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L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

A NEW SELF-POWERED FLUX DETECTOR

Nouveau collectron pour détecter les flux de neutrons en réacteur

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Chalk River, Ontario

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Résumé

On a constaté qu'il était possible d'employer un câble coaxial inconel-inconel comme collectron à réponse rapide si le fil de noyau a un assez grand diamètre. On donne les résultats d'essais effectués avec un détecteur de neutrons de ce genre dont le fil de noyau avait environ 1.5 mm de diamètre. On décrit, par ailleurs, d'autres matières pouvant servir d'émetteur dans un détecteur ayant ainsi un assez grand diamètre.

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ABSTRACT

It has been found that an Inconel-Inconel coaxial cable can be used as a fast-responding, neutron, self-powered flux detector if the core wire is sufficiently large. Test results obtained with such a detector, having a core wire $\sim$ 1.5 mm in diameter, are presented. Other materials suitable for use as an emitter material, in such a relatively large diameter detector, also are included.

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1. INTRODUCTION

Self-powered flux detectors are in wide-spread use in nuclear reactors. Typically, they consist of a coaxial cable, having a metallic outer sheath, frequently of Ni-Cr-Fe alloy, such as Inconel 600, a mineral oxide insulation layer, usually MgO or Al_2O_3, and a metallic central wire, usually called the emitter. When such a device is placed in a radiation field, for example the neutron field in the core of a nuclear reactor, and the central conductor is connected to the sheath through an ammeter, a current flows between the two electrodes without an external bias being applied. The magnitude of the current is proportional to the intensity of the radiation field, and hence can be used as a measure of the field strength.

In a nuclear reactor, the current induced in a coaxial cable, be it a detector or a lead cable, can be attributed to one of three main causes:

1. Neutron capture in the materials of the cable can result in the formation of radioactive daughter nuclides which decay by β-emission. These high-energy electrons, emitted by the daughter nuclides, are responsible for the current flow between the two electrodes. We shall refer to this interaction as the (n,β) interaction. The current is proportional to the neutron flux, but is delayed. The current follows changes in flux intensity with a time constant determined by the half-life of the daughter nuclide. This interaction is the dominant current-producing mechanism in detectors with a vanadium or rhodium emitter [1,2].

2. Neutron capture in the materials of the cable is normally accompanied by the emission of prompt-capture γ-rays. These γ-rays can then interact with the materials of the cable, liberating high energy electrons, via Compton and photo-electric processes, thus causing a current flow. We shall refer to this interaction as the (n,γ,e) interaction. The current is proportional to the neutron flux and is prompt, i.e. the current follows changes in flux intensity instantaneously. This is the main current-producing mechanism in detectors with cobalt emitters, at the start of life [1,3], and is an important current-producing mechanism in detectors having a platinum or molybdenum emitter [1,4,5].

3. Gamma rays from the reactor itself, impinging on the cable, can liberate free electrons, thus producing a current. We shall refer to this interaction as the (γ,e) interaction. In a reactor, these external γ-rays result from neutron capture in the fuel and the reactor hardware. Hence the γ-ray flux, and the (γ,e)-induced current, are proportional to the neutron flux. The basic detector interaction is prompt, but in a reactor a significant fraction of the γ-rays are delayed, i.e. those γ-rays arising from the decay of fission products and activation products. Hence, the (γ,e) current does not follow changes in flux instantaneously, but has a delayed component. The (γ,e) interaction is an important current-producing mechanism in detectors having a platinum or molybdenum emitter [1,4,5], and indeed in any detector in which the atomic number of the emitter is large, relative to that of the sheath.

For completeness, it may be pointed out that external electrons from the reactor hardware and materials, impinging on the detector, can contribute to the overall output current [6].

Such interactions, however, are considered parasitic, and an attempt is usually made to minimize them.

In any coaxial cable, all three interactions, (n,β), (n,γ,e) and (γ,e), occur, and the net current is the sum of the individual currents arising from the different interactions. For a self-powered detector, the materials and dimensions are chosen so that one or two of the interactions will dominate thus producing a relatively large net current. However for a lead cable, the dimensions are chosen so that the contribution of the lead cable to the total signal produced by a detector/lead cable combination is small.

Because the (n,γ,e) interaction produces a prompt signal, i.e. one which follows changes in neutron flux essentially instantaneously, while the (n,β) and (γ,e) interactions result in delayed signals, a detector in which the (n,γ,e) interaction dominates is preferable in many applications, and particularly if the detector is to be used in a reactor safety system. A detector having a cobalt emitter is such a device, at least at the beginning of its life.

Initially, the current from a cobalt detector is dominated by the (n,γ,e) interaction, caused by neutron capture in ^{59}Co. However, with time, currents attributable to the radioactive decay of ^{60}Co and ^{61}Co build up. At any given time, the current attributable to ^{60}Co can be considered constant, because of this nuclide's long half-life, 5.26 a, but the current attributable to ^{61}Co is proportional to the neutron flux, and follows changes in flux, but with a time constant of 130 minutes. Thus, with irradiation, the prompt (n,γ,e) current decreases as ^{59}Co burns out, while the delayed currents from ^{60}Co and ^{61}Co increase, so that the current from a cobalt detector becomes less and less prompt with time. In a CANDU heavy-water moderated, natural-uranium reactor, it has been observed that after a mere 3 years of operation, only ∿ 57% of the total signal from a cobalt detector is prompt, ∿ 19% of the signal being attributed to the decay of ^{60}Co and ∿ 23% to the decay of ^{61}Co.

In view of the above discussion, it is apparent that a cobalt self-powered detector has a relatively short useful lifetime in a high-flux power reactor. In general, this will be true of most self-powered detectors in which mainly (n,γ,e) interactions are responsible for the current. This is because the current results from a two-step process, neutron capture, in which a γ-ray is emitted, followed by the liberation of a free electron, via Compton and photo-electric interactions of the γ-ray with the materials of the detector. The inherent sensitivity of such devices is thus low. For example, the initial sensitivity per unit length of a cobalt detector, having an emitter 0.5 mm in diameter, is about a factor of 20 smaller than that of a detector with a vanadium emitter of the same diameter [1], even though cobalt has a neutron absorption cross section which is almost a factor of 8 times that of vanadium. Thus, to achieve a useful sensitivity, i.e. one such that the currents associated with the (n,β) and (γ,e) interactions are small, relative to the current produced by the (n,γ,e) interaction, and such that the total current produced in the detector is large, relative to the current produced in the detector lead cable, it is generally necessary to use an emitter material with a relatively large neutron capture cross section. However, if this cross section is large, the burn-out rate will be rapid, so that the detector sensitivity will decrease relatively rapidly. This is especially true in a heavy-water moderated, natural-uranium reactor, where the neutron flux is $\sim 2\text{x}10^{18}\text{n}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. In such a flux, an emitter having a neutron cross section of only 5 b (1 b = 10^{-28}m^2) will burn out at a rate of ∿ 3% per year.

As a result of an experimental program carried out at the Chalk River Nuclear Laboratories (CRNL), we have developed a new self-powered flux detector in which the current from (n,γ,e) interactions dominates, so that the device follows changes in neutron flux essentially instantaneously, but the detector employs an emitter material with a low neutron capture cross section, so that the burn-out rate is acceptably small.

2. EXPERIMENTAL PROGRAM LEADING TO THE NEW DETECTOR DESIGN

The new self-powered flux detector described in this report has resulted from an experimental investigation of mineral insulated (MI) cables, having Inconel 600 core wires and Inconel 600 sheaths. In a reactor, the active (i.e. the emitter) portion of a detector is connected to the measuring instrument by means of an MI lead cable. The lead cable itself acts as a self-powered detector but by an appropriate choice of materials and dimensions, the signal from the lead cable can be made small relative to the signal from the detector itself. For the detectors used in CANDU reactors, the lead cables are normally coaxial, with the central conductor and sheath being manufactured from Inconel 600, a nickel-based alloy containing nominally 76% Ni, 15.5% Cr and 8% Fe. The insulation is MgO. At present, the outside diameter of the lead cables used in most applications is 1.0 mm, and the current generated in it is ∿ a few percent of the total current generated in the detector.

The current generated in an Inconel-Inconel MI cable, as in any self-powered detector, is attributed to the three interactions described above, (n,β), (n,γ,e) and (γ,e). Thus, we can write

$$I_{Total} = I(n,\beta) + I(n,\gamma,e) + I(\gamma,e) \qquad (1)$$

where $I(n,\gamma,e)$ is the current which results primarily from neutron capture in the core wire of the lead cable. It is proportional to the neutron flux, is prompt and positive.

$I(\gamma,e)$ is the current which results from interactions of reactor γ-rays with the lead cable. $I(\gamma,e)$ is negative, i.e. external γ-rays cause a net flow of electrons from the sheath to the central electrode.

The interaction in the detector itself is prompt, but because some of the γ-rays in a reactor are delayed, the γ-ray current has a delayed component.

I(n,β) is the current which results from the β decay of ^{65}Ni and ^{56}Mn produced by neutron capture in ^{64}Ni and ^{55}Mn. The current is delayed, having a time constant of 325 s. Manganese is present as an impurity in Inconel 600, but for use in a reactor, Inconel 600 is specified to have a maximum concentration of 0.3 wt% Mn in Inconel. Depending on the relative amounts of manganese present in the core wire and sheath of the MI cable. this current may be either positive or negative, but it is usually negative.

Thus the net current from an Inconel-Inconel MI cable results, primarily, from three interactions, one of which is positive, one of which is negative, and one of which can be either. As a result, the total current will be positive or negative, depending on the dimensions of the cable and on the concentration of Mn present in the core wire and sheath. However, it was believed that the net, i.e. total, current per unit length would remain relatively small compared with the currents generated in the active portions of conventional detectors, such as those with vanadium, platinum or rhodium emitters, with changes in the geometry of the lead cable.

In a study of Inconel-Inconel MI cables carried out at CRNL, a number of cables, having outside diameters as large as 3.0 mm, were tested. The results of this study are reported in detail elsewhere [7]. Here we note that it was found that as the core-wire size was increased, the current produced by the Inconel-Inconel MI cable increased rapidly, approximately as the cube of the core-wire diameter, and that for the larger sizes, the current was dominated by the (n,γ,e) interaction.

Thus the study indicated that an Inconel-Inconel MI cable could be used as a prompt-responding self-powered flux detector if the core-wire diameter were sufficiently large.

In some applications, a measure of the average flux across a reactor core is desired, and for this application a constant diameter Inconel-Inconel MI cable could be used. An acceptable prompt fraction would be obtained with a core-wire diameter of $\sim$ 1 mm. It may be noted here that few, if any, self-powered flux detectors are perfectly prompt. Further, there is no general rule as to what value of prompt fraction is acceptable, as this depends very much on the particular application. Frequently the designer of the system, in which self-powered detectors are to be used, adjusts his design as required to accommodate the fact that the detector is not perfectly prompt.

In other applications, a measure of the average flux over a localized region of a reactor core is desired, rather than over the complete core. In such an application not only is the dynamic response important, but it is also important that the signal produced by the 'detector' be large relative to the signal produced in the lead cable, used to transmit the detector signal through the core of the reactor and through the reactor shielding to the measuring instrumentation. A practical, prompt-responding, self-powered detector can be manufactured, using Inconel 600 as both the emitter/core-wire material and sheath material, that has sufficient sensitivity to generate a signal which is large relative to that produced in the lead cable. This detector has a stepped detector lead cable design, such that the diameter of the core wire of the detector section, i.e. the emitter, is $\gtrsim$ 4 times that of the lead cable core wire. This design is illustrated schematically in Figure 1.

Such a stepped detector was irradiated in NRU. The dimensions of the detector are summarized in Table 1, while the important experimental results are summarized in Tables 2 and 3. Here it may be noted that prompt-responding detectors, having emitter sections $\sim$ 1 m long, are commonly used in heavy-water

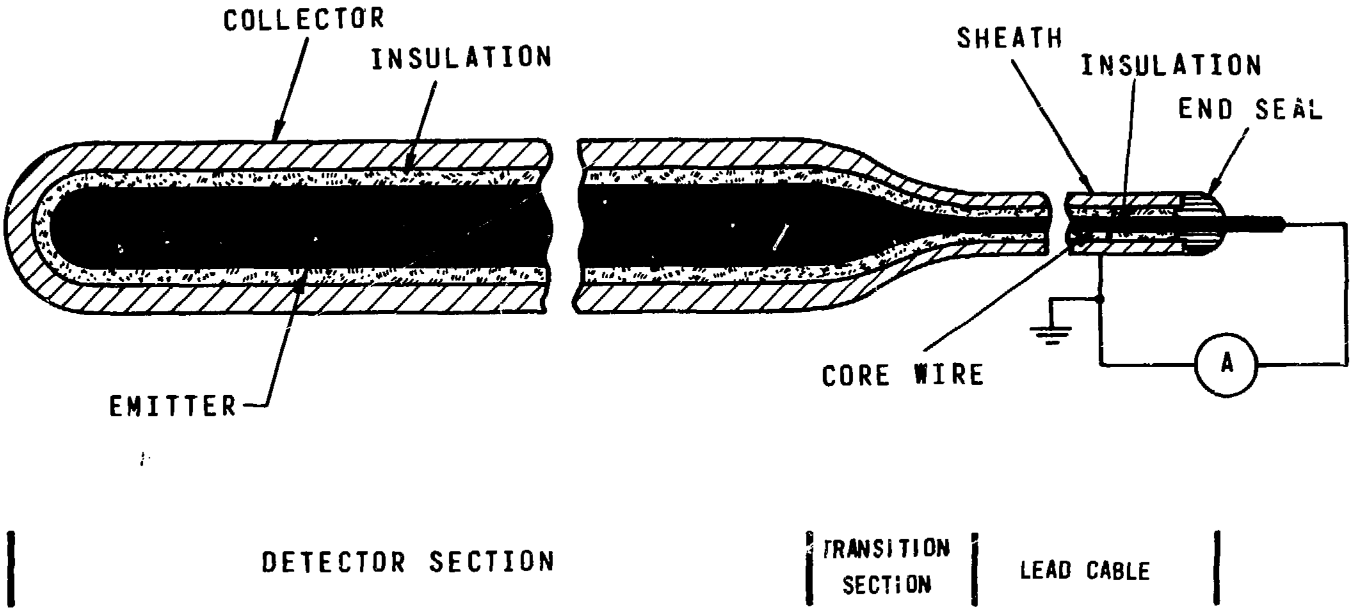


FIGURE 1 SCHEMATIC REPRESENTATION OF A "STEPPED" SELF-POWERED DETECTOR IN WHICH THE DIAMETER OF THE DETECTOR EMITTER EXCEEDS THAT OF THE LEAD CABLE CORE WIRE

moderated natural uranium reactors, in the reactor control system and both reactor safety systems.

TABLE 1

SUMMARY OF THE DIMENSIONS OF THE STEPPED INCONEL-INCONEL DETECTOR IRRADIATED IN THE NRU REACTOR AT CRNL

PARAMETER	DIMENSIONS: DETECTOR SECTION	DIMENSIONS: LEAD CABLE SECTION
Outside Diameter	3.01 mm	1.56 mm
Sheath Wall Thickness	0.52 mm	0.27 mm
Insulation Thickness	0.23 mm	0.33 mm
Emitter/Core-Wire Diameter	1.51 mm	0.37 mm
Length	1.012 m	1.353* m

*This is the length of the lead cable which passes through the core of the reactor. The actual length of the lead cable from the detector to the top of the reactor shielding is ∿ 6.3 m.

TABLE 2

SUMMARY OF THE IMPORTANT EXPERIMENTAL RESULTS OBTAINED FROM THE STEPPED DETECTOR, HAVING AN EMITTER 1.5 mm IN DIAMETER, OBTAINED FROM TESTS IN THE NRU REACTOR

PARAMETER	EXPERIMENTAL RESULT
Ratio of Detector Signal to Lead Cable Signal	∿ 32
Total Detector Sensitivity	$2.23 \times 10^{-25} A\cdot m^{-1}/(n\cdot m^{-2}\cdot s^{-1})$
Prompt Fraction	1.05 ± 0.02

As can be seen from Table 2, the detector is close to 100% prompt, and the lead cable contributed only ∿ 3% of the total signal. The prompt fraction exceeds unity. This is a consequence of the negative delayed signals, from delayed reactor γ-rays and from the decay of ^{56}Mn and ^{65}Ni, whereas the prompt current is positive. A prompt fraction slightly in excess of unity can be considered beneficial in a detector which is used in a reactor safety system.

The dynamic response of the detector was measured on four separate occasions by fitting the decay of the signal from the detector to the decay of the signal from a fission chamber, following a fast reactor shutdown, assuming the detector response consists of a prompt fraction plus a number of first order lags. The results are summarized in Table 3. Two cases were considered. In the one case the amplitudes of the prompt fraction and the delayed components were independently varied, while in the other the amplitudes were constrained to sum to unity. As can be seen, the amplitude of the prompt fraction varies somewhat between the two cases but the amplitudes of the delayed components are essentially the same in both cases.

The λ_2 component is attributed to the β-decay of ^{56}Mn and ^{65}Ni, which have approximately the same half-life, while the other components are attributed to delayed reactor γ-rays and activation products in Inconel such as $^{64,66}Cu$, ^{59}Fe and $^{51,55}Cr$. There is a suggestion that the amplitudes of the delayed components are slowly decreasing with irradiation but this is by no means certain. Note that the ^{56}Mn current is expected to burn out at ∿ 7% per year.

The results shown in Tables 2 and 3 clearly indicate that a prompt-responding self-powered detector, having good discrimination between the detector signal and the lead cable signal, can be achieved with a stepped detector/lead cable design, using Inconel for both the emitter/core wire and the

TABLE 3

SUMMARY OF THE RESPONSE CHARACTERISTICS OF THE INCONEL-INCONEL DETECTOR, AS DETERMINED FROM FOUR DIFFERENT MEASUREMENTS. FOR EACH MEASUREMENT, TWO CASES ARE SHOWN. IN CASE 1, THE AMPLITUDES OF THE DELAYED TERMS AND THE PROMPT FRACTION WERE INDEPENDENTLY VARIED, WHILE IN CASE 2, THE AMPLITUDES WERE CONSTRAINED TO SUM TO UNITY.

Parameter	Value (s^{-1})	AMPLITUDE OF PARAMETER F_p OR A_i							
		On 7 Nov 1978		On 5 Dec 1978		On 13 Mar 1979		On 26 Jun 1979	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
F_p	-	1.075	1.051	1.049	1.052	1.025	1.045	1.023	1.044
λ_0	1.05×10^{-2}	-0.0130	-0.0103	-0.0107	-0.0110	-0.0087	-0.0094	-0.0078	-0.0080
λ_1	6.5×10^{-4}	-0.0045	-0.0048	-0.0034	-0.0034	-0.0031	-0.0029	-0.0034	-0.0034
λ_2	7.5×10^{-5}	-0.0344	-0.0343	-0.0357	-0.0358	-0.0318	-0.0318	-0.0309	-0.0309
λ_3	3.0×10^{-6}	-0.0015	-0.0015	-0.0016	-0.0016	-0.0013	-0.0013	-0.0013	-0.0013

NOTE: A change in the detector output current, ΔI, is related to a change in neutron flux, $\Delta\phi$, by the transfer function

$$\frac{\Delta I(s)}{\Delta\phi(s)} = K\left[F_p + \sum_i \frac{A_i\lambda_i}{s+\lambda_i}\right]$$

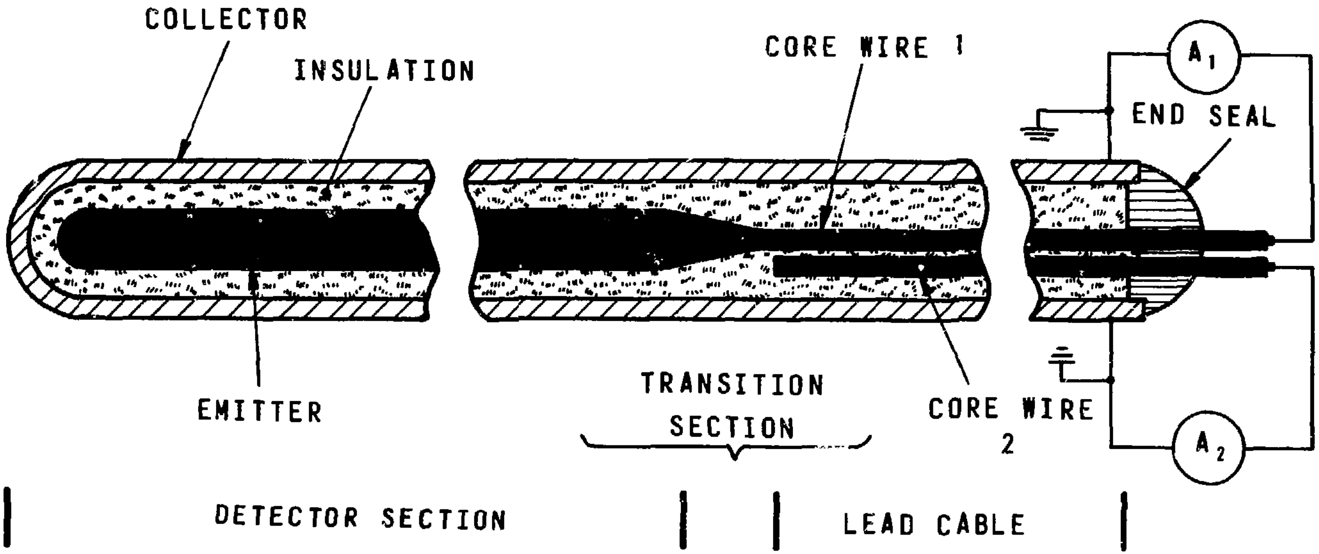
Where s = Laplace transform variable

K = Detector sensitivity per unit length sheath. If a coaxial (non-compensated) lead cable is used, the diameter of the detector emitter should exceed that of the lead cable core wire by about a factor of 4 or more. By compensating for the signal generated in the lead cable, for example by using a twin-cored lead cable, as illustrated in Figure 2, the ratio of emitter diameter to lead-cable, core-wire diameter can be reduced, but because the detector signal falls off almost as the cube of the emitter diameter, this ratio should not be appreciably smaller than 2.5.

An important advantage of a detector using Inconel as an emitter, compared with other prompt-responding, self-powered flux detectors, such as those employing a cobalt emitter, is the much smaller burn-out rate. The effective neutron-capture cross section for Inconel 600 is $\sim$ 4 b (1 b = 10^{-28} m^2) compared with 37 b for Co. Thus a self-powered detector having an Inconel emitter will burn out $\sim$ 9 times more slowly than a detector having a cobalt emitter. In fact, as will be discussed below, the sensitivity of the Inconel detector actually increases during the first few years of irradiation before it begins to decrease.

3. OTHER MATERIALS

A prompt-responding detector with a low burn-out rate can be achieved using emitter materials other than Inconel 600. To achieve a low burn-out, the neutron-capture cross section must be relatively small, although it cannot be so small as to preclude generating a useful signal. To achieve a prompt response, the materials of the detector must not transmute, to any significant extent, to β-active daughters, following neutron capture. Further, to achieve a prompt response, the γ-ray sensitivity of the detector must be relatively small, to prevent delayed reactor γ-rays giving an appreciable delayed signal. The results obtained by Shields [4] can be used as a guide in selecting materials so as to achieve a low γ-ray sensitivity.



$$I_{A_1} = I_{DETECTOR} + I_{CORE\ WIRE\ 1}$$

$$I_{A2} = I_{CORE\ WIRE\ 2} = I_{CORE\ WIRE\ 1}$$

$$\therefore\ I_{A1} - I_{A2} = I_{DETECTOR}$$

FIGURE 2 SCHEMATIC REPRESENTATION OF A SELF-POWERED DETECTOR WHICH EMPLOYS A TWIN-CORE LEAD CABLE TO COMPENSATE FOR THE SIGNAL INDUCED IN THE LEAD CABLE

They indicate that the atomic number of the sheath and the emitter should not differ by more than ∿ 15.

Taking into account the requirements outlined above, we have selected a number of materials suitable for use in a prompt-responding, low burn-out, stepped detector. The materials and their important properties are summarized in Table 4. Here we have also estimated the sensitivities, S (n,γ,e), for the various materials relative to that of Inconel 600. These sensitivities were obtained from equation (2) below.

$$\frac{S_x(n,\gamma,e)}{S_I(n,\gamma,e)} = \frac{\sigma_x \rho^2_x F_x}{A_x^2} \cdot \frac{A_I^2}{\sigma_I \rho_I^2 F_I} \qquad (2)$$

where $S_x(n,\gamma,e)$ is the (n,γ,e) sensitivity for an emitter of material x,

ρ_x is the density of material x

A_x is the atomic weight of material x

σ_x is the microscopic neutron capture cross section for material x

F_x is a function given by

$$F_x = \sum_{E_j} N_x(E_j)\ \sigma^{KN}_{INC,t}(x,E_j) \qquad (3)$$

where $N_x(E_j)$ is the number of capture γ-rays of energy E_j emitted per neutron capture in material x taken from reference [8]. We considered only γ-ray energies greater than 400 keV,

$\sigma^{KN}_{INC,t}(x,E_j)$ is the Compton cross section at an energy E_j for material x taken from reference [9],

and ρ_I, A_I, σ_I, $N_I(E_j)$ and $\sigma^{KN}_{INC,t}(I,E_j)$ are similarly defined for Inconel.

TABLE 4

SUMMARY OF THE IMPORTANT PROPERTIES OF THE MATERIALS SUITABLE FOR USE IN THE EMITTER AND SHEATH OF A PROMPT-RESPONDING, LOW BURN-OUT, STEPPED DETECTOR

Material	Z	A	ρ Mg/m^3	σ (b)	N	S(n,γ,e)	Principal β-Active Daughters	% of Captures Producing Principal β-Active Daughter	Use
Inconel-600	27	57.1	8.4	4.05	1.5	1.00	^{56}Mn, ^{65}Ni	1.2%*	Emitter and Sheath
Nickel	28	58.7	8.9	4.43	1.4	0.98	^{65}Ni	0.32	Emitter and Sheath
Iron	26	55.8	7.9	2.55	1.7	0.73	^{59}Fe	0.14	Emitter and Sheath
Chromium	24	52.0	7.1	3.1	1.9	1.15	^{55}Cr	0.27	Emitter and Sheath
Titanium	22	47.9	4.5	6.1	2.3	1.05	^{51}Ti	0.16	Emitter and Sheath
Zirconium	40	91.2	6.4	0.185	3.4	0.06	^{95,97}Zr	5.6	Sheath Only

*Assuming the Mn content is 0.3 wt%.

The estimates of the relative intensities cannot be considered to be highly accurate since electron transport has not been taken into account. Nonetheless, they serve as a useful guide and indicate that the neutron sensitivities of nickel, iron, chromium, and titanium are comparable to that of Inconel 600. Further, the relative intensities of delayed currents from the β-decay of radioactive daughters will be comparable to, or smaller than, the relative intensity of the delayed current produced in Inconel-Inconel MI cables by the β-decay of ^{56}Mn and ^{65}Ni. Since the atomic number of nickel, iron, chromium, and titanium are close to one another and to that of Inconel 600, the γ-ray sensitivities of MI cables produced from these materials will be close to that of Inconel-Inconel MI cable. Thus a prompt-responding, low burn-out detector can be manufactured using any combination of nickel, iron, chromium, titanium and alloys of these materials in the emitter/core wire and sheath of the device. If the detector is to be used to measure the flux over a localized region of a reactor core, it must be of the stepped design to achieve a sufficiently large detector current, relative to that produced in the lead cable. If the detector is to provide a measure of the average flux over the whole core, then it need not be stepped, but the emitter diameter should not be significantly smaller than 1.0 mm.

Using Table 4 as a guide, nickel, titanium and chromium appear to be essentially equivalent. However, in comparing various materials, one must take account of the variation in sensitivity with irradiation. The most abundant nickel isotope is ^{58}Ni which forms 68% of the natural element and which has a total cross section of 4.6 b. This isotope transmutes to ^{59}Ni when it captures a neutron, and ^{59}Ni has a total neutron cross section of 104 b. Thus every nuclide of ^{58}Ni which captures a neutron is replaced by a nuclide of ^{59}Ni which has a much larger neutron capture cross section, so that, initially, the detector sensitivity actually increases as a result of the irradiation, i.e. the detector breeds.

For the test detector fabricated from Inconel 600, which contains ∿ 76% Ni, the signal actually increased by ∿ 23% over a period of ∿ 0.75 years in a mean flux of 2.2×10^{18} $n \cdot m^{-2} \cdot s^{-1}$. For an Inconel detector assembly, the current, $I_I(t)$, following an irradiation for a time t in a flux, ϕ , is given by

$$I_I(t) = I_I(0)e^{-\sigma_I \phi t} + I_{59}(t) \tag{4}$$

where $I_I(0)$ is the initial current from the Inconel detector assembly,

σ_I is an effective cross section to describe the burnout of Inconel,

and $I_{59}(t)$ is the current generated by neutron capture in ^{59}Ni.

Since I_{59} results from capture in ^{59}Ni, it will be proportional to the relative number of ^{59}Ni nuclides per unit volume, χ_{59}, i.e.

$$I_{59} = K\chi_{59} \tag{5}$$

But since ^{59}Ni results from neutron capture in ^{58}Ni, we have

$$\frac{d\chi_{59}}{dt} = \sigma_{58}\phi\chi_{58} - \sigma_{59}\phi\chi_{59} - \lambda_{59}\chi_{59} \tag{6}$$

$$\frac{d\chi_{58}}{dt} = -\sigma_{58}\phi\chi_{58} \tag{7}$$

where χ_{58} is the relative number of ^{58}Ni nuclides per unit volume

and λ_{59} is the decay constant for ^{59}Ni.

Since $\lambda_{59} << \sigma_{59}\phi$ for typical reactor fluxes, we have

$$\frac{d\chi_{59}}{dt} \approx \sigma_{58}\phi\chi_{58} - \sigma_{59}\phi\chi_{59} \tag{8}$$

Solving equations (7) and (8) subject to the boundary conditions that at time 0

$$\chi_{58} = \chi_{58}(0) \quad (9)$$

$$\chi_{59} = 0 \quad (10)$$

we have

$$\chi_{59} = \frac{\chi_{58}(0)\sigma_{58}}{\sigma_{59}-\sigma_{58}} \left(e^{-\sigma_{58}\phi t} - e^{-\sigma_{59}\phi t} \right) \quad (11)$$

So

$$I_{59} = \frac{k\sigma_{58}}{\sigma_{59}-\sigma_{58}} \left(e^{-\sigma_{58}\phi t} - e^{-\sigma_{59}\phi t} \right) \quad (12)$$

$$= kf(\phi t) \quad (13)$$

where $$k = K\chi_{58}(0) \quad (14)$$

Hence we have, for the Inconel detector,

$$I_I(t) = I_I(0)e^{-\sigma_I \phi t} + kf(\phi t) \quad (15)$$

Experimentally we have found that, after an irradiation for a period of $\sim$ 0.75 a, in a mean flux of $\sim$ 2.2 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$, the signal from the test detector increased by a factor of 1.23.

Assuming σ_I = 4.6 b, we have

$$1.23 = (0.976) + \frac{k}{I(0)} 1.826 \times 10^{-2} \quad (16)$$

so $$\frac{k}{I_I(0)} = 13.9 \quad (17)$$

Equations (12), (15), and (17) can be used to estimate the change in the current generated by an Inconel detector assembly as a function of the irradiation history of the detector assembly. Table 5 summarizes the results obtained for a detector assembly irradiated in a mean flux of 2×10^{18} $n \cdot m^{-2} \cdot s^{-1}$. Also shown are the results to be expected using a pure nickel emitter. The initial sensitivity of the nickel detector is 2% smaller than that of an equivalent Inconel detector, but the value of $k/I_I(0)$, for the nickel detector, is a factor of 1.32 greater than that for the Inconel detector, since Inconel contains only 76% nickel. Here we have assumed that the effective cross section for burnout of both the Inconel and nickel detectors is 4.6 b.

TABLE 5

CHANGES IN SIGNALS FROM INCONEL AND NICKEL DETECTORS, AS FUNCTIONS OF TIME, IN A CONSTANT FLUX OF 2×10^{18} $n \cdot m^{-2} \cdot s^{-1}$

Time (a)	$I_I(t)$	$I_{Ni}(t)$
0	1.00	0.98
1	1.26	1.34
2	1.38	1.50
3	1.42	1.56
4	1.42	1.57
6	1.37	1.52
8	1.30	1.45
10	1.23	1.37
15	1.06	1.18
20	0.92	1.02

As can be seen, the signal from the Inconel detector increases for the first 4 years or so and then decreases. After ∿ 4 years, ^{59}Ni is burned out as fast as it is produced. Thereafter the signal decreases, as ^{58}Ni burns out and the ratio of I_{59} to the total remains approximately constant.

As can be seen, the signal from the nickel detector is predicted to increase more than that from the Inconel detector. In both cases the increase is significant, and after an irradiation of 20 years, the detector is still about as sensitive as when it was first installed. Based on the results shown in Table 5, nickel and Inconel 600 can be considered to be superior to the other materials considered.

From Table 4, we can see that zirconium, and hence zirconium-based alloys such as Zircaloy, are not suitable for use as the emitter of a prompt-responding self-powered detector because of zirconium's low neutron sensitivity. However, zirconium and zirconium-based alloys can be used as the sheath material in combination with iron, nickel, chromium, titanium and/or alloys of these materials, as the emitter. Such a detector would have a somewhat larger negative γ-ray sensitivity than if a lower Z material were used as the sheath, but the detector will still be close to 100% prompt. Zirconium and zirconium-based alloys can also be used as the core wire of the lead cable. However, there is a distinct advantage in using zirconium or a zirconium-based alloy in the sheath; the flux depression produced in such a detector, and the neutron load on the reactor, will be significantly smaller than if one of the other materials were used in the sheath. Thus, zirconium and alloys of zirconium are preferred materials for the sheath. Nickel is also a preferred material for the sheath because of the ease of fabrication using this material.

It should be noted that, in general, different materials may be used in the lead cable portion of the detector and in the emitter portion.

4. SUMMARY

As a result of an investigation of Inconel-Inconel MI cables, it has been found that prompt-responding, low burn-out, self-powered flux detectors can be made using nickel, iron, chromium, titanium and alloys of these materials as the emitter material and nickel, iron, chromium, titanium, zirconium and alloys of these materials as the sheath. To obtain a reasonable prompt-to-delayed signal ratio, the emitter diameter should not be significantly less than 1.0 mm. If the detector is to be used to measure the flux over a localized region of a reactor core, the diameter of the detector emitter section will have to be larger than the diameter of the core wire in the lead cable section of the detector. If a coaxial lead cable is used, without lead-cable compensation, the diameter of the detector emitter section should not be significantly smaller than 4 times the diameter of the core wire in the lead cable. By compensating for the signal generated in the lead cable, either by using a twin-core lead cable or by measuring the current from a second lead cable, provided for that purpose, the ratio of the emitter diameter to lead-cable diameter can be reduced. But this ratio should not be appreciably smaller than 2.5.

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