Radiological Assessments of the Doses arising from Short-lived Gases and the Doses from Organic Liquids containing Tritium and Carbon-14 used and disposed under the Substances of Low Activity Exemption Order

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Abstract

The Substances of Low Activity Exemption Order (SoLAEO) exempts the disposal of short lived gases and of organic liquids containing H-3 or C-14 from the authorisation requirement of the Radioactive Substances Act 1993, subject to certain conditions and limits. As part of a review of the exemption order, two radiological assessments have been made: one of the doses which may arise from the use and disposal of short lived gases and one of the use and disposal of organic liquids, under the provisions of the SoLAEO. The resulting doses have been compared with international criteria for exemption. The assessment shows that in both cases the doses arising from current usage are below the exemption criteria and therefore there is no requirement to change the provisions of the SoLAEO on radiological protection grounds. Minor revisions to clarify the position with respect to Kr-81m and O-15 are proposed.

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APPENDIX
1 Introduction

NRPB was asked to provide two radiological assessments in connection with a review of the Substances of Low Activity Exemption Order (SoLAEO)\(^1\). The first concerns the doses arising from the use and disposal of short-lived gases with a half life of less than 100 s under the provisions of the SoLAEO; the second, the use and disposal of organic liquids containing H-3 and C-14 under the provisions of the SoLAEO. This report describes both these assessments.

Each of the assessments includes a description of the SoLAEO conditions, the likely application of the EO, a description of the dose coefficients used, exposure scenarios, estimated doses and finally comparison with appropriate criteria.

2 Short-lived Gases (Half life < 100 s)

2.1 SoLAEO conditions

The SoLAEO states under section 3 that -

\[ Radioactive \text{ waste of the following descriptions is excluded from the provisions of section 6(1) and (3) of the Act (authorisation required to dispose of radioactive waste), namely -} \]

\[ \ldots \]

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

These short-lived gases are not exempt from registration, but the exclusion effectively allows an unlimited quantity of short-lived gases to be disposed of without authorisation.

The intention was to exempt the disposal of short-lived gases commonly used in hospitals for patient scanning. At that time the Radiochemical Inspectorate did not envisage any hazard from the disposal of these gases.

2.2 Uses and occurrence of short-lived gases

The current uses and occurrence of short-lived gases have been reviewed to enable realistic exposure scenarios to be generated. This research has shown that there is one main situation where short-lived gases are used (medical field) and two areas where short-lived gases are incidentally generated (particle beams and nuclear power).

2.2.1 Medical uses

In hospitals Kr-81m, with a half-life of 13 s, is used for lung imaging\(^*\). The use and associated doses of this short-lived gas were examined in the study as indicative of a medical use.

Kr-81m is produced from a Rb-81 generator. The Rb-81 is produced in a cyclotron and loaded into a column. The column is shielded and connected to an air supply. The air passes over the generator eluting off Kr-81m gas that the patient then inhales.

\(^*\) Strictly speaking, it is not clear if this Kr isotope meets the exemption conditions because its decay product Kr-81 has a half life in excess of 100 s (10\(^5\) y). A typical activity of 6 GBq Kr-81m produces 0.01 Bq of Kr-81, well below the Basic Safety Standards\(^2\) Annex 1 value. It is radiologically insignificant and therefore not considered further.
The diagnostic reference level for lung ventilation imaging using Kr-81m is 6 GBq. The resulting patient dose has been estimated to be 200 µSv. The patient inhales the gas from the generator through a facemask. The exhaled gas may either be passed through a short discharge pipe (perhaps 2 cm diameter and 1 m length) or simply be forced around the edges of the face mask and blown away from the patient using a fan. The gases are removed from the vicinity of the patient to prevent interference with the gamma camera imaging the lungs.

A number of other isotopes are currently in use in hospital cyclotrons for positron emission tomography (PET) scans, eg for bone, brain and heart scanning. These tend to be administered intravenously as liquids containing labelled compounds or occasionally as labelled C\textsubscript{15}O or C\textsubscript{15}O\textsubscript{2} and are emitted as short-lived gases by the patient exhaling the activity. The predominantly used isotope is O-15 (half-life 122 s), eg as \textsuperscript{15}O\textsubscript{2}, H\textsubscript{2}\textsuperscript{15}O, C\textsubscript{15}O\textsubscript{2}, C\textsubscript{15}O.

2.2.2 Particle beams

Proton and electron accelerators produce short-lived gases from the irradiation of air and cooling water. The products (of half lives < 100 s) are C-10 (19.3 s), C-15 (2.45 s), O-14 (70.6 s), O-19 (27.1 s), N-16 (7 s) and N-17 (4.17 s). The ventilation systems of accelerator facilities usually add a delay before the air around the accelerator is discharged into the environment to enable the activity of the short-lived nuclides to decay. These radionuclides have not been detected in the air other than in the cooling system of the accelerator because of their low production cross sections and short half lives. The production rate of each radionuclide in the cooling system is estimated to be between 1 and 100 MBq per day\textsuperscript{4}.

Additionally to accelerators, short-lived isotopes of N and O are by-products of the irradiation of air in beam rooms and irradiator cells. Entry systems which introduce typical entry delays of about 4 minutes are used to prevent entry into such rooms immediately after the beam is shut off\textsuperscript{5}. Concentrations in these rooms are usually checked with monitoring equipment (G-M tubes) before entry. Common levels of active gases in an irradiator cell are typically 10\textsuperscript{4} - 10\textsuperscript{5} Bq cm\textsuperscript{-3} at equilibrium\textsuperscript{6}. Concentrations of one or two Bq cm\textsuperscript{-3} are suggested as safe levels for entry.

2.2.3 Nuclear reactors

The UK power reactors comprise Magnox and advanced gas-cooled reactors, with a single pressurised water reactor at Sizewell. The gas-cooled nuclear reactors produce some short-lived gases. From information received from British Energy, the main short-lived radioactive gas emitted from the gas-cooled reactors is N-16 (7 s). It is produced from the reactions between O-16, neutrons and protons. N-16 is discharged continuously via carbon dioxide coolant leakage and instrument lines, and occasionally from deliberate coolant discharges to control coolant pressure or purity. It would not be present in major blow-downs to depressurise the reactors for an outage due to radioactive decay immediately following reactor shutdown. An approximate inventory is 25 TBq per reactor, and indicative annual discharges are around 100 TBq y\textsuperscript{-1} per reactor\textsuperscript{7}. Nuclear power plant operators do not normally rely on the SoLAEO to exempt discharges of short-lived gases. Power stations have authorisations under the Radioactive Substances Act (RSA) for radioactive discharge to atmosphere, although limits are imposed only on selected radionuclides.

2.3 Identification of short half life radioactive gases for assessment

ICRP reports generally contain data only on nuclides whose half-life is > 10 minutes\textsuperscript{8}. The JEF-2 database\textsuperscript{9} was therefore interrogated to establish a list of nuclides whose half-life is less than 100 s. This
resulted in a list of about 1,000 nuclides whose half life was less than 100 s, but these nuclides can exist normally in any physical form (ie solid, liquid or gas). Known gaseous nuclides (O, N, C, inert gases etc) were then extracted and the number of nuclides was reduced to around 125.

The radionuclides selected for this work were those that are known to have uses or are produced as a by-product of other activity (C-10, C-15, O-14, O-15, O-19, N-16, N-17 and Kr-81m). O-15 actually has a half-life slightly in excess of 100s but has been included in the assessment because of its widespread use in UK hospitals. A few other radionuclides that are likely to be more radiologically toxic (Cl-40, Br-72, I-136m) have also been included. These were used to illustrate levels of dose regardless of whether the radionuclide has known production or not and were selected by identifying the radionuclides with longer half lives, high energy and frequency of emissions. The selected nuclides are given in Table 1.

2.3.1 Inhalation dose coefficients

None of the short-lived gases with a half-life less than 100 seconds have published inhalation effective dose coefficients based on ICRP-60 dosimetry. Inhalation dose coefficients are required for a radiological assessment, so values were derived using the ICRP biokinetic models as described in the Appendix. The inhalation dose coefficients used are given in Table 1.

2.4 Radiological assessment

2.4.1 General

Exposures of members of the public are likely to arise from venting of the short-lived gases to atmosphere, giving rise to external exposure from immersion in the gas cloud and internal exposure from inhalation of the gas. Doses are expected to be small, because in many situations the production and release will be intermittent, and the resulting exposure times will be short due to the short half-lives of the nuclides. The activity concentration in air will decline significantly within 20 radioactive half lives (1 to 15 minutes depending on radionuclide) once production of the radionuclide ceases. However members of the public may be exposed to waste gases from more than one emission event in a year.

Exposure of members of the public may also occur during diagnosis or treatment of a patient if a family member or friend accompanies the patient, eg as a comforter. Predicted doses are expected to be higher than following release to the atmosphere because the waste gas may be produced continually for several minutes and be vented into the treatment room. However, the exposure of the comforter is more likely to be a one-off event.

Exposure of members of the public may also occur from continuous production and venting of short-lived gases such as nitrogen-16 during nuclear power production. Doses to members of the public beyond the site boundary may be expected to occur. However, the time taken for the gas to pass from the release point to the site boundary (usually > 100m) may be several tens of seconds, during which time significant radioactive decay will occur.

Individual doses were calculated to representative members of the critical group. Collective doses were considered more generally, see 2.8.

2.4.2 Methodology

The radiological assessments are based on inhalation and external exposure of individuals from the gases using the equations given below:

\textit{Inhalation}
E_{inh} = \text{Actconc} \cdot R_b \cdot \text{Inh}_{co} \cdot \text{occ}

where

- $E_{inh}$ = effective dose from inhalation (Sv per event)
- $\text{Actconc}$ = activity concentration in air (Bq m$^{-3}$)
- $R_b$ = breathing rate (m$^3$ h$^{-1}$)
- $\text{Inh}_{co}$ = inhalation dose coefficient (Sv Bq$^{-1}$)
- $\text{occ}$ = occupancy in the room or exposure time in the cloud (h per event)

The activity concentration in air was estimated from the release rate of the radionuclide and the time integrated air concentrations for a unit release rate. The latter were based on either a release lasting 30 minutes (for discrete production events) or a continuous release$^{10}$.

For a continuous release of N-16 from a nuclear reactor, radioactive decay was estimated from the time taken for an atom of N-16 to reach a member of the public at the site boundary fence, a distance assumed to be 100 m from the release point. Occupancy there was assumed to be 300 h y$^{-1}$ (dog walkers near the site fence). For Kr-81m and O-15, average air concentrations were estimated based on a 30 minute release duration. For particle beam production, an average air concentration was estimated assuming a continuous release model over a typical 7-hour production day and known production rates. Delay mechanisms are used in normal production of particle beams to contain the gases produced to allow radioactivity to decay. For the purposes of the scenario, no delay was assumed. In the case of particle beam production and medical imaging, no decay once outside the facility was assumed to allow for the possibility that a member of the public could be closer than 100 m from the release point. Occupancy time was based on 20 half-lives, ie sufficient time for significant decay. A day-averaged breathing rate was assumed.

External exposure from immersion in the gas cloud

External exposure to the gas cloud was estimated from:

$$E_{imm} = \text{Actconc} \cdot \left( (E_{gam} \cdot C_{gam}) + (E_{bet} \cdot C_{bet} \cdot w_{\text{skin}}) \right) \cdot \text{occ} \cdot H^{-1}$$

where

- $E_{imm}$ = effective dose from immersion (Sv per event)
- $E_{gam}$ = average photon energy per disintegration (MeV)
- $C_{gam}$ = effective cloud gamma dose from a semi-infinite cloud
  = $1.6 \times 10^{-6}$ Sv y$^{-1}$ per Bq m$^{-3}$ MeV$^{11}$
- $E_{bet}$ = average beta energy per disintegration (MeV Bq$^{-1}$)
- $C_{bet}$ = skin equivalent beta dose rate from a semi-infinite cloud
  = $2.0 \times 10^{-8}$ Sv y$^{-1}$ per Bq m$^{-3}$ MeV$^{11}$
- $w_{\text{skin}}$ = tissue weighting factor for skin (0.01)
- $\text{occ}$ = exposure time (h per event)
- $H$ = hours in a year (8,760 h y$^{-1}$)

The calculation assumes a semi-infinite cloud of gas, which is realistic for the beta component (short range in air) but is conservative for the photon component (50m range in air) by at least a factor of 10 when considering a cloud with the dimensions of a typical room. Radioactive decay and occupancy were as for inhalation (above).
2.5 Exposure from medical use of the gases.

Section 2.2.1 suggests that in medicine the only known use of gases with a half-life less than 100 s is of Kr-81m for lung imaging. Typical administrations are between 2 and 6 GBq. The Kr-81m is generated locally by passing moist air over a Rb-81 source. It is administered to a patient using a face mask and then exhaled. Hospital workers supervising the administration or operating the gamma camera could be exposed to the exhaled Kr-81m. If relatives attend to support the patient, they may also be exposed. Exhaled gas is removed from around the patient to prevent interference with the gamma camera, using discharge pipes or a fan. Doses to staff or relatives may be higher when a fan is used, because the exhaled Kr-81m will be largely dispersed into the room. Subsequent dispersion of the gases to the wider environment may occur, and expose members of the public in the hospital grounds.

The assessment considers exposure of staff and relatives in the vicinity of the patient and exposure of members of the public from release of the gases into the environment after exhaling.

2.5.1 Exposure of staff and relatives in the treatment room

Exposure of staff administering the Kr-81m and operating the gamma camera and relatives accompanying patients may occur via inhalation of the exhaled gases or immersion in the plume in the treatment room. An administration of 6 GBq over 10 minutes, ie 600 MBq min$^{-1}$, will produce a time integrated activity of 2 GBq min in the room, giving an average air concentration of $6.7 \times 10^6$ Bq m$^{-3}$ in a room of volume 30 m$^3$, if the effects of radioactive decay are considered but room air changes ignored.

The effective dose is dominated by the contribution from direct immersion in the plume. A reduction factor of 10 has been used to allow for the fact that the room is not a semi-infinite volume. The doses given in Table 2 are per patient administration and are doses likely to be received by a relative or friend accompanying the patient.

The annual effective dose to staff responsible for operating equipment can be estimated from the dose per administration and the total number of exposures to Kr-81m in one year. The latter can be estimated from the number of imaging studies carried out using a single gamma camera in one year (average of 1,300 in 1992$^{12}$) and the proportion of imaging studies that use Kr-81m (4.3% in 1990$^{13}$). These figures suggest an average of about 100 images per year using Kr-81m assuming a hospital has between one and two such generators$^{12}$. The annual effective dose to one staff member (assuming one staff member is always responsible for the use of these generators) is therefore less than 0.3 mSv, see Table 2.

It should be remembered that doses to staff and comforters are outside the remit of the RSA and are addressed by the Ionising Radiations Regulations 1999 (IRR99).

2.5.2 Exposure of the public outside

Exhaled Kr-81m from a patient may be released into the environment and members of the public may then be exposed. However, even assuming a high room ventilation rate of 10 room changes per hour (ie a residence time in the room of 6 minutes), the Kr-81m will have decayed before it is released to the environment (reduction factor $2 \times 10^8$) and hence the doses to the public will be totally insignificant. As an upper bound, it was assumed that the Kr-81m was extracted instantaneously with a maximum activity of 2 GBq leaving the treatment room. The time integrated ground level concentration from a 2 GBq release over 30 minutes at 100 m is $1.1 \times 10^7$ Bq m$^{-3}$. The time for 20 radioactive half lives to elapse is 4.3 minutes and this value is used for the maximum possible occupancy in the plume after production stops.
decay of Kr-81m is assumed during travel time to allow for the possibility that a member of the public could be closer than 100 m from the release point.

The effective dose at 100 m from the release point after one treatment is 9 nSv, which is dominated by the dose from immersion in the plume. This is an upper bound, assuming forced extraction of the exhaled Kr-81m.

Annual doses to members of the public will depend on the number of exposure events that the same member of public may be exposed to. The most exposed member of the public could be, for example, a hospital volunteer. Assuming such a volunteer spends a working year at the hospital, they could, in theory, be exposed to the waste gases from each imaging activity. Given that there is an average of 55 imaging events with Kr-81m per gamma camera and there are on average 2 gamma cameras per department, there would be on average around 100 Kr-81m imaging events per year. Therefore a hospital volunteer who is on site when all 100 occur could in theory receive an annual effective dose of the order of about one micro-Sievert, see Table 2, if the exhaled Kr-81m is extracted rapidly from the treatment room. The most likely scenario is that the Kr-81m decays within the treatment room leading to no dose to the public.

Hence, disposal of Kr-81m gas following lung imaging gives rise to trivial doses and should continue to be exempt. If the SoLAEO does not apply directly to Kr-81m because it has a long-lived daughter product (Kr-81), then perhaps the wording in the SoLAEO could be modified to specifically include it, or it could be added to the hospital’s EO.

2.5.3 Exposure to short-lived gases from PET scanning

Oxygen-15 is used for PET scanning in some medical research centres. It is used not only as molecular oxygen but also to label such compounds as H$_2^{15}$O, C$_2^{15}$O$_2$ and C$_4^{15}$O.

The following general information and data on which the assessment was based was provided by the Hammersmith MRC cyclotron unit. Most treatments use H$_2^{15}$O. These are ‘milked-off’ the cyclotron. The cyclotron is made ready and produces the gas in some form which is diverted to a waste stream until such time that the patient is ready for the treatment. The whole gas production time may be about 30 minutes per treatment, but a treatment is typically only two 5-minute sessions. The gas is produced at a flow rate of 450 ml min$^{-1}$ and a concentration of 3 MBq ml$^{-1}$. Therefore over the treatment period, the total gas production is ~40 GBq with the patient receiving ~13 GBq. It is assumed that half is exhaled, so the total inhaled activity is ~6 GBq for the 10 minute exposure time.

While the patient is receiving the activity, the waste gas is extracted straight to the top of the building which introduces a short delay, giving a reduction in activity of a factor 10$^6$, ie a real time delay of about 40 minutes. When the cyclotron is not being milked for the patient, the waste gas is discharged via a series of large tanks, which introduces a longer delay, giving a reduction in activity of a factor 10$^{11}$, ie a real time delay of about 80 minutes. A clinician is usually present at a distance of several metres. Current practice does not have a comforter present in the treatment room.

Effective doses to members of the public have been estimated using the methodology given in 2.5.2 and an estimated annual discharge of O-15 for the Hammersmith cyclotron of 728 kBq (1999). The results are given in Table 2.

Based on Hammersmith data, the individual effective dose to a member of the public from discharges of O-15 from a cyclotron facility is < 1 nSv y$^{-1}$ for normal operation. This meets current exemption criteria. The delay processes would have to be out of operation for more than two months in order for a member of the public to receive 10 µSv y$^{-1}$. This occurrence is highly unlikely.
The current EO has a half-life cut-off of 100 seconds whereas O-15 has a half-life of 122.2 seconds. There are a further 33 short-lived gases with half-lives between 100 and 125 seconds. Therefore, rather than increasing the cut-off half-life in the existing Exemption Order to 125 seconds, it is suggested that O-15 and compounds labelled with O-15 are explicitly named in any revision of the Exemption Order.

2.6 Particle beams

Particle beams are known to produce a number of short-lived gases in the ventilation and cooling systems of the beam, by irradiation of air and cooling water. The ventilation and cooling circuits around accelerators are usually designed with delay systems such that these radionuclides are not released into the environment. Isotopes are not usually produced at detectable levels in the air outside the ventilation systems. The short-lived gases produced are therefore very unlikely to give rise to exposure of members of the public. However, if the short-lived gases were inadvertently vented continually during use of the accelerator assuming forced extraction, members of the public within 100 m of the release point in theory could be exposed. Production rates of the various radionuclides have been estimated to be between 1 and 100 MBq per day\(^4\). Over a 7 hour working day, this gives rise to predicted time integrated air concentrations of between 4 \(10^{-2}\) Bq m\(^{-3}\) and 4 Bq m\(^{-3}\). Assuming that a member of the public spends an hour a day outdoors at 100 m or less from the release point, the effective dose from the sum of the radionuclides produced would not exceed 6 nSv. Assuming production occurs on 200 days per year and the delay system is not working all year, the effective dose in theory could be approximately 1\(\mu\)Sv y\(^{-1}\), see Table 2. This is an upper bound, assuming forced extraction of the short-lived gases.

In order to illustrate that the doses from the inadvertent release of any short lived gas with a half-life less than 100 seconds are likely to be below 1 \(\mu\)Sv y\(^{-1}\), doses were estimated using the methodology given in 2.5.2 assuming hypothetical releases of Br-72 and I-136m. No actual production was found and therefore an estimated production rate of 100 MBq d\(^{-1}\) for 200 days per year was assumed. The annual individual effective dose to a member of the public from both of these radionuclides was less than 1 \(\mu\)Sv, see Table 2.

2.7 Nuclear reactors

Gas-cooled nuclear reactors produce N-16 in the cooling systems, which is released to atmosphere from these systems. Production and release is thought to be a fairly continuous process at an average rate of 100 TBq y\(^{-1}\). Members of the public can be exposed from gas passing the site boundary. An exposure time of 300 h y\(^{-1}\) was used. At a gas production rate of 100 TBq y\(^{-1}\), the site boundary time integrated air concentration was 24 Bq m\(^{-3}\). For a site boundary occupancy of 300 h y\(^{-1}\), the effective dose is around 6 \(\mu\)Sv y\(^{-1}\), see Table 2.

2.8 Collective doses

Collective doses per facility were estimated for the UK population by estimating the number of people living in the area around each hospital, nuclear power station and particle beam accelerator\(^9\). The area was defined as the circle with a radius equal to the distance each short-lived gas could travel in ten half-lives for a wind-speed of 5 m s\(^{-1}\). This area did not include the first 100 m which was assumed to be prohibited for members of the public. The areas calculated were 39 km\(^2\) for a particle beam accelerator, using the nuclide with the longest half life, 0.36 km\(^2\) for a nuclear power station, 1.3 km\(^2\) for a lung-
imaging hospital and 120 km² for a PET scanning facility. Collective doses per facility were based on high and medium population densities for a lung-imaging hospital, a PET scanning facility and a particle beam accelerator and based on a low population density for a nuclear power station, see Table 3. The total collective dose from lung imaging was based on the annual number of lung images taken using a Kr-81m generator. This was estimated at around fifty thousand\textsuperscript{15}. The total collective dose from PET scans using O-15 was based on an estimate of the number of scans per year at each facility and the number of such cyclotron facilities in the UK. The number of scans per year per facility was approximately 220 and there are 4 cyclotron facilities in the UK producing O-15\textsuperscript{14}. There are currently a total of 34 UK nuclear power reactors on-line, 14 advanced gas-cooled reactors and 20 Magnox. It was estimated that there would be no more than 20 particle beam accelerators in the UK. The collective doses per facility and for the estimated number of such facilities are presented in Table 2.

The collective doses for 1 year’s operation of a single facility are less than 1 man Sv. The overall collective dose from all facilities is of the order of a few man Sv, depending on the population density near the facilities. When considering all the facilities in the UK it is more appropriate to use the medium or low population density since the high density applies to London only. Hence, current usage of lung imaging gives of the order of 1 man Sv per year of operation, and discharge of 1 MBq y\textsuperscript{–1} of any short lived gas with a half life of less than 100 seconds is likely to give of the order of 1 man Sv. The current production of short lived gases from nuclear power stations and particle beam accelerators, with delay systems, will give a total collective dose well below 1 man Sv per year of operation. The EC \textsuperscript{2} specifies a collective dose criterion for exemption from regulation of “of the order of 1 man Sv or that exemption is the optimum option”.

### 2.9 Summary for short lived gases

1. The Substances of Low Activity Exemption Order allows the disposal of unlimited quantities of gases with half lives less than 100 s without an authorisation.

2. It was originally intended to apply to short-lived gases produced from accelerators, used in hospitals for lung imaging and produced during nuclear power production.

3. The assessment has shown that there are approximately 125 gaseous radionuclides with half lives less than 100 seconds. However, only seven have been identified in the three situations described above. Oxygen-15 with a half-life of 122.2 seconds has also been considered in the assessment because of its use for PET scans in UK hospitals.

4. Six short-lived gases were assumed to be produced together for each operation of an accelerator. The estimated combined annual adult effective dose from these, even allowing pessimistically for no delayed venting, is well below 10 µSv.

5. The estimated annual adult effective dose to a member of the public at the site boundary from short-lived gases produced during nuclear power production, assuming continuous production, is well below 10 µSv.

6. For Kr-81m produced in hospitals for lung imaging, the highest estimated effective dose is a few µSv per event to a comforter in the treatment room. Members of the public receive less than 1 µSv y\textsuperscript{–1}. For O-15 produced in hospitals for PET scanning, members of the public receive less than 1 nSv y\textsuperscript{–1} from normal operation.
The estimated collective doses per year of operation from Kr-81m are of the order of 1 manSv. Hence the current usage of the SoLAEO meets the exemption criteria. If the usage of Kr81m for lung imaging increases by an order of magnitude or a new situation arises in which short lived gases in excess of 100 MBq y^{-1} are disposed of then this may need reconsidering.

Kr-81m has a daughter with a very long half-life and hence is not strictly within the remit of the SoLAEO. Hence, the SoLAEO should be revised to make sure that Kr-81m and Kr-81 grown in from Kr-81m are explicitly included.

The assessment has also calculated doses from O-15 used in UK hospitals. This radionuclide has a half-life of 122.2 seconds. Individual and collective doses from O-15 used in UK hospitals are well below exemption criteria. It is suggested that O-15 and compounds labelled with O-15 be explicitly named in any revision of the Exemption Order.

3 Organic liquids containing H-3 or C-14 (< 4 Bq ml^{-1})

3.1 SoLAEO conditions

The SoLAEO states under section 3 that -

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 -

... (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 4 Becquerels per millilitre.

These liquids are not exempt from registration, but the exclusion effectively allows an unlimited volume of organic liquid to be disposed of without authorisation, so long as the 4 Bq ml\(^{-1}\) concentration is not exceeded.

3.2 Uses of organic liquids containing H-3 and C-14

The likely current uses of organic liquids containing H-3 and C-14, including the original basis for the conditions in the SoLAEO, were investigated in order to define realistic exposure scenarios. The original purpose of this condition in the SoLAEO was for the disposal of organic scintillant fluid to a drainage system intended for foul water or trade effluent. More recently, C-14 is used in some hospital radio-pharmaceutical departments. No other uses or occurrences of organic liquids containing H-3 or C-14 have been found.

3.2.1 Liquid scintillant

Liquid scintillant is used in the measurement of H-3 and C-14 activity concentrations. There are various types but the majority appears to be xylene-toluene or di-iso-propynaphthalene based. It is used in 20 ml vials that generally contain 5-10 ml of scintillant. Some are likely to become contaminated with H-3 and C-14. Following use, a number of scintillant vials (around 50 -100) are placed in bags and then placed in a small drum (30 litres) in well ventilated locked storage (outdoors). A single drum could contain up to 1,000 vials before it is transferred to the disposer, although activity limits on the total activity per drum may reduce the number of vials allowed to be transferred.
Organic scintillant liquids are irritant, highly flammable and sometimes corrosive and as such are classed as special wastes and come under the Special Waste Regulations 1996. These Regulations set out stringent controls for the most difficult and dangerous forms of waste and through a consignment note system require the special waste to be tracked from production until it reaches a waste management facility. Prior authorisation of the movement of special waste is also required from the Environment Agency (EA) or the Scottish Environment Protection Agency (SEPA). Scintillant vials with low (or even zero) activities are consigned to an authorised disposer of radionuclide and special wastes (ReChem). The usual disposal route for flammable organic liquids is incineration. The SoLAEO is however never used for disposal of solvents on an industrial scale.

NRPB is only a small user of liquid scintillant and might use around 2 litres per week (0.1 m³ y⁻¹). A typical large user might dispose of the order 1 m³ y⁻¹. An upper bound for a typical large user of 10 m³ y⁻¹ would seem reasonable.

3.2.2 Radio-pharmaceuticals containing C-14

Carbon-14 is used in radio-pharmaceutical departments for diagnostic purposes. It is introduced into the body as glycocholic acid, para-amino benzoic acid or urea in amounts varying between 200 kBq and 400 kBq per administration. The activity would then be excreted from the body in the urine with a half-life of 40 days. The resulting average activity concentration from an intake of 400 kBq is 4 Bq ml⁻¹ in the first 40 days and 2 Bq ml⁻¹ in the next 40 days. For smaller administrations of 200 kBq, the resulting average activity concentrations of the waste would be halved.

3.3 Radiological assessment

The external exposure from H-3 and C-14 while in a container is effectively zero due to the low energy of the beta emissions of both nuclides. Doses arise when the contents of the container are released, either accidentally or routinely.

Six exposure scenarios have been considered. These illustrate the likely doses associated with the use, misuse and disposal of organic liquids. They are: accidental inhalation either by evaporation or fire; accidental spillage; routine landfill disposal; routine incineration; accidental or malicious disposal to river and accidental or malicious disposal to sewers. Hence, the assessment includes a number of possible disposal options, some of which are prohibited for liquid scintillant by current safety regulations. The disposal scenarios encompass the accidental disposal of liquid scintillant (or known disposal in contravention of regulations) as well as disposals of other organic liquids containing H-3 or C-14.

The dose coefficients used for this assessment are shown in Table 4.

The quantities of organic liquids disposed are difficult to establish so the calculations have indicated the quantity of organic liquid which can be disposed and still result in exposures at exemption levels (ie around 10 µSv y⁻¹). The estimated doses from these scenarios are given in Tables 5 and 6.

3.3.1 Inhalation of volatile liquids scenario

Work using these organic liquids is most likely to occur within a glove box or fume hood. However, the scenario represents an accidental situation where the liquid completely evaporates (or is evaporated in the event of a fire) into a small laboratory of volume 30 m³ and where the effective occupancy of personnel is only a short period as a result of room air changes or evacuation. The breathing rate assumed is a daily averaged intake.
For tritium, there are two components to the dose received from a cloud; inhalation and absorption through the skin. Doses were calculated for both tritiated water vapour (HTO) and organically bound tritium (OBT).

The contribution to the total dose from absorption of HTO through the skin for a male sedentary worker is half that from inhalation. Therefore, for a sedentary breathing rate, the inhalation dose is multiplied by a factor (F) of 1.5 to include the component from skin absorption. However, the greater the breathing rate, the smaller the skin absorption component relative to the inhalation component, and the smaller the multiplying factor. For a daily averaged breathing rate of $0.83 \text{ m}^3\text{h}^{-1}$ (equivalent to $2.3 \times 10^{-4} \text{ m}^3\text{s}^{-1}$), a factor (F) of 1.33 is used to scale the inhalation component to give the total dose from HTO from both components.

For immersion in a cloud containing OBT, it is assumed that the skin absorption pathway contributes at most an additional 10% of the dose from inhalation of OBT, see discussion in 3.3.2. The total dose taking into account any skin absorption of OBT is therefore the inhalation dose from OBT multiplied by a factor 1.1. Modelling the absorption through the skin in discussed further in section 3.3.2.

For C-14, there is only the inhalation component.

\[
E_{\text{tot}} = \frac{\text{Act} \cdot R_b \cdot DC \cdot \text{occ} \cdot F}{V_{\text{room}}}
\]

where
- $E_{\text{tot}}$ = total effective dose (Sv per event)
- Act = activity released to the room (Bq)
- $V_{\text{room}}$ = room volume (m$^3$)
- $R_b$ = breathing rate (m$^3$ h$^{-1}$)
- DC = dose coefficient for HTO, OBT or C-14 (Sv Bq$^{-1}$)
- occ = occupancy in the room, ie exposure time (h)
- F = scaling factor to account for absorption through skin
  (HTO = 1.33; OBT = 1.1; C-14 = 1.0)

A single vial is assumed to contain 10 ml of liquid having an activity of 4 Bq ml$^{-1}$. An occupancy of 1 hour is assumed.

For the evaporation of a single 10 ml vial (activity 40 Bq), the total dose from inhalation is $2.6 \times 10^{-11}$ Sv for HTO, $5.0 \times 10^{-11}$ Sv for OBT and $2.2 \times 10^{-9}$ Sv for C-14, see Table 5. A fire might volatilise all the liquid scintillant in a bag of 100 vials. These doses are also very small and well below 10μSv. It should also be remembered that a fire has a low probability of occurrence.

3.3.2 Liquid spillage scenario

This scenario represents the accidental situation where an organic liquid containing H-3 or C-14 has been spilt. The irritant properties of liquid scintillant would require gloves to be used when handling scintillant fluid. The gloves will attenuate all radiation emitted from H-3 and C-14. Any spillage onto bare skin is therefore a very conservative scenario.

A single vial containing 10 ml of liquid scintillant is assumed to spill on to a work surface. Ten percent of the spilt activity contaminates the backs of the hands. Therefore, 1 ml of liquid with an activity concentration of H-3 or C-14 of 4 Bq ml$^{-1}$ spreads over an area of skin equal to 100 cm$^2$. The spillage goes unnoticed for 10 minutes before the liquid is wiped off.
If C-14 is in contact with the skin of the back of the hands, a skin dose will be received. The skin equivalent dose for C-14 is derived as follows.

\[
H_{\text{skin}} = \frac{\text{Act} \cdot t \cdot \text{Skin}_{\text{co}}}{\text{Area}}
\]

where

- \(H_{\text{skin}}\) = skin equivalent dose (Sv)
- \(\text{Act}\) = activity spilt on the skin (Bq)
- \(\text{Area}\) = area of skin contaminated (cm\(^2\))
- \(t\) = time before washing off (h)
- \(\text{Skin}_{\text{co}}\) = C-14 dose coefficient for skin at 4 mg cm\(^{-2}\) (Sv h\(^{-1}\) per Bq cm\(^{-2}\))

The effective dose for C-14 is derived as follows.

\[
E = \frac{H_{\text{skin}} \cdot w_{\text{skin}} \cdot \text{Area}}{\text{UVR}}
\]

where

- \(E\) = effective dose from skin contamination (Sv)
- \(w_{\text{skin}}\) = tissue weighting factor for skin (0.01)
- \(\text{UVR}\) = UVR skin exposed area (3 \(10^3\) cm\(^2\))

For C-14, the skin equivalent dose is 6.0 \(10^{-10}\) Sv; the effective dose from skin contamination is 2.0 \(10^{-13}\) Sv, see Table 5. These are extremely small doses. The effective doses are well below the 10 \(\mu\)Sv exemption criteria.

When H-3 is spilt on the skin, the beta particles are absorbed by the outer skin layers, thus giving zero skin dose at a depth of 4 mg cm\(^{-2}\). However, volunteer studies have shown that absorption through intact skin is an important contributor to total absorption to blood following exposures to HTO vapour\(^{21,22}\). The absorption through the skin of OBT in an organic liquid, in an aerosol in a cloud or as a topical application, is less well understood. Absorption will vary considerably according to the chemical characteristics of the material. OBT is typically bound to other molecules, so absorption is dependent on the size of the molecules to which the OBT is bound, ie whether the molecules incorporating the OBT are sufficiently small or mobile to be absorbed by the skin. Data for \(^3\)H labelled pharmaceuticals under development for topical application suggest absorption over a period of hours may be from a few to a few tens of percent\(^{23}\). On the basis of the available data, it would appear reasonable to assume a range of 1-10 % absorption for unspecified forms of \(^3\)H retained on the skin for short periods (<10 minutes). In the 10 minutes the spillage goes unnoticed, the amount of HTO or OBT absorbed through the skin is conservatively estimated to be 10 percent of the activity on the skin.

Therefore, it is assumed that 0.4 Bq HTO is instantaneously and completely absorbed in the body. For an organic liquid containing OBT, it is assumed that the molecular structure of the OBT is sufficiently small or mobile to be absorbed by the skin. Therefore, 0.4 Bq OBT is completely absorbed and remains as OBT in the body. The absorption through the skin of HTO and OBT is modelled by direct injection into the soft tissue and blood stream. However, the dose coefficients for inhalation of HTO and OBT were also modelled by assuming direct injection\(^{24}\). Hence, the inhalation dose coefficients for HTO and OBT are used here.
The adult effective dose received from a spillage of organic liquid containing H-3 is calculated by multiplying the appropriate dose coefficient for HTO or OBT by the intake through the skin. The resulting effective dose from the spillage is $7.2 \times 10^{-12}$ Sv for HTO and $1.6 \times 10^{-11}$ Sv for OBT, see Table 5. These doses are well below the $10 \mu$Sv exemption criteria.

3.3.3 Landfill disposal

The disposal of unit concentrations of radionuclides to landfill sites has been considered in another report. The report considered 1 GBq y$^{-1}$ of H-3 or C-14 disposed to a landfill site over a period of 10 years, which is the equivalent of 250 m$^3$ y$^{-1}$ of organic liquid with a concentration of 4 Bq ml$^{-1}$ for ten years. The results for an older style of landfill, typically built without containment measures in a fairly permeable sub-soil, have been used here. This represents the worst case. The estimated risks to landfill operators, to the public from the migration of activity to local watercourses and probabilistic exposure scenarios are shown in Table 6 for unit disposals.

The highest risk comes from the migration of these radionuclides. Disposal of 1 GBq y$^{-1}$ of tritium gives rise to a peak risk of $2.2 \times 10^{-11}$ y$^{-1}$ and disposal of 1 GBq y$^{-1}$ of C-14 gives a peak risk of $4.1 \times 10^{-9}$ y$^{-1}$. The quantity of organic liquid containing C-14 at 4 Bq ml$^{-1}$ which could be disposed to a poor landfill site and still result in a level of risk considered trivial (ie $10^{-6}$ y$^{-1}$) is $6 \times 10^4$ m$^3$ y$^{-1}$. This is approximately $6 \times 10^4$ typical large users (see Table 7). This volume of solvent would generate problems even if not radioactive. The corresponding amount of organic liquid containing H-3 that could be disposed would be even larger.

3.3.4 Disposal by incineration scenario

The disposal of H-3 and C-14 contaminated materials by incineration has been considered in another report. The report calculates the peak annual effective doses to members of two hypothetical critical groups. One group represents a local resident at around 1 km from the incinerator, the other a farmer at 5 km from the incinerator. The resident is assumed to grow sufficient green and root vegetables and fruit to provide 20% of the critical intake, whilst other foods are assumed to be from sources elsewhere. The farmer is assumed to produce sufficient quantities of all food types to provide for a family consuming all foods at critical intakes. The disposal of incinerator ash to landfill is not considered directly as it will be less restrictive than the direct disposal of organic liquids to a landfill site.

The estimated doses from the incineration of 1 GBq y$^{-1}$ of organic liquids containing H-3 or C-14 are shown in Table 6. The highest doses are estimated to be to the farmer and are $1.1 \times 10^{-12}$ Sv y$^{-1}$ per GBq y$^{-1}$ of H-3 and $2.6 \times 10^{-10}$ Sv y$^{-1}$ per GBq y$^{-1}$ of C-14. The amount of organic liquid containing C-14 at 4 Bq ml$^{-1}$ that could be incinerated and still result in a trivial dose (ie around 10 $\mu$Sv y$^{-1}$) would be $10^7$ m$^3$ y$^{-1}$. This is equivalent to 10 million typical large users. For H-3, the corresponding amount of organic liquid that could be disposed is larger.

3.3.5 Disposal to river or estuary scenario

The disposal of H-3 and C-14 to an estuary (Thames) or a river has been considered in another report. The individual doses are the peak annual effective dose to members of hypothetical critical groups. For disposals to estuary an exposed group consuming critical group quantities (97.5th percentile) of fish and shellfish caught in the location of the disposal has been assumed. The group also has high beach occupancy. For disposals to river, the exposed group is assumed to consume freshwater fish at critical group quantities from the river section and to take all drinking water from the same section. High river bank occupancies are also assumed.
The estimated doses from the river or estuary disposal of organic liquids are shown in Table 6. The highest value has been estimated at 1.7 \( 10^{-6} \) Sv y\(^{-1} \) per GBq y\(^{-1} \) of C-14 disposed to river. Most of the other estimated doses are at least two orders of magnitude smaller than this. Constraining the peak dose to trivial levels (10 \( \mu \)Sv y\(^{-1} \)), the amount of organic liquid containing C-14 at 4 Bq ml\(^{-1} \) disposed to a river could be 1.5 \( 10^3 \) m\(^3\) y\(^{-1} \). This is equivalent to 1,500 typical large users using the same watercourse. The corresponding amount of organic liquid containing H-3 that could be disposed would be even larger.

### 3.3.6 Disposal to sewer or foul drain

The disposal of H-3 and C-14 to sewers has been considered in another report\(^26\). The results for Beckton sewage treatment works (STW) were used here. Table 6 gives dose estimates for workers in sewer pipes between the disposal point and the STW, for workers at the STW and doses associated with the disposal of sewage sludge incinerator ash to landfill. Other pathways, eg doses to the public from the discharge of effluent from the STW and from gases released from the sewage sludge incinerator, will give much smaller doses than those for incinerator and water course disposals.

The estimated doses from the disposal of organic liquids to drains or sewers are shown in Table 6. The largest dose has been estimated to be 2.8 \( 10^{-10} \) Sv y\(^{-1} \) per GBq y\(^{-1} \) of C-14 for sewer workers at a sewage treatment works. The amount of organic liquid containing C-14 at 4 Bq ml\(^{-1} \) disposed to a sewer or drain and still result in a peak dose at trivial levels (10 \( \mu \)Sv y\(^{-1} \)) could be 9 \( 10^6 \) m\(^3\) y\(^{-1} \). This is equivalent to 9 million typical large users in the same STW. This volume of solvent would generate problems even if not radioactive. The corresponding amount of organic liquid containing H-3 that could be disposed would be even larger.

### 3.4 Collective doses

The EC\(^2\) and IAEA\(^27\) specify a collective dose criterion for exemption from regulation of “of the order of 1 man Sv or that exemption is the optimum option”. The collective doses from accidental spillage or inhalation of volatile liquids will be less than 1 man Sv since there will not be many people exposed, and certainly less than 100,000 people in a year.

The collective doses from disposal can be estimated by assuming that the entire inventory is ingested. Hence a collective dose of 1 man Sv would arise from the disposal of at least 500 m\(^3\) of organic liquids containing H-3 and C-14 at or below 4 Bq ml\(^{-1} \). This is equivalent to 500 typical large users. The estimated upper bound largest user disposes about 10 m\(^3\) y\(^{-1} \). Hence, if there was an increase of a factor of 50 or more in usage of organic liquids then the situation would need to be reassessed.

### 3.5 Summary for organic liquids

1. The Substances of Low Activity Exemption Order allows the disposal of unlimited quantities of organic liquids containing H-3 and C-14 below 4 Bq ml\(^{-1} \) without an authorisation.
2. This part of the exemption order was intended for the disposal of liquid scintillant to drain. No other uses of organic liquids contaminated with H-3 were established. C-14 is also used in hospital radio-pharmaceutical departments.
3. The maximum average activity concentration of C14 entering drains as a result of its diagnostic use in radio-pharmaceutical departments is estimated as 4 Bq ml\(^{-1} \).
4. The assessments have shown that accidents involving liquid scintillant contaminated at 4 Bq ml\(^{-1} \) result in low doses.
Liquid scintillant is classed as special waste due to irritant, highly flammable and sometimes corrosive properties and the usual disposal route is to an authorised disposer for incineration. The quantity of liquid scintillant disposed of by a typical large user is around 1 m³ per year.

The volume of organic liquid contaminated with either H-3 or C-14 that could be disposed to landfill, incinerator, river/estuary or sewer/drain and still result in a peak dose at or below 10 µSv y⁻¹ has been estimated. Although the incinerator is the normal disposal route for liquid scintillant other disposal routes have been considered to account for unknown, large volume, organic liquids or scintillants disposed in contravention of regulations. The volumes that would result in doses at or below 10µSv y⁻¹ varies between 1.5 \(10^3\) m³ y⁻¹ and \(10^7\) m³ y⁻¹.

The assessment has shown that the present likely disposal rate of liquid scintillants containing 4 Bq ml⁻¹ is very small compared with the estimated volumes of organic liquids which might result in doses of 10 µSv y⁻¹. Similarly, the estimated collective dose from present likely disposals is less than 1 man Sv per year of practice.

4 Summary and conclusions

The Substances of Low Activity Exemption Order allows the disposal of unlimited quantities of gases with half-lives less than 100 seconds and organic liquids containing H-3 and C-14 below 4 Bq ml⁻¹ without an authorisation. Two assessments have been undertaken to examine the associated doses and to determine whether any changes are needed to ensure that doses remain at trivial levels.

The International Atomic Energy Agency sets an annual effective dose criterion of ‘a few tens of micro-Sieverts’ below which the use and disposal of radionuclides may be exempt from regulation⁷. The corresponding criterion for collective dose is ‘of the order of 1 man Sv or that exemption is the optimum option’. The European Basic Safety Standards use the same criteria for exemption from reporting or authorisation⁷. The assessments show that the present use of the SoLAEO for the disposal of short lived gases and organic liquids containing H-3 and C-14 meets these international exemption criteria. Hence, there is no need to modify the SoLAEO. If new practices involving the disposal of short lived gases in excess of 100 MBq y⁻¹ become apparent, then this will need to be reviewed. Similarly, if the disposal of organic liquids likely to be contaminated with H-3 and C-14 increases by an order of magnitude, then the situation would need to be reassessed.

Since it is not clear whether the SoLAEO strictly applies to Kr-81m, the SoLAEO should be revised to make sure that Kr-81m and Kr-81 grown in from Kr-81m are explicitly included.

It is suggested that the current Exemption Order be expanded to include O-15 and compounds labelled with O-15.

5 References

4 Paul Wright, RPA Rutherford Appleton Laboratory, Personal communication (1999).


JEF-2 (Joint Evaluated File library v2.2) part of JEF-PC v 1.0 software, Nuclear Data Services, OECD Nuclear Energy Agency, France (1994).


Page, B., Health Physicist, CSC Administration – Safety Section, MRC Hammersmith, Imperial College School of Medicine, Personal Comm. (2000).


Childs, P., Medical Physics Dept., Dudley Road Hospital, Birmingham, Personal Comm., (1999).


John D Harrison, NRPB. Personal communication (2000).

A Phipps, NRPB. Personal communication (2000).


Investigation of the Sources and Fate of Radioactive Discharges to Public Sewers (EA Report, to be published).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half life, s</th>
<th>Dose coefficients for inhalation, Sv Bq(^{-1})</th>
<th>Mean gamma energy per disintegration, MeV</th>
<th>Mean beta energy per disintegration, MeV</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-10</td>
<td>19.3</td>
<td>1.8 (10^{14})</td>
<td>0.72</td>
<td>-</td>
<td>Particle beam</td>
</tr>
<tr>
<td>C-15</td>
<td>2.4</td>
<td>3.2 (10^{14})</td>
<td>3.61</td>
<td>2.87</td>
<td>Particle beam</td>
</tr>
<tr>
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<td>4.5 (10^{13})</td>
<td>3.32</td>
<td>0.78</td>
<td>Particle beam</td>
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<td>1.02</td>
<td>0.734</td>
<td>PET</td>
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<tr>
<td>O-19</td>
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<td>1.9 (10^{12})</td>
<td>1.0</td>
<td>1.72</td>
<td>Particle beam</td>
</tr>
<tr>
<td>N-16 *</td>
<td>7.1</td>
<td>1.6 (10^{11})</td>
<td>4.62</td>
<td>2.69</td>
<td>Particle beam and nuclear power</td>
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<td>9.7 (10^{12})</td>
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<td>Particle beam</td>
</tr>
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<td>0.06</td>
<td>Lung imaging</td>
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<td>Cl-40</td>
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<td>2.94</td>
<td>2.79</td>
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<tr>
<td>I-136m</td>
<td>45</td>
<td>3.1 (10^{12})</td>
<td>2.13</td>
<td>2.17</td>
<td>None *</td>
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Notes:
# Dose coefficient expressed in Sv d\(^{-1}\) per Bq m\(^{-3}\)
* Included for illustrative purposes
### TABLE 2 Doses from assessment of scenarios for short-lived gases

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Individual dose per event, Sv</th>
<th>Annual individual dose, Sv</th>
<th>Collective dose per facility per year of operation, (population density) man Sv</th>
<th>Collective dose, all facilities per year of operation, (population density) man Sv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lung imaging, Kr-81m</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Treatment room, staff *</td>
<td>$3 \times 10^{-6}$</td>
<td>$3 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment room, comforter *</td>
<td>$3 \times 10^{-6}$</td>
<td>$3 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Member of public on-site *</td>
<td>$9 \times 10^{-9}$</td>
<td>$9 \times 10^{-7}$</td>
<td>$1 \times 10^{-2}$ (high)</td>
<td>$5$ (high)</td>
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<td>PET scanning (normal operation)</td>
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<td>$5 \times 10^{-11}$</td>
<td>$6 \times 10^{-5}$ (high)</td>
<td>$2 \times 10^{-4}$ (high)</td>
</tr>
<tr>
<td>Particle beam accelerator with no delay system *</td>
<td>$5 \times 10^{-10}$</td>
<td>$1 \times 10^{-7}$</td>
<td>$4 \times 10^{-2}$ (high)</td>
<td>$8 \times 10^{-3}$ (high)</td>
</tr>
<tr>
<td>C-15</td>
<td>$2 \times 10^{-9}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$2 \times 10^{-3}$ (high)</td>
<td>$4$ (high)</td>
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<tr>
<td>O-14</td>
<td>$2 \times 10^{-6}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$2 \times 10^{-1}$ (high)</td>
<td>$4$ (high)</td>
</tr>
<tr>
<td>O-19</td>
<td>$7 \times 10^{-10}$</td>
<td>$1 \times 10^{-7}$</td>
<td>$6 \times 10^{-3}$ (medium)</td>
<td>$1$ (medium)</td>
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<td>N-16</td>
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<td>$7 \times 10^{-9}$</td>
<td>$3 \times 10^{-3}$ (high)</td>
<td>$5 \times 10^{-2}$ (high)</td>
</tr>
<tr>
<td>N-17</td>
<td>$4 \times 10^{-11}$</td>
<td>$9 \times 10^{-9}$</td>
<td>$3 \times 10^{-3}$ (high)</td>
<td>$7 \times 10^{-2}$ (high)</td>
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<tr>
<td>Sum over nuclides</td>
<td>$6 \times 10^{-9}$</td>
<td>$1 \times 10^{-4}$</td>
<td>$5 \times 10^{-1}$ (high)</td>
<td>$1 \times 10^{0}$ (high)</td>
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<tr>
<td>Nuclear power generation, per reactor</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>N-16</td>
<td>-</td>
<td>$6 \times 10^{-4}$</td>
<td>$4 \times 10^{-1}$ (low)</td>
<td>$1 \times 10^{-2}$ (low)</td>
</tr>
<tr>
<td>Not known (illustrative only)</td>
<td>$2 \times 10^{-9}$</td>
<td>$4 \times 10^{-7}$</td>
<td>$2 \times 10^{-1}$ (high)</td>
<td>$4$ (high)</td>
</tr>
<tr>
<td>Br-72 *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-136m *</td>
<td>$1.6 \times 10^{-9}$</td>
<td>$3 \times 10^{-7}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

# Assumed 0.1 GBq per event, similar to particle beam production.

* Allowing for the finite size of the room

+ Upper bound, assuming forced extraction of short-lived gas

### TABLE 3 Population densities of UK towns

<table>
<thead>
<tr>
<th>Density</th>
<th>Typical towns or regions</th>
<th>Population per km²</th>
<th>Indicative values used for the assessment, per km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Kensington and Chelsea Inner London boroughs</td>
<td>$1.1 \times 10^{4}$</td>
<td>$10^{4}$</td>
</tr>
<tr>
<td>Medium</td>
<td>Manchester, Bristol Glasgow Oxford Exeter</td>
<td>$3.4 \times 10^{3}$</td>
<td>$2.8 \times 10^{7}$</td>
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<tr>
<td>Low</td>
<td>South Oxfordshire Rural</td>
<td>$1.9 \times 10^{5}$</td>
<td>$2 \times 10^{3}$</td>
</tr>
</tbody>
</table>
### TABLE 4 Data used in the assessment for H-3 and C-14

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half life, y</th>
<th>Dose coefficient for inhalation, Sv Bq^{-1}</th>
<th>Dose coefficient for ingestion, Sv Bq^{-1}</th>
<th>Beta dose coefficient for skin (4mg cm^{-2}), Sv h^{-1} per Bq cm^{-2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-3</td>
<td>HTO</td>
<td>1.8 \times 10^{-11}</td>
<td>1.8 \times 10^{-11}</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>OBT</td>
<td>4.1 \times 10^{-11}</td>
<td>4.2 \times 10^{-11}</td>
<td>0</td>
</tr>
<tr>
<td>C-14</td>
<td></td>
<td>2.10^{-9}</td>
<td>5.8 \times 10^{-10}</td>
<td>9.02 \times 10^{-7}</td>
</tr>
</tbody>
</table>

### TABLE 5 Doses from assessment of accidental scenarios for tritium (HTO and OBT) and C-14

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pathway</th>
<th>Individual dose, Sv</th>
<th>HTO</th>
<th>OBT</th>
<th>C-14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire, evaporation:</td>
<td>single 10 ml vial inhalation, total dose</td>
<td>2.6 \times 10^{-11}</td>
<td>5.0 \times 10^{-11}</td>
<td>2.2 \times 10^{-9}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bag of 100 vials</td>
<td>2.6 \times 10^{-9}</td>
<td>5.0 \times 10^{-9}</td>
<td>2.2 \times 10^{-7}</td>
<td></td>
</tr>
<tr>
<td>Spillage:</td>
<td>single 10 ml vial skin equivalent dose</td>
<td>-</td>
<td>-</td>
<td>6.0 \times 10^{-10}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>total dose</td>
<td>7.2 \times 10^{-12}</td>
<td>1.6 \times 10^{-11}</td>
<td>2.0 \times 10^{-13}</td>
<td></td>
</tr>
</tbody>
</table>

**Note**  
# Dose based on skin absorption
### TABLE 6  Risk and dose estimates for unit disposal of H-3 and C-14

<table>
<thead>
<tr>
<th>Disposal scenario</th>
<th>Exposure pathway</th>
<th>Best estimate peak risk, y⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>H-3</td>
</tr>
<tr>
<td>Landfill disposal</td>
<td>landfill operator doses</td>
<td>1.1 10⁻¹³</td>
</tr>
<tr>
<td></td>
<td>discharges of landfill gas</td>
<td>3.7 10⁻¹²</td>
</tr>
<tr>
<td></td>
<td>migration into groundwater</td>
<td>2.2 10⁻¹¹</td>
</tr>
<tr>
<td></td>
<td>Probabilistic exposure routes :</td>
<td></td>
</tr>
<tr>
<td></td>
<td>waste fire (short)</td>
<td>5.5 10⁻¹⁴</td>
</tr>
<tr>
<td></td>
<td>excavation of the site</td>
<td>1.4 10⁻¹⁸</td>
</tr>
<tr>
<td></td>
<td>residence on redeveloped site</td>
<td>3.4 10⁻¹⁴</td>
</tr>
<tr>
<td></td>
<td>construction of a well</td>
<td>4.7 10⁻₁⁵</td>
</tr>
</tbody>
</table>

**Peak individual dose, Sv y⁻¹ per GBq y⁻¹**

| Disposal scenario | Exposure pathway                  | H-3                          | C-14                         |
|-------------------|-----------------------------------|------------------------------|
| Incinerator       | atmospheric release resident      | 6.6 10⁻¹³                    | 4.5 10⁻¹¹                    |
|                   | farmer                            | 1.1 10⁻¹²                    | 2.6 10⁻¹⁰                    |
| Water course      | estuary                           | 4.9 10⁻¹⁴                    | 2.7 10⁻⁸                     |
|                   | river                             | 7.2 10⁻¹⁰                    | 1.7 10⁻⁶                     |
| Drains / sewers   | worker in pipes                   | 1.1 10⁻¹⁵                    | 3.8 10⁻¹⁵                    |
|                   | worker at sewage treatment works   | 1.3 10⁻¹³                    | 2.8 10⁻¹⁰                    |

**Notes**

# For landfill, unit disposal is 1 GBq y⁻¹ for ten years (ie 10¹⁰ Bq in total). For other scenarios, unit disposal is 1 GBq y⁻¹

@ Doses scaled down from reference 25 where assumed disposals were 3 10¹³ Bq y⁻¹ H-3 and 1.6 10¹² Bq y⁻¹ C-14.

### TABLE 7  Number of large users disposing of organic liquid contaminated with H-3 or C-14 that would give rise to peak individual doses of 10⁻³ Sv y⁻¹

<table>
<thead>
<tr>
<th>Disposal route</th>
<th>Number of large users</th>
<th>Typical size</th>
<th>Upper bound size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>6 10⁴</td>
<td>6 10³</td>
<td></td>
</tr>
<tr>
<td>Incineration</td>
<td>1 10⁷</td>
<td>1 10⁶</td>
<td></td>
</tr>
<tr>
<td>River / estuary</td>
<td>1 10³</td>
<td>1 10²</td>
<td></td>
</tr>
<tr>
<td>Drains / sewers</td>
<td>9 10⁶</td>
<td>9 10⁵</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX

Calculation of inhalation dose coefficients

Inhalation dose coefficients (committed effective dose per unit intake) for the short-lived gases considered in the assessments were calculated using ICRP lung models. The exact time a short-lived gas spends in passing through the lung membrane is not known (although it is likely to be a short period), therefore two bounding cases were considered using different SR classifications. The SR-1 classification considers a 5 minute passage time across the lung membrane before entry to the blood. The SR-2 classification considers no retention in the lung membrane and the radionuclide is modelled as being directly injected into the blood stream. The SR-1 classification results in the higher lung dose.

For the carbon isotopes C-10 and C-15, ICRP Publication 66 recommends SR-2 values. For the oxygen isotopes O-14, O-15 and O-19, ICRP Publication 66 makes no recommendation. Therefore, the SR-2 ‘injection’ values were used on the basis that oxygen travels quickly across the lung membrane into the blood stream. Nitrogen is an inert gas and therefore does not deposit in the lung so the SR classification is not appropriate. For the remaining radionuclides (Cl-40, Br-72 and I-136m), ICRP makes no recommendation as to which method is ‘more’ correct. Therefore, the more conservative SR-1 classification was used, being around a factor of 5-10 higher than the SR-2 ‘injection’ method. The inhalation dose coefficients for both methods for some of the short-lived gases used in the assessment are given in Table A1.

The inhalation dose coefficient for Kr-81m is for effective dose equivalent, taken from ICRP-53. The inhalation dose coefficient based on effective dose is unlikely to be significantly different, given that approximately 90% of the effective dose arises from equivalent dose to lung and the tissue weighting factor for lung is the same for both effective dose equivalent and effective dose.

The dose coefficients used for the assessments are given in Table 1 (main report).

Reference


TABLE A1 Comparison of inhalation dose coefficients for selected radionuclides

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Inhalation dose coefficients (committed effective dose), Sv Bq⁻¹</th>
<th>SR-1</th>
<th>SR-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-10</td>
<td>6.2 \times 10⁻¹⁴</td>
<td>1.8 \times 10⁻¹⁴</td>
<td></td>
</tr>
<tr>
<td>C-15</td>
<td>*</td>
<td>3.2 \times 10⁻¹⁴</td>
<td></td>
</tr>
<tr>
<td>O-14</td>
<td>4.1 \times 10⁻¹²</td>
<td>4.5 \times 10⁻¹³</td>
<td></td>
</tr>
<tr>
<td>O-15</td>
<td>5.8 \times 10⁻¹²</td>
<td>4.7 \times 10⁻¹³</td>
<td></td>
</tr>
<tr>
<td>O-19</td>
<td>*</td>
<td>1.9 \times 10⁻¹³</td>
<td></td>
</tr>
<tr>
<td>N-16</td>
<td></td>
<td>1.6 \times 10⁻¹¹</td>
<td></td>
</tr>
<tr>
<td>N-17</td>
<td></td>
<td>9.7 \times 10⁻¹²</td>
<td></td>
</tr>
<tr>
<td>Cl-40</td>
<td>5.3 \times 10⁻¹²</td>
<td>7.6 \times 10⁻¹³</td>
<td></td>
</tr>
<tr>
<td>Br-72</td>
<td>6.4 \times 10⁻¹²</td>
<td>1.4 \times 10⁻¹²</td>
<td></td>
</tr>
<tr>
<td>I-136m</td>
<td>3.1 \times 10⁻¹²</td>
<td>4.9 \times 10⁻¹³</td>
<td></td>
</tr>
</tbody>
</table>

Notes
- bold = used in the assessment
- + not determined for the assessment
- * Sv d⁻¹ per Bq m⁻³. Sr classification does not apply