LLW Repository Ltd

LLWR Environmental Safety Case

Assessment of the Disposal of Low Activity Sources at the LLWR

A report prepared by the Low Level Waste Repository Ltd.

LLWR/ESC/R(11)10037 **Issue 1** **Date: April 2011**

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Executive Summary

The report is concerned with low-activity radioactive sources, such as typically arise as redundant sources that have used for instrument testing and calibration, or similarly small, low-activity items. The LLWR aims to provide a route for disposal of such low activity disused sources.

The purpose of this report is:

- to review the current conditions for the disposal of low-activity radioactive sources at the LLWR and the information on the disposal of such sources at the LLWR;
- to discuss the applicable regulatory guidance levels and appropriate assumptions for assessment, and to set out a methodology to assess the impacts of disposal of low-activity sources at the LLWR that is cautious with respect to the regulatory guidance;
- to apply the methodology:
  - to calculate the potential post-closure impacts from the disposal of low-activity sources as it has been practiced at the LLWR, including assessing whether the present conditions and radioactive limits for disposal of sources are protective, and
  - to support the development of revised conditions and radioactive limits for the future receipt and disposal of low-activity sources at the LLWR that would offer some flexibility to consigners, while continuing to assure long-term radiological protection.

In 2005, as part of discussion over the UK Surplus Source Disposal Programme, the operator of the LLWR came forward with proposed Conditions for Acceptance for the disposal of low-activity sources, which, after clarification, were accepted by the Environment Agency (EA). The conditions include, amongst other things, limitation to sources of not more than 1 MBq, that after removal of extraneous packaging sources should be mixed with cement grout into 'paint-tin type' containers, and that each such container should declared as a specific waste stream.

We have examined information supplied by Consigner Support on radioactive source disposals both prior to and after 2005. We have also set out a methodology for the assessment of the potential long-term radiological impacts of such disposals.

We consider that the limiting assessment cases:

- will occur after the facility has been impacted by coastal erosion, source containers have been distributed with other waste on the beach and may be broken open by wave action on the cobble storm beach;
- involve a beach user, e.g. walker or beachcomber, either interacting with a single source container or finding and taking away one or a small number of individual sources.

Cautiously, we assess these events on the basis that they actually occur, although this is by no means certain. Assuming an event occurs, the impacts to assess are:

- the effective dose due to handling and/or proximity to a source container on the beach/foreshore (or similar situation);

- the effective dose due to prolonged proximity to an individual source taken away from the beach/foreshore (or similar situation);
- the equivalent dose to localised area of skin due to handling, or pocketing of an individual source (or similar situation).

There are issues over probability of events, source form/conditions and exposure conditions and duration that are difficult to quantify. It can be stated, however, that only very few individuals could be exposed, because of the small number of source containers. Nevertheless, assessing on the cautious basis that source containers and individual sources will be found, inspected and, in the case of individual sources taken away, effective doses are calculated that are consistent with an the GRA risk guidance level of 10^{-6} per year. Equivalent doses to skin are calculated that are consistent with the ICRP recommended annual limit for equivalent dose to skin of 50 mSv for public exposure.

We conclude that the conditions for acceptance and disposal of low-activity sources, as agreed with the EA in 2005, are highly protective in the case of sources from nuclear cycle operations and are protective in practice in the case of disposals of Ra-226 and Th-232 sources.

Based on our assessment results, and consideration of sources that may actually arise and be suitable for disposal at the LLWR, we have proposed modified conditions for disposal of low-activity sources. These take account of the hazard posed by sources of different radionuclides through a radionuclide grouping approach. The 1 MBq limit is retained for long-lived radionuclides that emit, or decay to short-lived progeny that emit, significant photon emissions, but relaxed to 10 MBq for other nuclides without such emissions or with half-life less than about 100 years, and to 100 MBq for radionuclides with half-life of less than about ten years. The total activity in any source container is limited by a sum of fractions approach based on the radionuclide grouping.

The limitations of individual source activity and total activity of a source container will allow source containers with specific activity above the definition of LLW, especially if containing larger sources of radionuclides with half-life less than 10 years; consistency with the definition of LLW must be shown at the consignment level. For Ra-226 and Th-232 sources, the proposed new total activity of a source container requirement is marginally stricter than implied by limiting to the definition of LLW.

We consider that the proposed modified conditions should be adopted since they provide flexibility to dispose of higher activity sources than under the existing conditions, and hence avoid the accumulation of such sources, while still providing a high level of long-term radiological protection.

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1 Scope and purpose of this report

This is a supporting (Level 3) report for the 2011 ESC for the LLWR [1]. It supports the assessment of low-activity sources as summarised in the 2011 ESC Level 2 report "*Assessment of Long-term Radiological Impacts*" [2] and proposals for future acceptance presented the 2011 ESC Level 2 report "*Waste Acceptance*" [3].

The report is concerned with low-activity radioactive sources, such as typically arise as redundant sources that have used for instrument testing and calibration, or similarly small, low-activity items. Such items are sometimes termed 'sealed sources', although in many cases the radioactivity is plated or evaporated onto a surface and, hence, not necessarily sealed. For this reason, the term 'low-activity sources' is preferred in this report.

The purpose of this report is:

- to review the current conditions for the disposal of low-activity radioactive sources at the LLWR and the information on the disposal of such sources at the LLWR;
- to discuss the applicable regulatory guidance levels and appropriate assumptions for assessment, and to set out a methodology to assess the impacts of disposal of low-activity sources at the LLWR that is cautious with respect to the regulatory guidance;
- to apply the methodology:
  - to calculate the potential post-closure impacts from the disposal of low-activity sources as it has been practiced at the LLWR, including assessing whether the present conditions and radioactive limits for disposal of sources are protective, and
  - to support the development of revised conditions and radioactive limits for the future receipt and disposal of low-activity sources at the LLWR that would offer some flexibility to consigners, while continuing to assure long-term radiological protection.

This report is based on a preliminary assessment of sources, and methodology, set out in an ESC Project Memo [4]. The present report, however, presents assessment calculations for a wider range of radionuclides and derives proposals for revised conditions and radioactive limits, whereas the Project Memo only identified the general potential for revised conditions and limits.

2 Background

2.1 Sealed sources, sources of low activity and the Surplus Source Disposal Programme

The term ‘sealed source’ applies to a radiation source of any magnitude in which the radioactivity is contained in a sealed form, but so that major photon emissions (gamma rays) are not contained. This includes sources of high-activity such as used for industrial radiography and medical external beam radiotherapy. Such high-activity sources would not be suitable for disposal at the LLWR.

On the other hand, numbers of lower activity sources are used, typically for instrument testing and calibration. In the case of commercially-produced, gamma test sources, the activity will be sealed, generally in a resin bead or similar. In the case of beta and alpha test and calibration sources, the activity must necessarily be on the source surface, for example, plated or evaporated onto a small stainless steel or other metal disc. Commercially-produced sources are usually returned to the manufacturer for disposal when they become redundant or expended. On the other hand, instrument test and calibration sources are often made at nuclear and research facilities at the site of use, so that there is no option for return to the manufacturer.

Test and calibration sources age by decay or loss of unsealed material and, hence, become unreliable, or are simply no longer needed, and in either case redundant. The sources are generally small in size and pose no problem to accumulate in the short term, but good housekeeping means that, in the longer term, it is preferable to collect together and dispose of such sources.

As reported by Williams et al. [5], between 2004 and 2009, the UK Government funded Surplus Source Disposal Programme (SSDP), managed by the Environment Agency, arranged and subsidised the safe disposal or recycling of more than 11 000 unwanted radioactive items containing in total more than $8.5\ 10^{14}$ Bq (850 TBq) of activity, from some 500 sites throughout the United Kingdom. Sources were removed principally from universities, schools and colleges, museums, and hospitals. Most of these sources have been sent to long-term storage at the Windscale, Sellafield and Harwell sites pending disposal, which for the higher activity sources will be disposal in a deep underground facility. Current legislative requirements under the High Activity Sealed Sources (HASS) Directive [6], which came into effect in 2005, will prevent a build-up of high-activity surplus sources in future. Williams et al. note, however, that continuing vigilance may be needed to avoid a build-up of lower activity disused sources.

The LLWR aims to provide a route for disposal of such low activity disused sources.

2.2 History and conditions of disposal of low-activity sources at the LLWR

Prior to about 2000, the LLWR did not accept radioactive sources for disposal. The issue with such sources is that even though the activity of a source may be low, the mass of such sources may be very low so that, unless some addition of material is allowed, the item falls above the definition of LLW. Such addition or dilution is not generally considered good practice, or allowable, for solid waste disposal.

During the late 1990s, however, it had been recognised that a large number of low-activity sources had been accumulated, notably redundant instrument test sources at Sellafield, and that it would be desirable to collect together and dispose of these. Disposals of low-activity sources at the LLWR are recorded from 2001 onwards. Initial disposals were in large pots included with other waste and confirmation that LLW limits were met were made against total consignment mass. From 2002 onwards, disposal were of lower total activity were made and confirmation that LLW limits were met were made against the mass of the loaded container in which the sources were disposed.

In 2005, as part of discussion over the set up of the Surplus Source Disposal Programme, described above, BNG Sellafield Ltd (the then operator of the LLWR) came forward with proposed revisions to the Conditions for Acceptance for the disposal of low-activity sources for consideration by the Environment Agency (EA). Conditions for the disposal of low-activity sources were proposed in the British Nuclear Group (BNG) letter of 13 September 2005 [7], which, after clarifications [8, 9], were accepted in the EA letter of 18 October 2005 [10].

The elements of the agreed arrangements were:

1. That the requirement to remove as much extraneous packaging and shielding from the sources remains.
2. That the sources are grouted in a small paint tin type container and have a maximum of 100mls of grout surrounding them. i.e. for 10 sources we would expect no more than 1 litre total encapsulant in a similar sized container.
3. That for the purposes of a disposal calculation, the weight of the grout and container is included to give the specific activity (activity per weight) for the small container.
4. That the constituent sources in their raw state, do not individually exceed 1E+06 Bq (1MBq total Alpha and Beta-Gamma activity).
5. That a specific wastestream characterisation is required for each small container disposal, detailing the normal required information as well as source registration references (if available), activity per source, number of discreet sources in container, isotopic detail and any half-life calculations.
6. That as part of the conditions for acceptance, both customer and WAMAC loading operations will incorporate a ruling of one source container per ISO-freight disposal, to mitigate intrusion scenario risks.

These arrangements were accepted by the EA following quantification/assurance from BNG that:

- such disposals over a three-year period would represent a minor fraction of the Authorised Annual Limits for individual radionuclides and radionuclide groups;
- the extant PCSC (the 2002 PCRSA) would not require amendment.

The BNG letter of 13 October 2005 [9] adequately supports the first point; the argument on the second point is less clear, see Section 4.

The requirement to identify and detail disposals of sealed source through the D5 process was included in to then LLWR Conditions for Acceptance (CFA) of waste [11], now superseded by Waste Acceptance Criteria (WAC) [12], and the conditions were included into the LLWR Guidance Notes for consigners.

3 Disposals of low-activity sources at the LLWR

3.1 General practice

Since 2005, disposal of low-activity sources has been carried out generally according to the conditions set out in Section 2.2.

The objective of these conditions was to allow disposal of small sources, up to 1 MBq, large numbers of which arise, for example, from instrument testing and calibration, and had been accumulated from the Surplus Source Disposal Programme.

As mentioned in Section 2.2, a concern around disposal of such sources, generally weighing only a few grams, is that the activity concentration in the raw source is liable to exceed the definition of LLW. The condition of a maximum 100 mls of grout per source was intended to give a maximum allowable amount of dilution that could be introduced in producing a conditioned waste package, i.e. a filled paint-tin-type container, for disposal as LLW [1]. The actual amount of grout per source added can be much less and still be consistent with the conditions. The key limits are no individual source is greater than 1 MBq and that the total activity and mass of the package are such that the package meets the definition of LLW, i.e. not more than 4 GBq/t alpha or 12 GBq/t other.

Since a waste stream characterisation document is required for each container and also to facilitate sensible handling and disposal, the practice has been to dispose in larger containers than the 1 litre example of condition 2 (above), with up to 15 litre containers being used in practice. Potentially, large numbers of smaller less active sources may be disposed in a single container with the bulk of the activity being due to relatively few higher activity sources, but still respecting the 1 MBq maximum per source.

The mixing with cement grout was intended to provide encapsulation of the sources, and/or protection against direct exposure to a source, but this function is not quantified in the conditions. The use of larger containers does in principle give the possibility of larger amounts of grout and thus more robust shielding/containment of the sources.

3.2 Information on sources disposed

Detailed information on sources consigned to LLWR has been provided by Consigner Support, see Table A1 in Appendix 1. The information lists sources, sometimes source types, radionuclide activities and in some cases total activity by radionuclide. In most cases, it does not give definite information about the size of container into which sources were disposed, and in no case does it give amounts of grout. Information relates to consignments, or sources for disposal both before and after October 2005. The information includes all consignments of sealed sources disposed after 2005 as specific waste streams and identified via the D5 process. Table 1, below, summarises information extracted on sources most relevant to assessment of post-closure radiological impact.

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[1] A single 1 MBq source of small mass mixed with 100 mls (ca. 170 g) of grout yields about 6 kBq/g = 6 GBq/t, cf. definition of LLW as not more than 4 GBq/t alpha or 12 GBq/t other.

Table 1: Sources most relevant to assessment of post-closure radiological impact, summarised from the information supplied by consigner support			
Radionuclide	Half-life	In consignments before 2005	In consignments after 2005
Ni-63	100 y	Uncommon 6 of 370 MBq, 1 of 550 MBq	None found
Sr-90	29.1 y	Hundreds of sources Mainly less than 0.1 MBq Frequently 0.1 to 1 MBq Sometimes > 1 MBq Twelve ca. 20 MBq Maximum 370 MBq (1 of)	Tens of sources Mainly less than 0.01 MBq Maximum 0.07 MBq
Cs-137	30.0 y	Hundreds of sources Mainly less than 0.1 MBq Frequently 0.1 to 1 MBq Sometimes > 1 MBq 5 of 300 to 600 MBq Maximum 1000 MBq (1 of)	Tens of sources Mainly < 0.01 MBq Maximum ca. 0.5 MBq (8 of)
Ra-226	1600 y	Uncommon 8 of 0.2 to 0.4 MBq several smaller	Uncommon 3 of ca. 1 MBq several smaller
Th-232	1.41 E10 y	None found	Very rare 2 of 0.002 MBq; 1 of 1 MBq
Np-237	2.14 E6 y	Only one found 0.04 MBq	Very rare 4 of 1 MBq
Pu-239	2.41 E4 y	Hundreds of sources Typically < 0.01 MBq Sometimes 0.01 to 0.1 MBq Maximum 3.7 MBq (1 of)	Tens of sources Always < 0.001 MBq Maximum 0.0002 MBq
Am-241	432 y	Hundreds of sources Typically < 0.01 MBq Frequently 0.01 to 0.1 MBq Maximum 0.54 MBq	Tens of sources Mainly < 0.01 MBq Several > 0.1 MBq Maximum 1 MBq
Based on examination of waste stream information (see Table A1, Appendix 1)		2x65/1 (4 "*pots*") Sellafield 2x65/2 (1 "*pot*") Sellafield 2x65/3 Sellafield 2x65/4 Sellafield 03H1B WS084 Hinkley Point	2x65/6 Sellafield 2x65/7 Sellafield 2x65/8 Sellafield 03HAR WS132 Harwell 01BNL 9R113 Berkley NL

The information indicates large numbers of sources have been disposed as single waste streams, and presumably therefore in a single container. Most of the sources are of very low to trivial activity with only a small fraction of sources exceeding even 1% of 1 MBq.

Information dated 2001 and 2002/3 on sources originating from Sellafield indicates disposal in large containers (ca. 117 kg) and disposal of some sources considerably greater than 1 MBq [2]. In later consignments from Sellafield all individual sources are less than 1 MBq.

Information concerning consignments from Harwell and Hinkley Point list sources all less than 1 MBq. Information concerning "*LLW sources*" identified at BNLS indicates ten sources at the 1 MBq level [3] and a further six >0.8 MBq.

Based on inspection of the detailed information, Table 1 lists typical and maximum activity sources for radionuclides most relevant to potential post-closure impacts. Shorter-lived radionuclides (including Co-60) are neglected as these will have decayed. There are large numbers of C-14 and Cl-36 sources, which are neglected on the basis of their emissions and hence low radiological impact in exposure cases of concern, see Section 5.2.

Table 1 indicates that prior to 2005 very large numbers of sources were disposed as a single consignment wherein a small fraction had activities above 1 MBq. A few Sr-90, Ni-63 and Cs-137 sources had activities above 100 MBq [4]. The information indicates that the sources were consigned in "*pots*" of 117 kg weight, which might indicate a container of about 50 litres volume.

After 2005 the information indicates smaller numbers of sources being disposed together consistent with a maximum container volume of 15 litres that has been advised by Consignor Support. The limit of 1 MBq per source is respected.

The waste stream characterisation for WS084 Hinkley Point B, which includes rather few and mainly trivial sources, notes: "*to be grouted into, and disposed of, in a 5L empty metal paint container (contaminated, and therefore to be disposed of anyway)*". This raises an issue as to whether it would be preferable to dispose in 'clean' containers or in any container to hand.

3.3 Disposals outwith the agreed conditions

In late 2009, a Customer Audit of Inutec Limited, based at Winfrith, by LLWR's Service Assurance Team identified a number of consignments that had been disposed that had not been notified through a D5 declaration and also, on several occasions, with more than one source container placed within a single HHISO/THISO, i.e. contrary to the agreed conditions. (The 1 MBq limit and grouting requirements were respected.) This incident was notified to the EA Site Regulator, fully investigated by LLWR, and subsequently formally reported to the EA, including the causes and remedial actions related to training and promulgation of the conditions for acceptance low-activity sources.

The assessment of the potential post-closure radiological impact of the disposals is given in the ESC Memo [4]. Therein, it is shown that:

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2 Up to 60 MBq Co-60, 370 MBq Sr-90, 1000 MBq Cs-137, 370 MBq Ni-63, 4 MBq Pu-239.

3 This includes four 1 MBq Np-237 sources (neutron dosimeters).

4 Although Ni-63 is of little concern having no gamma and only a relatively soft beta emission.

- only the disposed Ra-226 sources give any significant potential for exposures in the post-closure period;

- even in the 'worst case' and assuming that an individual managed to collect and inspect all five containers from the same HHISO, this would imply an estimated effective dose of about 6 µSv for the event;

- this is of low concern in view of the low likelihood and, even if the event is assessed as occurring, the assessed dose is less than an annual effective dose of 20 µSv, which corresponds to the risk guidance level of 10^{-6} per year as given in the GRA.

Nevertheless, the information on sources disposed is relevant here as indicating potential for future similar disposals and is included In Table A2, Appendix 1.

In summary, the information shows twelve HHISO/THISO consignments that included between 1 and 5 source containers each, with 25 containers in total disposed between 2002 and 2009.

The notable feature is the relatively large number of Ra-226 sources, a radionuclide highlighted as of special concern in the ESC Memo [4]. The disposed Ra-226 sources range from less than 0.001 up to 0.78 MBq, with a relatively large number being recorded as 0.185 MBq (5 µCi) and a smaller number around 0.74 to 0.78 MBq (20 µCi).

4 Assessment in the 2002 PCRSA

As mentioned in Section 2.2, the argument on acceptability of sealed source disposals on the basis of the 2002 Post Closure Radiological Safety Assessment (PCRSA) is unclear.

The BNG letter of 13 October 2005 refers to human intrusion, which was (reasonably at the time) considered as the limiting mode of exposure, and also refers specifically to condition 6, stating that this: *"will ensure that concentrations or hotspots will not occur and the intrusion scenario and radiological assessment therefore remain the same".*

Word searches and manual study of relevant sections (inventory and human intrusion assessment) of the 2002 PCRSA [13] reveal no mention of sealed sources, their disposal or of exposure to individual small items or assessment of 'hotspots'. All calculations therein assume an average concentration of radionuclides in waste for each of the trenches, Vault 8 and future vaults. This would be consistent with an assessment of human intrusion against a risk target and an argument that adopting an average concentration is equivalent to taking account of a low probability of intercepting higher activity/concentration items. (This approach will not be accepted by the EA in the 2011 ESC, see Section 5.1.)

Mathematically, the argument holds if both the radionuclide concentrations ('hot spots') in Vault 8 are randomly distributed and intrusion events also randomly located. Neither of these conditions is properly met, but especially the placing of more than one source container in a single HISO would undermine the argument.

More significantly there is no estimation of the impact of an intrusion that intercepts a single source container or 'hot spot' in the 2002 PCRSA. It is possible that such consideration was made in arriving at the conditions in Section 2.2, or that acceptability was judged by reference to measured dose rates associated with sources or contained sources, but we have not seen such evidence.

5 Assessment of low-activity sources under the current conditions for acceptance

This section presents a methodology for calculating and assessing potential post-closure impacts arising from the disposal of low-activity sources as developed in the ESC Memo [4]. It takes as its starting point the assessment of low-activity sources disposed according to the conditions set out in Section 2.2.

5.1 Discussion of cases, GRA view and mitigating arguments

Since 2002, substantial additional work has been carried out related to the local coast and coastal processes [14, 15]. The additional understanding and quantitative modelling leads to the conclusion that, in the absence of specific and effective measures to protect the site, the disposal vaults will begin to be eroded by wave undercutting on a timescale of a few hundred years to thousands of years after present. The cases that need to be considered in respect of the sealed sources within the vaults are therefore:

- human intrusion into the waste, possibly before erosion of the vaults commences but also excavation into the vault/waste cliff after erosion of the vaults has commenced;
- distribution of sealed source containers onto the beach by natural erosion processes: such containers may be initially intact but are liable to be degraded and broken open on the beach by wave action, so that individual sources may be distributed on the beach.

In both cases, the important exposure modes are similar – external dose due to inspection, carrying away or proximity to a container, or exposure to an individual source (skin dose) if the container is broken open either naturally or during a human intrusion. The environment agencies' Guidance for Authorisation (GRA) [16] distinguishes the cases, however.

According to the current GRA [16], human intrusion events must be assessed on the basis that they occur and against a dose guidance range of 3 to 20 mSv depending on the duration of exposure and other factors. That is we are no longer allowed to take account of the probability of intrusion as was the case in 2002 under the previous GRA. Rather, if an event is credible we must assess it as though it will happen. Since the event here is presumably rare (as the number of containers is small) we can assume an individual might only encounter one such container and the exposure would be received within a single year. In this case, it would be appropriate to compare the dose to a value toward the higher end of the dose guidance range. If more than one source container is in a single HHISO, and especially if the two or more containers are placed close together in the HHISO, then the case becomes inspection/proximity to however many containers are placed together.

In the case of natural erosion of the wastes, the GRA requires an assessment of the risk to a person representative of those at greatest risk against a risk guidance level of 10^{-6} per year. The EA, however, have asked us to assess the risk at the time at which wastes are exposed and being eroded. That is, the individual at greatest risk will be defined as the individual potentially present at the time when the wastes of highest activity or otherwise of concern (in this case a container of low-activity sources) are being eroded or are present on the beach. Further, the EA has advised that they do not consider the finding or inspection of contaminated items such as sealed sources on the beach as human intrusion, and is therefore to be assessed against the risk guidance level.

The individual at highest risk in our assessments of coastal erosion is envisaged as a dog walker, or similar, who spends time on the beach and frequently (daily) traverses the length of the beach below the exposed waste cliff. For this individual, the presence of a source container or individual sources is a small perturbation and is captured within the calculation of total activity present in the exposed cliff and on the beach and foreshore at any time.

It is prudent, however, to also assess the case of an individual who actually finds or inspects an item on the beach, e.g. a beachcomber. In this case, an individual who finds or inspects an item is the individual at greatest risk and it may be inappropriate to dilute the individual risk over individuals who do not find or inspect an item. This means that unless we can argue that the group of such individuals who find or inspect an item does not exist, we may have to assess as a probability of one. Thus, cautiously, we may have to assess the finding and inspection of a sealed source container against a dose level corresponding to the annual risk guidance level, i.e. an annual effective dose of 20 µSv (0.02 mSv). That is a criterion one hundred to one thousand times more stringent than for the human intrusion case (3 to 20 mSv).

In mitigation, we can argue the low probability of an individual traversing the beach happening to stop or inspect an item, which will not be that attractive, or equivalently that very few or possibly no individual with interest might encounter such an item. That is the possible number of individuals ever exposed in this way can only be very small to zero. It is difficult, however, to see how we can argue that it will never happen. Indeed, regardless of likelihood, the EA will expect us to assess this case.

Similarly, the case of a beach user that finds or inspects one or more individual sources must be assessed against risk guidance level. In the case of contained sources, it seems unlikely that a beach user will ever encounter more than one container. In the case of individual sources broken out from a container it might be possible for a beach user to encounter more than one source. It is also credible that a beach user might pick up and take away a source from the beach, whereas it would be unlikely for anyone to take away a degraded cement-filled can of several to a few tens of kg weight. In the case of individual sources, localised skin exposure must also be considered.

Appendix 2 sets out arguments and probabilities could be considered in assessing the radiological risks related to finding and handling a source container or individual sources on the beach/foreshore. In summary, suggestions can be made that the probabilities of (a) the presence of exposed source containers or individual sources, (b) encountering such if present, and (c) interacting with such if encountered, are all less than one and, moreover, would be multiplicative. Many of the probabilities are hard to quantify, however.

5.2 Definition of assessment cases and guidance levels

5.2.1 Limiting cases

Since the dose guidance level applicable to human intrusion (20 mSv for exposures of short duration) is a factor of 1000 less stringent than the dose corresponding to the risk guidance level (0.02 mSv), we consider that the limiting assessment cases:

- will occur after the facility has been impacted by coastal erosion, source containers have been distributed with other waste on the beach and may be broken open by wave action on the cobble storm beach;

– involve a beach user, e.g. dog walker or beachcomber, either interacting with a single source container [5] or finding and taking away one or a small number of individual sources.

According to an integrated understanding of the evidence, see [14, 15], it is expected that erosion of the LLWR may commence between a few hundred to thousands of years in the future. In assessments for the 2011 ESC [2], we consider erosion commencing at 300, 1000 and 3000 years after present, which we consider adequately spans the uncertainty. Here, we assess the finding of sealed sources at 300 years after disposal as a cautiously early time at which any such event could occur.

For the interaction with a source container the only exposure mode of concern is external exposure, primarily gamma irradiation assessed as effective dose. For the interaction with individual sources, localised skin dose is also relevant and beta emissions may be important depending on the form of the source.

For the interaction with a single source container we will consider the 15 litre grouted can. Limiting radionuclides are liable to be Ra-226 and Th-232 on account of their half-life and strong gamma emissions of their progeny (daughters etc.), which neglecting radon emanation can be assumed to be in equilibrium [6].

For the interaction with individual sources, Ra-226 and Th-232 are also likely to be important but other radionuclides may also be important, notably Sr-90 and Cs-137, because of the large number, and pre-2005 high activity, of such sources.

5.2.2 Assessment guidance levels

The EA has indicated that we should assess the above cases against the 10^{-6} annual risk guidance level, which corresponds to an annual effective dose of 0.02 mSv for an event with probability of one per year. We could argue a number of mitigating probabilities (see Appendix 2). The EA may consider, however, that if the facility is liable to be eroded on a timescale of a few hundred years, then items should not be placed in the facility that give potential for risks significantly above the guidance level. This would be similar to the position they take with regard to human intrusion, although in this case the guidance level is expressed as a dose related to the event.

There is a strong argument that although an individual may find a source container, it is very unlikely that the same individual will continue to find such containers over a number of years, because of the small number of such containers. That is, the risk is not recurring or sustained so that to apply the annual risk guidance level is cautious.

In the case of individual sources, dose to skin from contact is a concern. For protection of the skin ICRP [17] recommends annual limits on equivalent dose of 500 mSv for occupational exposure and 50 mSv for public exposure relating to the prevention of deterministic effects. The dose is to be calculated averaged over a minimum of 1 cm^2 of skin regardless of the area exposed. In this case, probability of occurrence is not immediately relevant unless the probability is zero, i.e. the event cannot happen. On the

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5 Even if two sealed source containers are placed in the same HHISO, wave action, especially related to the storm event in which they may have been released from the cliff will act to separate the containers.

6 Reasonable, as sealed sources such as radium beads and needles are liable to retain their integrity.

other hand, probability is relevant in considering what is the most appropriate time for exposure to select, i.e. prolonged contact may be much less probable than short inadvertent contact.

5.3 Dose factor calculations

5.3.1 For source containers

Section 5.2.1 identifies Ra-226 and Th-232 as likely limiting radionuclides.

Microshield calculations have been carried out by S&RM Sellafield [18], at LLWR request, for cases considering:

- the exposure rate and dose at distances of 1 cm and 1 m (100cm);
- from 1 and 15 litre containers with density range 1.4 to 2.0 g/cm^3;
- containing 1 MBq/litre of Ra-226 and of Th-232 with progeny in equilibrium.

Table 2 summarises results taking the mean of results for 1.4 and 2.0 g/cm^3, the effect of varying density in this range being rather small, about 10%.

Table 2: Exposure rates and effective dose at distances from 1 and 15 litre containers with 1 MBq/litre of Ra-226 and of Th-232 with daughters

See note [7]	Exposure rate, mR/h		Equivalent dose rate, µSv/h	
Ra-226	1 litre can	15 litre can	1 litre can	15 litre can
at 1 cm	5.91E+00	1.46E+01	63.7	157
at 100 cm	1.97E-02	2.02E-01	0.175	1.85
Th-232	1 litre can	15 litre can	1 litre can	15 litre can
at 1 cm	8.26E+00	2.06E+01	88.7	220
at 100 cm	2.75E-02	2.85E-01	0.255	2.61

It is useful to recognise that there are ratios between the Microshield results that are almost identical for Ra-226 and Th-232. That is for both radionuclides:

- the equivalent dose (H) at 1 cm from the 15 litre can is about 2.5x the H from the 1 litre can, at 100 cm the H from the 15 litre can is about 10x the H from the 1 litre can;
- the H at 100 cm from the 15 litre can is 0.012 of the H at 1 cm, the H at 100 cm from the 1 litre can is 0.0028 of the H at 1 cm.

In the ESC, because external dose calculations are required for a large number of radionuclides and geometric situations, a generic method of external dose calculation has

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[7] Exposure rate is deposited energy in air in Roentgen/hour. This is converted to deposited energy in tissue – absorbed dose – in Grays/hour taking account of a tissue factor 0.9, which because the quality factor for gamma emissions is unity is numerically equal to the equivalent dose in Sv/h. This is a dose in tissue at the given location. The memo by Cranke incorrectly refers to this as effective dose equivalent giving units of Sv/hour. See Appendix 3.

been devised [19]. This relies on a demonstration of a consistent ratio of dose rates close to a large (2 m radius) sphere and above a semi-infinite slab each containing unit concentrations of radionuclides, and the mathematical derivation of dose rates at different distances from spheres of smaller radii. The relation to the semi-infinite slab is useful because effective doses have been systematically and correctly worked out for this geometry taking account of source and receptor geometry and attenuation [20].

ESC external dose calculations can be compared with the above Microshield calculations. As a spot check, the ESC method was used to calculate the dose rate at 1 m from spheres of 10 and 20 cm radii containing total activity of 15 MBq of Ra-226 and of Th-232 with all daughters. These radii are chosen spanning the radius of a 15 litre sphere, which is 15.3 cm, also noting the Microshield calculations actually considered a cylinder of radius 12.6 cm and height 30 cm.

Table 3: Dose rate at 1 m from 15 litre container with 15 MBq calculated by the ESC method and Microshield

µSv/h	10 cm radius sphere	20 cm radius sphere	Microshield, as above
Ra-226	1.90	1.24	1.85
Th-232	2.73	1.77	2.61

Given the good agreement between the ESC method for the 10 cm radius sphere and the Microshield cylinder, it seems reasonable to combine the Microshield results and ESC method of equivalence to generate results for dose rates from other radionuclides. This involves:

- the effective dose rate for a semi-infinite slab for each radionuclide (with progeny as appropriate) at unit activity [20];
- scaling taking account of the ratios between Microshield results which are equivalent doses, see above and Appendix 3.

This method will work well for higher-energy gamma-emitting radionuclides, such as Cs-137 and Co-60, but less well for lower energy emitters such as Am-241 (low energy gamma) and Sr-90/Y-90 (bremsstralung from beta emission). Comparisons made within the derivation of factors for the ESC show, however, that the deviation is likely to be less than about 30% for the 15-litre container [19].

Hence, equivalent dose rates for all radionuclides of concern (with progeny in equilibrium) are calculated for a 15 litre container containing 15 MBq (1 MBq/litre) at disposal and after 300 years as given in Table 4.

The external dose rates for exposure to a semi-infinite slab are given as Sv/s per Bq/m^3 in the USEPA Federal Guidance Report No.13 [20], and also tabulated in the LLWR Radiological Handbook [21]. Values in Sv/h per Bq/kg, as in Table 4, are obtained by dividing by 3600 seconds/hour and a density of 1700 kg/m^3, which is appropriate for a grouted source container. Values are included for all nuclides and their progeny in equilibrium, including those for which the dose is zero or effectively zero, i.e. low energy beta emitters with no significant photon emissions.

Table 4: Equivalent dose (H) from 15 litre container with 15 MBq calculated via ratios method at time of disposal and after 300 years						
Radionuclide	Semi-infinite slab, Sv/h per Bq/kg	H for 1 MBq/litre at disposal, µSv/h		H for 1 MBq/litre at 300 years, µSv/h		Half life, years
		at 1cm	at 100cm	at 1cm	at 100cm	
C-14	3.61E-16	0.00	0.00	0.00	0.00	5700
Cl-36	8.14E-14	0.00	0.00	0.00	0.00	3.01E+05
Co-60	5.00E-04	224.00	2.65	0.00	0.00	5.267
Ni-63	0.00E+00	0.00	0.00	0.00	0.00	100
Sr-90	7.60E-07	0.34	0.00	0.00	0.00	29.12
Cs-137	1.05E-04	47.04	0.56	0.05	0.00	30
Ra-226	3.45E-04	154.64	1.83	135.80	1.61	1600
Th-232	4.98E-04	223.11	2.64	223.11	2.64	1.41E+10
Np-237	3.39E-05	15.19	0.18	15.19	0.18	2.14E+06
Pu-239	9.10E-09	0.00	0.00	0.00	0.00	2.41E+04
Am-241	1.35E-06	0.60	0.01	0.37	0.00	432.9

* Blue text highlights non-negligible values of equivalent dose at 300 years.

The results illustrate the impact of radioactive decay leaving Ra-226 and Th-232 as the most important nuclides, at 300 years, with Np-237 and Am-241 of secondary importance and a small remaining contribution from Cs-137.

Note these results are still equivalent doses, i.e. the dose in a small tissue sphere at the given locations. For higher energy photon emitters and at a distance of 1 m these will be a reasonable approximation for equivalent dose over the whole body and hence effective dose. At the closer distance, geometry effects become important (front to back reduction in dose) and, for higher energy photons, the given equivalent dose will overestimate the effective dose by a factor of about 2 [8]. For lower energy photons, attenuation in the body leads to an even greater front to back reduction in equivalent dose, and hence greater overestimate of effective dose.

5.3.2 For individual sources

Inspection of the consignment information (see Section 3.2) indicates that some items described as sealed sources are substantial items of up to several hundred grams, but for the most part the items are small and of only a few grams weight and it is cautious to treat such sources as point sources. If a small source is handled or placed in a pocket it may be in contact with the skin or almost so. With some movement during handling or transport, however, it is reasonable to consider the dose at a closest distance of 1 cm. This is

[8] Consider the human torso as an elliptical cylinder, 24 cm deep on the short axis, and the container as a line source 13 cm from the torso surface on the short axis (cf. the radius of the 15 litre container is 12.6 cm). Then without attenuation the dose equivalent at centre of the torso is 0.52 of that at the front surface; the dose equivalent at back surface of the torso is 0.35 of that at the front surface.

consistent with the source having a finite size, and also takes account of ICRP advice that the dose to skin should be averaged over an area of 1 cm^2.

The photon dose rate (air kerma values) at 1 m from a point source is given in ICRP Publication 107 [22] for all radionuclides. These do not include beta emissions, which would be significant for unshielded sources in close contact. Within the ESC project, Thorne has calculated dose due to beta emissions *in vacuo* for point sources at 1 m [23], and values of both photon and beta dose rates at 1m *in vacuo* are tabulated in the LLWR Radiological Handbook [21. Both photon and beta doses at 1 m can be converted to the dose at 1 cm by the inverse-square relation (factor of 10^4). Table 5 shows photon doses at 1 m for a point source, and photon and beta doses from a point source at 1 cm, including emissions from short-lived progeny in equilibrium. Values are given for a 1 MBq source, with no attenuation, at disposal and after 300 years. The values are absorbed doses in tissue, or equivalent doses since the quality factor for photons and beta particles is one.

Table 5: Equivalent dose rates from a 1MBq point source at the time of disposal and after 300 years

Radionuclide	Photon dose rate at 1 m, µGy/h	Equivalent dose at 1 cm from the point source, µGy/h				Half life, years
		at disposal		at 300 years		
		photon	beta	photon	beta	
C-14	0.00 E+00	0.00E+00	1.54E+05	0.00E+00	1.49E+05	5700
Cl-36	1.94 E-05	1.94E-01	1.84E+05	1.94E-01	1.84E+05	3.01E+05
Co-60	3.07 E-01	3.07E+03	2.27E+05	2.21E-14	1.64E-12	5.267
Ni-63	0.00 E+00	0.00E+00	6.30E+04	0.00E+00	7.88E+03	100
Sr-90	5.94 E-06	5.94E-02	3.71E+05	4.71E-05	2.94E+02	29.12
Cs-137	7.70 E-02	7.70E+02	2.30E+05	7.53E-01	2.25E+02	30
Ra-226	2.70 E-01	2.70E+03	7.37E+05	2.37E+03	6.47E+05	1600
Th-232	3.74 E-01	3.74E+03	8.11E+05	3.74E+03	8.11E+05	1.41E+10
Np-237	1.30 E-01	1.30E+03	3.60E+05	1.30E+03	3.60E+05	2.14E+06
Pu-239	4.00 E-03	4.00E+01	2.79E+04	3.96E+01	2.76E+04	2.41E+04
Am-241	3.53 E-02	3.53E+02	1.23E+05	2.18E+02	7.59E+04	432.9

* Blue text highlights non-negligible values of equivalent dose at 300 years.

The dose a 1 m from a point source (column 2) results for Ra-226 and Th-232 (0.27 and 0.37 µSv/h) are consistent with the Microshield case of a one litre can at 1 metre (0.18 and 0.26 µSv/h, see Table 2), the differences being related to self-shielding in the can and geometry.

If the source is unshielded or minimally shielded, e.g. a radionuclide electroplated onto a stainless steel disc, the beta dose will dominate. On the other hand, any type of shielding, e.g. self-shielding in a pellet or casing, will rapidly attenuate the beta dose, so that the photon doses will dominate. The importance of radioactive decay is also apparent.

5.4 Dose calculations

5.4.1 For source containers

For a source container, we postulate the finding of a 15 litre container on the beach that has broken out of any surrounding ISO grout, probably degraded (corroded) but still intact; the container weighs about 25 to 30 kg.

Considering the case of idle curiosity for what is a relatively unattractive item we will assume close contact (at 1 cm), as in handling the container or carrying it a short distance the better to inspect it, for a relatively short time, say 2 minutes. The inspecting individual might also be in proximity to the item (at 1 m), e.g. while resting or inspecting other items, for a maximum of about an hour.

(a) Reference container

For the reference container activity of 1 MBq/litre (total 15 MBq of stated nuclide with progeny in equilibrium), taking equivalent dose at 1 m to approximate to effective dose at 1 m and taking equivalent dose at 1 cm to approximate to twice effective dose (see footnote [8]), this yields effective doses for the event as shown in Table 6. For the given choice of exposure times, the dose due to the 2 minutes at 1 cm provides about 60% of the total dose for each radionuclide.

Table 6: Effective doses from inspection of a 15 MBq container

Radionuclide	Effective doses for the event, µSv			
	2 min at 1 cm	1 hour at 1 m	Sum	Sum at 300 y
C-14	0.00	0.00	0.00	0.000
Cl-36	0.00	0.00	0.00	0.000
Co-60	3.73	2.65	6.38	0.000
Ni-63	0.00	0.00	0.00	0.000
Sr-90	0.01	0.00	0.01	0.000
Cs-137	0.78	0.56	1.34	0.001
Ra-226	2.58	1.83	4.41	3.870
Th-232	3.72	2.64	6.36	6.358
Np-237	0.25	0.18	0.43	0.433
Pu-239	0.00	0.00	0.00	0.000
Am-241	0.01	0.01	0.02	0.011

(b) Maximally loaded containers

To comply with the definition of LLW and also §L2.2 of the WAC [12] and the maximum allowed specific activity is (i) 4 GBq/t alpha-emitting nuclides and (ii) 12 GBq/t not included in (i). It is also stated in §L2.2 that "*in accounting for radioactivity against these limits, the activity of short half-life decay products with half lives of less than three months shall not be accounted if they are present in amounts not exceeding those which could be present through decay of accounted nuclides.*"

Hence, the maximum activity content of a container of weight 25 kg that is treated as a single consignment or waste stream is 100 MBq alpha-emitting nuclides and 300 MBq other.

Sr-90, Cs-137 and Np-237 all have very short-lived daughters and are treated as single nuclides. C-14, Cl-36, Co-60, Pu-239 and Am-241 all decay to stable nuclides or much longer-lived nuclides so that they are also treated as single radionuclides. The positions of Ra-226 and Th-232 are anomalous.

- Ra-226 presents 5 alpha emissions in its decay to Pb-206, but the only daughters with half lives greater than three months are Pb-210 (22.3 y, beta decay) and Po-210 (138 days, alpha decay).

- Th-232 presents 6 alpha emissions in its decay to Pb-208, but the only daughters with half lives greater than three months are Ra-228 (5.75 y, beta decay) and Th-228 (1.91 y, alpha decay).

Inspection of the activity summations for sealed source consignments indicates that in practice the presence of ingrown Pb-210 from Ra-226 and ingrown Ra-228 from Th-232 are neglected so that effectively Ra-226 and Th-232 are both counted as single radionuclides in assessing total activity under the conditions for disposal.

This would imply that under the current conditions a 25 kg container could contain 100 MBq of either Ra-226 or Th-232, i.e. 100 individual sources of 1 MBq each. In practice, this will not occur because such large numbers of Ra-226 or Th-232 sources are not encountered. It is more reasonable to assess for a more credible container activity of 15 MBq, i.e. 15 sources of 1 MBq in a single container.

For radionuclides Co-60, Sr-90, Cs-137, Pu-239 and Am-241, much larger numbers of sources arise (see Table 1), although rather few approach the 1 MBq limit. As noted above a 15 litre (25 kg) container at LLW limits could contain 100 MBq alpha and 300 MBq other sources. Also, since the condition is a maximum of 100 mls of grout per source, and neglecting the volume of the sources, a filled 15 litre container must contain at least 150 sources although it could contain many more.

Hence, we could consider a maximally loaded container as one including 100 MBq each of Co-60, Sr-90 and Cs-137, and 50 MBq each of Pu-239 and Am-241. In practice, because most sources are much smaller than 1 MBq and probably no more than about 300 sources could be loaded in a 15 litre container while still allowing a sensible amount of grout to be added, a more reasonable content of 30 MBq each of Co-60, Sr-90 and Cs-137, and 15 MBq each of Pu-239 and Am-241 can be considered. The presence of C-14, Cl-36 and Ni-63 sources are of no consequence due to lack of photon emissions and lower beta energies (no bremsstrahlung).

Calculated doses for each of these cases are presented in Table 7. Effective doses are presented for time of disposal and for 300 years after disposal, although only the latter are relevant to the assessment under the ESC.

Table 7: Effective doses for inspection and proximity to a 15 litre source container			
Case	Content	Effective doses for the event, µSv	
		at time of disposal	at 300 years
Maximally loaded container meeting the definition of LLW	100 MBq Ra-226	29	26
	100 MBq Th-232	42	42
Reasonable maximum loaded container in practice	15 MBq Ra-226	4.4	3.9
	15 MBq Th-232	6.4	6.4
Maximally loaded container meeting the definition of LLW	100 MBq alpha 300 MBq other see *	51.6	0.045
Reasonable maximum loaded container in practice	30 MBq alpha 90 MBq other see **	15.5 82% Co-60, 17% Cs-137	0.013 20% Cs-137, 79% Am-241

* 100 MBq each of Co-60, Sr-90 and Cs-137, plus 50 MBq each of Pu-239 and Am-241.
** 30 MBq each of Co-60, Sr-90 and Cs-137, plus 15 MBq each of Pu-239 and Am-241.

(c) Assessment against the risk guidance level risk

Assessing against the risk guidance level risk but assuming an event probability of unity, see Section 5.2.2, the risk guidance level is equivalent to an annual effective dose of 20 µSv. Thus, only the Ra-226 or Th-232 'maximally loaded containers' pose a risk exceeding the guidance level. In practice, such containers have not arisen.

For the event considered, the Ra-226 or Th-232 'reasonable maximum loaded containers' pose a risk below the guidance level. The mixed nuclear [9] alpha and fission product containers, whether maximally loaded or reasonable maximum loaded, both pose risks that are small fractions of the risk guidance level by virtue of radioactive decay at 300 years.

It is interesting that examination of the reasonable maximum loaded mixed nuclear container presents a risk close to, but below, the guidance level even at the time of disposal. This provides robust assurance that such containers are unlikely to pose any significant risk in the longer term. This would be true for encountering a single container or multiple containers, as might occur if more than container was placed in a single HHISO.

Cases can be postulated involving more prolonged examination of a source container, and hence a higher dose per event. It is hard to see, however, what the motive for more prolonged examination would be, unless the individual had specific knowledge. For example an individual equipped with a hand-held radiation monitor who was specifically looking for higher activity items. In this case, the event becomes an informed or partially informed act and we do not consider that the risk guidance level should apply. We believe that the risk guidance level is appropriate to acts that are more or less random and taken without knowledge, as in the case of the individual who walks along the beach oblivious to the

[9] That is containing radionuclides typically from the nuclear fuel cycle, not naturally occurring radionuclides, such as a Ra-226 and Th-232.

presence of radioactivity waste or nature of the eroding waste, and ‘happens’ to come across an item.

5.4.2 For individual sources

For individual sources, we postulate a case of finding on the beach of a single 1 MBq source that has broken out the source container and grout. This may be placed in a pocket as an unknown item and later examined and or left in a draw or around the home.

We assume close contact (at 1 cm), as in handling the source or carrying it in a pocket, for say 1 hour. The beta dose received will depend on source construction and orientation of the source, and will be attenuated, even by relatively light fabric or similar. Hence, we suggest a reduction factor of between 0.5 (could just be related to orientation) to 0.1 (allowing some attenuation of beta emissions between the source and exposed tissue) and a reference value of 0.2. For attenuation factors in this range the tissue dose received will still be dominated by beta emissions if present, see Table 5.

Left in a relatively frequently used room in a home, we might imagine exposure by proximity to the source (assumed to be at 1 m) for maximum of 25% of the time, i.e. 6 hours per day. This will be photon emissions only, with beta emissions being absorbed in air or any intervening materials.

(a) Close contact (tissue dose)

Estimated maximum tissue (skin) doses for close contact with a 1 MBq source for one hour as described above are given in Table 8. The appropriate value to assess against is the ICRP equivalent dose limit of 50 mSv for public exposure, which relates to the prevention of deterministic effects, see Section 5.2.2.

Table 8: Equivalent tissue doses for close contact with a 1 MBq source for 1 hour

Radionuclide	Tissue dose at time of disposal, mSv			At 300y, mSv
	Photon	Beta x 0.2	Photon + beta	Photon + beta
C-14	0.00E+00	3.08E+01	31	30
Cl-36	1.94E-04	3.69E+01	37	37
Co-60	3.07E+00	4.54E+01	49	0.000
Ni-63	0.00E+00	1.26E+01	13	1.6
Sr-90	5.94E-05	7.42E+01	74	0.058
Cs-137	7.70E-01	4.60E+01	47	0.046
Ra-226	2.70E+00	1.47E+02	150	132
Th-232	3.74E+00	1.62E+02	166	166
Np-237	1.30E+00	7.20E+01	73	73
Pu-239	4.00E-02	5.57E+00	5.6	5.6
Am-241	3.53E-01	2.46E+01	25	15

Assessed in this way, and assuming one hour in close contact with the same skin area, it can be seen that the calculated doses (photon + beta) for 1 MBq at the time of disposal of most single beta emitters (C-14, Cl-36, Co-60, Cs-137, Sr-90) lie around the 50 mSv limit.

At 300 years, the calculated doses for the shorter-lived nuclides (Co-60, Cs-137, Sr-90) fall to trivial levels.

For nuclides with progeny and thus multiple beta emissions (Ra-226 and Th-232) doses are above the 50 mSv limit. Typically, however, Ra-226 and Th-232 sources consist of metal needles or resin beads that would substantially attenuate beta emissions, and if the sources are surface sources then the progeny would be largely absent due to loss of radon and subsequent progeny from the sources. The assessed photon doses from the 1 MBq Ra-226 and Th-232 sources are about 5% and 7% the 50 mSv limit.

In general, the actual tissue (localised skin) doses that might be received from handling a source as it might be found on the beach are rather difficult to estimate. If the source is a sealed source, such as resin bead, the beta dose will be substantially attenuated. If the source is a surface source, then it is likely that a large fraction of the original radionuclide activity will have been leached, corroded or abraded away and no longer present. Finally, one hour in close contact with the same area of skin indicates either an adhering particle or a source deliberately placed in a pocket. Hence, the dose values calculated in Table 8 should be regarded as very cautious and probably overestimate doses that might occur by a substantial margin. Considering these factors, we judge that the values given in Table 8 are liable to overestimate actual doses for a handling event by about an order of magnitude.

(b) Prolonged proximity (effective dose)

Estimated annual effective doses for prolonged proximity to a 1 MBq source for 6 hours a day as described above are given in Table 9. The appropriate value to assess against is an annual effective dose of 20 µSv, which corresponds to the GRA risk guidance level for an annual probability of unity.

Table 9: Annual effective doses for prolonged proximity with a 1 MBq source (6 h/day)

Radionuclide	Annual effective dose, µSv	
	At time of disposal	At 300 y
C-14	0.000	0.000
Cl-36	0.002	0.002
Co-60	28	0.000
Ni-63	0.000	0.000
Sr-90	0.0005	0.000
Cs-137	7.0	0.007
Ra-226	25	22
Th-232	34	34
Np-237	12	12
Pu-239	0.36	0.36
Am-241	3.2	2.0

Assessed in this way, it can be seen that the calculated effective doses for 1 MBq at the time of disposal of Co-60, Cs-137, Ra-226, Th-232 and Np-237 fall in the range 10 to 30 µSv. At 300 years, the calculated doses fall to trivial levels except for Ra-226, Th-232 and Np-237. The calculated effective doses are due only to photon emissions, so the form of the source is not so important. In the case of Ra-226 and Th-232, it relies on all daughters (i.e. radon and thoron) being contained within the source, but such sources are generally constructed in such a way that this would be the case.

(c) Finding multiple individual sources

The case of an individual finding and taking away several individual sources can also be considered.

If sources are found on the same occasion and placed in the same pocket, in the case of sources such as surface-plated/coated discs, only the beta dose from one of the sources could be received, the beta dose from others being shielded. If collected on separate occasions then it is unlikely that the sources would be placed such as to irradiate exactly the same small area of skin.

Multiple sources could be accumulated in the home and, in this case, the calculated effective doses due to gamma irradiation as in Table 9 would be additive. On the other hand, the systematic collecting of sources indicates some knowledge or special interest, similar to the case discussed at the end of Section 5.4.1. We would argue that collection of multiple sources is an informed or partially informed act, so that the risk guidance level should not apply.

(d) Assessment against the tissue dose limit and risk guidance level risk

As remarked in Section (a) above, the actual tissue (localised skin) doses that might be received from handling a source as it might be found on the beach are rather difficult to estimate and depend on the form of the source, its condition at the time of finding and the duration of close contact time. The dose values calculated in Table 8 should be regarded as very cautious and probably overestimate doses for a handling event, especially the contribution from beta emissions, by about an order of magnitude.

It can be added that, once any extraneous packaging is removed, the sources are generally very small and liable to be quickly lost, either dropping between beach cobbles or buried in the foreshore sand. Hence, the probability that a beach user will actually encounter and handle such an item is very low.

These factors included, we consider that the 1 MBq limit is protective against the chance finding of an individual source (or sources) of any radionuclide. For some radionuclides, a higher limit could be allowed.

5.5 Summary of the assessment

(a) Limiting cases

As discussed in Sections 5.1 and 5.2.1, we consider that the limiting assessment cases:

- will occur after the facility has been impacted by coastal erosion, source containers have been distributed with other waste on the beach and may be broken open by wave action on the cobble storm beach;
- involve a beach user, e.g. walker or beachcomber, either interacting with a single source container or finding and taking away one or a small number of individual sources.

The earliest time that we consider for coastal erosion of the LLWR is 300 years after present and we cautiously assume source containers and individual sources may be present on the beach or foreshore at that time. Key radionuclides are liable to be Ra-226 and Th-232 because of their long half-lives and photon emission of their short-lived progeny.

The individual at greatest risk as a result of radiation exposure local to the erosion of the LLWR, as assessed in [2], is a recreational beach user spending 300 hours per year on the local beach and foreshore, e.g. a dog walker or beachcomber who traverses the area of beach and foreshore beneath the eroding repository twice a day on 300 days per year. The annual dose and risk to this individual includes the dose/risk due to the presence of source containers and individual sources on the beach/foreshore, since these are included in the total activity of eroding waste.

(b) Inspection of a source container

The probability that such an individual will actually encounter and take time to inspect a source container or source is less than one per year, but difficult to estimate. Cautiously, therefore, we assess the case that the individual at greatest risk is an individual that actually encounters and inspects a source container or a source. That is we assign a probability of one to the event, although noting that the risk will not be sustained, i.e. the same individual is very unlikely to also encounter and inspect a source container in subsequent years, since the number of such containers is low.

Even assessed in this cautious fashion, we calculate effective doses (see Table 7) from inspecting source containers loaded at a 'reasonable maximum' level taking account of actual numbers and activity of sources arising (see Sections 3.2 and 3.3), are of the order:

- 4 to 6 µSv for a container loaded with Ra-226 or Th-232 sources [10], and
- 0.01 µSv for a container loaded with mixed nuclear sources [11].

These values may be compared with an annual effective dose of 20 µSv that corresponds to the risk guidance level of 10^{-6} per year.

(c) Inspection/keeping of individual sources

For individual sources, we assess the case of finding on the beach of a single 1 MBq source that has broken out the source container and grout. This may be put in a pocket and taken home. This is a low probability event since the sources are generally very small and are liable to fall between the cobbles of the storm beach or become buried in the sand of the foreshore.

The limiting concern is localised equivalent dose to skin that might be received from handling a source or placing it in a pocket. Such doses are difficult to estimate and depend on the form of the source, its condition at the time of finding and the duration of close contact time. The equivalent dose values calculated in Table 8 should be regarded as probably overestimating doses for a typical handling event by about an order of magnitude.

On this basis, the localised skin dose from handling and pocketing a 1 MBq disposed source at 300 years after disposal are in the range zero to a few mSv depending on the radionuclide, form of the source (e.g. contained source or surface source), and its condition.

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10 15 MBq of Ra-226 or 15 MBq of Th-232.

11 30 MBq each of Co-60, Sr-90 and Cs-137, plus 15 MBq each of Pu-239 and Am-241.

This estimate may be compared with the ICRP recommended annual limit for equivalent dose to skin of 50 mSv for public exposure, which relates to the prevention of deterministic effects.

Annual effective doses due to taking home and prolonged exposure to a low-activity (1 MBq at disposal) source kept in the home are trivial for most radionuclides but potentially significant (in the range 10 to 30 µSv) for Ra-226, Th-232 and Np-237 sources.

These values may be compared with an annual effective dose of 20 µSv that corresponds to the risk guidance level of 10^{-6} per year; the low probability of the event and cautious exposure conditions (6 h/day at 1m distance) should also be considered.

(d) Conclusion

There are issues over probability of events, source form/conditions and exposure conditions and duration that are difficult to quantify. Nevertheless, assessing on the cautious basis that source containers and individual sources will be found, inspected and, in the case of individual sources taken away, effective doses are calculated that are consistent with an the GRA risk guidance level of 10^{-6} per year. Equivalent doses to skin are calculated that are consistent with the ICRP recommended annual limit for equivalent dose to skin of 50 mSv for public exposure.

We conclude that the conditions for acceptance and disposal of low-activity sources, as agreed with the EA in 2005, are highly protective in the case of sources from nuclear cycle operations and are protective in practice in the case of disposals of Ra-226 and Th-232 sources.

6 Proposed conditions for future acceptance of low-activity sources

6.1 Approach and radionuclide grouping

The assessments detailed in Section 5 shows that the current conditions for acceptance of low-activity sources, as set out in Section 2.2, provide a high level of protection.

The assessments are cautious in that impacts are assessed for cases in which source containers and sources will actually be found and inspected, and this is by no means certain. We consider that the assumed exposure conditions and duration are also cautiously defined, but acknowledge this is a subjective judgment, and that the actual exposure conditions and duration if a source container or source were found and inspected could be different. We also note that the form and condition of individual sources will have a significant influence on the potential for exposure, especially for beta sources and localised equivalent dose to skin.

Considering these uncertainties, we do not think that it is appropriate to derive limits on disposal of low-activity sources for individual radionuclides. Rather, we prefer to define groups of radionuclide groups such that, within each group, sources of a given activity offer a hazard of a similar order of magnitude, considering across the cases assessed in Section 5. This will also make the conditions for acceptance of low-activity sources clearer and easier to follow for consigners.

6.1.1 Limits on individual source activity

The first control on radiological hazard is the limitation on the maximum activity of individual source that can be accepted. The assessments in Section 5 indicate that while the I MBq limit is appropriate for long-lived radionuclides that present significant photon emissions, the limit could be much higher for alpha or beta only sources, and for shorter-lived radionuclides. Based on examination of the assessment results we propose the following groupings.

Table 10: Radionuclide groups for low activity sources

	Characteristics	Examples	Limit
Group A	Long-lived radionuclides that emit, or decay to short-lived progeny that emit, significant photon emissions	Ra-226, Th-232, Np-237	1 MBq
Group B1	Long-lived radionuclides that do not emit, or decay to short-lived progeny that emit, significant photon emissions	C-14, Cl-36, Pu-239, Am-241	10 MBq
Group B2	Radionuclides with half-life less than about 100 years that emit, or decay to short-lived progeny that emit, significant photon emissions or bremsstralung	Sr-90, Cs-137	10 MBq
Group C1	Radionuclides with half-life less than about 100 years that do not emit, or decay to short-lived progeny that emit, significant photon emissions or bremsstralung	Ni-63	100 MBq
Group C2	Any radionuclides with half-life less than about 10 years	Co-60	100 MBq

This grouping takes account that the hazards of concern are:

- effective dose due to handling and/or proximity to a source container on the beach/foreshore (or similar situation);
- effective dose due to prolonged proximity to an individual source taken away from the beach/foreshore (or similar situation);
- equivalent dose to localised area of skin due to handling, or pocketing of an individual source (or similar situation).

It also takes account that a single radionuclide decays to 0.1 of its initial activity in 3.3 half-lives. So, for example, in 100 years, 10 MBq of Sr-90 or Cs-137 ($T_{0.5}$ ~ 30 years) decays to about 1 MBq, and 100 Bq of Co-60 ($T_{0.5}$ ~ 5.27 years) decays to about 0.0002 MBq.

If worked out strictly, according to the cases set out in Section 5, much higher activity limits could be derived, especially for shorter-lived radionuclides. This, however, might place undue emphasis on the definition of cases that we acknowledge contain a degree of subjectivity. On the other hand, the relaxation by factors of ten and one hundred relative to Ra-226 and Th-232 is clearly cautious based on radionuclide characteristics alone.

Relaxation of the 1 MBq limit will imply the possibility of source containers above the definition of LLW, so that meeting of LLW limits would have to be shown at the consignment level. This can be justified because it allows safe disposal of redundant sources that would otherwise not be promptly disposed.

6.1.2 Limits on source container activity

The second control on radiological hazard is the limitation on the maximum activity of that can be contained in a source container.

We propose to amend the condition of "*a maximum of 100 mls of grout per source*" to "*with sufficient grout … to provide reasonable containment of each source*"; we consider that about 100 mls of grout per source will generally be sufficient. This, firstly, provides sufficient grout to offer some primary shielding and a mixing medium for the sources, and, secondly, gives some latitude that allows a sensible size range of containers to be used to contain any number of sources. For example, allowing 50 to 200 mls per source:

- a one litre container could contain 5 to 20 sources;
- a five litre container could contain 25 to 100 sources; and
- a fifteen litre container could contain 75 to 300 sources.

The simplest way to then control source container activity is via activity per unit volume, taking account of the assessed results for the 15 litre container (as given in Table 7), which is cautious, plus the radionuclide grouping scheme indicated in Table 10. Based on Table 7, we judge an activity of 5 MBq/litre of Ra-226 is acceptable. (Note that at a density of 1.7 kg/litre this corresponds to 2.9 GBq/t, i.e. within the definition of LLW for alpha nuclides.) Based on Th-232 a lower limit of 3 MBq/litre might be inferred, but whereas Ra-226 source are common, Th-232 sources are very uncommon, and the value of 5 MBq/litre will be cautious for other long-lived photon emitters such as Np-237.

Then by applying the group scheme in Table 10, we judge that the total activity of a source container should be constrained such that:

$$[Q_A + Q_B/10 + Q_C/100] / V \leq 5 \text{ equivalent MBq/litre}$$

where Q_A, Q_B and Q_C are the activities of radionuclides of Groups A, B and C respectively, and V is the volume of the container.

Under this formulation the "*maximally loaded container meeting the definition of LLW*" considered in Table 7 that contains 100 MBq each of Co-60, Sr-90 and Cs-137, plus 50 MBq each of Pu-239 and Am-241 'scores' as an equivalent of

$$[0 + 300/10 + 100/100] / 15 = 2.1 \text{ equivalent MBq/litre}$$

and is accepted. The caution built into the scheme is shown by the value of 0.045 µSv calculated for inspection and proximity of this container in Table 7.

6.2 Proposed conditions for acceptance of low-activity sources

We propose conditions for acceptance of low-activity sources at the LLWR should be as set out in the Table 11, which also explains the rationale for each condition.

Based on our assessments, we do not see the need for the condition of only one source container per ISO-freight disposal (condition 6 in Section 2.2), i.e. allowing more than one source container per consignment.

The limitations of individual source activity and total activity of a source container will allow source containers with specific activity above the definition of LLW, especially if containing larger sources with half-life less than 10 years, and consistency with the definition of LLW must be shown at the consignment level. For example: the theoretical maximum activity of a container with Group B radionuclides only is about 50 / 1.7 = 30 MBq/kg (= GBq/t); the theoretical maximum activity of a container with Group C radionuclides only is about 500 / 1.7 = 300 MBq/kg (= GBq/t).

For Ra-226 and Th-232 sources, the proposed new total activity of a source container requirement is marginally stricter than implied by limiting to the definition of LLW. For example, for the 15 litre (~25 kg) container considered in Table 7, the maximum allowed according to the definition of LLW is 100 MBq (4 GBq/t). The proposed new total activity limit is 5 MBq/l or 75 MBq in a 15 litre container.

We consider that the proposed modified conditions should be adopted since they provide flexibility to dispose of higher activity sources than under the existing conditions, and hence avoid the accumulation of such sources, while still providing a high level of long-term radiological protection.

Table 12 provides a more complete listing of example radionuclides that occur as sources under each group.

Table 11: Proposed conditions for acceptance of low-activity sources		
	Condition	Rationale
1.	The activity of any individual source shall not be greater than 1 MBq for Group A, 10 MBq for Group B and 100 MBq for Group C radionuclides.	To limit the hazard from individual sources, see Section 6.1.1.
2.	As much extraneous packaging as practical must be removed, and sources that might be potentially attractive should, as far as reasonably practicable, be disfigured.	To make sources unattractive and eliminate buoyancy.
3.	The sources shall be mixed with sufficient grout [12], in a clean paint-tin-type container, in order to provide reasonable containment of each source. The container should be 'topped up' to full with grout so as to minimise any air space or void within the container and the tin closed tight.	Provides limited shielding (for beta emissions) and primary containment of the sources. Topping up prevents buoyancy and crushing of the container.
4.	The total activity of a source container should be constrained such that: $[\ Q_A + Q_B/10 + Q_C/100\ ] / V$ < or = 5 MBq/l where Q_A, Q_B and Q_C are the activities of radionuclides of Groups A, B and C respectively, and V is the volume of the container.	To limit the hazard from source containers, see Section 6.1.2.
5.	A specific waste stream characterisation is required for each container disposal detailing the normal required information as well as source registration references (if available), number of discrete sources in container, radionuclide(s) and activity of each source, and total activity of each radionuclide at the time of consignment for disposal.	Assurance of consistency with conditions 1, 3 and 4 and record keeping.

Table 12: Radionuclide groups for low activity sources – example radionuclides		
Group A	Ag-108m, Ra-226, Th-232, Np-237, Cm-247/248	1 MBq
Group B1	C-14, Cl-36, Ca-41, Ni-59, Tc-99, I-129, Cs-135, Th-230, U-234/235/238, Pu-239/240, Am-241	10 MBq
Group B2	Sr-90, Cs-137, Eu-152, Pu-238/241	10 MBq
Group C1	Ni-63, Nb-93m, Pb-210	100 MBq
Group C2	Na-22, Mn-54, Fe-55, Co-57, Co-60, Ru-106, Ag-110m, I-125, Ba-133, Cs-134, Ra-228, Th-228	100 MBq

[12] About 100 mls of cement grout per source is generally a sufficient amount, see Section 6.1.2.

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Appendix 1: Source consignment information

Detailed information – listings of number, form and activity of sources, plus total activities disposed – was provided by Consigner Support for consignments identified by D5 declarations as listed in Table A1.

Table A1: Consignments of sources to the LLWR, 2001 to date

Identifier	From	Document reference and comments *
Prior to October 2005		
2x65/1	Sellafield	THORP EH&S Technical Report 2001/05 ? Consisting of 4 "*pots*", transferred to Drigg skip no. 2921/0079, 7/3/01. Each pot weight (nominally?) 0.1175 te; skip weight 4.7 te. 867 sources, 9.4 GBq total activity, sources > 1 MBq
2x65/2	Sellafield	THORP EH&S Technical Report 2002/03 Weight 117.1 kg 213 sources, 0.38 GBq total activity, sources > 1 MBq
2x65/3	Sellafield	SEIG/02/3567, dated August 2002 179 sources, 4.85 MBq total activity, 1 source ~ 1 MBq
2x65/4	Sellafield	SEIG/04/3819, dated February 2004 About 70 sources, all < 0.1 MBq
03H1B WS084	Hinkley Point B	HINB/R/TET/766, December 2003 5 litre metal paint tin, 18 sources, all < 0.1 MBq
After October 2005		
2x65/6	Sellafield	SEIG/05/4088, dated January 2006 Weight not given but total number of sources and activities look consistent with October 2005 conditions. About 70 sources, all < 0.1 MBq
2x65/7	Sellafield	WASTE/C&C/FORM 010, dated 10/06 31 sources, all < 0.1 MBq
2x65/8	Sellafield	C&C Ref: CC.2x65-08.05.01, May 2008 46 sources, 0.88 MBq total activity, all < 1 MBq
03HAR WS132	Harwell	HAR/TH/R/016/284, August 2007 103 sources, all < 1 MBq
01BNL	Berkeley NL	P0001-10246, September 2008 Identified as "*at BNLS*", i.e. not at that time consigned? About 270 sources, ca. 167 at ~ 1 MBq
Undated		
07UOB	Nuffield Cyclotron University of Birmingham	Only one consignment has been made under 7UOB. The description, total mass and activities declared on the D4 corresponds to a table of activated metal parts (of the order kg to tonne weights) with only short-lived radionuclides present. The other listings provided, headed 'closed sources' appears not to have been consigned to LLWR.

* All activities refer to "*decay corrected activities*".

Consigner Support also provided detailed information on consignments by Inutec from Winfrith not identified by D5 declarations, See Table A2.

Table A2: Consignment of sources by Inutec from Winfrith, 2002 to 2009				
Date	HISO/TISO ref	No. containers	No. sources	Predominant radionuclides and total activity, MBq, and (number of sources)
04/02/02	2910/2131	1	5	Ra-226 – 0.6 (5)
24/04/03	2910/3469	1	1	Ra-226 – 0.2 (1)
10/03/04	2910/3572	1	13	Ra-226 – 2.0 (11)
26/05/04	2910/3573	2	7	Ra-226 – 1.2 (7)
14/12/04	2910/4035	4	233	Co-60 – 4.8 (17) Sr-90 – 10.6 (23) Cs-137 – 3.9 (18) Ra-226 – 21.7 (152) Am-241 – 1.5 (16) Th – 0.4 (4)
22/03/05	2910/3980	2	27	Cl-36 – 0.5 (2) Ra-226 – 3.9 (13)
Post September 2005				
26/10/05	2910/3996	3	72	Co-60 – 1.5 (10) Sr-90 – 2.3 (16) Ra-226 – 4.4 (18) Am-241 – 0.4 (9)
14/12/05	2910/4799	1	18	Ra-226 – 3.9 (13)
29/06/06	2910/4993	5	136	Co-60 – 1.2 (11) Sr-90 – 2.8 (18) Cs-137 – 1.2 (8) Ra-226 – 23.6 (69) Am-241 – 1.5 (14) HEU – 0.7 (1)
19/12/06	2910/5600	2	12	Ra-226 – 1.6 (10)
31/01/08	2910/0438 ?	2	31	Ra-226 – 6.8 (22) U – 0.6 (1) Th – 0.6 (2)
29/06/09	2910/0500	1	5	Sr-90 – 3.0 (4) Ra-226 – 0.5 (1)

* Blue text highlights the two cases of highest activity and number of Ra-226 sources disposed.

Appendix 2: Probabilities related to assessing risk from low-activity sources

Various arguments and probabilities can be considered in assessing the radiological risks related to finding and handling a source container or individual sources on the beach/foreshore. These are summarised and commented on below.

Arguments and probabilities related to assessing risk from low-activity sources		
	Mitigating argument or probability (P)	Comment on probability (P)
Encounters with source containers	P that a source container is present on the beach in a given year.	P<1? Could be calculated based on number of source containers in vaults, erosion rate and residence times on beach.
	P that in a year a beach user (e.g. a dog walker or beach comber) encounters such a container.	Being less dense than the beach cobbles, containers will tend to sit on the beach surface, e.g. at the tide line. Hence, P might be near 1 over a year of beach visits if a container is present.
	P that the beach user stops to inspect such container.	P<<1 for dog walker? But higher for beachcomber. Difficult to justify P. The EA may consider the appropriate exposed group are those that actually inspect a container (homogeneity of dose criterion).
	P that the beach user 'takes home' such container.	A higher dose case than simple inspection, but can argue P<<1 based on lack of any obvious attraction.
Encounters with individual sources	P that individual sealed sources are present on the beach in a given year.	As for source container. Sources may persist longer on the beach but tend to be buried. Large numbers may be present but only relatively few with significant activity.
	P that a beach user encounters (sees) one or more sources.	The sources themselves are generally small dense objects that will tend fall between the beach cobbles or be buried in sand, so conceivably P<<1 but difficult to quantify.
	P that the beach user who encounters (sees) a source picks up or inspects the source.	P<1 for dog walker but P=~1 for beachcomber.
	P that the beach user 'takes home' one or more sources.	A higher dose case than simple inspection. P<1 but difficult to quantify.

Appendix 3: Dose terms

Absorbed dose

Absorbed dose is a measure of the energy deposited in a medium by ionising radiation. It is equal to the energy deposited per unit mass of medium, and so has the unit J/kg, which is given the special name gray (Gy).

Equivalent dose (H)

Equivalent dose (H) is a measure of the radiation dose to tissue taking account of the different relative biological effects of different types of ionizing radiation.

Equivalent dose (H) is calculated by multiplying the average absorbed dose to the organ or tissue by the radiation weighting factor. The weighting factor is 1 for x-rays, gamma rays and beta particles, but higher for protons, neutrons, alpha particles etc.

The unit for equivalent dose is the sievert (Sv).

Effective dose (E)

Effective dose (formerly called effective dose equivalent) is used to assess radiation doses summed over different body tissues taking account of the relative radio-sensitivity of those tissues. The effective dose (E) to an individual is found by calculating a weighted average of the equivalent dose (H) to different body tissues, with the weighting factors (W) specified to reflect the different radiosensitivities of the tissues:

$E = \sum_i H_i W_i$

The unit for effective dose is the sievert (Sv), i.e. the same unit as equivalent dose.