Technical University of Denmark

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Publication date:
1982

Document Version
Publisher's PDF, also known as Version of record

RISØ-M-2339

SHIELDING FACTORS FOR VEHICLES TO GAMMA RADIATION FROM ACTIVITY DEPOSITED ON STRUCTURES AND GROUND SURFACES

Bente Lauridsen and Per Hedemann Jensen

Abstract. This report describes a measuring procedure for the determination of shielding factors for vehicles passing through areas that have been contaminated by activity released to the atmosphere from a reactor accident. A simulated radiation field from fallout has been approximated by a point source that has been placed in a matrix around and above the vehicle. Modifying factors are discussed such as mutual shielding by nearby buildings and passengers. From measurements on different vehicles with and without passengers shielding factors are recommended for ordinary cars and busses in both urban and open areas, and areas with single family houses.

INIS descriptors: REACTORS ACCIDENTS; EXTERNAL RADIATION; GAMMA RADIATION; RADIATION DOSES; FALLOUT DEPOSITS; SURFACE CONTAMINATION; SHIELDING; VEHICLES; BUILDINGS; ROADS; URBAN AREAS.

UDC 614.73:629.114.5/.6

April 1982
Risø National Laboratory, DK 4000 Roskilde, Denmark

ISBN 87-550-0841-0
ISSN 0418-6435

Risø Repro 1982

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1. INTRODUCTION

In studies of the potential radiological consequences from hypothetical nuclear reactor accidents where radioactivity is released to the atmosphere, attention has been given in the past few years to the long-term radiation doses originating from activity deposited on structures and ground surfaces. In particular, the discussions have focused on sites where nuclear power plants have been placed near large population centers giving a potential long-term contamination risk from radionuclides such as ^{137}Cs to urban areas.

When calculating the long-term population doses from deposited long lived radionuclides, one must know the shielding factors fairly accurately for vehicles passing through contaminated areas. This is important because a large part of the long-term population doses originates from transportation in cars and buses. Even though indoor residence in the contaminated areas takes place during most of the day, the shielding factors for buildings - especially in urban areas - are much better than for vehicles.

In order to determine shielding factors for different vehicles an experimental procedure has been carried out, and shielding factors in open areas have been determined for gamma radiation from deposited ^{137}Cs. Corrections for mutual shielding by nearby buildings have been made so the shielding factors can be used for urban as well as open areas.

2. STRUCTURAL SHIELDING AGAINST RADIATION FROM A SURFACE SOURCE

2.1. Definition of the shielding factor

The shielding factor is defined as

$$S = \frac{\dot{X}}{\dot{X}_o}$$

where $\dot{X}$ is the actual exposure rate and $\dot{X}_o$ a reference exposure rate.

In this study the reference exposure rate is chosen as the exposure rate 1 meter above an infinite, smooth surface source.

2.2. Reference position

The photon flux density from an infinite plane source with the surface source concentration S_o is calculated in the following way with reference to Figure 1.

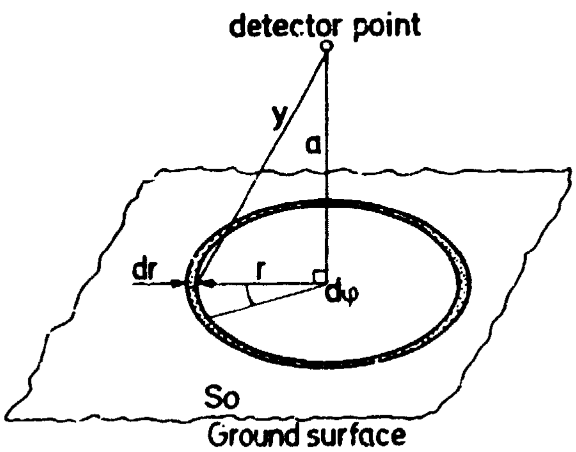

Fig. 1 Geometry for calculating the exposure rate from an infinite plane surface source.

The activity in the infinitesimal ring element with radius from r to r + dr is

$$dq = \int_{\phi=0}^{2\pi} S_o \cdot r \cdot dr \cdot d\phi = 2\pi \cdot S_o \cdot r \cdot dr$$

From the source point to the detector point the photon flux density will experience build-up as well as attenuation in air.

With regard to this, the photon flux density at the detector point from the ring element is given by :

$$d\Phi = 2\pi \cdot \frac{S_o \cdot r \cdot dr}{4\pi \cdot y^2} \cdot B(\mu \cdot y) \cdot e^{-\mu y}$$

where $y = \sqrt{r^2 + a^2}$, B is the dose build-up factor in air, and μ is the linear attenuation-coefficient for air.

The total photon flux density is then

$$\Phi = \int_o^\infty S_o \cdot r \cdot dr \cdot \frac{2\pi}{4\pi y^2} \cdot B(\mu \cdot y) \cdot e^{-\mu y}$$

Setting the height to 1 meter and using

$$\dot{X} = k \cdot \Phi$$

the reference exposure rate is found as

$$\dot{X}_o = k \cdot \int_o^\infty S_o \cdot \frac{2\pi \cdot r}{4\pi \cdot y^2} \cdot B(\mu \cdot y) \cdot e^{-\mu y} \, dr \qquad (1)$$

The calculated reference exposure rate from Eq. 1 by numerical integration is shown in Figure 2.

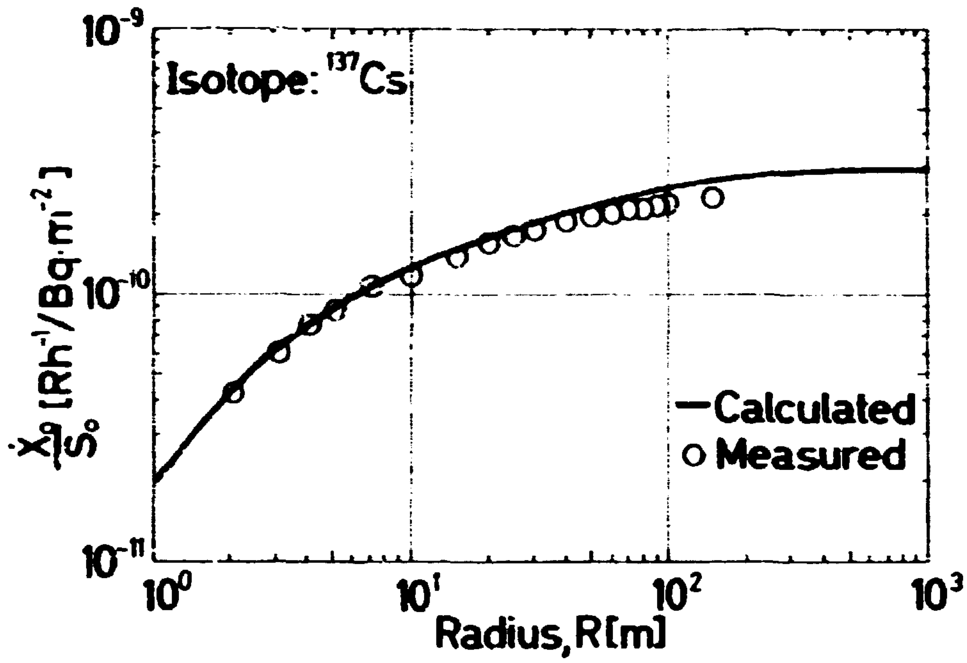

Fig. 2 Calculated and measured reference exposure rate.

2.3. Exposure rate from activity deposited on roads and houses in urban and single family house areas

The photon flux density from a plane source with the source concentration S_0 deposited on a road of infinite length and a width w is calculated as follows with reference to Figure 3.

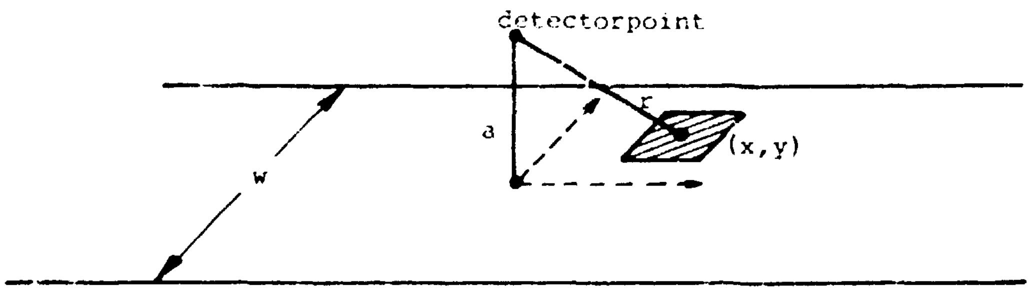

Fig. 3. Geometry for calculating the exposure rate from a road of infinite length and a width w or from a building of infinite length and height w.

The activity in the infinitesimal road element around (x,y) is

$$dq = S_o \cdot dx \cdot dy$$

Taking build-up and attenuation in air into consideration gives the following expression for the photon flux density at the detector point from the infinitesimal road element

$$d\Phi = \frac{S_o \cdot dx \cdot dy}{4\pi \cdot r^2} \cdot B(\mu r) \cdot e^{-\mu r}$$

$$r^2 = x^2 + y^2 + a^2 \quad , \; a = 1m$$

This gives the total flux density

$$\Phi = \int_{-\infty}^{\infty} \int_{0}^{w} \frac{S_o}{4\pi r^2} \cdot B(\mu r) \cdot e^{-\mu r} \cdot dx \cdot dy$$

Using

$$\dot{X} = k \cdot \Phi$$

gives the exposure rate at a point 1 m above a road of infinite length and a width w as

$$\left(\frac{\dot{X}}{S_o}\right)_{road} = \frac{k}{4\pi} \int_{-\infty}^{\infty} \int_{0}^{w} \frac{1}{r^2} \cdot B(\mu r) \cdot e^{-\mu r} \, dx \cdot dy \qquad (2)$$

The exposure rate from a building of infinite length and height h is calculated in the same way

$$\left(\frac{\dot{X}}{S_o}\right)_{wall} = \frac{k}{4\pi} \int_{-\infty}^{\infty} \int_{0}^{h} \frac{1}{r^2} \cdot B(\mu r) \cdot e^{-\mu r} \cdot dx \cdot dy \qquad (3)$$

Figure 4 shows the calculated exposure rate from activity deposited on a wall of infinite length and height of 10 m. The detector distance from the wall is 7.5 m and the distance above ground is 1 m.

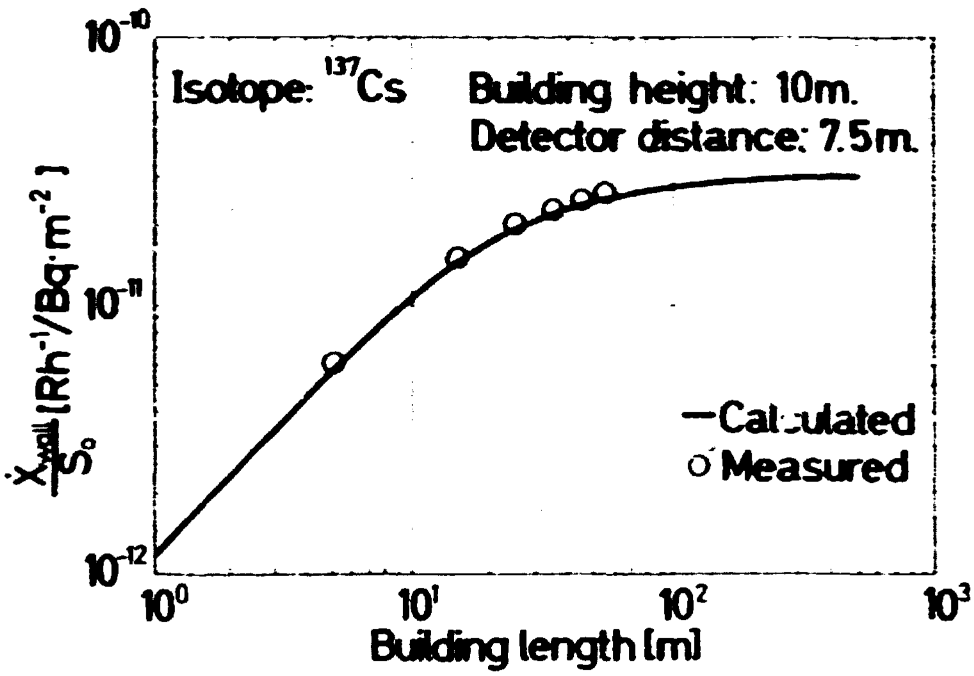

Fig. 4. Calculated and measured exposure rate from activity deposited on a wall.

2.4. Effect of ground roughness

The shielding factor is defined as the exposure rate in a car from activity deposited on a surface with a certain roughness divided by the exposure rate 1 meter above an infinite smooth surface source. The measurement procedure implies that the exposure rate within the car is measured as that from a smooth surface source. In order to correct for the ground roughness a correction factor is needed. Burson (Ref. 1) recommends a roughness factor of 0.85-1.0. In this study a factor of 0.9 was chosen.

If it is assumed that

$$\frac{\dot{X}_{car,smooth}}{\dot{X}_{\infty,smooth}} = \frac{\dot{X}_{car,rough}}{\dot{X}_{\infty,rough}}$$

with

$$\dot{X}_{rough} = 0.9 \cdot \dot{X}_{smooth}$$

we find the following expression for the shielding factor corrected for ground roughness:

$$\frac{\dot{X}_{car,rough}}{\dot{X}_{\infty,smooth}} = \frac{\dot{X}_{car,smooth}}{\dot{X}_{\infty,smooth}} \cdot 0.9$$

3. EXPERIMENTAL APPROACH

3.1. Shielding factors for open ares

The exposure rate from an infinite source can be approximated by the exposure rate from a disc source with radius R greater than 150-200 m, as the contribution to the exposure rate from source elements at greater distances is negligible (see Figure 2).

As the space required for a disc source of 300-m diameter is rather large , this is simulated, in the experimental procedure, by a line of points in which the radioactive source is placed.

The exposure rate at a height a above the center of a disc source with radius R is

$$\dot{X}_{disc} = \int_{o}^{R} 2\pi S_o \cdot r \cdot dr \cdot e^{-\mu\sqrt{r^2+a^2}} \cdot B(\mu \cdot \sqrt{r^2+a^2}) \cdot \frac{\Gamma}{r^2+a^2}$$

or

$$\left(\frac{\dot{X}}{S_o}\right)_{disc} = \int_{o}^{R} 2\pi \cdot \frac{Q}{Q} \cdot r \cdot dr \cdot e^{-\mu\sqrt{r^2+a^2}} \cdot B(\mu \cdot \sqrt{r^2+a^2}) \cdot \frac{\Gamma}{r^2+a^2}$$

where Q is the activity of a point source placed in a distance r from the center of the disc source, and Γ the exposure rate constant.

The exposure rate $\dot{X}_{point}$ from a point source at distance r is given by

$$\dot{X}_{point} = Q \cdot e^{-\mu\sqrt{r^2+a^2}} \cdot B(\mu \cdot \sqrt{r^2+a^2}) \cdot \frac{\Gamma}{r^2+a^2}$$

If the integration is replaced by a summation the following expression

$$\left(\frac{\dot{X}}{S_o}\right)_{disc} = \frac{2\pi}{Q} \cdot \sum_{i=1}^{N} \dot{X}_{point,i} \cdot r_i \cdot \Delta r_i \qquad (4)$$

can be used for calculating the exposure rate from a smooth surface source from the measured exposure rate $\dot{X}_{point,i}$ with the source at different distances.

To see how well this fits the theoretical expression for the exposure rate from an infinite surface source (see section 2.2) Eq. 1 was compared with Eq. 4 in which the measured values of $\dot{X}_{point}$ as well as data for the source were used. The result is shown in figure 2 and it is seen that Eq. 4 is a good approximation.

To compensate for the unsymmetrical construction of a car the exposure rate is calculated as the sum of four terms. The four terms are the exposure rate contributions from the 90° disc segments: behind, in front , and at the two (assumed equal) sides of the car.

The exposure rate inside the car from a disc source is then calculated from Eq. 4 as

$$\dot{X} = 0.25\cdot\dot{X}_{back} + 0.25\cdot\dot{X}_{front} + 0.50\cdot\dot{X}_{side}$$

which leads to

$$S_{open} = 0.25\cdot S_{back} + 0.25\cdot S_{front} + 0.50\cdot S_{side}$$

3.2. Shielding factor for urban areas

In an urban area the exposure rate in the middle of a street with houses on both sides originates from deposited activity on the streets as well as on the buildings. Therefore, to determine shielding factors for vehicles passing through urban areas, measurements of the exposure rate from a point source placed in the vertical plane have to be included.

The exposure rate at a given position at the road from activity deposited on an infinite long wall is given by

$$\dot{X}_{wall} = \int_{-\infty}^{\infty}\int_{0}^{h}\frac{S_o}{r^2}\cdot\Gamma\cdot B(\mu r)\cdot e^{-\mu r}\cdot dx\cdot dy$$

or

$$\left(\frac{\dot{X}}{S_o}\right)_{wall} = \int_{-\infty}^{\infty}\int_{0}^{h}\frac{Q}{Q}\cdot\frac{\Gamma}{r^2}\cdot B(\mu r)\cdot e^{-\mu r}\cdot dx\cdot dy$$

The meaning of dx, dy, h, and r can be seen from figure 5.

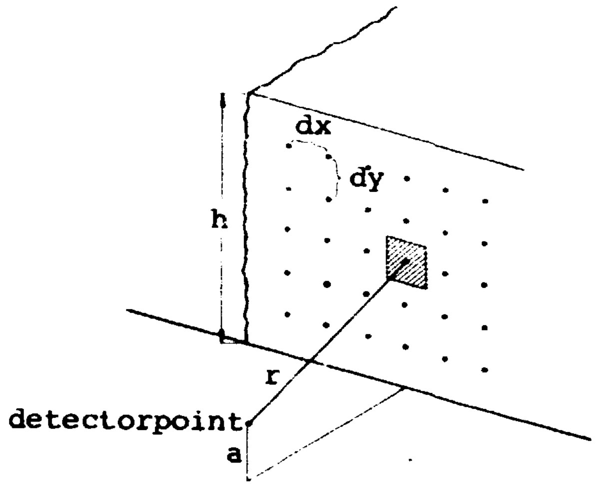

Fig. 5. The geometry for measuring the exposure rate from a contaminated house wall.

The exposure rate $\dot{X}_{ij}$ from a point source with the source strength Q placed in a grid point at the wall is given by

$$\dot{X}_{ij} = \Gamma \cdot \frac{Q}{r^2} \cdot B(\mu r) \cdot e^{-\mu r}$$

Replacing the integration with a summation and introducing $\dot{X}_{ij}$ for the measured exposure rate from one grid point in the expression for $(\dot{X}/S_o)_{wall}$ gives

$$\left(\frac{\dot{X}}{S_o}\right)_{wall} = \sum_i \sum_j \frac{1}{Q} \cdot \dot{X}_{ij} \cdot \Delta x_i \cdot \Delta y_j \qquad (5)$$

Instead of moving the source in the horizontal direction, the detector is placed along this direction at different points on the road on both sides of the source.

At Figure 4 (see section 2.3) eq. (5), in which the measured values of $\dot{X}_{ij}$ and data for the source were used, is compared with eq. (3) and the agreement is seen to be very good.

If the grid points in the vertical and horizontal directions are placed equidistant, the shielding factor for the radiation from activity deposited on the wall can be expressed as :

$$S_{wall} = \frac{\left[\sum_j \sum_i \dot{X}_{ij}\right]_{car}}{\left[\sum_j \sum_i \dot{X}_{ij}\right]_{no\ car}}$$

An urban shielding factor S_{urban} can be defined as

$$S_{urban} = \frac{\dot{X}_{urban}}{\dot{X}_o}$$

$$= \frac{\dot{X}_{front} \cdot \frac{\frac{1}{2} \cdot \dot{X}_{road,no\ car}}{\dot{X}_o} + \dot{X}_{back} \cdot \frac{\frac{1}{2} \cdot \dot{X}_{road,no\ car}}{\dot{X}_o} + 2 \cdot \dot{X}_{wall,car} \cdot \frac{\dot{X}_{wall,no\ car}}{\dot{X}_{wall,no\ car}}}{\dot{X}_o}$$

$$= \frac{1}{2} \cdot \left(\frac{\dot{X}_{road,no\ car}}{\dot{X}_o}\right)_{cal} \cdot (S_{front} + S_{back}) + 2 \cdot \left(\frac{\dot{X}_{wall,no\ car}}{\dot{X}_o}\right)_{cal} \cdot S_{wall}$$

where $\dot{X}_{road,no\ car}$ and $\dot{X}_{wall,no\ car}$ are calculated by numerical integration from Eqs. 2 and 3 for a road width of 15 m and a building height of 10 m, $\dot{X}_o$ from Eq. 1, and S_{front} and S_{back} from Eq. 4 (see Section 3.1).

When calculating the contribution to the exposure rate from activity deposited on the road, the front garden, and the walls in an area with single family houses it was assumed that the activity deposited in the front garden was 10 times the deposition on the road and on the house walls. The road width + pavement was set to 14 m, the front garden to 3 m, and the height of the houses to 4 m.

The following results for $(\dot{X}_{road,no\ car}/\dot{X}_o)_{cal}$ and $(\dot{X}_{wall,no\ car}/\dot{X}_o)_{cal}$ were obtained.

	$\left(\frac{\dot{X}_{wall,no\ car}}{\dot{X}_o}\right)_{cal}$	$\left(\frac{\dot{X}_{road,no\ car}}{\dot{X}_o}\right)_{cal}$
urban areas	0.11	0.50
single houses	0.03	1.26

3.3. Radiation source

The source used in the experiment consisted of 3 uranium pellets from a commercial fuel element. Each pellet was of 1.3-cm diameter and 1-cm height. The burn-up was 25,000 MWd/tU and the cooling time of the fuel element was 6 years, so the gamma-emitting fission product content consisted mainly of ^{137}Cs and ^{134}Cs This was rather suitable for the experiment as the long-term radioactive contamination after a hypothetical large reactor accident is due mainly to these two nuclides. The source activity was measured by means of gamma spectrometry to $1.53 \cdot 10^{11}$ Bq (4.14 Ci) of ^{137}Cs.

3.4. Instrumentation

The exposure rate was measured with a plastic scintillator instrument of the type 2414 Studsvik Gammameter. Due to fluctuations and a logarithmic scale it was rather difficult to read the exposure rate directly, so its voltage output was fed into a Hewlett-Packard digital voltmeter type 3654A. The voltmeter sampled the output from the instrument 300 times in 10 seconds and wrote out the mean value. A calibration curve of voltage versus μR/h, determined with certified gamma sources was used for converting the mean voltage to exposure rate.

3.5. Measurement procedure

3.5.1. Open areas

The points for simulating the disc source were placed at a distance of 2,3,4,5,10,15,20,25,30,40,50,60,70,80,90,100,110, 120,130,140,and 150 meters from the detector point. Figure 6 shows the experimental set-up.

First, the exposure rates from the source placed successively at the 21 points were measured with the detector placed 1 m above the ground. The procedure was then repeated with the car's front, back, and side towards the source. In the last three cases the detector was placed 15 cm above the driver's seat and situated just above the detector point. The source was moved by means of a radio controlled model car from a distance of 40 meters.

Shielding factors were measured for 6 cars representing some of the most common models in Denmark. For one of them the shielding factors were measured both with and without passengers. Shielding factors for a 50-passenger public bus were measured both with and without passengers and with the detector placed at both the driver's seat and a passenger seat located in the middle of the bus.

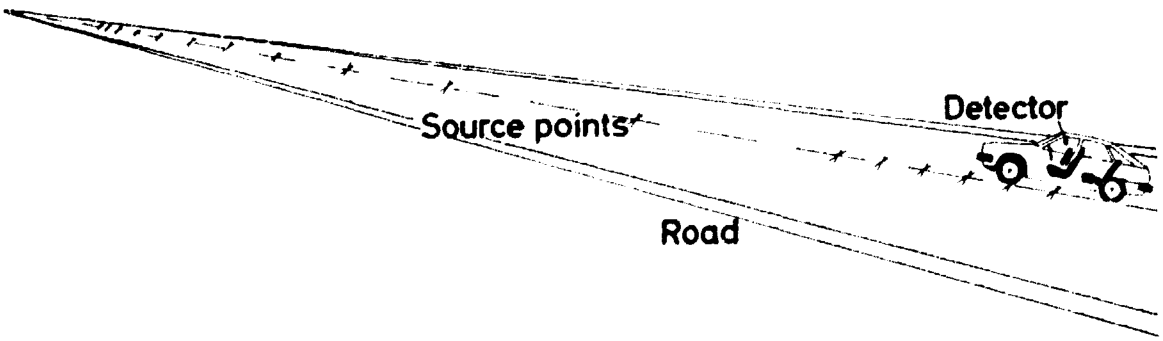

Fig. 6 The experimental set-up for determination of the shielding factor for open areas.

3.5.2. Urban areas and areas with single family houses

The shielding factor of the vehicle for radiation from deposited activity on front walls of houses can be measured in a similar way as for deposited activity on the ground. Figure 7 shows the experimental set-up. The source simulating the activity deposited on a wall was in case of urban areas placed at 1, 3, 5, 7, 9 m in the vertical direction. For single family houses the 1 and 3 m positions were used. The detector positions at the road used to simulate the horizontal source positions, were placed at 5 m's intervals up to 50 m on each side of the vertical source positions. For one of the cars S_{wall} was measured both with and without passengers and these values were used as representative for all others.

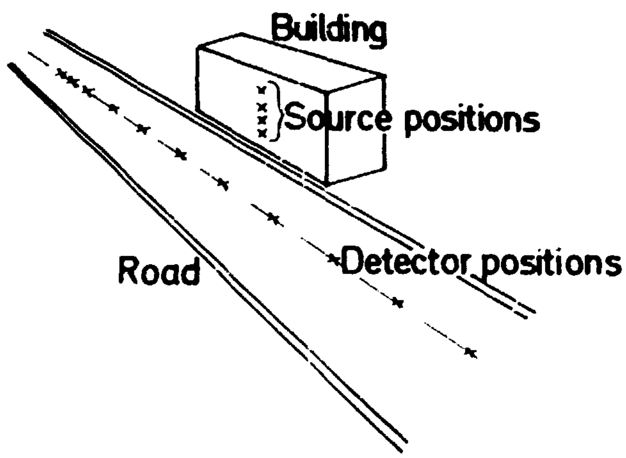

Fig. 7. The experimental set-up for determination of the shielding factors for urban areas.

4. RESULTS

The measured results for the shielding factors for empty cars and those with passengers are shown in Tables 1 and 2, respectively.

Type of vehicle	Shielding factor		
	open areas	single house	urban areas
Morris Mascot St.car	0.72	0.59	0.38
Mercedes 220 Diesel	0.59	0.51	0.35
Polski Fiat Stationcar	0.58	0.38	0.30
Saab 99 GL	0.62	0.54	0.36
Fiat 127	0.64	0.43	0.32
Talbot Horizon	0.66	0.53	0.36
Bus, driver's seat	0.40	0.37	0.30
Bus, passenger seat	0.33	0.19	0.22

Table 1. Shielding factors for empty vehicles.

Type of vehicle	Shielding factor		
	open areas	single house	urban areas
Talbot Horizon	0.41	0.32	0.25
Bus, driver's seat	0.51	0.40	0.28
Bus, passenger seat	0.26	0.11	0.16

Table 2. Shielding factors for vehicles with passengers.

5. CONCLUSION

In the event of a nuclear reactor accident it may be important to consider the long-term doses to persons who are transported through contaminated areas by cars or buses.

For this purpose gamma-ray shielding factors provided by civilian vehicles are of interest and might be calculated. However, because of the complex structure of a vehicle, the results of theoretical calculations could be rather uncertain. A more direct method for estimating the shielding factors for vehicles has been carried out by measuring the exposure rate reduction inside different vehicles for gamma radiation from the radionuclide ^{137}Cs.

The method has been found applicable for estimating the shielding factor for a vehicle moving in open areas as well as urban areas. Based on measurements on different transportation vehicles with and without passengers, the following shielding factors are recommended as representative for open, single house, and urban areas:

		cars	buses
open areas	passengers	0.40	0.40
	no passengers	0.60	0.35
single houses	passengers	0.30	0.25
	no passengers	0.35	0.30
urban areas	passengers	0.25	0.20
	no passengers	0.30	0.25

Because most calculational models use an exposure rate one meter above an infinite smooth plane source as reference, the above mentioned shielding factors have been evaluated with reference to this hypothetical source configuration. The reducing effect on exposure rate caused by ground roughness as well as buildings has been included in the figures.

Reference : Burson,Z.G. and Profio,A.E., Structure Shielding in Reactor Accidents. Health Physics, 33, pp. 297-299, 1977.

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Department or group

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Group's own registration number(s)

20 pages + tables + illustrations

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