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LITTLE FOREST LEGACY SITE - TECHNICAL REPORT

Dose rate estimates to humans and wildlife for a range of potential future scenarios

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Mathew P. Johansen, Timothy E. Payne, M. Josick Comarmond, Jennifer J. Harrison, Robert Blackley and Alamgir Kabir

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Purpose

The objective of this report is to describe the human and wildlife dose-modelling used to compare various potential management options for the Little Forest Legacy Site (LFLS).

Scope

This work aligns with international standards and guidance which are primarily set forth in a series of documents published by the International Atomic Energy Agency (IAEA), Vienna (IAEA, 2011, 2012, 2014). The process envisioned by the IAEA was developed primarily for planned disposal facilities, but is also applicable to existing sites such as the LFLS:

> • SSG-23 (P.90, 6.86) "The approach to support the decision-making process . . . is also directly applicable to existing facilities (IAEA, 2011, 2012, 2014)."

The IAEA documents address a scope that includes the Safety Case and Safety Assessment. This report focuses specifically on a human dose assessment for the post-closure period (assumed 100-year Institutional Control Period and through to 1000 years into the future).

The dose work compares modelled radiological dose rates to hypothetical human receptors under a range of future management options and conditions at the LFLS. Five types of management options and multiple receptor types were evaluated. The approach used here is site-specific as it uses measurements of site samples, data from site documents, local meteorological and hydrological data as well as local site configuration and layout.

The document also includes a wildlife dose assessment consistent with international best practice and, for Australia, the Radiation Protection of the Environment Guide (ARPANSA, 2015).

The model results reported here address many different scenarios which, while not covering every possibility, are intended to provide a sufficient range of useful input data into selection of a sound management plan for the future of the LFLS. Following selection of an option a more detailed dose assessment should be performed to optimise the design.

This dose assessment was conducted within, and relies on data from, a multi-year project that assessed the waste characteristics and environmental setting of the LFLS as described in a series of reports and papers (Cendón et al., 2015; Hankin, 2013; Hughes et al., 2011; Ikeda-Ohno et al., 2014; Johansen et al., 2012a; Payne, 2012, 2015; Payne et al., 2013; Payne et al., 2015).

Contents

1. Summary

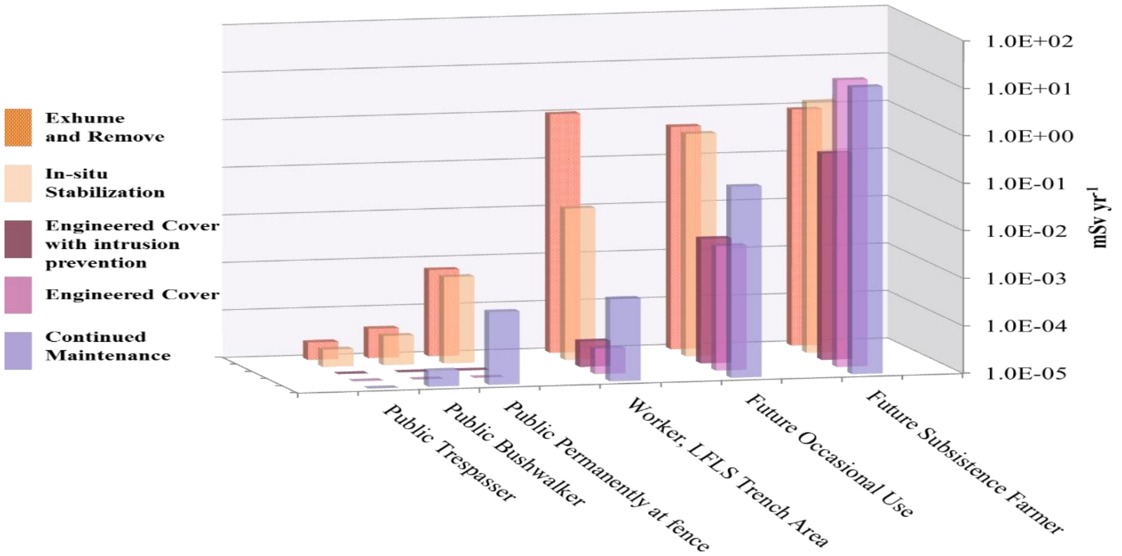
Potential radiological dose rates to hypothetical human receptors were assessed for a range of possible medium and long-term management options at the Little Forest Legacy Site (LFLS). The management options were:

1) Exhume and Remove
2) In-situ Stabilization (e.g. grouting)
3) Placement of an Engineered Cover to minimise water infiltration and future intrusion
4) Placement of an Engineered Cover to minimise water infiltration only
5) Continued Maintenance (continue as is with no major changes).

For each of these options, multiple exposure scenarios to hypothetical human receptors were evaluated within three groups:

1) Public (evaluated over the 0-100 year period during which the site is assumed to be under Institutional Control)
2) Workers (evaluated over the 0-100 year period during which the site is assumed to be under Institutional Control),
3) Future Public Members (evaluated over the 100-1000 year period after assumed loss of institutional control).

The resulting potential dose rates range over six orders of magnitude. In the near term (0-100 years) all dose rates to the public are well below the relevant regulatory criteria of 1 mSv/year for doses from all planned exposure situations, and a dose constraint of 0.3 mSv/year from a single facility. The highest dose rate for worker scenarios (Exhume and Remove) was about 1 mSv/year (at the public limit, but below the 20 mSv/year radiation worker limit). For the period after institutional control (100-1000 years) several scenarios of future use by the public (e.g. Subsistence farmer after 100 years) surpass the 0.3 mSv/year dose constraint (Summary Figure).



Summary Figure: Annual dose rates (mSv yr^{-1}) from LFLS exposures to hypothetical human receptors for a range of site management options. The dose rates shown are in addition to natural background and used conservative (overestimated) exposure assumptions.

Key points:

- When assuming Institutional Control for the near future, modelled dose rates to members of the public (trespassers, public at the fence boundary) are orders of magnitude below the 1.0 mSv yr^{-1} benchmark.
- For the near future in existing conditions, modelled dose rates for typical workers (e.g. lawnmowers, etc.) were well below the benchmark for public exposure. The benchmark for public exposure is relevant as the type of employees involved will typically not be classified as "radiation workers."
- Modelled dose rates to workers who may implement the proposed management options varied widely depending on the degree of exposure and duration of work. The In-situ Stabilisation worker was higher than that of the Continued Maintenance worker, but still below the 1.0 mSv yr^{-1} benchmark for the public. The Exhume and Remove worker dose rate was about 1.0 mSv yr^{-1}, which is at the benchmark for members of the public, but well-below the 20 mSv/year radiation worker limit. In that scenario, the increase in dose rates was mainly from the assumed direct exposure to wastes (e.g. worker near wastes) and to longer respective assumed work durations. All modelled dose rates were below the 20 mSv yr^{-1} benchmark for radiation workers.
- Modelled dose rates for members of the public in the future, after the end of the Institutional Control period (100-1000 years), varied greatly with the lowest being a Future Occasional Use receptor (hunter/gatherer or recreationalist) on an Engineered Cover. The highest (about 10 times more than the public exposure benchmark) were for a Future Subsistence Farmer in scenarios where the trench wastes were left in place and could be accessed (e.g. options that do not have intrusion prevention measures). In these scenarios, it was conservatively assumed the wastes are penetrated and mixed with surface soils which caused dose directly and via farmed crops.
- Regarding dose rates to biota, the site passes the standard international screening test (ERICA Tier 1) in which highly conservative assumptions are made. Additional analysis (ERICA Tier 2) indicated dose rates now and into the future are below international benchmarks for representative biota under a range of conservative exposures. However biointrusion into the wastes should be prevented/minimised.

Study results are site-specific in that they were calculated from measurements on site samples and data from site documents, utilised local meteorological and hydrological data as well as site configuration and layout as far as possible. They are conservative in that the factors such as occupancy, dust concentrations in the air and other exposure assumptions used overestimated amounts (e.g. more dust than would usually be expected).

The IAEA process also calls for assessment of uncertainties. Therefore, dose rates were also modelled using a range of assumptions that are possible, but that are highly conservative (lead to over predicting possible dose rates). Examples include:

- When assuming all the wastes at the site are represented by the maximum measured values for each radionuclide, then the dose rate estimates increase by an average factor of 4.5 across all scenarios. Even, when using this conservative assumption, the near-term public dose rates are still well below benchmarks.
- The modelling assumed that ^{238}U progeny are in secular equilibrium with their parent. This assumption overestimates the activity concentrations of the progeny which are known to not be in equilibrium (have activity concentrations that are less than equilibrium). It has been suggested (by records of the wastes) that the ^{238}U progeny in wastes are actually only about 4% of that of their parent. If this is the case, then the dose rates reported here are too high by a factor of about 5.5. While re-equilibrium will eventually occur, it will be on timescales beyond those considered in this document due to the long half lives of ^{230}Th and ^{226}Ra.

- When assuming exaggerated exposures such as frequent upwelling of wastes (bathtubbing) across the entire trenchtop surface, then higher total dose rates of up to 44 mSv yr^{-1} were possible for the Future Farmer scenario.
- When assuming the entire cover is eroded away and a Future Farmer is directly and continuously exposed to the wastes (a highly unlikely & conservative assumption), then dose rates of up to 200 mSv yr^{-1} were possible.

These final two scenarios (frequent upwelling of wastes and erosion/loss of entire cover) indicate that some protective action should be considered to minimise future exposures. In the model outcomes, most of the dose came from non-water pathways (e.g. direct exposure, instead of water-associated exposures such as drinking from a shallow well and irrigation of crops from the same well). This suggests efforts to minimise future dose should focus on protecting against intrusion as well as restricting infiltration.

2. Background

This report describes the approach and results of human and environmental dose assessments conducted in support of ANSTO's assessment of the LFLS site as undertaken to fulfil the LFLS licence requirement of providing ARPANSA with a plan for the medium and long term management of the site. It relies on antecedent reports on subjects including the history of waste disposal and other reports on the waste characteristics and environmental setting of the LFLS (Cendón et al., 2015; Hankin, 2013; Hughes et al., 2011; Ikeda-Ohno et al., 2014; Johansen et al., 2012a; Payne, 2012, 2015; Payne et al., 2013; Payne et al., 2015).

A human health dose assessment was included in the previous LFLS Safety Assessment (ANSTO/T/TN/2013-10 rev 0). This earlier dose assessment remains valid. However, it did not include assessment of a range of engineered management options for the site. The current dose assessment updates the prior assessment to include a wider range of management options which included consideration of an increased number of radionuclides over a wider range of human receptor scenarios.

The assessment uses up-to-date data that have become available from site investigations conducted by ANSTO over the past ten years. It also uses past routine monitoring information as well as available historical documents (Payne, 2012, 2015, 2020a). This information was used within the RESRAD dose modelling software (RESidual RADioactivity computer code, Argonne National Laboratory, US Department of Energy) which has a well-documented basis of development and testing protocols. Assessment was performed by a team of ANSTO personnel, with input and quality assurance advice from external parties including Argonne National Laboratory and input from staff of the Radiation and Nuclear Science, Forensic and Scientific Services, Department of Health Queensland.

3. Terminology

ARPANSA; Australian Radiation Protection and Nuclear Safety Agency

ERICA-Tool (ERICA) The ERICA Tool is a computerised, flexible software system that has a structure based upon the ERICA Integrated Approach to assessing the radiological risk to biota (Brown et al., 2016).

IAEA; International Atomic Energy Agency

ICRP; International Commission on Radiological Protection RESRAD; The RESidual RADioactivity

(RESRAD) computer code developed under the US Department of Energy and the US Nuclear Regulatory Commission (Cheng and Yu, 1993).

4. Management Options and Scenarios

4.1. Assumed Management Options

Five generic types of management options were evaluated in the dose assessment (detailed below):

- Exhume and Remove.
- In-situ Stabilisation (e.g. grouting)
- Engineered Cover to minimise intrusion and water infiltration
- Engineered Cover to minimise water infiltration only
- Continued Maintenance

Specific design information was not available. Therefore, the dose assessment relied on assumed performance criteria rather than specifying design details (e.g. the engineered cover was assumed to reduce infiltration by specific amounts, which could be achieved by a range of possible technical designs that may be detailed in a later engineering analysis).

4.1.1 Exhume and Remove Option

In the simulated Exhume and Remove Option, all of the wastes from within the original trenches, and the adjacent contaminated soils, are assumed to be removed and disposed of in an approved facility. Workers are exposed during excavation, and future public receptors are exposed to any residual contamination. This analysis assumed that, consistent with typical practice, exhumation would be performed until an agreed-upon soil remediation level is achieved (some residual contamination residues would remain). The amount of remaining contamination is not known and depends on any future remediation agreements. In this simulation, it was assumed that remaining residuals are, on average, 5% of the activity concentration of the trench wastes, or, equal to the existing soil activity concentrations, whichever is higher. This is thought to be conservative as new clean fill would likely be used to backfill over the excavated trenches. Decay corrections are on a 2018 basis.

4.1.2 In-situ Stabilisation Option

The simulated In-situ Stabilisation Option assumes that the wastes in the trenches are stabilised in place, via grouting or similar technology, such that they are made resistant to leaching and penetration. It is assumed that the stabilisation is effective in reducing leaching by 90%. To accomplish this, it is assumed the trench wastes will be penetrated on a closely-spaced pattern to emplace grout. This penetration of wastes is assumed to bring contamination to the surface on drilling equipment, excess soil, etc. The amount of waste brought to the surface is unknown. For this analysis we have conservatively assumed workers and future receptors are exposed to residual radionuclide contamination that is equal to 5% of the activity concentration of the trench wastes, or, equal to the existing trench-top soil activity concentrations, whichever is higher. This 5% assumption is likely conservative given that worker safety controls would require careful handling and disposal of equipment and any disturbed wastes. Decay corrections are on a 2018 basis.

4.1.3 Engineered Cover Options

The simulated Engineered Cover Options assume that an engineered cover is emplaced over the top of the trenches without disturbing the wastes beneath. Local uncontaminated soils are used as cover fill. Two designs are modelled:

- Engineered Cover to minimise intrusion and water infiltration
- Engineered Cover to minimise water infiltration only

Both designs are assumed to reduce infiltration to 5% of precipitation. The first design includes a passive barrier (e.g. concrete or rip-rap layer) to prevent inadvertent penetration into the trenches in the future (e.g. individuals using hand tools or small excavators). If desired at some time in the future, this rip-rap layer may be purposely removed by heavy equipment (the wastes are still removable).

4.1.4 Continued Maintenance Option (0-100 years).

The Continued Maintenance Option assumes the current conditions and Institutional Controls at the site are maintained including maintenance of a grass cover, top dressing of any contamination surfacing events, fence and signage maintenance, and security monitoring to minimise trespasser activities. It is assumed that current (2018) radionuclide levels on the surface will be subjected to radionuclide decay and transport/dispersion processes at typical rates with some heightened erosion scenarios considered (Section 6.6).

4.2. Assumed Receptors

Multiple receptors were evaluated within three groups:

- Public during Institutional Control (0-100 yrs)
- Workers during Institutional Control (0-100 yrs)
- Future Public (100-1000 years).

Within these groups various scenarios were evaluated as detailed in Table 1 and Sections 4.2.1 through 4.4 below.

Table 1. Summary of Management Options and Receptor scenarios.

Option	Receptors	Timeframe
Continued Maintenance	**Public during 0-100 years Operational Control period** – (1) Public At Fence, assumed to be at closest point outside of fence 100% of time. (2) Recreational user (bushwalker) has once per year exposure to 5 L unfiltered water from most likely contaminated water source (Turtle Creek receives runoff and groundwater from the LFLS). (3) Trespassers exposed to surface soils, dusty, once per year (0.8 hrs, consistent with past evaluations) **Worker**- Assumed 60 hours per year in dusty conditions (e.g. lawn mowing).	0-100 yrs
Engineered Cover Options	**Public during 0-100 years Operational Control period** – (1), (2) and (3) , same as above except trench area is capped with background soils. **Worker** -Workers placing new cap material for 1.5 worker-months. No penetration into trenches. **Future Public**- (1) Future Subsistence Farmer, 100% onsite, occupying a house on LFLS trenches (50% indoors). Diet is from plants grown on the trenchtop area and livestock grown adjacent to the trenches. A shallow well at the edge of the trenches provides drinking and irrigation water. Unless prevented, the farmer penetrates into the trenches and the house & gardens are on a mixture of residual soils and wastes (assumed 50% activity concentration of wastes). (2) Future Occasional Use , trench area surface used for camping/recreation/hunting/gathering. The wastes are not penetrated and water is from the nearby Turtle Creek.	0-100 yrs 0-100 yrs 100-1000 yrs
In-situ Stabilisation	**Public during 0-100 years Operational Control period** – (1), (2) and (3) Same as above except trench area is assumed to have residual contamination from grouting (small amounts of trench wastes brought to the surface during grouting/drilling operations such that soils activity concentrations are 5% that of trench wastes. **Worker** –Same as above, except these workers are exposed for 350 hours to site soils under grouting/drilling. **Future Public**- Same as above, except surface soils have residual contamination from grouting/drilling that is estimated to be 90% successful in solidifying wastes in the 100-1000 year time frame. After penetration/mixing by the farmer, it is assumed surface soil activity concentrations are 10% of trench wastes.	0-100 yrs 0-100 yrs 100-1000 yrs
Exhume and Remove	**Public during 0-100 years Operational Control period** – (1), (2) and (3) Same as above except trench area has higher residual contamination (assumed 5% of wastes). **Workers** –same as above, except these workers are exposed for 4+ worker months (1000 hrs) to the open trench wastes. Assume a "worst-case-worker" is positioned in the trench 1m from the face of the wastes. Assume routine worker conditions (no accidents) and only minimal protective equipment (gloves, but no dust mask). **Future Public**, same as above, except all soils (to 3m) have residual from excavation (5% of original waste contamination) available for mixing into surface soils or transport by groundwater.	0-100 yrs 0-100 yrs 100-1000 yrs

Public Receptors (0-100 years)

4.2.1 Public receptor from local background conditions

Location: Resides outside of the ANSTO buffer zone, but within the general local area. No assumed pathways exist to the receptor from LFLS contamination.

Assumed Exposure: Exposure is to direct radiation, inhalation, and ingestion of local dust/soils.

Key assumptions: It is assumed that a member of public spends 100% of their time outdoors in the local area exposed to local soils with natural and fallout radionuclides present. Standard conservative exposure criteria were applied as per RESRAD guidance (e.g. 36.5 grams of soil ingested per year, 0.0001 grams per cubic metre mass loading from the soil into the air column, 8400 cubic metres per year inhalation rate). Radionuclide activity concentrations are from various ANSTO monitoring/studies of the local area and are on 2018 basis (50 years following 1968 cessation of disposal).

4.2.2 Public at Fence (PAF) of the LFLS boundary

Location: assumed to spend 100% of their time just outside of the LFLS fence at the location of maximum potential exposure to fugitive dust (eastern boundary, offset from the midpoint of the trench area).

Assumed Exposure: Exposure is to direct radiation, inhalation, and ingestion of windblown dust from the trench area.

Key assumptions: This receptor has the same characteristics as the public “background” receptor, except they are assumed to reside 100% at point of highest exposure along the LFLS fence boundary. Radionuclide activity concentrations depend on the residual contamination associated with future management options. Contamination is via windblown transport from the trench-top area to the receptor location. All radionuclides are on 2018 basis and it is assumed there has been a 50-year build-up of transported dust.

4.2.3 Public Trespasser

Location: Trench-top area within the LFLS

Assumed Exposure: Exposure is to direct radiation, inhalation, and dust/soil ingestion.

Key assumptions: It is assumed that this receptor (the trespasser) enters the LFLS fence and engages in dusty activities within the trench area (e.g. motorcycle riding). The amount of time used in this assessment (0.8 hours) is the same as was adopted in the prior ANSTO LFLS Safety Assessment (ANSTO/T/TN/2013-10 rev 0) which reflects the time likely spent on trench areas relative to other areas within the fenced area. The scenario considers active signage, fence maintenance, and response by ANSTO security during the 0-100 year control period. We also consider longer periods of occupancy (up to 8 hours) which are conservative given the trench area is a fraction of the enclosed restricted site and given ANSTO’s abilities to detect and remove trespassers. Radionuclide activity concentrations are from recent sampling of the trench-top soils and are on a 2018 basis.

4.2.4 Public receptor Bushwalker near LFLS

Location: The most prominent surface water drainage exiting the LFLS (drainage into what is often referred to as Turtle Creek) just outside of the LFLS fence.

Assumed Exposure: Ingestion of natural, fallout, and LFLS-transported contaminants in creek water.

Key assumptions: It is assumed that a receptor drinks 5L per year of unfiltered water from the water in this ephemeral drainage. The creek is ephemeral and water is often not available. When available, the water usually has a cloudy appearance (from natural sedimentation processes) that would discourage most people from drinking it. Radionuclide activity concentrations are from recent sampling of the creek water which indicated that runoff is largely free of LFLS constituents with however some trace amounts in the range of normal background fallout radionuclides which are detectable by highly sensitive analysis. All radionuclide activity concentrations are on a 2018 basis.

Worker Receptors (0-100 years)

4.2.5 Workers in local background conditions.

This hypothetical local off-site worker is included for comparison with onsite LFLS workers.

Location: Works within or outside of the ANSTO buffer zone, but within the general local area. No pathways exist to the receptor from LFLS contamination.

Assumed Exposure: Exposure is to direct radiation, inhalation, and dust/soil ingestion.

Key assumptions: It is assumed that a worker is exposed to local soils with natural and fallout radionuclides present but uncontaminated by the LFLS. Standard conservative exposure criteria were applied for workers in dusty conditions as per RESRAD guidance (e.g. 73 grams of soil ingested per year, 0.0006 grams per cubic metre mass loading from the soil into the air column, and 8400 m^3 yr^{-1} breathing rate). Radionuclide activity concentrations are from various ANSTO monitoring/studies of the local area and are on 2018 basis (50 years following 1968 disposal).

4.2.6 Worker, Continued Maintenance (60 hours per year)

Location: trench-top area.

Assumed Exposure: Exposure is to direct radiation, inhalation, and dust/soil ingestion.

Key assumptions: Similar to the above background worker, except it is assumed that a worker spends 60 hours per year (conservative overestimate) outdoors exposed to trenchtop soils with natural, fallout, and LFLS residual radionuclides present. Conditions are dusty (e.g. lawn mowing).

4.2.7 Worker, Engineered Cover (350 hours)

Location: Trench-top area during cover emplacement.

Assumed Exposure: Exposure is to direct radiation, inhalation, and dust/soil ingestion.

Key assumptions: Similar to the above background worker, except it is assumed that, during cover construction, a worker spends 350 hours per year outdoors emplacing/grading/seeding the soils being used to cover the trenches. The soils are assumed to be local and contain natural and fallout radionuclides in the same concentrations as local background surface soils (conservative assumption given that much of the soil mass would be sourced from deeper soil layers where fallout radionuclides are at lower concentrations).

4.2.8 Worker, In-situ Stabilisation (528 hours)

Location: Trench-top area.

Assumed Exposure: Exposure is to direct radiation, inhalation, and dust/soil ingestion.

Key assumptions: Similar to the above background worker, except it is assumed that a worker spends 528 hrs (3-worker months) outdoors exposed to trenchtop soils which have existing residual LFLS contamination, plus an assumed increase in contamination from grout emplacement. During grouting, the trenches are assumed to be penetrated on a closely-spaced pattern. This penetration is assumed to bring contamination to the surface on drilling equipment, excess soil, etc. The amount of waste brought to the surface is unknown. For this analysis we have conservatively assumed workers and future receptors are exposed to residual radionuclide contamination that is equal to 5% of the activity concentration of the trench wastes, or, equal to the existing trench-top soil activity concentrations, whichever is higher. This 5% assumption is likely conservative given that worker safety controls would require careful handling and disposal of equipment and any disturbed wastes. Decay corrections are on a 2018 basis.

4.2.9 Worker, Exhume and Remove (1000 hours)

Location: Within trenches, or otherwise exposed to an open face of the wastes being excavated.

Assumed Exposure: Exposure is to direct radiation, inhalation, and dust/soil ingestion.

Key assumptions: Similar to the above scenarios, except it is assumed that a worker spends 1000 hrs (4+ worker months) positioned 1m from the face of the exposed trench wastes. The worker avoids direct contact with the wastes by using hand tools, boots, gloves, etc. However, they are assumed to not wear a dust-mask (highly conservative assumption as a dust mask or other inhalation controls would likely be required particularly given that co-disposed beryllium is present). This dose assessment of routine exposures assumes safe work practices are followed (does not consider accidents or unusual events which would be considered in an activity-specific assessment to be conducted if this option is pursued). This analysis assumed that, consistent with typical practice, exhumation would be performed until an agreed-upon soil remediation level is achieved (some residual contamination residues would remain). The amount of remaining contamination is not known and depends on any future remediation agreements. In this simulation, it was assumed residuals remain that are 5% of the activity concentration of the trench wastes, or, equal to the existing soil activity concentrations, whichever is higher. This is thought to be conservative as new clean fill would likely be used to fill and top over the excavated trenches. Decay corrections are on a 2018 basis.

Future Public (100-1000 years)

4.2.10 Future local background farmer

Location: Resides outside of the ANSTO buffer zone, but within the general local area. No pathways exist to the receptor from LFLS contamination.

Assumed Exposure: Exposure is to direct radiation, inhalation, and dust/soil ingestion of local soils. Additional exposure pathways include ingestion of plants, milk, and meat (all farmed on local soils), and ingesting of drinking water from a shallow local well. The radon pathway is also considered.

Key assumptions: It is assumed that a member of public spends 100% of their time locally in an agricultural scenario that could be described as "subsistence farming." In this conservative scenario the resident farmer occupies a house built on local soils. They grow and eat plants using shallow well water and drink the water. Standard conservative exposure criteria were applied as per RESRAD guidance (e.g. 36.5 grams of soil ingested per year, 0.0001 grams per cubic metre mass loading from the soil into the air column, 8400 cubic metres per year inhalation rate). Radionuclide activity concentrations are from various ANSTO monitoring/studies of the local area and are on 2118 basis (100 years from current day 2018).

4.2.11 Future Subsistence Farmer (FSF) on LFLS after loss of Institutional Control

Location: Resides on the LFLS trenchtop contamination area.

Assumed Exposure: As above, exposure is to direct radiation, inhalation, and dust/soil ingestion of local soils. Additional exposure pathways include ingestion of plants, milk, and meat (all farmed on LFLS soils), and ingesting of drinking water from a shallow well located at the downgradient edge of the trench area. The radon pathway is also considered.

Key assumptions: Similar to the above "subsistence farmer," but it is assumed that due to some unforeseen disruption previous fences, warning signs, regulations, and records become ineffective at controlling the LFLS site. As a result, a hypothetical receptor spends 100% of their time on the trenchtop area. 100% of their diet comes from home-grown food. They use a shallow well located at the trench area boundary for drinking water and irrigation. They occupy a house built over the trenches, and spend the remaining time on farming leafy vegetables, fruit, and cattle (40% indoors, 60% outdoors). The leafy vegetables and fruit are grown on the trench area using well water irrigation and the cattle are raised adjacent to the trench area.

Two scenarios are considered:

1) Wastes are penetrated by the farmer (e.g. during house construction or digging a pond) and the excess soils are mixed with the topsoils of the dwelling area, the garden, fruit orchard and paddock. The mixture of residual soils and wastes is assumed to have activity concentrations that are 50% that of the original trench wastes (after decay).
2) Future Subsistence Farmer scenarios are also considered with no waste penetration (due to an engineered layer designed to prevent/minimise inadvertent future penetration into the trenches). The subsistence farming is carried out on surface soils that may have residual surface contamination from previous management, but do not include trench wastes excavated by the farmer.

Standard conservative exposure criteria were applied as per RESRAD guidance (e.g. 36.5 grams of soil ingested per year, 0.0001 grams per cubic metre mass loading from the soil into the air column, 8400 cubic metres per year inhalation rate). Radionuclide activity concentrations are from various ANSTO monitoring/studies of the local area and are on 2118 basis (100 years from current day 2018).

4.2.12 Future Occasional Use on the LFLS after loss of Institutional Control

Location: Visits the LFLS trenchtop contamination area 3 months per year for camping, hunting, gathering.

Assumed Exposure: As above, exposure is to direct radiation, inhalation, and dust/soil ingestion of local soils. Additional exposure pathways include ingestion of plants, meat, and water.

Key assumptions: Similar to the above, it is assumed that due to some unforeseen disruption previous fences, warning signs, regulations, and records become ineffective at controlling the LFLS site. As a result, a hypothetical receptor spends three months per year on the trenchtop area (e.g. seasonal visit). During this time, their diet comes from the local area but is not farmed. Such diets would require gathering over relatively larger areas per person. However, in this assessment we conservatively assumed that during the three months stay, 100% of diet came directly from the LFLS trenchtop area and that the receptor would spend 100% of their time on the trenchtop area (e.g. at camp, which for this type of scenarios is highly conservative as a recreationalist or hunter/gatherer would typically roam over much wider areas).

5. Modelling Approach

5.1 RESRAD Software

The RESRAD-Offsite code Version 3.2 (2016) was used for calculating dose rates to various receptors at the LFLS. The code is well documented (Cheng et al., 2013; Kamboj et al., 2005; Mills et al., 1997) including input parameter guidance (Yu et al., 2015) and is supported by ongoing training offered at Argonne National Laboratory, US, and other locations around the world. The RESRAD codes are used widely internationally, and have been successfully applied elsewhere in Australia (e.g. in evaluating the Ranger Uranium mine (Doering et al., 2018, 2019)).

5.2 Range of pathways assessed

A range of potential exposure pathways were used to assess the 11 receptors (7 with LFLS pathway exposures and 4 background control) under the four different management options. The most common exposure pathways were by direct exposure, inhalation, and ingestion (e.g. of soil, and in one case of unfiltered creek water). The scenarios examining future (100-1000 years) conditions also included dietary consumption pathways (consumption of garden and fruit crops, meat and milk, all farmed onsite as well as consumption of drinking water from a shallow well located at the downgradient edge of the trench area).

5.3 Soils and Waste Activity Concentrations

The radionuclides at the site (source term) exist in site soils and in the trench wastes. Site-specific measurements of surface soils were available for most radionuclides (Figure 1; Appendix). No recent sampling of trench wastes has been performed and therefore historical records were used to estimate trench waste and site soil activity concentrations (Payne, 2015; Payne et al., 2020b). Data on the source term was compiled in report LFLS-03 “Estimate of quantity of radionuclides disposed at the Little Forest Site” (compiled in the Appendix).

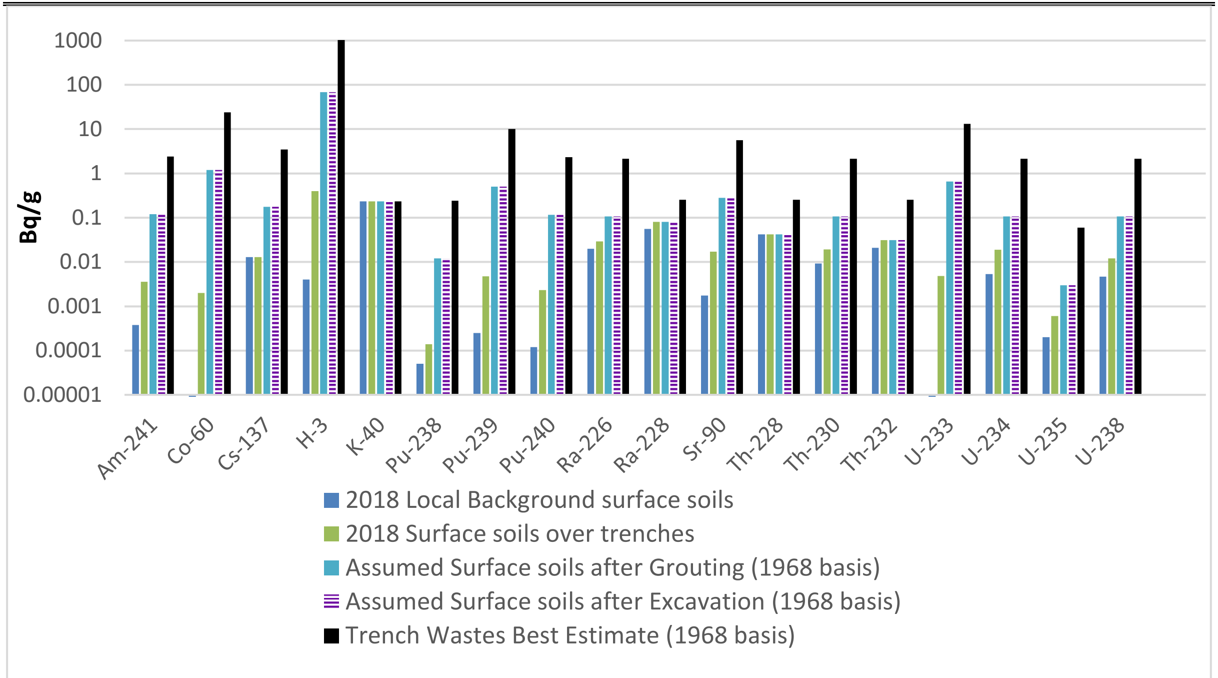


Figure 1. Activity concentrations (Bq/g) for soils and wastes. Shown are site averages in Bq/g (for trench wastes, best estimate values are shown). See Appendix for maximum values and details. The activity concentrations change over time due to radioactive decay. In this Figure, the wastes are decay corrected to 1968 (when disposal stopped) and the surface soils to 2018 (the date of assessment).

5.4 Atmospheric Transport

Offsite receptors (e.g. public at fence) may be exposed to windblown dust which required use of RESRAD-Offsite atmospheric transport module. The assessment used data from the nearby meteorological station at Holsworthy, NSW. This station had the necessary local cloud cover, wind, temperature and other data to develop an atmospheric stability file (STAR file) within RESRAD. The STAR file was developed by Argonne National Laboratory at ANSTO's request. The STAR file uses six atmospheric stability classes (A-F; used for calculation of transport of contaminants and dust in air) which reflect local conditions (Figure 2).

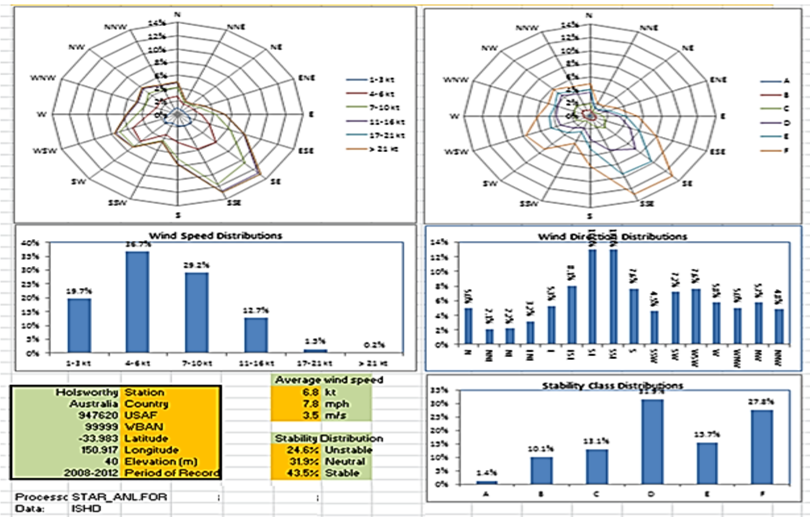


Figure 2. Data on meteorological stability classes used (see Appendix for details).

5.5 Groundwater Transport

Some receptors (e.g. future subsistence farmer) may be exposed to LFLS contamination by drinking local groundwater and via irrigation of crops with groundwater. Transport of contaminants from the trench area to a well (located near the downgradient edge of the trench area) required use of RESRAD-Offsite groundwater transport module.

Data from LFLS studies were used as parameters in this module, the most important being: Hydraulic conductivity mean of 30 m/yr (compares with site estimates of 0.5 to 50 m/yr), porosity mean of 0.4 which matches well with site soils, Hydraulic gradient mean of 0.04 which compares with site estimates of 0.04-0.05. Kds were site specific where LFLS measurements/estimates were available and otherwise from IAEA references (see Appendix for parameter values). When using these parameters, the model slightly over-predicted contaminant transport of tritium (red line, Figure 3) as compared with the observed data from a well near the downgradient edge of the trench area (OS2, green line show observed data). Tritium levels were also slightly over-predicted at two nearby locations where water was sampled from two freshly drilled coreholes (CH13 and CH27). Tritium was used for this comparison because of data availability, mainly from Hughes et al. (2011). Because tritium does not adsorb to the host matrix as it moves through groundwater systems, it indicates conservative movement of a contaminant. The other radionuclides that adsorb will move slower and not as far according to their adsorption/desorption characteristics. The comparison here indicates that the hydrological model would conservatively over-predict tritium activity concentrations at the location of a shallow well to be used by a future Subsistence Farmer.

Although the RESRAD groundwater transport model was shown to be conservative, it is highly simplified. This study assumed the top of the saturated groundwater layer (permanently saturated groundwater) was located at the bottom of the trenches. This is highly conservative as data from numerous site investigations have established that the soils below the trenches are mostly dry (down to at least 12m). Some amount of subsurface water moves in thin, variably wet layers that have complex connectivity. These complex vadose zone conditions were not able to be modelled in RESRAD and if important would require a separate bespoke modelling effort. The approach used in the current RESRAD study was conservative because assuming the layers were saturated allowed for significant transport of contaminants out of the trenches, which would otherwise be prohibited by dry soils.

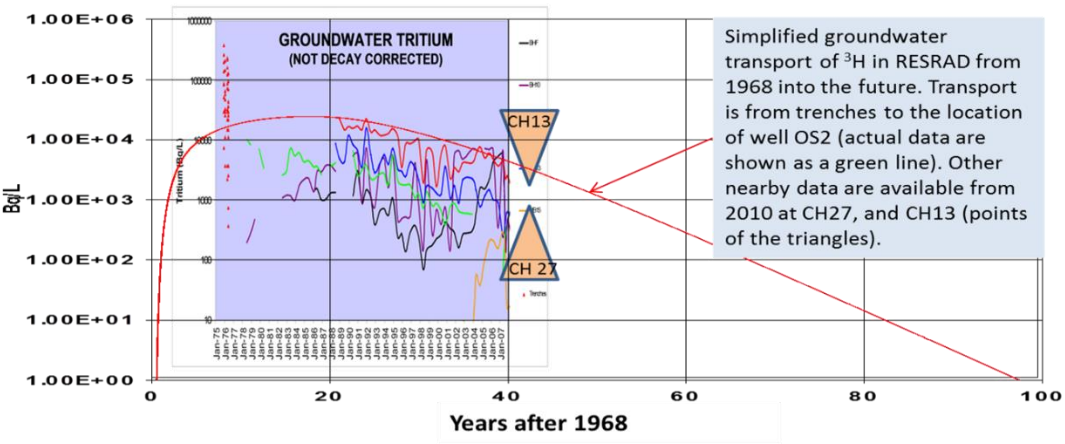


Figure 3. Comparison of modelled tritium activity concentrations with measured data at the location OS2 well (green line) and other Coreholes CH13 and CH27 (points of triangles).

5.6 How Study results relate to ambient background dose rates

The modelling results presented in section 6 provide 1) the dose rates from exposures to LFLS soils and wastes, and 2) those from background radionuclides for comparison (natural + fallout radionuclides). This approach ensured that all scenarios and Management Options were evaluated on the same basis – the dose contribution from the LFLS soils/wastes relative to background. Consistent with this approach, the dose results do not include other typical exposures that have nothing to do with the LFLS (e.g. cosmogenic radiation, medical exposures, etc.). In the graphs below, the background rates are indicated (orange), while the LFLS dose rates are indicated in blue and also numerically. Background dose rates to public from soil exposure pathways (direct, soil ingestion and dust inhalation) were 0.3 mSv/year (does not include medical, diet, radon, cosmogenic and other pathways). The relative Background dose rates for some scenarios (e.g. trespasser, workers, etc.) are lower in proportion to their respective exposure times.

6. Outcomes of Modelling

6.1. Dose rates to hypothetical Public receptors during the 0-100 year Institutional Control

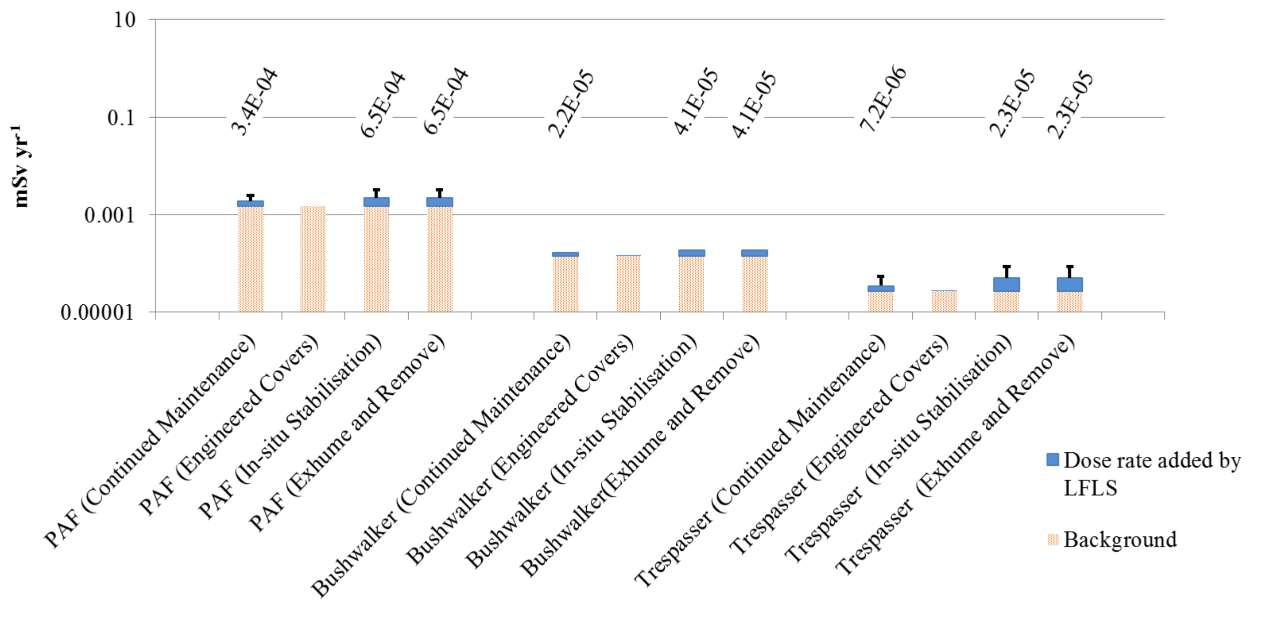


Figure 4. Mean dose rates (mSv yr^{-1}) to hypothetical public receptors during the 0-100 year Institutional Control period. (PAF=public at fence). The data labels are the amounts from LFLS soils and wastes (blue) that are in addition to background dose rates (orange). All dose rates are for direct, inhalation and ingestion pathways relative to soils and do not include other sources such as cosmogenic radiation, medical procedures and food consumption.

Public members during the 0-100 year Institutional Control period may be exposed to site soils during brief trespassing events onto the LFLS trenchtop areas, or exposed just outside the LFLS fence to windblown dust (PAF=Public at Fence scenario) or contaminated water that moves offsite (Bushwalker scenario). Under these scenarios, the additional dose rates received from LFLS exposures (negligible to 0.0007 mSv yr^{-1}) were orders of magnitude below that from yearly natural background (see section 5.6) for the same exposure assumptions (Figure 4). Details include:

- The dose rates for Trespasser are for an assumed short duration (0.8 hours) that, if extended ten times to 8 hours would result in ten times higher dose rates (up to 2E-04 mSv yr^{-1}). Under Institutional Control, the current level of maintenance is assumed such that biointrusion, erosion, or other events that may cause surface expression of wastes are prevented or, if they occur, are quickly remediated.
- The Public at Fence (PAF) scenario considers offsite transport of contamination by wind to a receptor that spends 100% of their time (365 days per year) at the point of highest exposure along the LFLS fence boundary.
- The Bushwalker scenarios consider 5L ingestion of surface water and groundwater transport offsite to Turtle Creek, just outside of the LFLS boundary. It is assumed the bushwalker drinks 5L of this water without filtration (despite its cloudy, unappealing appearance). These scenarios are during a period of Institutional Control where the site remains maintained and secured and it is assumed that the public are effectively deterred from intrusions that breach into any subsurface trench wastes.

When comparing among the different management options for exposures to the public during the Institutional Control period,

- The Engineered Cover options (both) resulted in negligible additional dose rate above background since the cover material was assumed to be from local uncontaminated soils (Figure 4).
- The Continued Maintenance option had slightly higher dose rates that reflect the existing slightly elevated contamination in surface soils at the site.
- The In-situ Stabilisation options result in slightly higher dose rates due to assumed contamination brought to the surface during operations and that would remain after the actions are completed.
- The Exhume and Remove option also assumed exposure to the public via the residual contamination. This conservative, but realistic assumption follows precedents in Australia and internationally in which, during a remediation action, it is deemed impractical to clean soils up to background levels. Rather it is ensured that soils are cleaned up to below safe target levels based on regulatory guidance levels. In the above scenarios it was assumed the Exhume and Remove as well as the In-situ Stabilisation resulted in an average soil mixture that had activity concentrations equal to 5% of that of the original trench wastes. The results therefore provide useful initial data for considering potential future actions. But if such actions are pursued, an expanded analysis of dose from residual soils would be needed.

6.2 Dose rates to hypothetical Worker receptors during the 0-100 year Institutional Control

Workers may implement the various management options during which they may be exposed to site soils (direct exposure, dust inhalation and ingestion). These scenarios used the current (2018) radionuclide activity concentrations (decay to later dates was not assumed).

Modelled dose rates varied by four orders of magnitude due to differing soil activity concentrations associated with the four Management Options, and due to the exposure durations assumed (Figure 5).

- The lowest modelled dose rates from LFLS wastes and soils were for the Continued Maintenance scenario (0.0005 mSv yr^{-1}) for a worker who spends 60 hours per year in dusty conditions on the trenchtop area (e.g. lawnmower). This dose rate is the increment added by LFLS contamination in addition to the background level of 0.002 mSv yr^{-1} for the same worker in off-site conditions (the total for the LFLS worker would be 0.0025 mSv yr^{-1}).
- The highest rates were for the Exhume and Remove scenario (1.0 mSv yr^{-1} added by LFLS exposures) of a worker who is assumed to spend 1000 hours near the wastes (1m from waste surface) during their removal under dusty but otherwise routine work conditions. The above dose rates largely depend on exposure durations which were assumed. If different durations were assumed, the dose rates would scale proportionally as long as exposure conditions were the same. Therefore, the above data provide a useful range of potential exposure conditions that can be further scaled if different exposure durations are explored.
- The modelled dose rates for the Exhume and Remove workers are near the 1.0 mSv yr^{-1} guidance level for chronic exposure to public members, but are below the 20.0 mSv yr^{-1} guidance level for radiation workers.

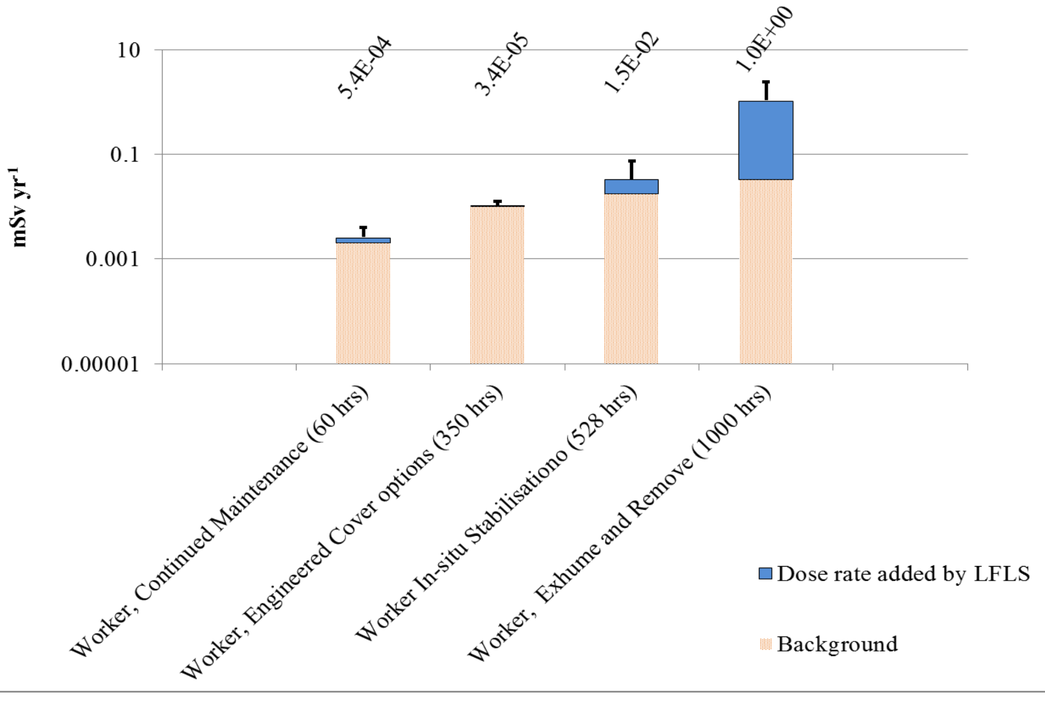


Figure 5. Mean dose rates (mSv yr^{-1}) to hypothetical worker receptors during the 0-100 year Institutional Control period. The data labels are the amounts from LFLS soils and wastes (blue) that are in addition to background dose rates (orange) for the same scenarios. All dose rates are for direct, inhalation and ingestion pathways relative to soils and do not include other sources such as cosmogenic radiation, medical procedures and food consumption.

The above results suggest that planning for any work that breaches the trenches should include a more detailed worker dose/hazard assessment to ensure worker exposures remain below guidance limits. The scenarios are intended to be conservative as the receptor is assumed to be positioned 100% of the work time as standing on the surface soils (in the case of the Exhume and Remove the worker is 1m from the trench wastes) with no shielding and in dusty conditions. No inhalation protection was assumed for all scenarios.

6.3 Dose rates to hypothetical future Public receptors during the 100-1000 year period after Institutional Control

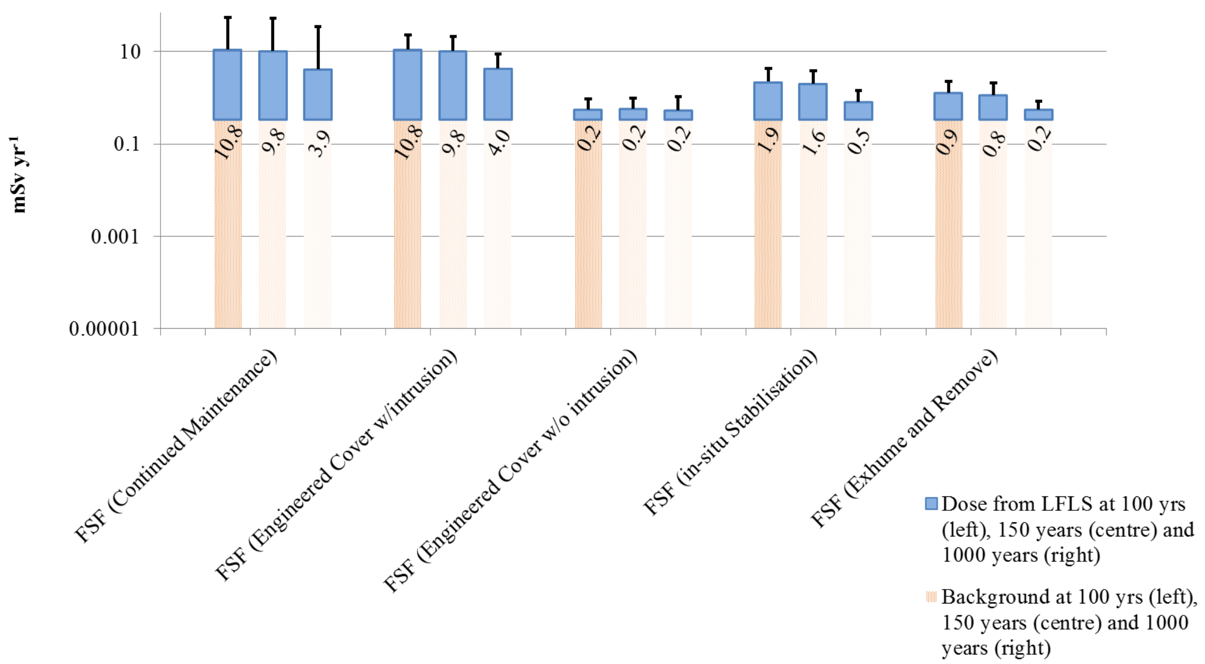


Figure 6. Dose rates (mSv yr^{-1}) to hypothetical Future Subsistence Farmer (FSF) during the 100-1000 year period following an assumed loss of Institutional Control. The data labels are the dose rates from LFLS exposures (blue) that are added to background (orange). For each scenario, three time periods are shown: at 100 years from present (left), at 150 years (centre) and at 1000 years (right). All scenarios assume the same pathways (direct, inhalation and ingestion from home-grown diet and LFLS water pathways). Dose rates do not include dose from other sources such as cosmic radiation, medical procedures, natural and fallout radionuclides.

6.3.1 Future Subsistence Farmer

For the post- Institutional Control period (100-1000 years), a Future Subsistence Farmer may be exposed while living full time on the LFLS soils. The scenario is conservative as the receptor spends 100% occupancy on the LFLS site and 100% of their diet comes from food and shallow groundwater at the site. It is assumed that, unless prevented, the trenches can be penetrated (e.g. during home construction, bioturbation, human removal of the cover) and trench wastes mixed with the topsoils of the homestead and food growing areas.

- The lowest modelled dose rates (0.2 mSv yr^{-1}) were for an Engineered Cover scenario that prevents future intrusion/penetration into the trenches (Figure 6).
- The highest dose rates were for the Continued Maintenance and Engineered Cover with intrusion (both up to approximately 11.0 mSv yr^{-1}). These options have no protection against future penetration into the trenches and mixing of the wastes onto the surface.
- The modelled dose rates for In-situ Stabilisation (up to 1.9 mSv yr^{-1}) and Exhume and Remove (up to 0.9 mSv yr^{-1}) options reflect their respective assumed levels of residual contamination.

For the future Subsistence Farmer scenarios, the dose rates were highest initially at 100 years and less thereafter. This is mainly due to decay of the radionuclides in site soils/wastes. Dose rates from these radionuclides (mainly direct exposure and uptake to food crops) were orders of magnitude higher than those from the groundwater pathway (drinking and irrigation). This reflects the relative ease of intrusion into the trenches in some scenarios as well as the low solubilities of the long lived radionuclides in the wastes along with the high adsorption capacities of the clayey site soils. Emplacing a cover with an infiltration barrier reduced dose rates via the well water pathway (drinking and irrigations), but these reductions were small compared with covers that prevented penetration/intrusion into the wastes.

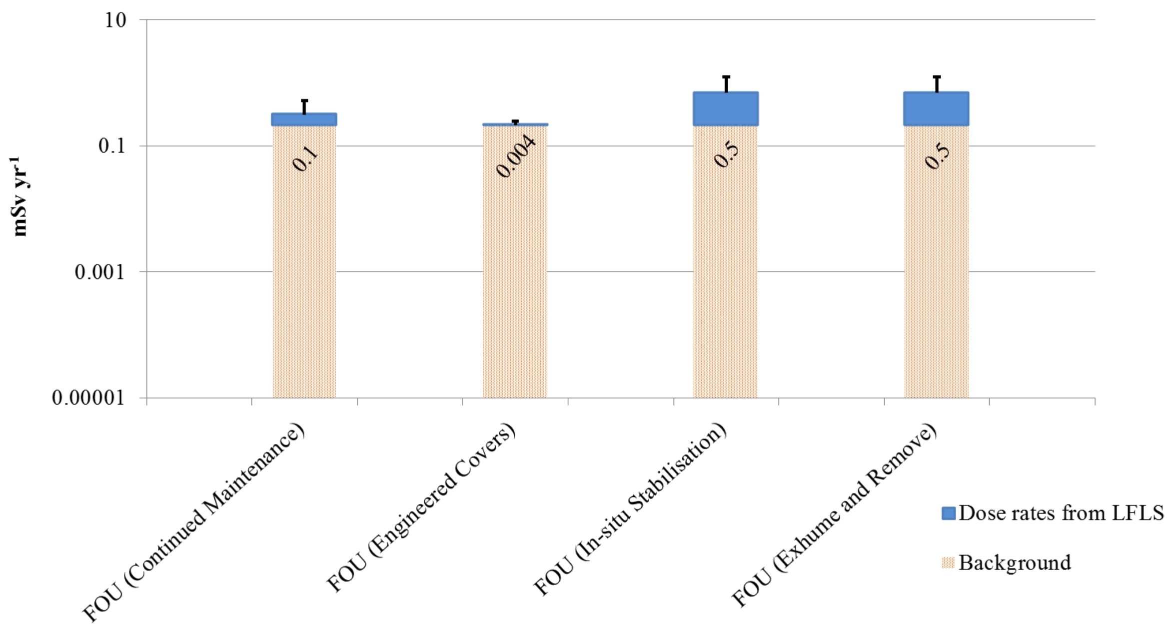


Figure 7. Dose rates (mSv yr^{-1}) to hypothetical Future Occasional Use receptor (FOU; recreationalist or hunter/gatherer) during the 100-1000 year period following an assumed loss of Institutional Control. Data labels are the dose rates from LFLS exposures (blue) that are added to background (orange). All scenarios assume the same pathways (direct, inhalation and ingestion of soils/dust as well as ingestion of local diet items and surface water sources). Dose rates do not include dose from other sources such as cosmic radiation, medical procedures, natural and fallout radionuclides.

6.3.2 Future Occasional Use receptor

During the post- Institutional Control period (100-1000 years), a Future Occasional Use receptor (e.g. recreationalist or hunter/gatherer) may be exposed while camping on the LFLS soils (assumed three months per year) and eating non-farmed diet and drinking from the local Turtle Creek. The scenario is conservative as 100% occupancy and diet from the LFLS trenchtop area is assumed during the 3-month exposure period instead of a more probable wide-ranging hunting/gathering behaviour (away from the LFLS area). A further conservative assumption is that all drinking water comes from the ephemeral Turtle Creek, which receives some contamination mainly through surface water runoff.

- The lowest Dose rates (0.004 mSv yr^{-1}) are for the Engineered Cover options. No intrusion into the wastes was assumed for the casual/seasonal visitor who camped on the covers made from local clean soils (for both cover options). The dose rates reflect some ingestion pathway via drinking from the ephemeral Turtle Creek during the 3-month stay (128 L).
- The highest rates were for the In-situ Stabilisation and Exhume and Remove options (both approximately 0.5 mSv yr^{-1}), for which it is assumed the operations result in slight residual soil contamination that remains into the future (Figure 7).

Similar to the Future Subsistence Farmer scenarios, the modelling indicated that the highest dose rates were at 100 years, just after loss of institutional control. Thereafter, the contamination in the soil is decreased by radioactive decay as well as dispersion by natural processes. There is potential for extreme events in which trench wastes are uncovered and these are addressed in Section 6.6.

6.4 Relative dose contributions from different radionuclides

Results indicate that the relative contributions of radionuclides varied depending on the scenario/receptor:

- For the Public Background scenario, the largest percentage of dose comes from natural radionuclides (e.g. Ra and Th isotopes) with lesser contribution from global fallout (e.g. ^{137}Cs and Pu isotopes; Figure 8). Pathways include direct, dust inhalation and soil/dust ingestion relative to local soils not impacted by the LFLS.
- For the Public at Fence (PAF) scenarios, higher proportional dose contributions come from LFLS anthropogenic radionuclides (e.g. ^{60}Co, Pu isotopes) and from natural radionuclides (e.g. ^{226}Ra) which are present in LFLS wastes. Tritium has an elevated proportional contribution because of vapour/atmospheric transport in the PAF scenarios.
- For the scenarios involving the Engineered Cover and no penetration into the wastes, the dose rates are the same as for background because it is assumed local background soils are used in Cover construction.

6.5 Relative dose rates from different pathways

In the Future Farmer scenarios most of the dose rate (about 63%) was associated with ingestion of plants grown on contaminated soils (contaminated through "bathtubbing" transport as well as mixing after penetration of the trenches). While the plants were irrigated with local well water, the groundwater pathway was minor (total of about 3% of the total dose). Compared with this water pathway, dose rate from direct ground radiation is about ten times greater (Figure 9).

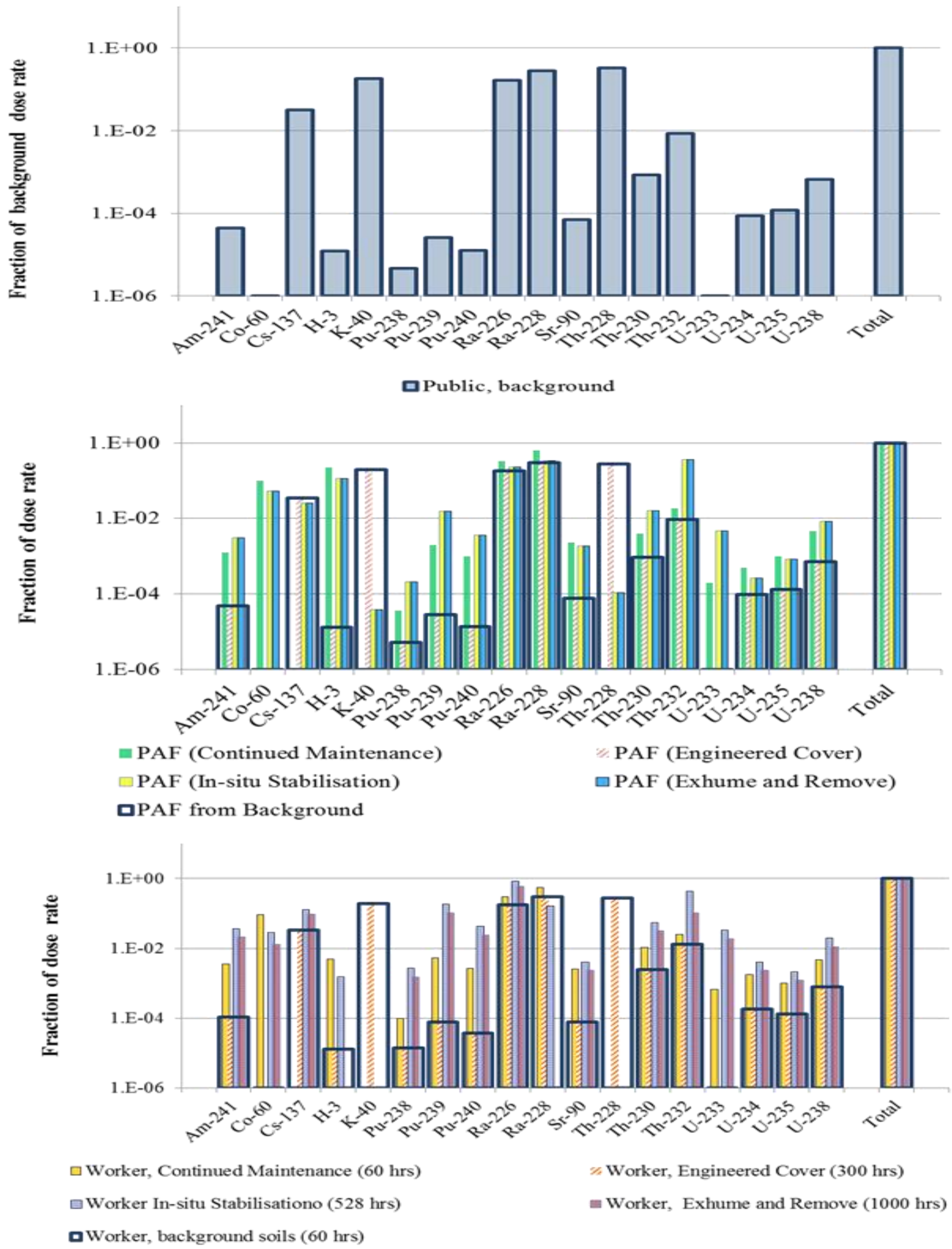


Figure 8. Relative dose contributions from study radionuclides for Public from background soils (top), Public at LFLS Fence (PAF, middle) and LFLS Worker Scenarios (bottom).

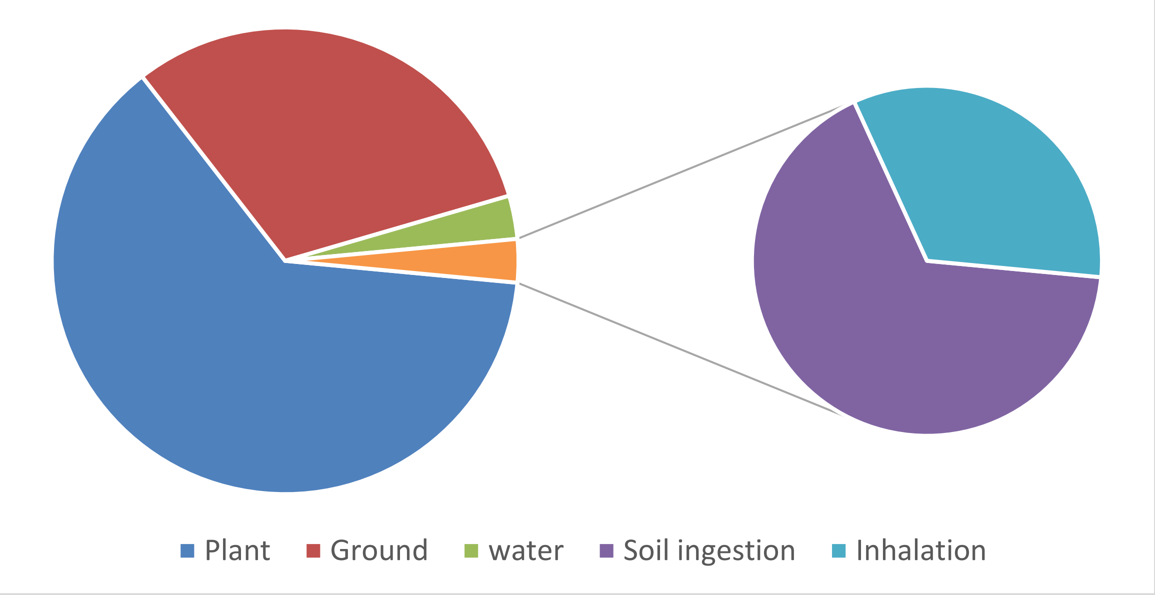


Figure 9. Relative mean dose contributions from different pathways for the Future Subsistence Farmer (Continued Maintenance Option). Plant = dose from ingestion of garden crops, Ground = dose directly from contaminated soil, Water = dose from contaminated drinking water. The orange slice of the pie chart on the left includes Soil ingestion = dose from inadvertent ingestion of contaminated soil, and Inhalation = dose from breathing contaminants in the air.

6.6 Evaluation of Uncertainty and Considerations for Interpreting and Using Results

Study results are site-specific in that they were calculated from measurements on site samples and data from site documents, utilised local meteorological data as well as site configuration and layout. However, even with site-specific data, the consideration of future scenarios necessarily involves making assumptions about exposure parameters such as where the receptor is located relative to the trench area, how long they may be exposed for, as well as consideration of their diet and behaviours (e.g. would a future occupant ignore the cloudy appearance of creek water and drink it anyway or will it always be cloudy?).

Because the future is unknown, the analysis used a specific set of assumptions that represent a range of possible exposure scenarios all of which are intended to be conservative (e.g. over-predict exposure). The key factors such as occupancy, dust concentrations in the air, diet consumption and other exposure assumptions entered into the model are overestimated and therefore lead to overestimating the dose rates. For example, the Public at Fence receptor is assumed to spend 24 hours a day, 365 days a year at the point on the LFLS boundary that has the highest dust transport based on known wind data. The resulting dose rate is higher than would be expected for other more realistic scenarios where public members spent most of their time outside the ANSTO buffer zone.

The RESRAD model has been used around the world for similar assessments and has been subject to a range of validation and model comparison studies that provide additional confidence in its use. However, the RESRAD model's contaminant fate and transport modules are relatively simplistic and therefore RESRAD serves as an initial tool that can be used to identify when more complex modelling may be useful (e.g. finite element computation, etc.). In this study, the following Table identifies areas that may be focused on in order to provide better input into future dose calculations.

Table 2. Dose outcome when considering uncertainty in key assumptions.

Adult vs. child	The Future Farmer and Future Occasional Use scenarios would reasonably be assumed to involve children/infants. The results above are for adults to allow comparison with the worker and other scenarios. When the receptor is changed from Adult to Infant in the RESRAD software (Dose Conversion Factor Package 3.02 INFANT), with no other changes, the dose rate increased by a factor of 6.8 for infants in the Future Farmer scenario, and by 2.8 for infants in the Future Occasional Use scenario.
Heightened bathtubbing or erosion events	The modelling study also examined extreme events that cause the trench wastes to appear in soils at the ground surface via biointrusion, erosion of the cover, or upward hydraulic transport (e.g.“bathtubbing effect”). These events would likely occur at discreet “hotspots (e.g. as occurred in the 2011 bathtubbing event described in Payne et al. 2013). Here we report results for model scenarios that are highly conservative in that rather than limiting the contamination to discrete areas (“hotspots”), it was assumed that wastes were brought to the surface across the entire trench-top area (e.g. maximum activity concentrations measured from the 2011 bathtubbing event were used across the entire trenchtop area). Using these conservative assumptions, the resulting dose rates for the various receptors were:

Public at fence (2018) mSv yr^{-1}	Trespasser (2018) mSv yr^{-1}	Worker LFLS Trench Area – 60 hrs (2018) mSv yr^{-1}	Future Subsistence Farmer (2118) mSv yr^{-1}	Future Occasional Use (2118) mSv yr^{-1}
2.1E-03	4.7E-05	3.5E-03	4.4E+01	4.1E-01

One of these highly conservative dose estimates (future farmer) exceeds the benchmark value of 1 mSv yr^{-1} for public exposure by more than one order of magnitude. Further, if it is assumed the cover erodes completely, and exposes the trench wastes directly across the entire LFLS trench area, then the dose rates in the above table would increase substantially (up to about 200 mSv yr^{-1} for the Future Farmer scenario and proportionally less for the other scenarios depending on their occupancy durations and exposure routes.

U and Th Progeny assumptions	The preliminary dose modelling was performed using an assumption that the progeny of ^{238}U and ^{232}Th were in secular equilibrium. This assumption fits well for the ^{232}Th decay chain, and for many radionuclides in the ^{238}U decay chain that have short half-lives (e.g. ^{222}Rn and ^{210}Po have <1 yr half-lives) but not for others (^{234}U and ^{226}Ra have a relatively long >1000 yrs half-lives). A firm estimate of progeny activity concentrations was not available at the time of modelling, and may not be possible for pre-1968 wastes. However, recent evaluation of records of wastes produced after 1968 (just after the LFLS disposal period) suggest activity concentrations of key progeny such as ^{234}U and ^{226}Ra may be as little as ~4% of the ^{238}U parent. If this same ratio is true for the pre-1968 wastes, then the initial modelling assumption of secular equilibrium is overly conservative as the progeny will be overestimated. To assess this, we evaluated the most important scenario (future farmer) using a range of ^{238}U progeny assumptions. The results indicate that if the progeny below ^{234}U are only 4% of the ^{238}U, then total dose rates are substantially decreased by up to a factor of 5.5.
Other radionuclides	The eighteen radionuclides used in this analysis were selected as being present in LFLS wastes and potentially important for dose. According to model output, other radionuclides that may be present contribute comparatively very small dose rates. For example, because Pu is present, it is known that the ^{241}Pu isotope is present. However, the ^{241}Pu isotope was not included in the dose modelling. Estimates of the ^{241}Pu inventory, confirmed by tests on water samples from the trench water, as well as core samples from near the trenches, indicate the 2018 activity concentrations of ^{241}Pu to be very similar to that of ^{239}Pu. For dose calculation, however, the Dose Conversion Factors for both ingestion and inhalation (DCFs; ICRP 119) of ^{241}Pu are about 50 times less than that of ^{239}Pu. Therefore, dose rates calculated today for ^{241}Pu would also be about 50 times less than that of ^{239}Pu (e.g. add about 1/50th to today's total Pu dose rate when including ^{241}Pu). The increment added by ^{241}Pu will be even smaller for future doses (e.g. after the end of the 100-year ICP) as it has a relatively short 14.4-year half-life. As it decays, the ^{241}Pu transfers dose potential to its progeny ^{241}Am which was included in the modelling scenarios. By including ^{241}Am, the dose modelling captured most of the original potential for ^{241}Pu's dose contribution. We also tested additional potential radionuclides such as ^{210}Pb and found their added dose rate was less than 1/1000 of total dose. Overall, the summed dose rates from the list of eighteen radionuclides used here is thought to be representative of total dose rates.
Soil vs groundwater pathway exposures	In the Future Farmer scenarios where shallow site groundwater is routinely ingested as the primary drinking water source, the dose rate associated with this pathway is about 3% of the total dose. It is about ten times less than the dose rate from direct ground radiation. The main reason for the relatively low water pathway result is that the site soils are clay rich and provide high adsorption capacity for the persistent radionuclides of concern in the future (e.g. Pu). In the model scenarios, it is assumed that the shallow well is at the downgradient edge of the trench area along the most likely flow path. The model was calibrated with ^{3}H data. However, the model was highly simplified and a thorough vadose zone/preferential flow model may provide different results.

The above model result is consistent with site monitoring data of trench waters gathered from a trench sampling port (2012 data). If a person ingests 510L of trenchwater directly (yearly consumption), their dose rate would only be 1.4 mSv yr^{-1} (using ICRP 41 ingestion DCFs for adults). Any transport through the clay-rich media surrounding the trenches will result in reduced dose rates due to adsorption and dispersion.

Vadose zone fate and transport considerations

This study assumed the top of the saturated groundwater layer (permanently saturated groundwater) was located at the bottom of the trenches. This is highly conservative as data from numerous site investigations have established that the soils below the trenches are mostly dry (down to at least 12m). Some amount of subsurface water moves in thin variably wet layers that have complex connectivity. These complex vadose zone conditions were not able to be modelled in RESRAD and, if important, would require a separate bespoke modelling effort. The approach used in the current RESRAD study was conservative because assuming the layers were saturated allowed for greater transport of contaminants out of the trenches that would otherwise be prohibited by dry soils.

However, given that the calculated dose rate for drinking trenchwater directly (yearly consumption),was only be 1.4 mSv yr^{-1} (see above), detailed refinement of vadose zone transport may provide interesting results on extent and rate of movement of subsurface radionuclides, but it would not largely change the overall dose assessment.

Varying breathing rates

Most scenarios were run assuming the standard RESRAD breathing rate of 8400 m^3 yr^{-1}. However, ICRP recommends a worker breathing rate of 10512 m^3 yr^{-1} (ICRP, 2012). For the worker scenarios, using the higher breathing rate would increase total doses by 2.5%. This small increase reflects the relatively minor contribution from inhalation as compared with other pathways.

7. Environmental Protection- Screening Assessment

A screening assessment was performed on potential dose rates to environmental receptors (wildlife) associated with the LFLS site, Lucas Heights, NSW. The purpose of this assessment was to use a standard screening approach to determine if potential dose rates to local wildlife from current and near-term future exposures at LFLS are below international benchmarks.

The assessment used methods from international best practice as laid out by the ARPANSA Guide: Radiation Protection of the Environment (ARPANSA, 2015) which is consistent with current approaches set forth by the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA).

Results of the standard screening (ERICA Tier 1) for current and near-term conditions (assuming no major remediation) indicate risk quotients for all radionuclides are orders of magnitude below 1 (Table 3). This indicates the site passes the international screening (harmful effects to environmental receptors are not expected) in its current condition and in the near-term future.

Table 3. Current activity concentrations and resulting risk quotients.

	Current soil (trench-top) activity concentrations Bq/g	Risk Quotient (ERICA Tier 1)
Sr-90	0.017	8.36E-06
H-3	0.4	1.52E-04
Co-60	0.002	2.74E-07
Cs-137	0.235	1.03E-04
Ra-226	0.029	1.05E-03
Ra-228	0.081	6.31E-06
Th-228	0.042	1.09E-03
Th-230	0.0193	7.14E-05
Th-232	0.0314	9.98E-05
U-234	0.0188	1.62E-04
U-235	0.0006	7.94E-06
U-238	0.012	9.02E-05
Pu-239	0.00473	6.25E-06
Pu-240	0.00233	2.50E-06
Am-241	0.0036	4.64E-05

An additional dose assessment (ERICA Tier 2) was also performed to provide baseline information. The assessment considered exposure to a range of terrestrial organisms (Table 4) comprised of Site Representative Organisms that actually dwell at or visit the LFLS. Dose rates to these organisms were estimated using the ERICA tool with soil radioactivity concentrations comprising the same site-specific data as used in the human dose assessment. Three scenarios were considered: current conditions (2018), near future conditions after a major remediation (exhume and remove scenario above) and a highly conservative scenario where the organisms are exposed to trench wastes directly (e.g. burrowing or surface expression of the wastes). The approach used conservative assumptions in this screening assessment, such as 100% occupancy for wallabies even though a small number visit only at night.

Results indicate that grass was the organism that had the consistently highest modelled dose rates although annelid and mammal dose rates were only slightly less (grass dose rates shown in Figure 10). The dose per each radionuclide as well as total dose indicate all projected doses at the site are less than the most conservative international benchmark (10 µGy/hr) (Andersson et al., 2009; Garnier-Laplace et al., 2008). This supports the Tier 1 Screening result and further indicates the site is unlikely to pose substantive harm to wildlife. The above uses standard approaches. It may be possible to predict higher dose rates when using specific approaches such as assessing only the roots of trees that access the wastes (Johansen et al., 2012a), which indicates that potential biointrusion (e.g. trees, burrowing animals) should be further considered in the design and management of all future options pursued for the LFLS. It also indicates that biointrusion should be minimised in current and near-term management plans.

Table 4 Terrestrial Organisms considered in this study. The left column is the standard organism category used in ERICA. The right columns indicate representative organisms present at the site within the ERICA category.

Standard organism	Site Representative organism	
Grasses & Herbs	*Poaceae spp.*	Grass
Tree	*Acacia longifolia*	Acacia tree
Annelid	*Lumbricidae spp.*	Earthworm
Arthropod	*Acrididae spp.*	Grasshopper
Reptile	*Varanus varius*	Goanna
Mammal - small	*Wallabia bicolour*	Swamp Wallaby

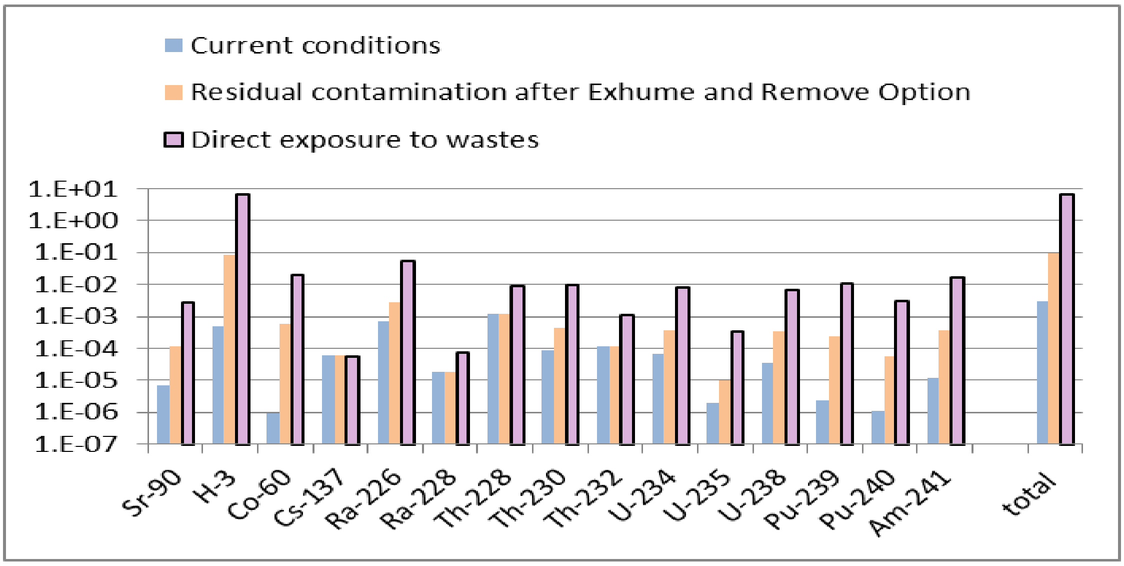


Figure 10. Dose rates (µGy hr^{-1}) to grass (which appears to be the limiting organism) from site radionuclides under current conditions, assumed conditions following exhumation and removal, and direct exposure to wastes (e.g. loss of cover or excessive bathtubbing). Dose rates are below the most conservative international benchmark (10 µGy/hr).

8. Key Points of the Human and Environmental Dose Assessments

When comparing to a benchmark value of 1.0 mSv yr^{-1} for chronic exposure to members of the public (ICRP, 1999), the following conclusions can be drawn:

- For the near future, modelled dose rates to members of the public (trespassers, public at the fence boundary) are orders of magnitude below the 1.0 mSv yr^{-1} benchmark when assuming Institutional Control.
- For the near future, modelled dose rates for typical workers (e.g. lawnmowers, etc.) were well below the benchmark for public exposure. The benchmark for public exposure is relevant as the type of employees involved will typically not be classified as "radiation workers."
- Modelled dose rates to workers who may implement the management options varied widely. The dose rate for the In-situ Stabilisation worker was higher than that of the Continued Maintenance worker, but still below the 1.0 mSv yr^{-1} benchmark. The Exhume and Remove worker dose rate was at the benchmark. The increase in dose rates was due to a more direct exposure to wastes and to longer respective assumed work durations. For comparison, all modelled dose rates were below the 20 mSv yr^{-1} benchmark for radiation workers.
- Modelled dose rates for members of the public in the future, after the end of the Institutional Control period (100-1000 years), varied greatly with the lowest being a Future Occasional Use receptor (hunter/gatherer or recreationalist) on an Engineered Cover. The highest modelled dose rates (about 10 times more than the benchmark) were for a Future Subsistence Farmer in the scenarios where the trench wastes were left in place and could be accessed (e.g. Continued Maintenance and Engineered Cover without intrusion prevention measures). In these scenarios, it was conservatively assumed the wastes are penetrated and mixed with surface soils which caused dose directly and via farmed crops.
- The mean/best case dose estimates presented here are intended to be conservative. A key assumption - that the ^{238}U progeny are in secular equilibrium - is likely highly conservative. Recent review of reports suggest key progeny may be only ~4% of their parent. Other assumptions and uncertainties (section 6.6 above) should also be considered when interpreting results.
- The modelling in this report is preliminary in that a specific management alternative has not yet been selected. Future modelling can be refined and used to support/optimise any selected management approach for the site.
- Regarding dose rates to biota, the site passes the standard international screening test (ERICA Tier 1) in which highly conservative assumptions are made. Additional analysis (ERICA Tier 2) indicated that for representative biota under a range of conservative exposures the dose rates are below international benchmarks that would indicate potential harm.
- Table 5 provides the key model outcomes. See text above for assumptions, details and discussion of ranges due to uncertainty.

Table 5. Summary of annual dose rates (mSv yr^{-1}) added by LFLS exposures to a range of hypothetical human receptors. Values are means/best case (with conservative exposure assumptions and mean site activity concentrations).

	Future Subsistence Farmer	*Future Occasional Use*	*Worker, LFLS Trench Area*	*Public at fence*	*Public Bushwalker*	*Public Trespasser*
Exhume and Remove	9.2E-01	4.8E-01	1.0E+00	6.5E-04	4.1E-05	2.3E-05
In-situ Stabilisation	1.9E+00	4.8E-01	1.5E-02	6.5E-04	4.1E-05	2.3E-05
Engineered Cover (intrusion prevention)	2.2E-01	4.2E-03	3.4E-05	1.0E-09	1.0E-09	1.0E-09
Engineered Cover	1.1E+01	4.2E-03	3.4E-05	1.0E-09	1.0E-09	1.0E-09
Continued Maintenance, Monitoring	1.1E+01	1.0E-01	5.4E-04	3.4E-04	2.2E-05	7.2E-06

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10. Revision Details

Rev	Description of Revision	Reviewed
0	Issued for review by MJ 29 April 2019	TEP, JC
1	Issued for review by MJ 15 August 2019	TEP, AK, RB
2	Issued final Draft 18 December 2019	MJ, TEP
3	Issued Final ANSTO Report March 2020	MJ

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12. Appendices

Table A1. Parameters used in RESRAD modelling.

	Units	RESRAD default	Used in standard LFLS analysis	Comments
General				
RESRAD version			7.0	Most recent version
Dose library and risk factors		DCFPak 3.02		Adult, Child
Progeny cut-off half-life	days	180		
Exposure duration	years			See Scenarios. Varies by scenario.
Contamination & Cover				
Dimensions of contaminated area to be modelled	m^3		60mx120m	60mx120m. RESRAD does not allow for complex (multi-trench) sources. As conservative approach, we consider the entire 60mx120m to be contaminated uniformly. Activity concentrations are true to actual estimates (not diluted by the larger modelled source volume).
Depth of contaminated layer	(m)		1-3 m	Note, for scenarios exposed to surface soils (e.g. lawn mower in current conditions, public in background conditions) the model considers surface soil as the "contaminated layer" which simply reflects that the current surface soils have some residual LFLS contamination as well as natural radionuclides and atmospherically-deposited fallout.
Total porosity & effective porosity of	fraction	0.4	0.4	

contaminated material				
Dry Bulk Density of contaminated material	g/cm^3	1.5	1.5	
Soil erodibility factor	tons/acre	0.4	0.4	
Field capacity of top-layer	fraction	0.3	0.3	
Hydraulic conductivity of contaminated material	m/yr	10	30	
b parameter of contaminated material		5.3	5.3	
Long. dispersivity		0.05	0.05	
Vol water content of cover		0.05	0.05	
Length of contam. parallel to gw flow	m	124	124	
Depth of soil mixing layer	m	0.15	0.15	
Deposition vel of dust	m/s	0.001	0.001	.001 for all dust-sorbed rads
Irrigation	m/y	0.2	0.2	
Evapotransp. coeff		0.5	0.7	
Runoff coefficient			0.4	
Rainfall Runoff factor		160	160	
Slope-steepness factor		0.4	0.4	
Cover thickness	m	0	1	For scenarios where the receptor is exposed to surface soils (e.g. worker, trespasser), the surface soil activity concentrations were used (e.g. cover=0m).
Cover and Management factor		0.003	0.003	

Support Practice factor		1	1	
Cover total porosity & effective	fraction	0.4	0.4	
Cover Dry Bulk Density	g/cm^3	1.5	1.5	
Cover Soil erodibility factor	tons/acre	0.4	0.4	
evapotranspiration coeff	fraction	0.5	0.5	GNIP
Wind speed		2	2.86	ANSTO MET ave.
precipitation	m/yr	1	1.01	
Saturated & Unsaturated zone parameters				
Sat. thickness	m	100	100	Saturated thickness is unknown. If needed, a groundwater model should be developed for the site with software that can accommodate site complexity.
Distribution Coeff (Kd)	cm^3/g	Var. by nuclide	Var. by nuclide	Site Specific Kds were used for Co (450), Cs (1300) and Sr (310) based on ANSTO laboratory work. Other Kds were from IAEA documents for silty-clayey soils (Am=4300, Pu=1100, Ra=2500, Th=1900, U=200)
Sat. Z. Dry Bulk Density	g/cm^3	1.5	1.5	
Sat. Z. tot. porosity	fraction	0.4	0.4	
Sat. Z. eff. porosity	fraction	0.2	0.2	
Sat. Z. Field capacity		0.3	0.3	
Sat. Z. Hydraulic conductivity	m/yr	100	30	The value of 30 fits well within the range of field estimates for LFLS. It also was the "best fit" when calibrating the model to known H-3 data (see report).
Sat. Z. Hyd gradient to well		0.04-0.05	0.04-0.05	

Sat. Z. depth of aquifer contributing	m	10	10	
Sat. Z. long. dispersivity	m	3	10	
Sat.Z. horiz. lateral dispersivity	m	.4	1	
Sat. Z. vert. lateral dispersivity	m	0.02	0.02	
Well pumping rate	m^3/yr	5100	5100	
Unsat thickness (2 unsat zones)	m	4	3	The saturated zone assumption was highly simplified with the top beginning at base of bottom of the trenches (3m.) This has some basis as at LFLS thin saturated/semi-saturated lenses intersect the trenches with a prominent one at base of trenches. However, the full (0-12m) vadose zone was too complex to model, so the above simplified and conservative assumption was made.
Leach rate		Var. by nuclide		
Distribution Coeff (Kd)	cm^3/g	Var. by nuclide		
Unsat. Dry Bulk Density	g/cm3	1.5	1 to 1.5	
Unsat. Soil erodibility factor	tons/acre	0.4		
Unsat. tot porosity	fraction	0.4	0.4, 0.4	
Unsat. Field capacity		0.3	0.3	
Unsat. Hydraulic conductivity	m/yr	10	50	
Unsat. b parameter of contaminated material		5.3	5.3.	
Unsat. long. dispersivity	m	0.1	0.1.	

Distance, cont edge to well	m		15	
Distance, cont centre to well	m		51	
Convergence criteria		.001	.001	
Air Transport				
Release height	m	1	1	
Release heat flux	cal/s	0	0	
Anemometer height	m	10	10	
Ambient temp.	K	285	290	
AM atmosph. mixing height	m	400	400	
PM atmosph. mixing height	m	1600	1600	
Grid spacing for areal integ.	m	10	10	
Met Star File			Holsworthy	Used a STAR file for RESRAD OFFSITE from the nearby Holsworthy station (ANSTO MET data did not have sufficient cloud cover data record). The basic data (e.g. wind rose) from Holsworthy appears very consistent with that of ANSTO.
Exposure locations				
-age class				Adult, child
Fraction of time exposed (occupancy)	fraction	Varies by location and receptor		See Scenarios.
inhalation rate	m^3/yr	8400	8400	
mass loading for inhalation	g/m^3	0.0001	0.0001 to 0.0006	Public=0.0001, Workers =0.0006. Workers should have higher mass loading than public. The 0.0006 is suggested as a reasonable maximum from RESRAD Hand Book p 116.

Mean onsite mass loading	g/ m^3	0.0001	0.0006	0.0006 for workers, trespasser, and agricultural scenarios.
Indoor/outdoor dust conc.		0.4	0.4	
Dwelling External gamma penetration factor		0.7	0.7	
Soil ingestion	g/yr	36.5	36.5 to 73	Workers have higher soil ingestion than public. (x2=73 for workers)
Dwelling Irrigation	mm/yr	0.2	0	
Dwelling Evapotransp.		0.5	0.5	
Dwelling Surface material runoff coefficient	fraction	0.2	0.2	
Dwelling Depth of soil mixing layer	m	0.15	0.15	
Dwelling Soil volumetric water content	t/yr	0.3	0.3	
Dwelling soil dry bulk density	g/cm ^{3}	1.5	1.5	
Dwelling soil erodibility factor		0	0	
Dwelling Slope-steepness factor		0.4	0.4	
Dwelling Cover and Management factor		0.003	0.003	
Dwelling Support Practice factor		1	1	
Ingestions Pathways				
Crops/pasture area over contamination				

CRs for: Veg Leafy veg Pasture Livestock feed grain Meat Milk Fish crustacea	Ratio soil-to-org, water-to-org	Var. by nuclide	Var. by nuclide
Crops/pasture Irrigation	(mm/yr)	0.2	0.2
Crops/pasture Surface material runoff coefficient	fraction	0.2	0.2
Crops/pasture Depth of soil mixing layer	m	0.15	0.15
Crops/pasture Soil erodibility factor	t/yr	0.4	0.4
Crops/pasture Slope-steepness factor		0.4	0.4
Crops/pasture Cover and Management factor		0.003	0.003
Crops/pasture Support Practice factor		1	1
Water consumption: Humans Beef dairy	L/yr	1.4, 50, 160	1.4, 50, 160
Food storage times	d		
Milk ingestion	L/yr	92	92
Meat ingestion	kg/yr	63	63
Fruit, grain, non-leafy veg	kg/yr	160	160
Leafy veg.	kg/yr	14	14

Soil (incidental)	g/yr	36.5	36.5	
Livestock water				
Livestock fodder intake for meat	kg/d	68	68	
Livestock fodder intake for milk	kg/d	55	55	
Livestock water intake for meat	L/d	50	50	
Livestock water intake for milk	L/d	160	160	
Livestock intake of feed & feed factors	varies	varies	varies	
Livestock intake of soil	kg/d	varies	varies	
Depth of soil mixing layer for ingestion pathway	m	0.15	0.15	
plant factors	varies	varies	varies	Used default CRs in all cases which are thought to be conservative (e.g. overpredict uptake).

Table A2. Soil and waste activity concentrations (Bq/g) for background (local area not impacted by LFLS) and a range of scenarios conditions.

	2018 Local Back- ground surface soils (Bq/g)		2018 Surface soils over trenches (Bq/g)		Assumed Surface soils after Grouting (1968 basis) (Bq/g) (1968)		Assumed Surface soils after Excavation (1968 basis) (Bq/g) (1968)		Trench Wastes Best Estimate (1968 basis) (Bq/g) (1968)		Trench Wastes Max Estimate (1968 basis) (Bq/g) (1968)	
Am-241	0.00038	1, 2	0.0036	2	0.12	7	0.12	7	2.4	10	5.2	10
Co-60	1.00E-09	5	0.0020	2	1.20	7	1.2	7	24	10	40.2	10
Cs-137	0.013	1, 2	0.013	2	0.17	7	0.17	7	3.5	10	5.9	10
H-3	0.004	3	0.4	3	69	7	69	7	1380	10	5396	10
K-40	0.23	4	0.23	6	0.23	6	0.235	6	0.235	6	0.24	6
Pu-238	0.00005	1, 2	0.00014	2	0.01	7	0.012	7	0.24	10	0.52	10
Pu-239	0.00025	1, 2	0.0047	2	0.51	7	0.506	7	10.12	10	21	10
Pu-240	0.00012	1, 2	0.0023	2	0.12	7	0.117	7	2.34	10	6.1	10
Ra-226	0.02	4	0.029	8	0.11	7	0.107	7	2.15	8	2.23	8
Ra-228	0.056	4	0.081	9	0.08	7	0.081	7	0.25	9	0.27	9
Sr-90	0.0017	2	0.017	2	0.28	7	0.28	7	5.6	10	6.62	10
Th-228	0.042	4	0.042	2	0.04	7	0.042	7	0.25	9	0.26	9
Th-230	0.0092	2	0.019	2	0.11	7	0.107	7	2.15	8	2.23	8
Th-232	0.021	2	0.031	2	0.03	7	0.031	7	0.25	10	0.27	10
U-233	1.00E-09	5	0.0048	2	0.65	7	0.655	7	13.1	11	26.3	11
U-234	0.0053	2	0.019	2	0.11	7	0.107	7	2.15	9	2.23	9
U-235	0.0002	2	0.0006	2	0.003	7	0.003	7	0.06	10	0.06	10
U-238	0.0047	2	0.012	2	0.11	7	0.107	7	2.15	10	2.23	10

[1] Smith et al., 2016

[2] J.Harrison 2012-2015 data

[3] From Hughes et al., 2011 (10 Bq/L) * 0.4 porosity

[6] using background value (not enhanced in wastes)

[7] Max of 5% Trench wastes or current Trench top soils

[8] Ratioed from U-238 chain (assumed in equilibrium)

[4] From ANSTO nr Bld 20b and 96 (data from R. Blackley, 2018)

[9] Ratioed from Th-232 chain (assumed in equilibrium)

[5] U-233 is assumed to be at trace levels (instead of 0) in bkg soils

[10] from Payne (2020b)

(the Background U-234 value included U-233 at trace levels).

[11] note that average U-233/U-234 ratio is 3.2 from Harrison et al 2016 (ranges from ~0.1-17.1)

Table A3. Kd summary for Co, Cs and Sr based on ANSTO testing of corehole samples. AM = arithmetic mean; GM = geometric mean; GSD = geometric standard deviation; N = no of samples.

	Kd (mL/g)		
	Co	Sr	Cs
AM	450	310	1300
Std dev	730	380	890
LOW	18	11	310
HIGH	3300	2300	4100
GM	210	180	1000
GSD	3.2	2.9	1.9
N	64	69	66