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Self-Powered Neutron and Gamma Detectors for In-Core Measurements

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SELF-POWERED NEUTRON AND GAMMA DETECTORS FOR IN-CORE MEASUREMENTS

by

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ABSTRACT

The performance of various types of self-powered neutron and gamma detectors intended for control and power distribution measurements in water cooled reactors is discussed. The self-powered detectors are compared with other types of in-core detectors and attention is paid to such properties as neutron and gamma sensitivity, high-temperature performance, burn-up rate and time of response. Also treated are the advantages and disadvantages of using gamma detector data for power distribution calculations instead of data from neutron detectors.

With regard to neutron-sensitive detectors, results from several long-term experiments with vanadium and cobalt detectors are presented. The results include reliability and stability data for these two detector types and the Co^{60} build-up in cobalt detectors. Experimental results which reveal the fast response of cobalt detectors are presented, and the use of cobalt detectors in reactor safety systems is discussed. Experience of the design and installation of complete flux probes, electronic units and data processing systems for power reactors is reported.

The investigation of gamma-sensitive detectors includes detectors with emitters of lead, zirconium, magnesium and Inconel. Measured gamma sensitivities from calibrations both in a reactor and in a gamma cell are given, and the signal levels of self-powered neutron and gamma detectors when applied to power reactors are compared.

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CONTENTS

1. INTRODUCTION

For control and power distribution measurements in water cooled power reactors various types of self-powered detectors can be utilized. So far only self-powered neutron detectors have been considered in conjunction with power reactor in-core measurements [1 - 4], but also self-powered gamma detectors may become of importance. The most commonly used neutron detectors are those with emitters of cobalt, vanadium and rhodium. Suitable emitter materials for self-powered gamma detectors are, for instance, lead and magnesium.

The fast response of self-powered cobalt detectors make these detectors useful for reactor control and excess power protection. On the other hand the very low burn-up rate of vanadium detectors make such detectors of particular interest for flux mapping in large power reactors. The burn-up rate of rhodium detectors is high (3.9% per month at 10^{14} n/cm^{2}s) compared to cobalt and vanadium detectors. Therefore rhodium detectors have not been considered in the present investigation. Self-powered gamma detectors have both an inherent fast response and an inherent low burn-up rate, but very little experience has been gained concerning the performance of self-powered gamma detectors in power reactors.

When discussing the properties of self-powered detectors in power reactors the complete monitoring system has to be considered, i e the properties of signal cables, current amplifiers, data processing systems, as well as detector probes. As for many other types of in-core detectors, the limitations are due to phenomena in the signal cables as much as in the detectors.

2. METHODS OF IN-CORE POWER DISTRIBUTION MEASUREMENTS

Several reviews of in-core instrumentation systems have previously been published [1, 4, 5, 6]. These reviews deal mainly with power distribution measurements by means of neutron detectors, but recently also the possibility of utilizing gamma detector information for calculation of power distributions has been discussed [7, 8]. At present only three types of detectors or monitors seem to be really important in power reactors. These three types are:

- Activation monitors
- Fission chambers
- Self-powered detectors.

When activation technique is adopted for flux mapping, either wires, foils, balls or gas samples serve as activation monitors. The most commonly used system is the Aero-Ball system in which small steel balls with a known content of manganese are propelled pneumatically in guide tubes into the reactor core and back to the detector. The activity of the balls is measured with a gamma-sensitive ionization chamber or a scintillation counter. In a newly designed system vanadium balls are used and the activity of the balls is scanned in parallel by means of 30 silicon diodes [9].

Generally fission chambers for flux monitoring in the power range have ^{235}U coating and are operated as current-type chambers. In-core fission chambers have small dimensions and can withstand high temperatures. Fission chambers have a fast transient response, and therefore some of the chambers in a flux mapping system are usually connected to the safety instrumentation system. At present the only serious limitation of the ^{235}U fission chamber seems to be the high burn-up rate. This high burn-up rate often necessitates installation of a complicated system for frequent calibration of the chambers. High-flux fission chambers with lower burn-up rates than standard ^{235}U chambers, in which a fertile isotope compensates for the burn-up of ^{235}U, have been developed. However, these regenerative fission chambers have not yet been extensively used in power reactors.

As mentioned above, there are three types of neutron-sensitive self-powered detectors which are of interest in power reactors, i e cobalt, vanadium and rhodium detectors. These self-powered detectors consist of three main parts - emitter, insulator and collector - usually arranged as coaxial cylinders. In cobalt detectors thermal neutrons produce capture gamma rays in the emitter which give rise to energetic Compton and photo electrons. The electrons penetrate the insulator but are stopped in the collector. When the electrons leave the emitter it becomes positively charged and the current measured between emitter and collector is proportional to the neutron flux. In vanadium and rhodium detectors thermal neutrons give rise to high-energy beta radiation which can penetrate the insulator.

In this connection also so-called gamma thermometers and neutron thermometers may be mentioned, although they have a limited importance in power reactors at present. The heat generated in a target by gamma or neutron radiation is measured with thermocouples in these devices.

3. COBALT AND VANADIUM NEUTRON DETECTORS

The experimental investigations carried out with cobalt and vanadium detectors during the last years have comprised long-term tests in the Halden and R2 reactors, measurement of gamma sensitivity, transient response and linearity, optimizing of the insulator thickness, and, for cobalt detectors, measurement of the Co^{60} build-up. Also some experiments concerning the high-temperature performance of Al_2O_3 and MgO insulated detectors and cables have been started. The vanadium and cobalt detectors are all of type 5503-B and 5503-C (AB Atomenergi). These detectors have an emitter diameter of 2 mm, an outer diameter of 3.5 mm and a sensitive length of either 100 or 210 mm. Generally the insulator material is Al_2O_3 and the sheath material Inconel 600.

The long-term tests of vanadium and cobalt detectors started in 1968 in the R2 reactor at Studsvik and in the Halden reactor. Especially the test in the Halden reactor is comprehensive; the total number of detectors of type 5503 installed from September 1968 to March 1971 is 54. Sixteen of the vanadium detectors were installed in September 1968.

The operating temperature in the Halden reactor is 240°C and the operating pressure 34 bar. The reactor is usually shut down for about a month three to four times per year. As the reactor power is also frequently varied, the calculation of the integrated neutron flux for the various detectors is tedious. At full power the thermal neutron flux at the detector positions is $1\text{-}6 \cdot 10^{13}$ n/cm^{2}s.

Of the installed detectors in the Halden reactor six have failed. However, at least four of these failures seem to be related to the work going on in the reactor hall during a shut-down period from February to April 1969. In Table I the fluences for the detectors which were in operation in October 1970 are given. Also the leakage resistances of the detectors are frequently recorded. The accumulated testing time for the six cobalt detectors and the sixteen vanadium detectors first installed is about $5 \cdot 10^5$ h. The long-term tests in the Halden reactor have, in a very convincing way, proved the excellent reliability of self-powered detectors.

The expected burn-up rate is 0.012% per month for vanadium detectors and about 0.1% per month for cobalt detectors at a neutron flux of 10^{13} n/cm^{2}s. Although the neutron flux in the Halden reactor is measured also by means of gamma thermometers and an Aero-Ball system, it has not yet been possible to verify these burn-up rates. However, it should be possible later on to determine the burn-up rate at least for the cobalt detectors.

During shut-down periods it has been possible to measure the signal current due to Co^{60} in the cobalt detectors. The measured values for the various detectors are plotted in Fig 1. Some of these detectors have been in operation since February 1969. The calculated curve is based on a steady neutron flux of 10^{13} n/cm^{2}s [10].

In the R2 reactor a limited number of cobalt and vanadium detectors have been tested. The neutron flux is about $2 \cdot 10^{14}$ n/cm^{2}s in this reactor, and high burn-up values can therefore be reached in a comparatively short time. For one cobalt detector the fluence is $5 \cdot 10^{21}$ n/cm^2 (April 1971). A high-temperature experiment with eight cobalt detectors will soon be started in the R2 reactor. Four of these detectors have Al_2O_3-insulated cables and four MgO-insulated cables. The operating temperature of the detectors will be 400°C and the test is expected to continue for two years. A long-term experiment with eight cobalt and four vanadium detectors has also recently started in the Oskarshamn I power reactor (see Sect 5).

In the R2-0 reactor the linearity of response of cobalt detectors has been investigated at thermal neutron fluxes up to 10^{13} n/cm^{2}s. No saturation tendencies or other non-linearities in the response of the cobalt detectors could be found. In the R2-0 reactor experiments with cobalt detectors with various insulator thicknesses but with the same emitter diameter have also been carried out. The experiments show that the neutron sensitivity of the cobalt detector can be increased somewhat by increasing the insulator thickness, which in the standard detectors is 0.5 mm. An investigation of the gamma sensitivity of cobalt detectors with a sensitive length of 210 mm gave the value $6.6 \cdot 10^{-17}$ A/R/h in a gamma cell. The value for a vanadium detector of the same length is slightly higher.

The transient response of cobalt detectors has been investigated in the R2 and R2-0 reactors on several occasions. It was nevertheless decided to test a cobalt detector in the TRIGA reactor in Vienna [11]. The neutron flux pulse in this reactor has a width at half-maximum of 40 ms and a peak value of 10^{16} n/cm^{2}s. During the TRIGA reactor experiments the response of the cobalt detector was compared with that of an ionization chamber. In Fig 2 a record of the reactor pulse is shown as measured with the two detectors. It is clear that the cobalt detector has a response as fast as the ionization chamber. Certainly the cobalt detector is fast enough to be utilized in safety instrumentation systems.

When summarizing the results obtained with cobalt and vanadium self-powered detectors it follows that the reliability and low burn-up rate make these detectors suitable for in-core applications in water cooled power reactors. Also such detector properties as high-temperature performance, linearity of response, neutron-to-gamma sensitivity and response time are very satisfactory.

4. GAMMA DETECTORS

Recent in-core measurements with ionization chambers have shown a close agreement between the gamma and neutron flux distributions in power reactors [7, 8], and the use of gamma detectors in systems for protection of reactors has been discussed [12]. Both for power distribution measurements and for reactor protection, gamma measurements seem to have some advantages compared to neutron measurements. One such advantage is that a gamma-sensitive detector measures the power density in a larger volume than a neutron detector. Another advantage of gamma detectors is the generally negligible burn-up rate.

Among the limitations when the gamma flux is measured is the gamma background from fission products, which gives rise to a detector current that is not proportional to reactor power. For instance, calculations have shown a ratio of prompt-to-delayed gamma radiation of only 2.49 in a power reactor for that fraction of the gamma radiation that escapes the fuel [7].

Calibrations of self-powered gamma detectors have been carried out both in the test reactor R2-0 and in a Co^{60} gamma cell. These calibrations should also be supplemented by measurements with other gamma sources in order to determine the spectrum sensitivity of the detectors. As the prompt gamma radiation in a reactor core has a higher energy than that from the fission products, it is advantageous if an in-core gamma detector has an enhanced sensitivity for high-energy gamma radiation. To ascertain the performance of gamma detectors for power density measurements in power reactors, further investigations of the gamma spectrum in reactor cores seem to be needed.

A gamma detector intended for in-core measurements should have high gamma-to-neutron sensitivity which severely restricts the number of suitable emitter materials. As the detector has to withstand high temperatures, the number of usable emitter materials is further limited. Our self-powered gamma detectors tested have emitters of lead, zirconium, Inconel 600 and magnesium. Both design and dimensions of the gamma detectors are the same as for the standard cobalt and vanadium neutron detectors (sensitive length = 210 mm). The sensitivity of the gamma detectors can, of course, be increased simply by changing the detector dimensions somewhat.

The measurements with the gamma detectors in the R2-0 reactor are summarized in Table II. The response of the detectors was measured both with and without a shield for thermal neutrons surrounding the detectors. When calculating the gamma sensitivities given in Table II, the detector current $I_e - I_c$ measured with the neutron shield surrounding the detector is considered.

Some results from the measurements in the Co^{60} gamma cell are presented in Fig 3 (average gamma dose rate = 0.78 MR/h). In this figure the average detector currents are given as a function of the atomic numbers of the emitter materials. (For Inconel 600 an atomic number of 27.1 is assumed.) A gamma detector with graphite emitter and the same dimensions as the other detectors was also tested in the gamma cell. This graphite detector showed a sensitivity somewhat higher than that of the magnesium detector.

In the core of a light-water power reactor the gamma flux level is typically about $5 \cdot 10^8$ R/h, and the signal current for a lead detector of the type considered would then be 0.4 µA. A vanadium neutron detector with the same dimensions as the lead detector has a sensitivity of $1.0 \cdot 10^{-20}$ A/n/cm^{2}s, and in a typical neutron flux of 10^{14} n/cm^{2}s the detector current would be 1.0 µA. Under the same conditions a cobalt detector would give about 0.6 µA. As far as detector sensitivity is concerned, self-powered gamma detectors with lead emitters can be utilized for measurement of power density and distribution in light-water reactors. It seems also possible to use magnesium detectors which have the advantage of a much better high-temperature performance than the lead detectors.

5. FLUX MONITORING SYSTEMS WITH SELF-POWERED DETECTORS

There are two main applications for self-powered detectors in water cooled reactors, i e in fast systems for reactor safety and control and in accurate systems for calibration and flux mapping. A fast system with cobalt detectors and an accurate system with vanadium detectors seem at present to be the most promising arrangement.

Compared to the fission chamber, which is frequently used in both systems, the vanadium and cobalt detectors have the advantage of a much lower burn-up rate. In this connexion also the simplicity of design of the self-powered detector should be considered, as well as the price.

As self-powered detectors have small dimensions and can withstand high temperatures and pressures, the mechanical design of in-core flux probes is usually simple. Flux probes for water cooled reactors can either be of the wet or the dry type. When wet flux probes are used, the detectors come into direct contact with the coolant, but both the detectors and the thermocoax cables have sheaths of Inconel, which is highly resistant to corrosion. In some cases it may be favourable to use dry flux probes. The detectors are then fixed to a support tube and placed in a thimble tube which prevents the detectors from coming into contact with the coolant. In dry flux probes the gamma heating of the detectors should be considered. At temperatures higher than, say, 300 - 400°C, it may be advantageous to use MgO-insulated instead of Al_2O_3-insulated detectors and cables in dry probes.

The signal currents from self-powered detectors can be measured with standard current amplifiers, although the signal currents are much lower than those from fission chambers. For cobalt and vanadium detectors a current amplifier should have a gain of about 5 V/μA. Recorders, remote meters and data loggers can be connected directly to such an amplifier. In large flux mapping systems it may be economically favourable to measure the detector currents by means of a low-level scanner and a single current amplifier.

Experience with self-powered detectors, and all other equipment in a flux mapping system with such detectors, will be gained this year when the Oskarshamn I power reactor reaches full power. Twelve self-powered detectors in two wet flux probes are installed in this boiling light-water reactor. Each probe contains four cobalt detectors (type 5503-C) and two vanadium detectors (type 5503-B). In Fig 4 the positions of the self-powered detectors in the reactor core are shown. The detectors have 2 mm thermocoax cables, 15 - 16 m long, with both a signal conductor and a compensating conductor. Coaxial cables of type RG 108A/U with a length of about 80 m connect the detectors to the current amplifiers. Signal currents are measured and recorded by means of a digital voltmeter and a data logger.

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Detector		Start of irradiation	Fluence (10^{20} n/cm^2)				
IFA-No	AE No		1969-03-27	1969-09-17	1970-04-01	1970-10-01	1971-03-15
302 ND1	V43	1968-09-17	2.41	3.38	5.90	7.03	7.44
ND2	V44		4.01	5.69	10.02	11.90	12.52
ND3	V45		4.10	5.69	9.64	11.49	11.98
ND4	V46		1.96	2.65	4.07	4.80	4.97
304 ND1	V56	1968-09-17	2.22	3.24	6.13	7.40	8.64
ND3	V59		3.34	4.88	9.60	11.51	11.88
ND4	V58		1.30	1.90	3.87	4.67	4.80
305 ND1	V51	1968-09-17	1.93	2.88	5.27	6.32	6.72
ND2	V60		3.29	4.80	8.54	10.17	10.82
ND4	V62		1.41	1.96	3.38	3.94	4.15
306 ND2	V49	1969-02-16	0.60	1.70	4.20	5.40	5.81
ND6	V47		0.80	2.50	6.55	8.48	9.13
ND11	V48		0.70	2.28	6.22	7.93	-
ND18	V50		0.30	0.95	2.66	3.35	3.59
306 ND3	Co2	1969-02-16	0.59	1.47	3.88	4.97	5.39
ND4	Co1		0.59	1.47	3.88	4.97	5.39
ND8	Co3		0.80	2.51	6.58	8.52	9.17
ND9	Co4		0.80	2.51	6.58	8.52	9.17
ND12	Co6		0.74	2.29	6.25	7.96	9.32
ND15	Co5		0.74	2.29	6.25	7.96	9.32
307 ND2	V64	1970-06-18	-	-	-	3.11	4.01
307 ND1	Co40	1970-06-18	-	-	-	1.99	2.56
ND3	Co41		-	-	-	3.11	4.02
ND4	Co42		-	-	-	3.02	3.84
ND5	Co43		-	-	-	3.02	3.85
ND6	Co44		-	-	-	1.22	1.55
308 ND1	Co45	1970-06-18	-	-	-	1.61	2.21
ND2	Co46		-	-	-	2.69	3.73
ND3	Co47		-	-	-	2.69	3.65
ND4	Co48		-	-	-	1.07	1.37
309 ND1	Co49	1970-06-18	-	-	-	1.60	2.02
ND2	Co50		-	-	-	2.31	2.95
ND3	Co51		-	-	-	2.27	2.72
ND4	Co52		-	-	-	0.88	1.04

Table I. Thermal fluences for vanadium and cobalt detectors installed in instrument test assemblies in the Halden reactor.

Detector No	Emitter material	Z	Measured currents (pA)						Sensitivity (10^{-16} A/R/h)
			Without boron shield			With boron shield			
			I_e	I_c	$I_e - I_c$	I_e	I_c	$I_e - I_c$	
Pb1	Lead	82	530	3.1	527	536	1.3	535	9.1
Pb2			473	5.4	468	450	4.0	446	7.6
Zr1	Zirconium	40	87.0	3.1	83.9	63.4	1.2	62.2	1.05
Zr2			83.0	-1.2	84.2	60.5	-0.6	61.1	1.04
In1	Inconel 600	≈27	76.2	4.5	71.7	-27.6	2.8	-30.4	0.52
In2			56.5	5.0	51.5	-42.6	4.0	-46.6	0.79
Mg1	Magnesium	12	-91.2	2.8	-94.0	-108.0	1.4	-109.4	1.9
Mg2			-83.1	3.0	-86.1	-99.4	1.5	-100.9	1.7

Table II. Measured currents for the various detectors in the R2-0 reactor at 10 kW. I_e = current in emitter conductor, I_c = current in compensator conductor. The detector sensitivities given refer to measurements with the boron neutron shield.

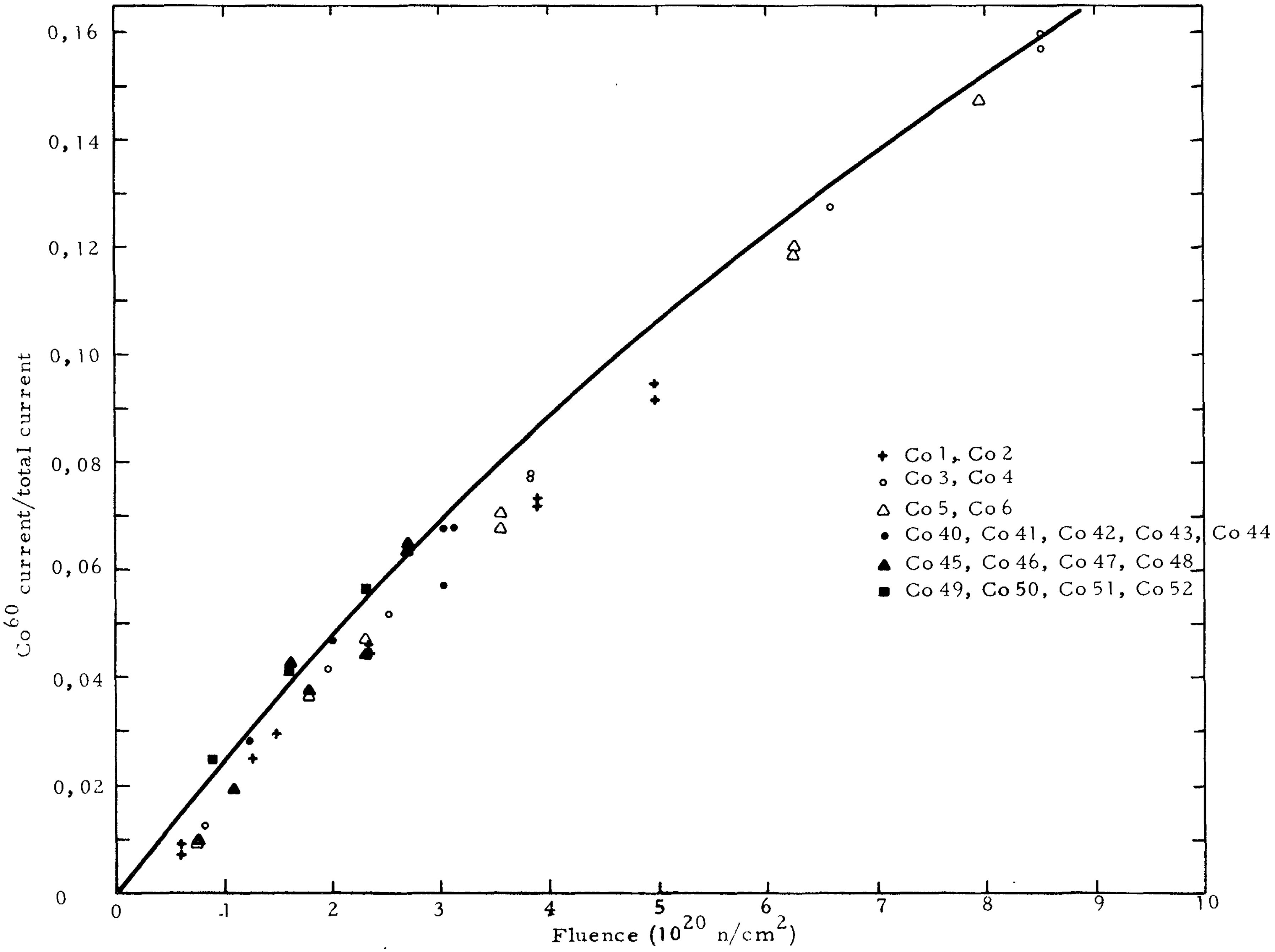

Fig 1. Relative detector current due to Co^{60} as a function of the thermal fluence. The curve refers to calculations for a steady thermal neutron flux of 10^{13} n/cm^{2}s.

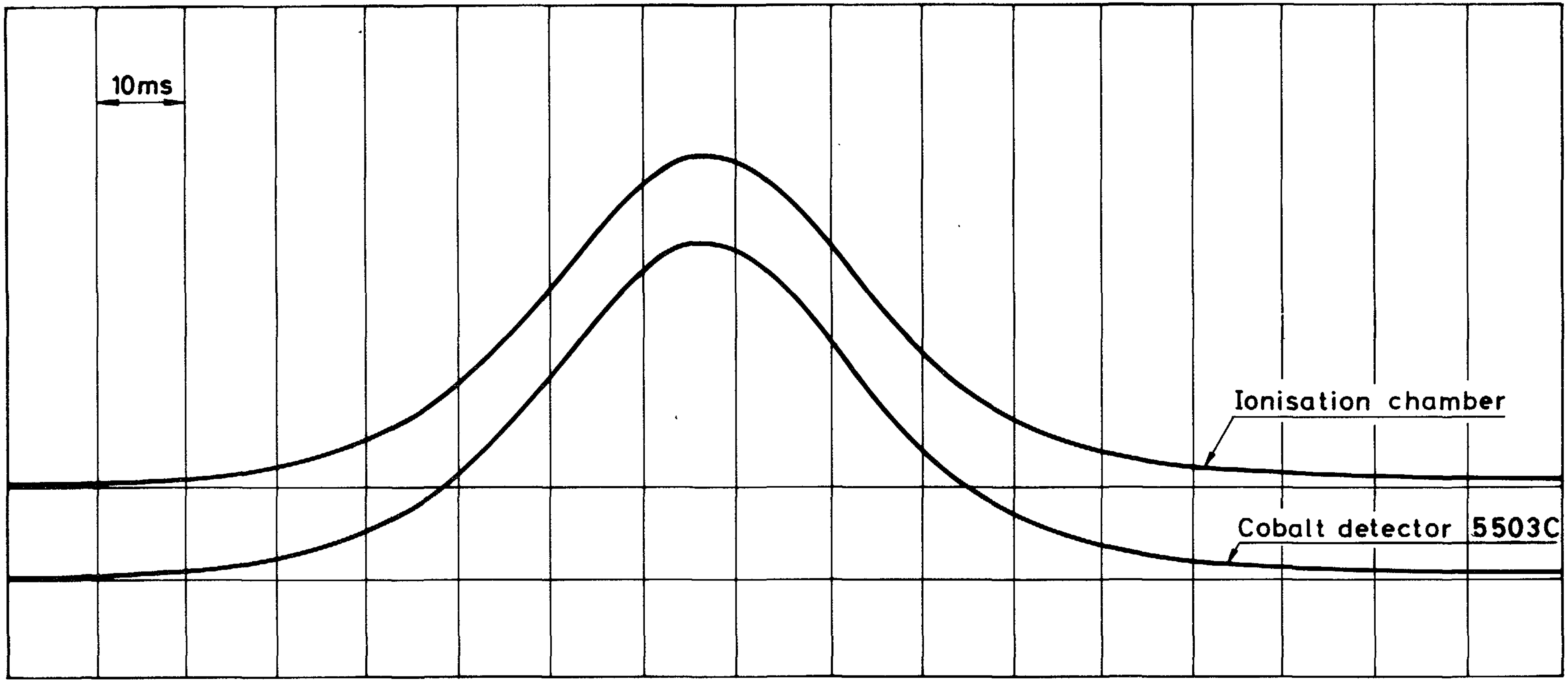

Fig 2. Response of a cobalt detector compared to that of an ionization chamber when tested in the TRIGA reactor. The peak neutron flux is 10^{16} n/cm^{2}s.

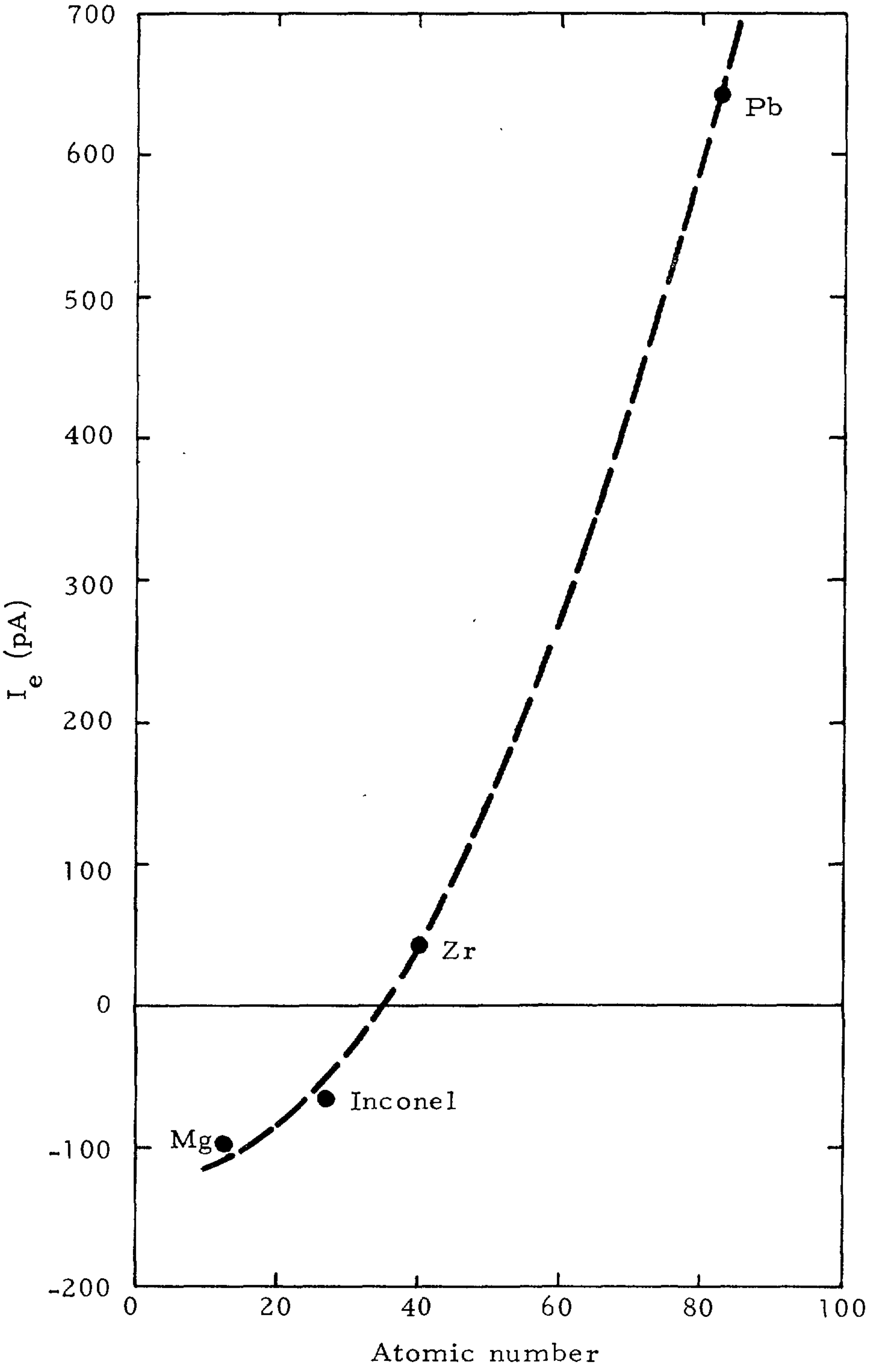

Fig 3. Detector current vs atomic number of the emitter material. The measured currents refer to experiments in the Co^{60} gamma cell. The current in the compensator conductor (I_c) is neglected.

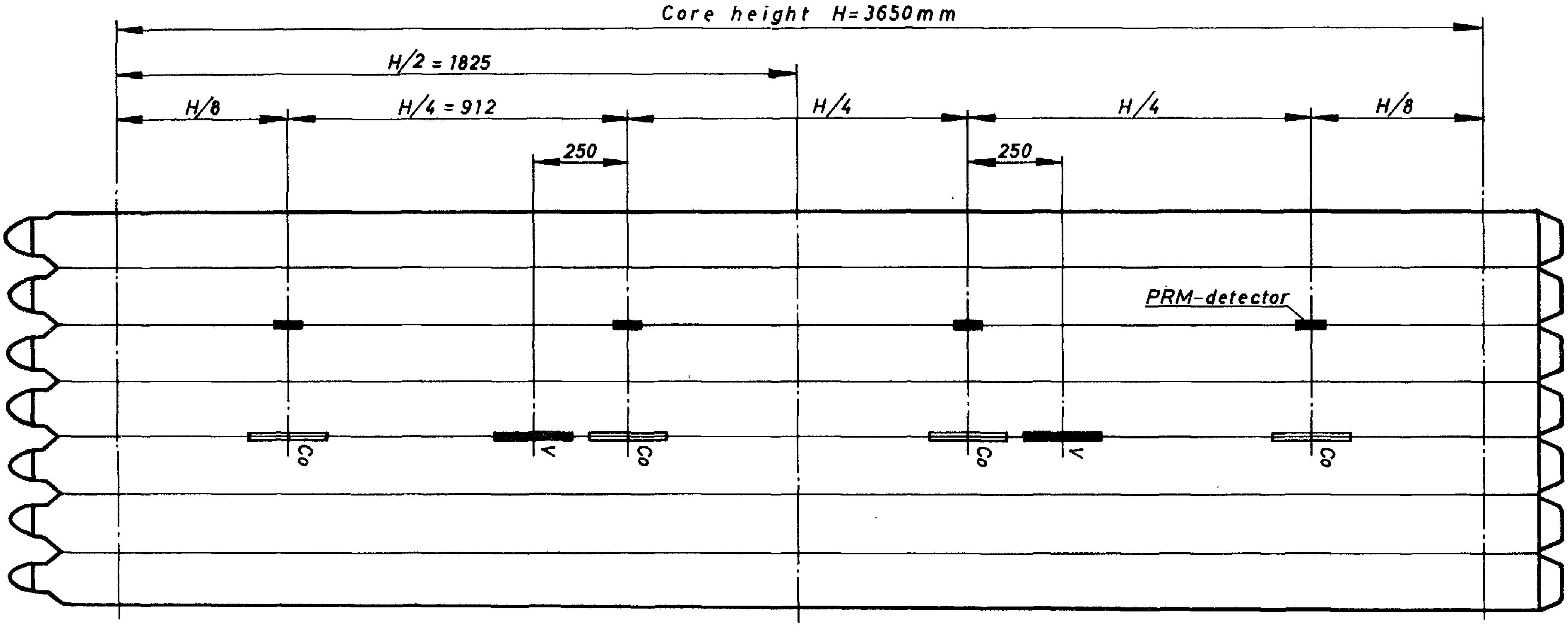

Fig 4. Positions of self-powered detectors and fission chambers (PRM detectors) in the Oskarshamn I reactor.

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