\beta} = + (nv, No, \sigma, C, T_{\lambda}, B, E, G, Te) \\ - (n_1 v_1, No_1, \sigma_1, C, T_{\lambda 1}, B_1, E_1, G_1, Te_1) \dots \\ \pm (n_n v_n, No_n, \sigma_n, C, T_{\lambda n}, B_n, E_n, G_n, Te_n)$$

where

i_{β} = Beta generated output current

nv = Thermal flux

No = Atoms of emitter materials

σ = Thermal neutron cross section

$C = 1.6 \times 10^{-19}$ Coulombs/unit charge

T_{λ} = Half life time delay factor

B = Burnup factor

E = Beta particle energy factor

G = Geometry factor

Te = Temperature factor

The first group of terms represents the useful beta current. The other groups result from competing reactions such as Compton scatter electrons, other beta current emissions

from surrounding material, and from (n, α) or (n,p) reactions that could cause an ion chamber effect. Even at the low operating voltage of these detectors, there may be collection of ion pairs caused by reactions that release heavy ions in the emitter material.

The E and G factors combine to form a beta escape efficiency which determines the percentage of theoretical current obtained as output. Unfortunately, an involved complex calculation based on energy and geometry conditions is required to calculate the escape efficiency.

In general, the temperature term reflects changes in the resistivity of electrical insulators in a chamber. Higher operating temperatures cause greater leakage currents through electrical insulators of a detector.

THEORETICAL BETA CURRENT CALCULATIONS

The beta release in the emitter material, represented by the (nv No σ) term can be calculated readily. This term provides a convenient theoretical maximum value for comparing the performance of various candidate emitter materials.

A typical calculation of a theoretical output current using ^{11}B and ^{103}Rh as emitters follows. The output is expressed as a signal current in terms of neutron flux and a one gram quantity of emitting materials.

$$A_1 = nv \text{ No } \sigma \text{ C} = nv \text{ m } \frac{\text{A } (1) \sigma (1.6 \times 10^{-19})}{\text{A}}$$

$$A_2 = \frac{\text{A } (1) \sigma (1.6 \times 10^{-19})}{\text{A}}$$

$$A_1 = nv \text{ m } (A_2)$$

where

$$A_1 = \text{Theoretical output current}$$

A_2 = Output current/nv m

$\overset{\circ}{A}$ = Avogadro number

A = Atomic weight

σ = Thermal neutron cross section

m = Grams of emitter material

C = 1.6×10^{-19} Coulombs/ion pair

(1) $\sim$ 1 gram of emitter material

For Boron-11:

$$\sigma = 5 \text{ mb } (5 \times 10^{-27})$$

$$A_2 = \frac{0.602 \times 10^{24} (1) 5 \times 10^{-27} (1.6 \times 10^{-19})}{11}$$

$$A_2 = 4.5 \times 10^{-23} \text{ A nv}^{-1} \text{ m}^{-1}$$

For Rhodium-103:

$$\sigma = 150 \text{ b}$$

$$A_2 = \frac{0.602 \times 10^{24} (1) 150 \times 10^{-24} (1.6 \times 10^{-19})}{103}$$

$$A_2 = 1.48 \times 10^{-19} \text{ A nv}^{-1} \text{ m}^{-1}$$

Calculation of theoretical maximum current for a ^{103}Rh detector with one gram of emitter material placed in a neutron flux of 1×10^{13} nv:

$$A_1 = A_2 \text{ m nv}$$

$$A_1 = (1.48 \times 10^{-19}) 1 (1 \times 10^{13}) = 1.48 \times 10^{-6} \text{ A}$$

$$A_1 = 1.48 \text{ } \mu\text{A (theoretical maximum output current).}$$

BURNUP OF EMITTER MATERIAL*

The burnup factor (B) determines the proportion of emitter atoms that have been removed by nuclear reactions after an irradiation exposure.

* *Friedlander and Kennedy. Nuclear and Radiochemistry, John Wiley and Sons Inc., New York, p. 137, Equation 5-11.*

The burnup factor is calculated using the following formula:

$$n/No = e^{-B_1 t^*}$$

where

$$B_1 = nv \sigma$$

n = Amount of emitter material at any time, t

No = Original amount of emitter material

t = Exposure time

nv = Thermal neutron flux

σ = Thermal neutron cross section.

$$B = 1 - n/No = 1 - e^{-B_1 t}$$

BURNUP OF ^{27}Al

When this emitter material is exposed to 10^{14**} nv for one year,

$$B_1 t = (1 \times 10^{14}) (0.23 \times 10^{-24}) (3.15 \times 10^7 \text{ sec})$$

$$B_1 t = 0.725 \times 10^{-3}$$

$$B = 1 - e^{-7.25 \times 10^{-4}} \approx 0.$$

Thus, the burnup of ^{27}Al is negligible for this exposure.

Typical values for beta current release and burnup are presented in the following Table:

* Friedlander and Kennedy. *Nuclear and Radiochemistry*, John Wiley and Sons Inc., New York, p. 137, Equation 5-11.

** An exposure typically experienced at the ETR

COMPARATIVE DATA FOR BETA CURRENT EMITTER ISOTOPES

Thermal Neutron Flux Detection

	Cross Section, Barns	Half Life, sec	Maximum B Energy, MeV	Beta Current Release per nv per Gram, $A \text{ nv}^{-1} \text{ m}^{-1}$	Calculated Burnup in 10^{14} nv for 1 year
Li ⁷	0.033	0.85	13.0	4.5×10^{-22}	negligible
B ¹¹	0.005	0.02	13.4	4.5×10^{-23}	negligible
Al ²⁷	0.23	158	2.9	8.2×10^{-22}	negligible
V ⁵¹	4.5	226	2.6	8.5×10^{-21}	0.14%
Tc ⁹⁹	22	16	3.4	2.1×10^{-20}	7%
Rh ¹⁰³	150	42 and 264	2.4	1.5×10^{-19}	38%

BETA PARTICLE ABSORPTION ESTIMATE

An exponential curve* can be drawn to represent the absorption of beta particles from a continuous energy spectrum source with a maximum energy of 0.1 to 4 Mev. In making the beta particle absorption estimate, the portion of the beta particle beam remaining after passing through a given thickness of material will be considered the beta escape factor. The following calculations show the beta escape factor for a beta particle beam of 2.4 MeV maximum energy passing through 0.010 in. of Al_2O_3 and for a beam passing through 0.010 in. of Al_2O_3 + 0.010 in. of rhodium. This thickness of Al_2O_3 is typical of that found in the electrical insulator surrounding the rhodium emitter. The thickness of aluminum plus that of rhodium is equivalent to the thickness of the material from the center of a rhodium emitter to the collector.

* W. J. Price. *Nuclear Radiation Detection*, McGraw-Hill Book Co., New York, p. 19, Equations 1-19 and 1-20.

$$E_B = e^{-\mu_m d_m}$$

E_B = Beta escape factor (fraction of beam remaining through distance d_m)

μ_m = Mass absorption coefficient

d_m = Absorber thickness

E_m = Max beta energy

$$\mu_m = \frac{17}{E_m^{1.14}} = 6.3.$$

Given: Absorber Al_2O_3 of 0.010 in. = 0.025 cm = 100 mg-cm⁻²

$$E_B = e^{-6.3 \times 0.1} = e^{-0.63} = 0.53$$

$$E_B = 53\%.$$

Given: Absorber Al_2O_3 of 0.010 in. = 0.025 cm = 100 mg-cm⁻²

plus Rhodium of 0.010 in. = 0.025 cm = 300 mg-cm⁻²

Total = 400 mg-cm⁻²

$$E_B = e^{-6.3 \times 0.4} = e^{-2.52} = 0.08$$

$$W_B = 8\%$$

Thus, 53% of a beta particle beam will penetrate through 0.010 in. of Al_2O_3 insulator while only 8% will go through the same amount of Al_2O_3 plus an additional 0.010 in. of rhodium.

DISTRIBUTIONNumber of Copies

3	<u>Argonne National Laboratory</u> A. Amorosi J. M. Harrer (2)
9	<u>Atomic Energy Commission</u> Division of Reactor Development Technology Washington, D. C. R. E. Feit N. Grossman F. C. Legler (6) C. E. Poyet
4	<u>Atomic Energy Commission, Richland</u> Office of Senior RDT Site Representative W. E. Fry P. G. Holsted (2) A. G. Hosler
2	<u>AECL - Pinawa</u> Manitoba, Canada J. W. Hilborn (2)
298	<u>Division of Technical Information Extension</u>
4	<u>Douglas United Nuclear</u> Richland, Washington T. W. Ambrose A. E. DeMers N. L. Hildreth J. E. Kavekis
3	<u>General Electric Company</u> Richland, Washington G. C. Fullmer M. C. Leverett W. S. Nechodom

Number of Copies

3

Richland Operations Office

C. L. Robinson
R. K. Sharp
Technical Information Library

45

Battelle-Northwest

E. R. Astley
T. R. Billeter
D. P. Brown
W. L. Bunch
R. G. Clark
R. R. Cone
D. L. Condotta
G. M. Dalen
G. E. Driver
G. F. Garlick
D. L. Hovorka
C. N. Jackson Jr. (6)
V. I. Neeley
R. S. Paul
L. T. Pedersen
L. D. Philipp
J. T. Russell
J. C. Spanner
W. G. Spear (10)
C. D. Swanson
K. L. Swinth
M. R. Wood
F. W. Woodfield
D. C. Worlton
Technical Publications (2)
Technical Information Files (5)