

Radiation Control Group Note

Abstract

This RCG note (90-001) sets out the technical basis for the use of dose rate measurements for determining release of activated material. The proposed criteria are intended to assist in establishing CEBAF policy in this area.

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On the Measurement of Induced Radioactivity and Suggested Criteria for Release of Activated Materials

G. Stapleton

Introduction

It is often stated that the largest personnel doses and most of the collective dose equivalent on accelerators are due to induced radioactivity and arise during maintenance and modification. It is important to understand that such doses are mainly caused by gamma radiation from deep activation of solid, often thick, objects by penetrating radiation. As a result, external gamma radiation usually sets the limits of exposure. For thick objects, the relative beta dose rates are low. It is unusual to experience significant levels of easily removable radioactivity, although it is obviously wise to confirm this by monitoring. Because we are generally dealing with deep activated thick objects it is possible to use surface gamma dose rate measurements as a method of determining specific activity. This is particularly valuable for setting screening standards for the release of activated material for disposal as trash or just simply regarding it non-radioactive.

Method of Calculation

The method of calculation is based on a simple energy balance concept; that is, in an infinite homogeneous and uniformly radioactive medium, the energy absorbed per unit mass equals the energy emitted per unit mass (Pri57) (Per87).

The simplest case is a large tank of water containing a gamma emitting nuclide, taking tissue as being equivalent to water. The energy balance concept leads to an energy emission and absorption rate of:

$$S E \text{ (MeV g}^{-1}\text{s}^{-1}\text{)}$$

where S is the photon emission rate ($\text{g}^{-1}\text{s}^{-1}$)
 E is photon energy (MeV).

Since $1 \text{ MeV} = 1.6 \cdot 10^{-13} \text{ joule}$
and $1 \text{ rad} = 10^{-5} \text{ joule g}^{-1}$
 $1 \text{ gray} = 10^{-3} \text{ joule g}^{-1}$

1 MeV g^{-1} leads to an absorbed dose of:

$$1.6 \cdot 10^{-8} \text{ rad or } 1.6 \cdot 10^{-10} \text{ gray.}$$

This simple concept leads to the familiar expression for surface dose rates, which is in effect half the value derived above without any correction for material or the missing backscatter. Thus

$$D_s = \frac{1}{2} SE \cdot 1.6 \cdot 10^{-8} \cdot 3600 \cdot 3.7 \cdot 10^4$$

$$= 1.07 SE \text{ (rad h}^{-1} \text{ per } \mu\text{Ci g}^{-1} \text{ and } E \text{ in MeV)}$$

and similarly

$$D_s = 0.288 SE \text{ (Gy h}^{-1} \text{ per GBq kg}^{-1} \text{ and } E \text{ in MeV).}$$

Perry has provided a rather nice correction factor for these expressions for material and backscatter, having the form (Per87):

$$D_s = 1.07 SE F(Z, E).$$

He calculated values of $F(Z, E)$ for representative material:

water, carbon, aluminum, iron and lead.

He made these calculations on slabs some 3λ or 5λ in thickness (figure 1), but also showed how $F(Z, E)$ varied with thickness down to 0.001λ (figure 2). At energies of about 0.5 MeV (positron annihilation) the value of $F(Z, E)$, except in the case of lead, does not greatly differ from unity, and for thicknesses down to say 1λ the correction factor seems to remain reasonably constant.

For monitoring objects under geometrical conditions that cannot be taken as 2π , then some estimate of solid angle subtended by the object at the detector position and a further correction applied:

$$D_s = 1.07 SE F(Z, E) \frac{\Omega}{2\pi}.$$

As an example calculation we assume a radionuclide specific activity of 10 pCi g^{-1} in which every disintegration gives rise to a 1 MeV photon. Assuming surface dose measurement under 2π conditions and $F(Z, E)$ is approximately 1, then

$$D_s = 1.07 \cdot 10^{-5} \simeq 11 \mu\text{rad h}^{-1}.$$

The value of approximately 10 pCi g^{-1} is considered to be exempt for certain conditions of radioactive substances under an exemption order to the UK radioactive substances act (see attachment), since there is no equivalent US equivalent de minimis value for radioactive substances we will use the UK value as an example.

This calculation implies a uniform distribution of radionuclides throughout the solid. For materials activated by accelerator neutron spectra where the activating mean free path is considerably longer than the photon λ then this is a reasonable assumption and a

reasonable method of measurement. For mixtures of radionuclides, some estimate of the mean product of photon energy and the number of photons released per disintegration is required.

Estimation of Photon Energy per Disintegration from Accelerator Produced Radionuclides

The so called $k\gamma$ -factor for a given radionuclide is the specific dose rate per disintegration and is often given in units of $\text{rad h}^{-1} \text{ Ci}^{-1}$ at 1 m from a point source. Thus

$$D_p = \frac{k\gamma C}{r^2} \text{ rad h}^{-1}$$

where C activity in Ci
r distance in m

By restricting our attention to photons of energy between (say) 0.05 and 4 MeV and noting that the fluence to dose conversion coefficient has been expressed as (ICRP71):

$$\frac{1.734}{E \text{ (MeV)} \left(\frac{\mu_{en}}{\rho} \right)} \text{ photons/cm}^2 \cdot \text{s per mrem/h}$$

and the value of $\frac{\mu_{en}}{\rho}$ (water) is approximately constant ($3 \cdot 10^{-3} \text{ m}^2/\text{kg}$) over the energy range, we can assume that dose rate varies with photon energy, thus:

$$\frac{5.78 \cdot 10^2}{E \text{ (MeV)}} \text{ photon/cm}^2 \cdot \text{s per mrad/h} \quad (\text{rem} = \text{rads for photons})$$

rearranging and changing units we can derive a point dose rate expression as follows:

$$D_p \simeq \frac{1.73 \cdot 10^{-6} E C \cdot 3.7 \cdot 10^{10}}{4\pi \cdot 10^4 r^2}$$

$$\simeq \frac{0.51 E C}{r^2} \text{ rad h}^{-1}$$

where C is activity in curies
r is distance from point source (m)

equating with the $k\gamma$ expression:

$$k\gamma \simeq 0.51 E .$$

Remembering that E is the photon energy emitted per disintegration we can return to our earlier expression:

$$D_s \simeq 1.07 S E$$

and which now becomes

$$D_s \simeq 2.1 S k\gamma$$

Taking an average value for $k\gamma$ for radionuclides of mass number less than 60 (after Barbier) based on the tabulation given by Barbier (Bar69) and with half-lives greater than one day, we obtain $k\gamma = 0.64$ ($\text{rad h}^{-1} \text{ Ci}^{-1} \text{ m}^2$). Because most constructional material lies within this mass-number grouping, we will use this value of $k\gamma$ (0.64) to represent accelerator radiated material, thus:

$$D_s \simeq 2.1 \times 10^{-5} \times 0.64$$

However, it is likely that a "weighed" mean taking into account actual yields would give a higher value.

Using the 10 pCi g^{-1} de minimis as discussed earlier we obtain for limiting surface dose rate:

$$D_s \simeq 2.1 \times 10^{-5} \times 0.64 = 13 \mu\text{rad h}^{-1}.$$

Thus we conclude that a contact dose rate of between $10\text{--}20 \mu\text{rad h}^{-1}$ above background should provide a screening value for the UK RSA exemption order.

It is of interest to see what point source strength would give rise to $20 \mu\text{rad h}^{-1}$ at (say) 15 cm and 30 cm, again assuming $k\gamma = 0.64 \text{ rad h}^{-1} \text{ Ci}$ at 1 m.

$$C_{15} = \frac{20 \times 10^{-6} \times 0.15^2}{0.64} = 0.7 \mu\text{Ci}$$

$$C_{30} = \frac{20 \times 10^{-6} \times 0.30^2}{0.64} = 2.8 \mu\text{Ci}$$

Practice in the USA

In the USA there are definitions of radioactivity that are exempt from licensing or regulation, but this does not necessarily mean that they can be trashed as non radioactive waste. However, definitions of such exempt quantities are given as follows:

1. Commonwealth of Virginia
Radiation Protection Regulations 1988 (CVRPR88)
2. The United States Nuclear Regulatory Commission
 - (a) 10 CFR 30.70 rules for licensing by-product material
 - (b) 10 CFR 71 packaging and transport regulations
3. The United States Department of Transportation
49 CFR 173.403 requirements for shipment and packaging

The authority (1) above list exempt quantities for both specific activity and total activities, these are consistent with the NRC values given in 2(a) examples being:

<u>Nuclide</u>	<u>Concentration</u> <u>$\mu\text{Ci/g}$</u>	<u>Total</u> <u>μCi</u>
Be-7	$20 \cdot 10^{-3}$	-
Cr-51	$20 \cdot 10^{-3}$	1000
Mn-54	$1 \cdot 10^{-3}$	10
Na-22	-	10
Co-60	$0.5 \cdot 10^{-3}$	1

It is of consequence that because of half-life considerations the Co-60 (when present) tends to dominate along with Na-22 in activated material aged for a year or so and for Co-60 the photon energy per disintegration is much greater than the average value assumed in the earlier calculation using activation products with half lives greater than one day.

Authority (2(b)) and (3):

According to these, radioactive is material defined as material of specific activity greater than $2 \cdot 10^{-3} \mu\text{Ci g}^{-1}$.

In summary a conservative representative value of concentration and total activity would be that corresponding to the Co-60 values, namely $0.5 \cdot 10^{-3} \mu\text{Ci g}^{-1}$ and $1 \mu\text{Ci}$, respectively.

We also note that the concentration, $0.5 \cdot 10^{-3} \mu\text{Ci g}^{-1}$ is 50 times higher than the 10 pCi g^{-1} given in the UK exemption order. This suggests that 10 pCi g^{-1} is a reasonably conservative release value to use in the USA for accelerator material.

It is of interest that by using the $k\gamma$ for Co-60, ($1.26 \text{ rad h}^{-1} \text{ m}^2 \text{ Ci}^{-1}$), we obtain a surface dose rate for 10 pCi g^{-1} of

$$D_s \simeq 2.1 \cdot 10^{-5} \cdot 1.26 = 26 \mu\text{radh}^{-1}$$

which is twice the dose rate using the average $k\gamma$ for accelerator radiated material.

Considering now the point source calculation we see that by using the Co-60, $k\gamma$, we obtain for the 15cm and 30cm dose rates of $20 \mu\text{rad h}^{-1}$ a total point source strength of:

$$C_{15} = \frac{20 \cdot 10^{-6} \cdot 0.15^2}{1.26} = 0.36 \mu\text{Ci}$$

$$C_{30} = \frac{20 \cdot 10^{-6} \cdot 0.30^2}{1.26} = 1.4 \mu\text{Ci}$$

We see that for point sources our dose rate criterion of $20 \mu\text{rad h}^{-1}$ results from point sources approximating to the exempt from licensing values. However, it is stressed that for objects of significant size such as a nut and bolts significant self-absorbtion will occur and thus reduce the measured dose rate. Thus the use of $10 \mu\text{rad h}^{-1}$ at 15 cm (6 inches) from a smallish object should provide a reasonable screening method, but for many such objects, they should be heaped together and monitored using contact methods.

For very small objects such as targets and beam windows, it will be necessary to utilize greater care but such small objects can be quite easily retained or other disposal procedures can be arranged at a small cost.

Practice at Other Accelerator Laboratories

1. Stanford Linear Accelerator Center.

SLAC adopted a contact dose rate criterion of $20 \mu\text{rad h}^{-1}$ above normal background of $5\text{-}10 \mu\text{rad h}^{-1}$ for the outside of storage containers containing sundry trash (SLAC OHP procedure #4).

SLAC also has a tagging procedure for material removed from the vicinity of the beam line. If the external gamma exposure rate is $> 0.02 \text{ mRh}^{-1}$ at 30 cm (1 foot) it is tagged as radioactive.

2. Brookhaven National Laboratory

It is of interest that Brookhaven National Laboratory have an agreed criterion for release of possibly activated materials (August 7, 1989) as follows (US DOE89):

"For normal materials such as aluminum, copper, iron, concrete, earth, etc., and objects heavier than 1 kg, the gamma level measured with a meter which reads out in μR or μrem calibrated with ^{137}Cs shall not exceed an indicated $10 \mu\text{R/hr}$ above background at a distance of 15 cm from the object. Small similar objects such as bolts from the same unit may be grouped together to satisfy the mass criteria.

For exotic materials exposed around a reactor (no spallation reactions generating many isotopes), an isotopic analysis shall also be performed and the results evaluated against both the NRC exempt concentrations listed in 10 CFR 30.70 and the DOT Standard of 2 nCi/gm ."

The Brookhaven study was based on point source calculations using the US DOT criteria or the US NRC exempt concentrations. The Brookhaven study also considered the dose impact of someone taking home an item giving rise to $10 \mu\text{rem h}^{-1}$. This was shown to be less than 0.25 mrem per year.

3. Fermilab

The standards for release by Fermilab are based on a survey where the following standards must be met:

- a. Radiation levels throughout the facility are less than 2000 cpm as measured in a low background with a standard Thyac or Bicorn gamma scintillation probe on the X10 scale.
- b. Removable surface contamination levels throughout the facility are less than $0.5 \text{ nCi}/100 \text{ cm}^2$.

In the context of this note we are only concerned with (a).

The count-rate meters used by Fermi give an approximate dose equivalence of 2000 cpm as $10 \mu\text{rad h}^{-1}$.

Conclusion

The evaluation of irradiated material for release to the environment may be determined by contact dose rate taking into account the various geometric considerations discussed in this note. It is proposed on the basis of common practice at other accelerator laboratories, the low risk nature of objects irradiated by accelerator radiation, and a highly conservative implied de minimus concentration of radioactivity, that a contact dose rate above background of $20 \mu\text{rad per hour}$ provide a screening measurement for the release of irradiated material to the environment. Irradiated materials of an exotic nature such as those found in an atomic reactor are not generally found in an accelerator environment and are not covered by this screening method.

In general measurements in point source geometry should be confined to determining the activity of small sources such as targets or windows. Such small but relatively high specific activity sources should be retained until their activity is substantially less than $1 \mu\text{Ci}$ in total, use of the BNL criterion of $10 \mu\text{rad h}^{-1}$ at 15 cm may be appropriate for these items.

However, in general contact dose rates are favored and for smallish objects such as nuts and bolts; a useful determination of contact dose rate under reasonably good geometry may be obtained by heaping the bolts together so as to provide the required thickness and lateral extent of the source.

Contact dose rate measurements may be replaced by a point source dose rate of $10 \mu\text{rad h}^{-1}$ at 15 cm (6") for small objects for which contact dose rates are inappropriate.

References

- Pri57 B. T. Price, C. C. Horton, K. T. Spinney, "Radiation Shielding", p. 308, Pergamon Press, 1957.
- Per87 D. R. Perry, "Surface Gamma Dose Rates from Thick Sources and Danger Parameters for Radioactivity Induced by Accelerator Radiation", Proceedings of the 20th Midyear Topical Symposium of the Health Physics Society, p. 217. Reno, Nevada, Feb. 8-12, 1987.
- CVRP88 Commonwealth of Virginia, Radiation Protection Regulations, Virginia Department of Health. Richmond, Virginia, 1988.
- US DOE89 Criteria for Release of Activated Material, Memorandum from Acting Director Environment Safety Health Division, US DOE Chicago Operations Office, Argonne, IL 60438, dated September 29, 1989.
- Bar69 M. Barbier, "Induced Radioactivity", John Wiley & Sons, 1969.

SURFACE DOSE RATE CORRECTION FACTOR, $F(Z, E)$. THICKNESS = 3 LAMBDA EXCEPT H_2O & $C = 5$ LAMBDA

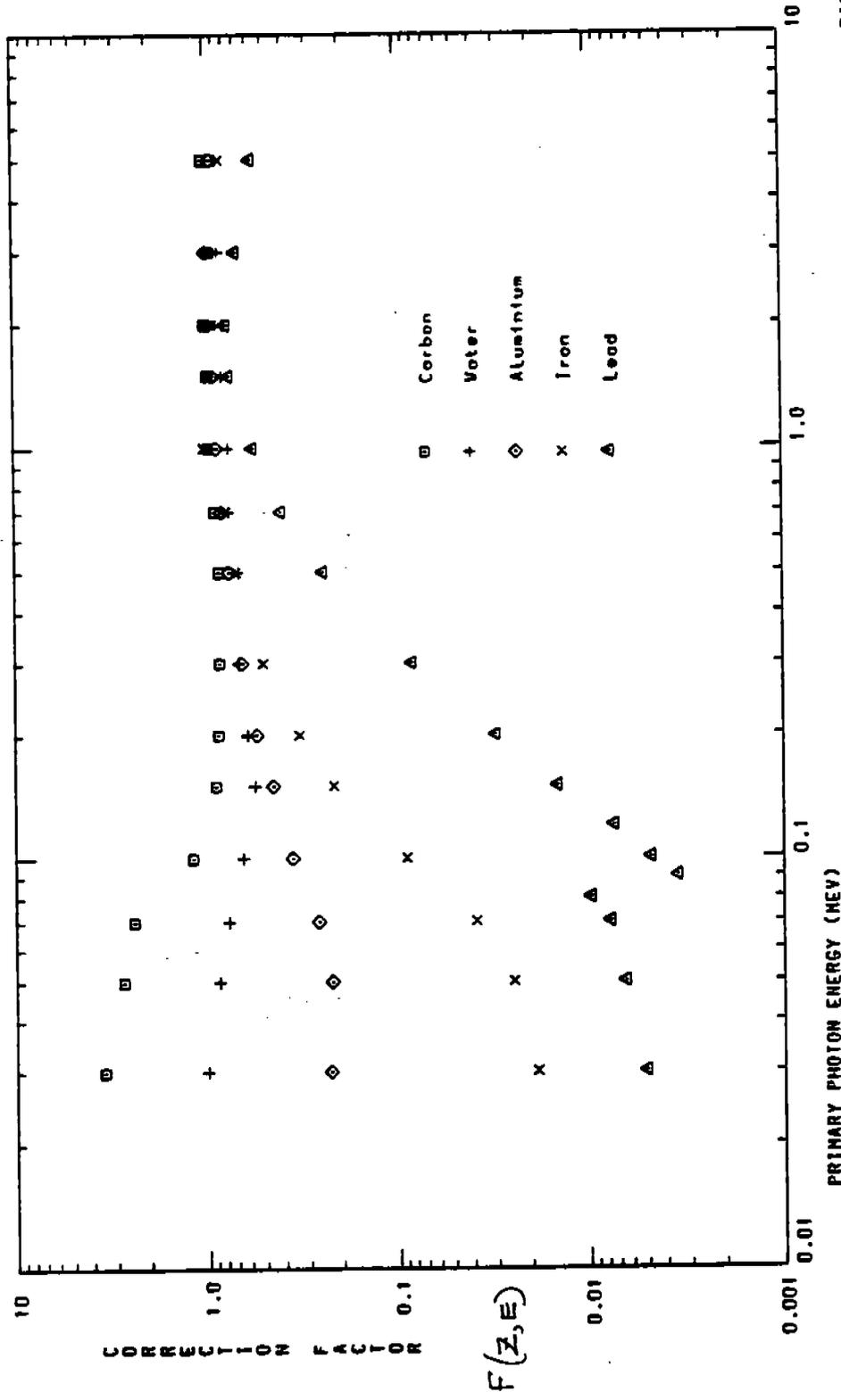


FIG. 1

taken from ref:
(Per 87)

SURFACE DOSE RATE CORRECTION FACTORS FOR DIFFERENT THICKNESSES

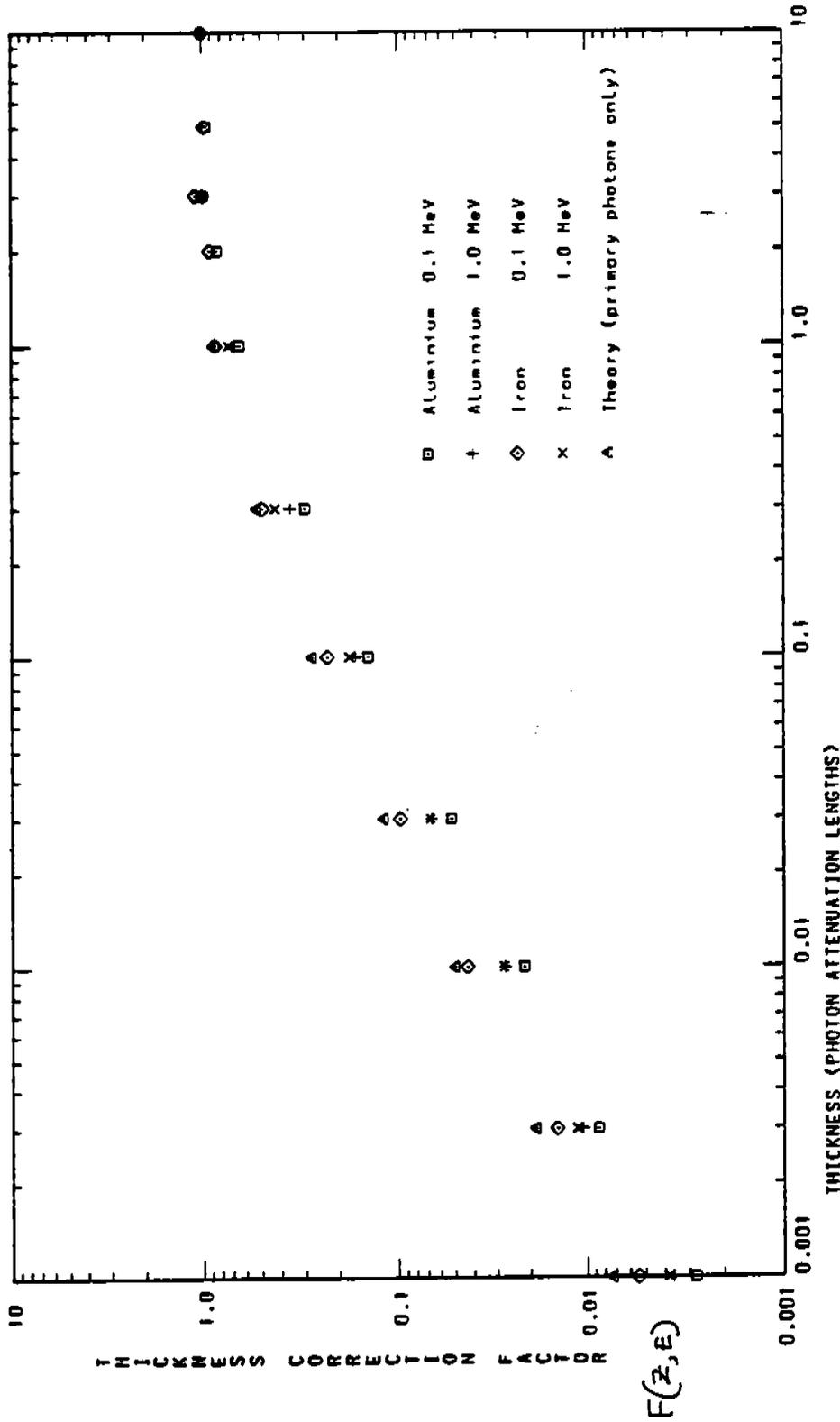


FIG. 2
taken from ref:
(Per 87)

1986 No. 1002

ATOMIC ENERGY AND RADIOACTIVE SUBSTANCES

The Radioactive Substances (Substances of Low Activity)
Exemption Order 1986

<i>Made</i>	<i>12th June 1986</i>
<i>Laid before Parliament</i>	<i>23rd June 1986</i>
<i>Coming into Operation</i>	<i>14th July 1986</i>

The Secretary of State, in exercise of powers conferred by sections 2(6), 6(5), 7(4) and 20(a) of the Radioactive Substances Act 1960(a) and of all other powers enabling him in that behalf, hereby makes the following order:—

Citation, commencement, application and interpretation

1. —(1) This order may be cited as the Radioactive Substances (Substances of Low Activity) Exemption Order 1986 and shall come into operation on 14th July 1986.

(2) This order applies to England, Wales and Scotland.

(3) In this order—

“the Act” means the Radioactive Substances Act 1960;

“activity”, expressed in becquerels, means the number of spontaneous nuclear transformations occurring in a period of one second in a radioactive substance;

“closed source” means an object free from patent defect which is radioactive material solely because it consists of one or more radionuclides firmly incorporated on or in, or sealed within, solid inert non-radioactive material so as to prevent in normal use the dispersion of any radioactive material;

“decay products” means, in relation to any radionuclide, the radionuclides succeeding it in the radioactive series in which it and they occur; and

“half life” means the time taken for the activity of a radionuclide to lose half its value by decay.

(4) In determining the activity of any solid radioactive material or waste for the purposes of article 2 or 3(a) of this order there shall be disregarded the activity of any element specified in column 1 of Schedule 1 to this order

(a) 1960 c. 34. The relevant powers are vested in the Secretary of State in relation to England and Wales by S.I. 1970/1681.

to the extent that the activity of any such element does not exceed the activity per gram mentioned opposite thereto in column 2 of that Schedule.

Exemption from registration under section 1 of the Act

2. All persons are exempted from registration under section 1 of the Act in respect of the keeping and use on any premises of solid radioactive material, other than a closed source, which is substantially insoluble in water, the activity of which does not exceed 0.4 becquerels per gram of mass.

12 ml/ltr

Exclusion of radioactive waste from section 6 of the Act

3. Radioactive waste of the following descriptions is excluded from the provisions of section 6(1) and (3) of the Act (authorisation required to dispose of radioactive waste), namely—

(a) a solid, other than a closed source, which is substantially insoluble in water, the activity of which, when it becomes waste, does not exceed 0.4 becquerels per gram of mass;

(b) an organic liquid which is radioactive solely because of the presence of carbon 14, or tritium (or both), the activity of which, when it becomes waste, does not exceed 0.4 becquerels per millilitre; or

(c) a gas containing one or more radionuclides none of which, nor the decay products of which, has a half life greater than 100 seconds.

Revocation

4. The orders mentioned in Schedule 2 to this order are hereby revoked.

SCHEDULE 1

Article 1(4)

SPECIFIED ELEMENTS

Column 1 (Element)	Column 2 (Becquerels per gram)
Actinium	0.37
Lead	0.74
Polonium	0.37
Protoactinium	0.37
Radium	0.37
Thorium	2.59
Uranium	11.10

REVOCATIONS

Orders revoked	References
1. The Radioactive Substances (Civil Defence) Exemption Order 1962.	S.I. 1962/2641.
2. The Radioactive Substances (Civil Defence) Exemption (Scotland) Order 1962.	S.I. 1962/2767 (S.127).
3. The Radioactive Substances (Thorium-X) Exemption Order 1963.	S.I. 1963/1834.
4. The Radioactive Substances (Attachment to Lightning Conductors) Exemption Order 1963.	S.I. 1963/1835.
5. The Radioactive Substances (Thorium-X) Exemption (Scotland) Order 1963.	S.I. 1963/1880 (S.97).
6. The Radioactive Substances (Attachments to Lightning Conductors) Exemption (Scotland) Order 1963.	S.I. 1963/1881 (S.98).
7. The Radioactive Substances (Tokens for Vending Machines) Exemption Order 1968.	S.I. 1968/935.
8. The Radioactive Substances (Vouchers for Encashment Machines) Exemption Order 1968.	S.I. 1968/936.
9. The Radioactive Substances (Vouchers for Encashment Machines) Exemption (Scotland) Order 1968.	S.I. 1968/953 (S.99).
10. The Radioactive Substances (Tokens for Vending Machines) Exemption (Scotland) Order 1968.	S.I. 1968/954 (S.100).
11. The Radioactive Substances (Thorium-X) Exemption (Scotland) (Amendment) Order 1974.	S.I. 1974/488 (S.36).
12. The Radioactive Substances (Thorium-X) Exemption (Amendment) Order 1974.	S.I. 1974/500.

4th June 1986.

Nicholas Ridley,
Secretary of State for the Environment.