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AN ANALYSIS OF SHIELDING EFFICIENCY FOR ^{14}C COUNTERS

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ABSTRACT. The "shielding" efficiency of the guard counters has been a main scope of the present investigation. Our special guard counters consist of closed shells (ca 3cm thick) filled with propane at 1.2 atmospheres pressure. These guard counters are nearly 100 percent efficient against charged particles, and 1 to 2 percent against gamma and neutrons. The efficiency has now been studied more in detail in an arrangement with four guard shells around a ^{14}C counter. For each extra guard shell, the cosmic fraction of the counter background was reduced by ca 13 percent. The reduction does not involve penetrating high energy charged particles, but is related to γ ray showers penetrating the guards. A thicker old lead shield between ^{14}C counter and the guard counters also reduces the background and serves the same purpose. In order to approach underground conditions for the 1.5 liter counter background (0.32 ± 0.01 c/min), most of the shielding material has to be put inside guard shells. An ordinary guard counter combined with an extra guard on top of the iron shield is very efficient. A background of 0.48 ± 0.01 c/min has already been obtained.

INTRODUCTION

Optimal shielding of counters for radiocarbon dating in order to obtain better measuring accuracy has, up to now, been one of the main research goals in our laboratory. For several years we have frequently observed effects that have given better understanding and led to improvement of the shielding.

A summary of our previous shielding systems is given in figure 1. The 1956 shielding (A) was similar to that introduced by Libby (1952) at the beginning of the ^{14}C dating era. The 1962 system (B) was a major step forward, mainly due to a 3.5cm thick layer of old lead and a closed guard shell with multiple wires (Nydal, 1962). The 1976 system (C) with more lead (9.5cm) and a double guard shell was an attempt to approach underground conditions for the counter background. In the underground laboratories in Bern and Seattle (Oeschger, 1976; Stuiver, 1976) the influence of cosmic radiation in counter background is greatly reduced.

Thick layers of old lead between the ^{14}C counter and the guard counter are important. We, therefore, considered putting all shielding material inside guard shells in order to obtain optimal conditions in our ground level laboratory. In a previous investigation (Gulliksen and Nydal, 1976) an unexpectedly high reduction in counter background was observed with extra guard shells. This was not quite understood, as the guard counters are regarded to be nearly 100 percent efficient against charged particles and only 1 to 2 percent against soft gamma and thermal neutrons.

The main purpose of the present investigation is to study the efficiency of guard counters, thus gaining better understanding of how an optimal ground level shielding must be arranged.

Experimental arrangement and results

The previous arrangement, allowing experiments with three guard shells surrounding the ^{14}C counter (Gulliksen and Nydal, 1976), is shown in figure 2A. Guard counters are closed shells with multiple wires filled

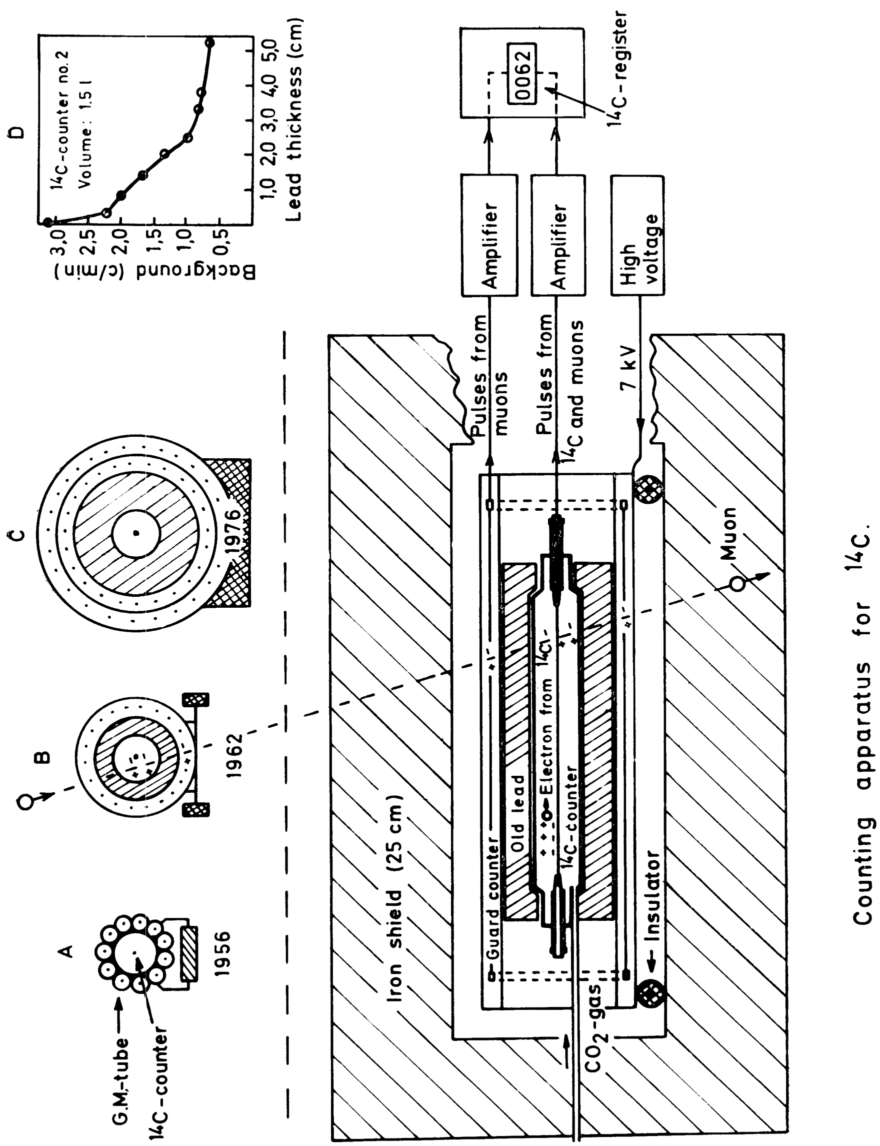

Fig 1. The counting system and different shielding systems with A — single geiger tubes, without old lead (1956), B — guard shell, 3.5cm old lead (1962), C — double guard shell, 9.5cm old lead (1976).

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to 1.2 atmospheres with propane. A new small guard counter was designed to obtain a system with four guard shells, shown in figure 2B. Counter no. 7, with an effective volume of 1.2L, was wrapped in 2.5cm old lead and placed at the center. The whole system was situated in a 25cm thick iron shield. With only the outermost guard shell in operation, the counter background was 0.94 ± 0.02 c/min. Successive adding of the three other shells caused a drop in background to 0.75 ± 0.01 c/min, as shown in figure 3. The decrease in background for each additional shell is approximately the same, on average 0.063 ± 0.005 c/min. This is in very close agreement with the results obtained earlier with three guard shells and 6.5cm old lead shielding (fig 2a). As shown in figure 3, these measurements (open circles) gave an average background decrease of 0.065 ± 0.007 c/min per added shell.

To examine whether the large background reductions could be caused by some mysterious information loss, the modern standard, NBS oxalic acid, was measured with the different guard shell configurations. The results show that this explanation can be excluded.

The sensitivity of the guard counters for thermal neutrons was studied in the same arrangement with a radium-beryllium source placed on the top of the 25cm thick iron shield. A layer of 10cm paraffine was used for thermalization. With a neutron net count of 9.3 ± 0.1 c/min with the outermost guard shell working, the effect of additional shells was studied (fig 3).

The sensitivity for gamma radiation was also studied with a ^{137}Cs source placed in the chamber close below the counting unit. The γ-radiation of 0.66 MeV, too weak to cause pair-production, had to pass an iron thickness of 4 to 5cm before reaching the counter assembly. The net gamma count rates obtained for different number of active guard shells are shown in figure 3.

All measurements are performed with an upper level discriminator adjusted to give a window covering the whole ^{14}C beta energy range. Count rates are normalized to constant loss of information due to guard action, corresponding to an active outer shell.

Detection efficiency

Anticoincidence guard counters are expected to take care of penetrating charged particles such as muons. The fact that a muon count rate of typically 200 c/min in the ^{14}C counter is reduced to a background of less than 1 c/min by the action of a single guard shell, clearly demonstrates that detection efficiency is >99.5 percent. Consequently, addition of a second guard shell should leave less than 0.5 percent of any remaining muon contribution undetected, *ie*, <0.005 c/min. Thus, a third shell should give no background reduction. Our measurements, with a nearly constant drop in background for each added shell, strongly indicate that detection efficiency for muons is practically 100 percent for a single guard shell.

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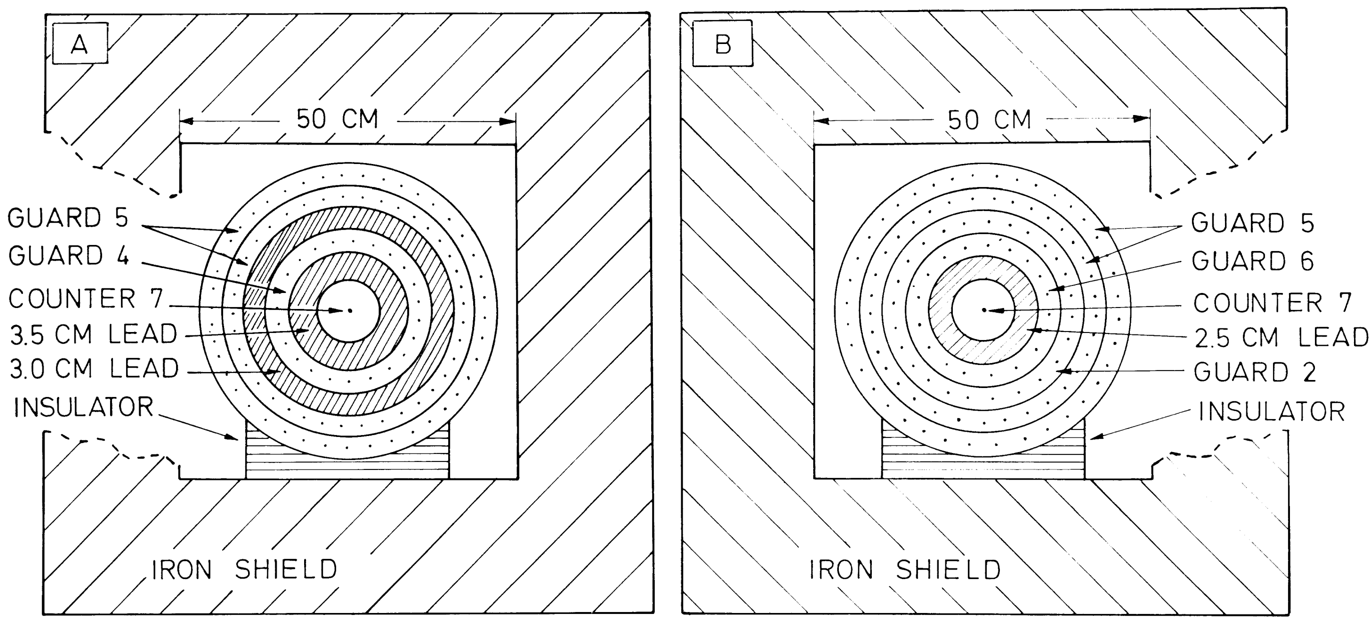

Fig 2. Experimental arrangements for investigating guard shell efficiencies. A — 3 guard shells, 6.5cm old lead (Gulliksen and Nydal, 1976), B — 4 guard shells, 2.5cm old lead (this paper).

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This conclusion is also reached by considering the probability P_1 for a charged particle to form an ionpair in a counter gas (Curran and Craggs, 1949):

$$P_1 = 1 - e^{-kx}$$

x is the track length of the traversing particle, and k, the average number of ionpairs formed per unit track length at atmospheric pressure. When introducing the probability ω for 1 ionpair to initiate sufficient discharge in the counter to be detected, the probability P_2 for detecting a penetrating charged particle is given by

$$P_2 = 1 - e^{-w \cdot k \cdot p \cdot x}$$

where p is the gas pressure.

In a proportional guard counter working at 1.2 atmospheres pressure ($p = 1.2$), the chosen values for k and ω is 25 ionpairs/cm and 0.1, respectively. The value for k is from ionization in air at atmospheric pressure (Curran and Craggs, 1949), and it may be somewhat different in propane at 1.2 atmospheres. The value for ω may be slightly lower than for a geiger counter where ω is close to one. For $x = 3$cm (the thickness of the guard shell), the typical values give

$$P_2 = 1 - e^{-11.7}$$

which will leave less than 0.001 of 200 muons penetrating the ^{14}C counter per minute undetected by a single guard shell.

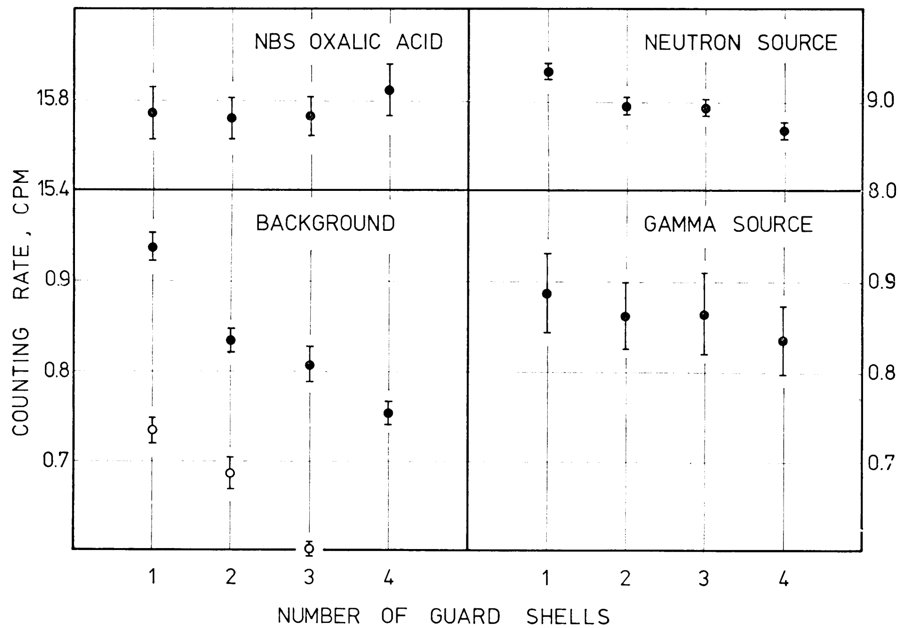

Fig 3. Counting rates obtained for NBS oxalic acid, background, thermal neutrons and soft gamma with different number of guard shells in operation. Background measurements marked with open circles are from previous experiment with 6.5cm old lead (fig 2A), and without upper level discriminator.

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With the neutron source we obtained a reduction in neutron background of 2.4 ± 0.5 percent per guard shell added. This agrees well with the expected 1 to 2 percent detection efficiency for neutrons, and the results for the gamma source indicate an efficiency in the expected range, 1 to 2 percent.

DISCUSSION

From data obtained in an underground experiment in a mine pit 380m below ground, the minimum background for counter no. 7 (due to radioactive contaminations in the counter material) was calculated to 0.44 ± 0.02 c/min. This was measured with no guard and without an upper level discriminator. Corrected for the estimated effect of a window discriminator and normalized to an information loss of 2.5 percent, the minimum background is ca 0.35 c/min. The cosmic contribution to the background measured in this experiment is therefore ca 0.50 c/min, giving an average drop in background per shell of ca 13 percent. A similar effect was found by G W Barendsen (1955) who experimented with two geiger guard counters, but with no old lead. He got a background reduction for a ^{14}C counter of 4 to 7 percent (of the total background) with the second guard in operation, which he explained by assuming different sensitivity for the two guard shells.

It is quite obvious that this effect is in disagreement with the normal detection efficiencies of a guard shell for various penetrating radiations, which are verified in this experiment. The high sensitivity of our guard counters must be due to the fact that we are counting showers, *ie,* several gamma quantum and particles arising from the same event. These events are caused by muons and high energy protons, penetrating into the iron shield. Primary protons with energies of the order of 1 GeV are able to initiate nuclear interactions (stars) in the iron shield, which result in a shower of neutrons, gamma radiation, and electron pairs.

The muons that have a half-life of $1.52 \cdot 10^{-6}$s and a rest energy of 107 MeV, are mainly formed in the atmosphere at about 10km. Due to the relativistic effect and their weak interaction with matter, they reach ground level in relatively large numbers. The muons disintegrate into an electron and two neutrinos ($\mu \rightarrow e^- + \nu + \bar{\nu}$). The electrons that receive energies up to 53 MeV (middle energy about 10 MeV) start showers with gamma radiation (Bremsstrahlung), pair production, etc.

Protons and muons that are intersecting a guard counter are detected with ca 100 percent efficiency by a single guard shell. When the particles end their path in the iron shield and initiate showers, which are intersecting the counting system, the guard counters will respond to the gamma showers with reduced sensitivity (~13%). Consequently, the showers will give a significant cosmic contribution to counter background. The existence of showers are well known (Rossi, 1964) and are also documented for our shield in the lead absorption curve.

Comparison with earlier measurements with three guard shells and 6.5cm old lead (fig 3) clearly demonstrates that extra guard shells can be substituted by increasing the thickness of the inner lead shield, giving the ^{14}C counter better protection against the gamma showers.

Both in our experiment and that of Barendsen (1955) the lowest background with a single shell was obtained with the outer shell in operation. This can be expected, as the larger surface of this shell will detect gamma showers more effectively than the inner shells.

Optimal shielding in a ground level laboratory

The shielding in a ground level laboratory must not be too complicated if it should be of general interest. Our arrangement with four guard shells is only for background studies, and not a permanent setup for ^{14}C dating. The single guard counters have to be used in separate counting units later on.

The efficiency of the guard counters is 100 percent for charged particles and about 13 percent for showers. Thus, it is possible, according to figure 3, to reach the minimum background with a large number of guard shells and a small amount of old lead (2.5cm) inside the iron shield. However, it is easier and more effective to use more old lead inside the guard counter and reduce the number of guards. A layer of old lead (5cm) is also a better protection against radioactive contamination in the guard counter and iron shield.

The very large double guard counter (fig 1) was made for the advantage of putting most of the shielding material inside the guard shells.

Figure 4 summarizes the results obtained. The top guard used was $5 \times 60 \times 120 cm^3$, covering a major part of the iron shield. It may be advantageous to make the top guard counter slightly larger, but it will not be necessary to cover the sides of the shield. The top guard counting

Counter no.	Eff. volume (ℓ)	Anticoinc. system	Iron shield (cm)	Lead shield (cm)	Background (cpm)	Recent standard (cpm)	Location
7	1.2	4 guard shells	25	2.5	0.76±0.01	15.3	Trondheim laboratory
		3 guard shells	25	6.5	0.51±0.01		
		1 guard shell	30	3.8	0.67±0.02		
		1 guard shell + top guard	30	3.8	0.57±0.02		
		No guard	15	9.5	0.39±0.01		Mine pit 380 m below ground
2	1.5	1 guard shell	30	3.4	0.74±0.02	19.3	Trondheim laboratory
		1 guard shell	30	5.3	0.60±0.02		
		1 guard shell + top guard	30	5.3	0.48±0.01		
		1 guard shell	none	15 + 3.4	0.32±0.01		Bern undergr. lab. 57 m below ground

Fig 4. Backgrounds obtained with various shielding systems. Backgrounds are either measured with an upper level discriminator, or corrected for an estimated effect of such a device. Backgrounds are all normalized to 1 percent loss of information (due to action of guards), to which the listed modern net counts correspond.

rate is 8000 c/min, and it is important to minimize the anticoincidence pulse length ($<200\mu s$) in order to prevent severe information loss.

A top guard is very valuable for the detection of high energy charged particles before they enter the iron shield (Nydal, Gulliksen, and Lövseth, 1975), especially those initiating showers that otherwise would contribute to the counter background. The background of counter no. 2 was reduced from 0.60 ± 0.002 c/min to 0.48 ± 0.001 c/min by introduction of the top guard, corresponding to a decrease in the cosmic fraction of more than 40 percent! The final background is only 0.16 ± 0.015c/min higher than that obtained with the same counter in the Bern underground laboratory (0.32 ± 0.01c/min).

An excellent compromise of complexity and efficiency is thus the system shown in figure 5. It must, however, be pointed out that additional shielding, especially against neutrons and protons, is provided by the four-story concrete building (equivalent to 1m concrete thickness) above our counting room. A lining of 3cm old lead inside the counter chamber will give additional shielding for γ-radiation from iron. A 10cm layer of paraffine mixed with boric acid is indicated for neutron protec-

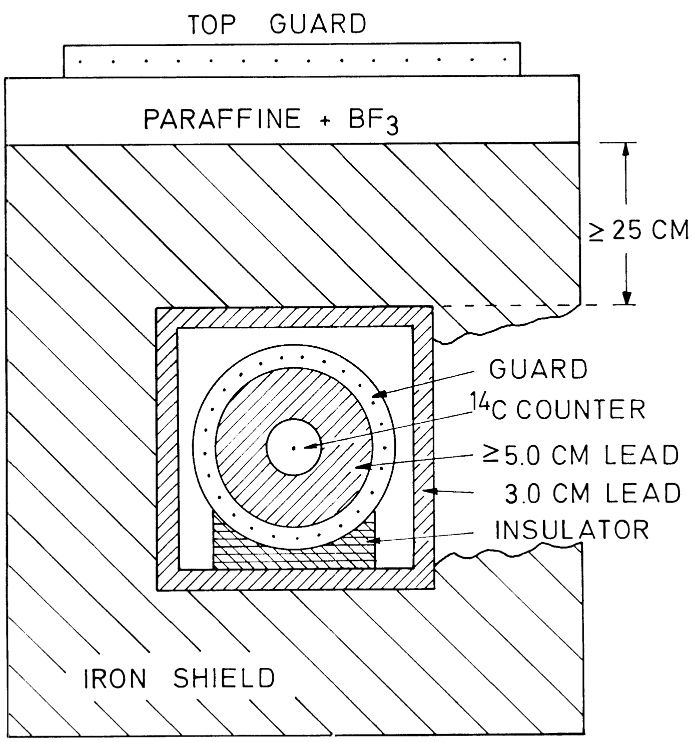

Fig 5. Optimal shielding system in a ground level laboratory, with 25 to 30cm iron shield, counting chambers lined with ca 3cm old lead and ^{14}C counter wrapped in ca 5cm old lead. Single guard shell inside chamber and top guard covering ca 10cm layer of paraffine/boric acid on top of the iron shield.

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tion. We have not yet been able to measure accurately the effect of either the paraffine layer or the lead lining. Although the top guard certainly will detect most of the protons that could initiate neutrons by interactions in the shield, it is expected that any other neutron contribution to the background will be reduced with the paraffine. Especially when propane or hydrogen participates in the counting gas for tritium measurements, this could be important.

As protection against γ-radiation from showers and contamination in the iron field is so important, it is possible to get an alternative shielding system with a scintillation guard counter with up to 70 percent efficiency for γ-radiation. A combination of such a guard and an ordinary proportional guard counter will probably give a satisfactory result. Shielding with old lead would still be necessary.

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