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| Activation Study of Various Alloys in the Beam Extraction Area |
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# Executive Summary

A variety number of different alloys are studied to evaluate contact dose rates as a function of time close to the neutron beams. Based on these inputs, a list of allowed materials and a list of forbidden materials are presented meeting ALARA dose rate objectives for different maintenance schemes.

# Purpose

This document is a list of materials that are considered to be allowed for use. This is a standard issued by NOSG that restricts the materials that can be used in areas experiencing high neutron fluxes, particularly in the bunker area, but more generally along the beam axes, in order to meet access requirements for maintenance, and to adhere to the ALARA principle (“As Low As Reasonably Achievable”).

# Scope

This document is intended to apply to any material within 1 metre of a high flux region, which mostly will apply to the beam axis, but could apply to other regions depending on scattered beams etc. Ongoing neutronics studies, particularly of the bunker, will guide this development as the project matures. The beam spectrum changes significantly after you lose line of sight of the target, and leave the bunker. For this reason, this page will result in two documents, one for the bunker area, and one for cold/thermal beams outside line of sight. The grey area of straight beams outside the bunker will require subsequent effort.

# Contributors

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# Currently Forbidden Materials

Tungsten

Allowed only in T0 chopper hammer.

Europium

PPB levels in sand and aggregates in concrete may be unacceptable, and these isomer processes (long lived excited states) appear to be not fully modelled in some of the physics software.

Antimony

Standard alloying ingredient in **lead** and some **bronzes**. Antimony-free lead must be ordered specially, but other impurities are problematic at very low levels (Silver, gold later in this table).

Cobalt

Impurity in **nickel**, finds its way into Ni-based stainless steels and other Ni components, making many stainless steels a waste issue. Some high-energy channels produce Co-60 (via e.g. reaction in copper) but this can be acceptably low for hands-on maintenance (see copper below).

Uranium

Depleted uranium shielding has been used as “free” high performance fast neutron shielding at some accelerator facilities, but it breeds Pu amongst other problematic elements.

Inconel

NiCr alloy typically used in aerospace, and consequently choppers. It can only be used in chopper hammers and nowhere else.

Zinc

Zinc activates fairly strongly in **brasses** (Zn-65, 100s contact dose), and when used as plating in mild steel it forms oxides as fine white powder. Even though Ni may contain a little Co impurity, all plating on mild steel near the neutron beams needs to be Ni.

Silver

Impurity in **lead** and other heavy metals, Ag-110 is a problem above 0.02% by mass in lead.

Gold

Impurity in **lead** and other heavy metals, 0.01% by mass is borderline.

Tin

Ingredient in **bronzes** (where shielding from other materials seem to reduce the activation significantly) but also zircaloy4, which creates a long term issue in the form of Sb-125 (10 contact dose).

Hafnium

Generated in **tungsten**.

Iridium

Sometimes used as a convenient soft metal seal.

Scandium

Tantalum

Generated in **tungsten**.

Terbium

Thorium

Strontium

Cesium

# Method

The calculations were performed using PHITS v3.0 [1] to generate the spallation products, and the output from the resulting dchain tally was processed using dchain v2001 (part of the PHITS package) to yield the activation as a function of time.

In fig. 1, a geometry of the PHITS simulation is sketched, where the cell used for the activation calculations is labelled “106”.

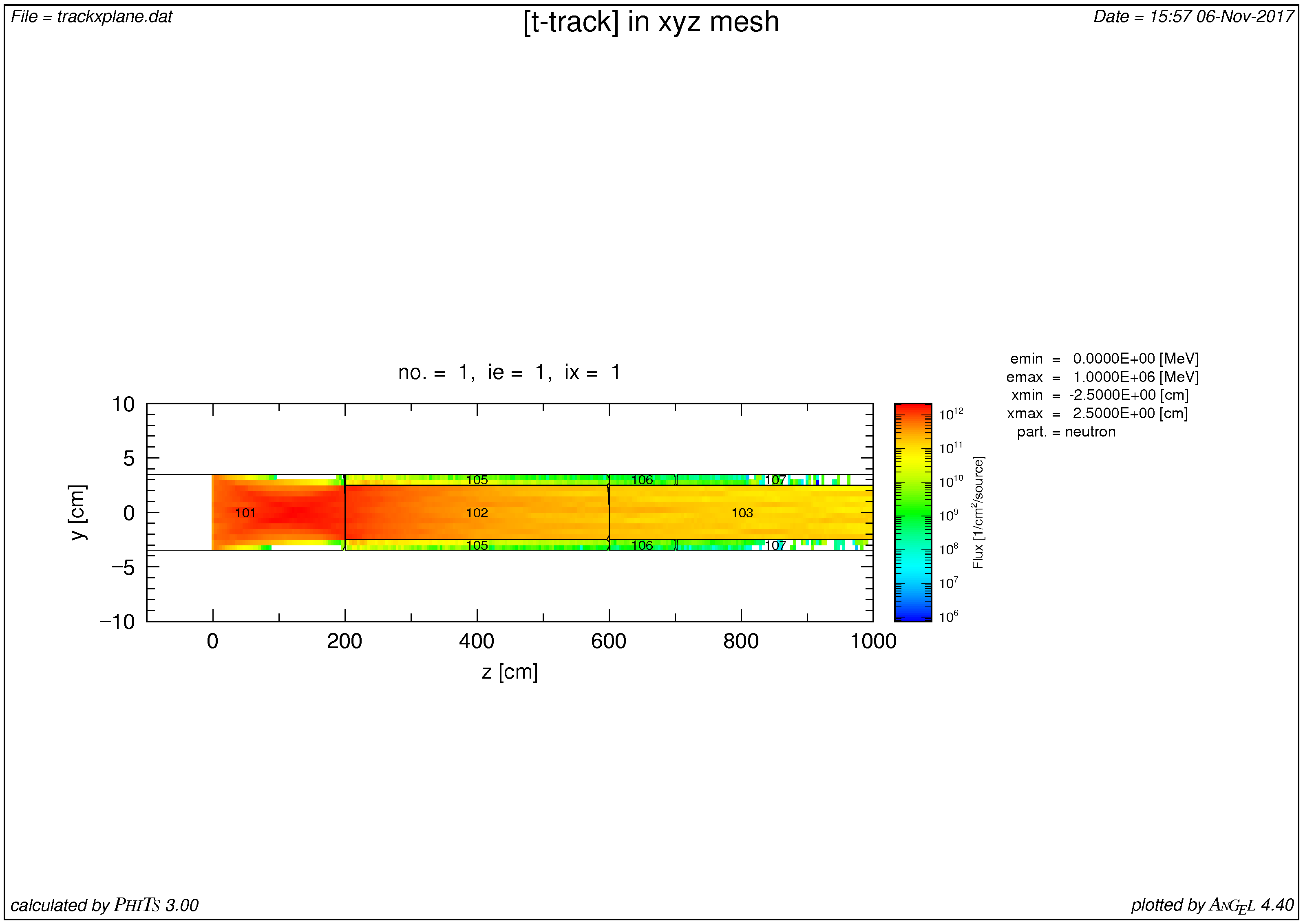


Figure 1: Geometry of the simulation, in this case AISI 1005 mild steel.

Supermirror physics is turned on, with an *m*-value of 3.0. The current NMX source term (from Valentina Santoro) was used as a source spectrum. 50,000 source trajectories were used, with duct-source variance reduction to illuminate uniformly between 2-8 m and dpf=1.0E-02. The results were benchmarked against similar calculations, performed independently by two people in the target division using MCNP and CINDER, and were in good agreement.

The time evolution of the contact dose was calculated by dchain version 2001, and integrated over a 20x20 cm2 area. If there is a different integral standard at ESS this can be adjusted extremely quickly.

For the stainless steels, it was assumed that the total Co impurity of Ni was 0.2%, as described by Outokumpu as their nuclear-grade requirement.

# Contact Dose Rate Requirements

If the dose rate is below 3 , we assume that it is OK for hands-on maintenance.

If the dose rate is below 25 , we assume that it meets the requirements for rad-workers to perform hands-on maintenance. The ALARA principle still needs to be used fully in the design process, so materials in this category need to be minimised in favour of those below the 3 category.

If the dose rate is above 25 , we assume that the material is unacceptable.

# Results

## Overview of Material Types

In fig. 2, a representative selection of compliant alloys are shown. This figure should be used *as a guide* to the optimisation of the worker dose rate, in order to minimise it as much as possible. For example, for structural supports, vacuum housings, etc., there is an obvious benefit in all cases to *use approved aluminium alloys wherever possible*.

For shielding things become slightly more complex. For access after 3 days there is a clear advantage in the use of lead and copper instead of steel. On the other hand, a 1 day access is the opposite - lead and copper would actually increase the dose rate compared to steel. It is therefore imperative that realistic working plans are used for this optimisation. It is not acceptable to assume and design for a 1 day working access, when in reality the equipment cannot be disassembled faster than 4 days. To do so would permanently place the workers in a blue radiation zone instead of a green radiation zone. In the following sections, it is generally assumed that the longer shutdowns are more strongly weighted, since that is where worker dose would mostly accumulate.

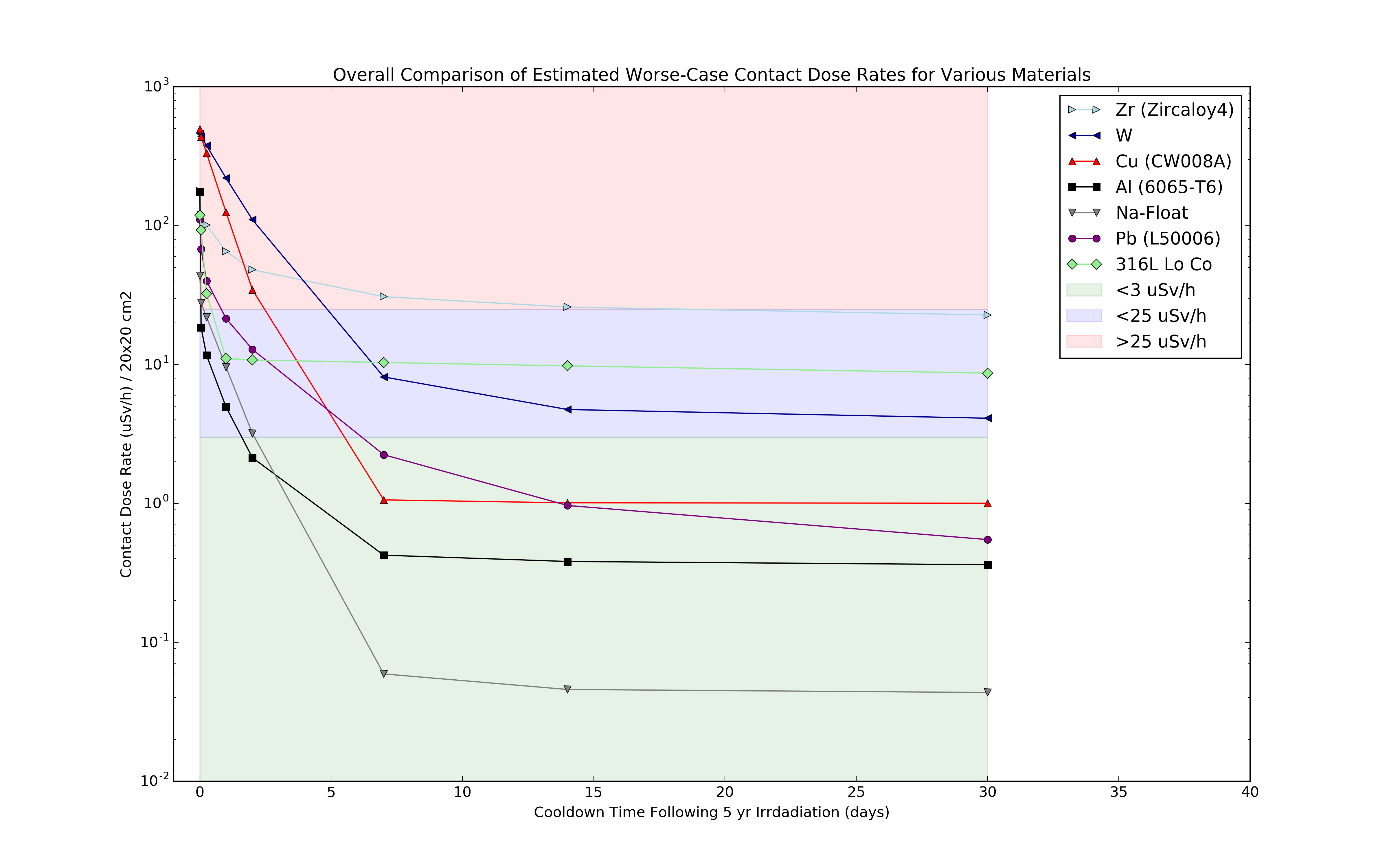


Figure 2: Simulated contact dose rates for various materials, as a material guide for worker dose minimisation in the bunker area.

In the following sections, we examine the types of alloy by category.

## Allowed Aluminium Alloys

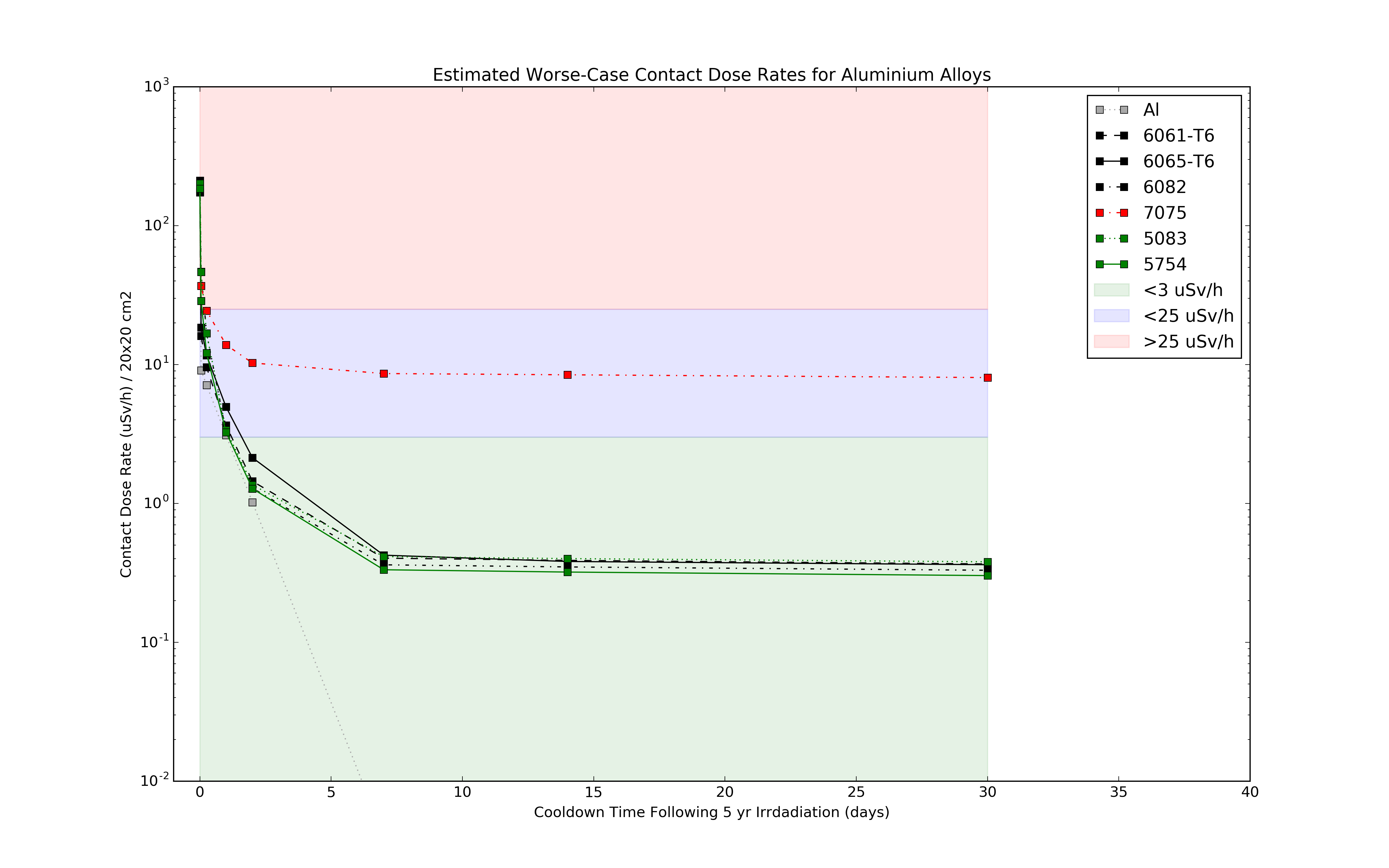


Figure 3: Simulated contact dose rates for different aluminium alloys in the bunker area.

Allowed materials providing hands-on maintenance after 1-2 days:

* 6061-T6
* 6065-T6
* EN AW 5083
* EN AW 5754
* EN AW 6082 (DIN AlMgSi1)

## Allowed Copper Alloys

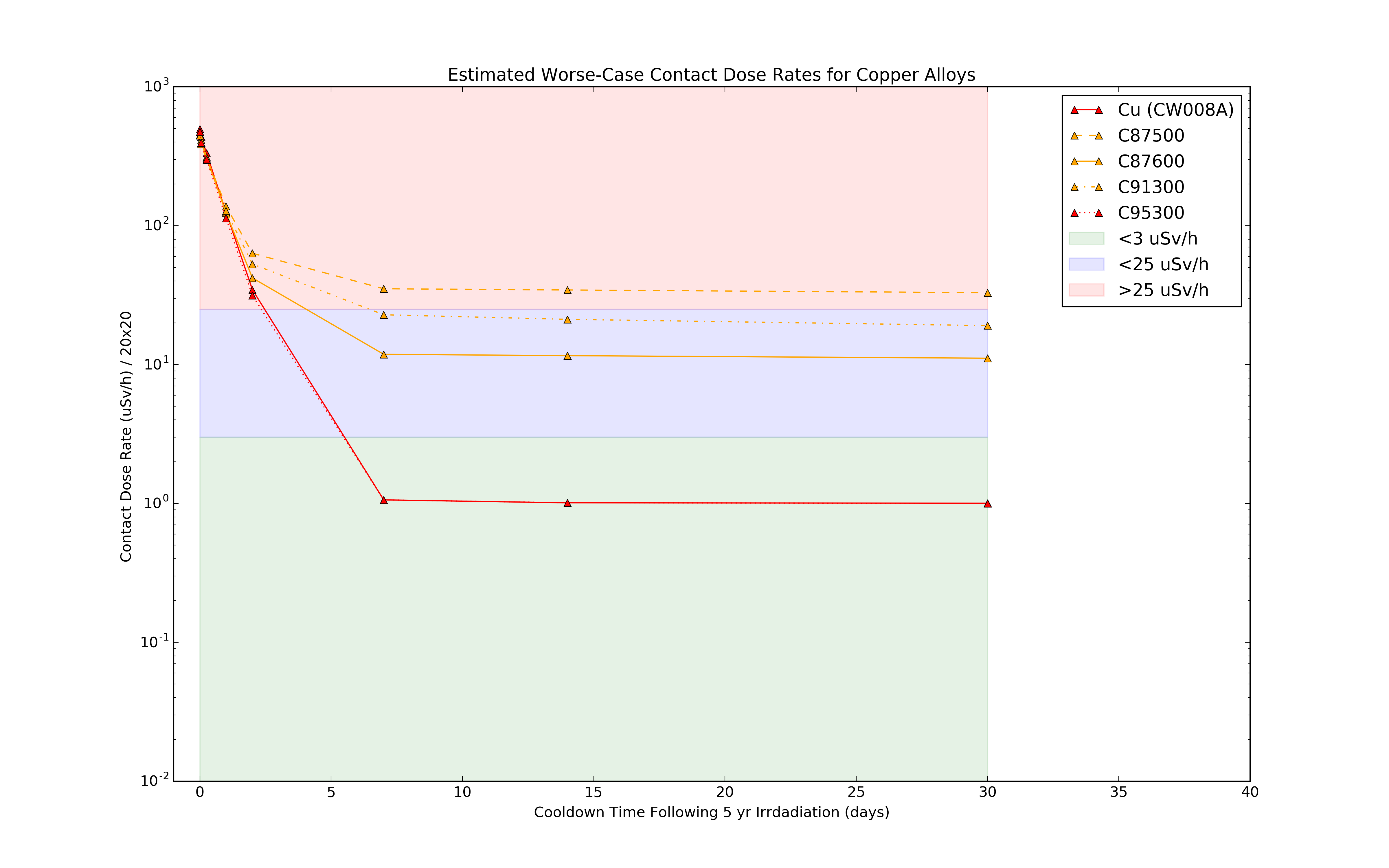


Figure 4: Simulated contact dose rates for different copper alloys in the bunker area.

Hands-on maintenance after >7 days. The residual activation after 1 month (contact dose is around 1 even at the monolith wall) is dominated by tiny amounts of Co-60, which are produced from copper via reactions.

Alloys must be antimony-free and low cobalt. Many bronzes have lead, antimony, or nickel with cobalt impurities. There is one currently allowed bronze that meets the requirements.

* CW008A or equivalent
* C95300 is almost identical to pure copper in terms of activation

CW008A can be used for guide substrates, but equally can be used in other high-flux regions (e.g. bunker) as shimming material with good cool-down properties (ALARA).

## Allowed Steels

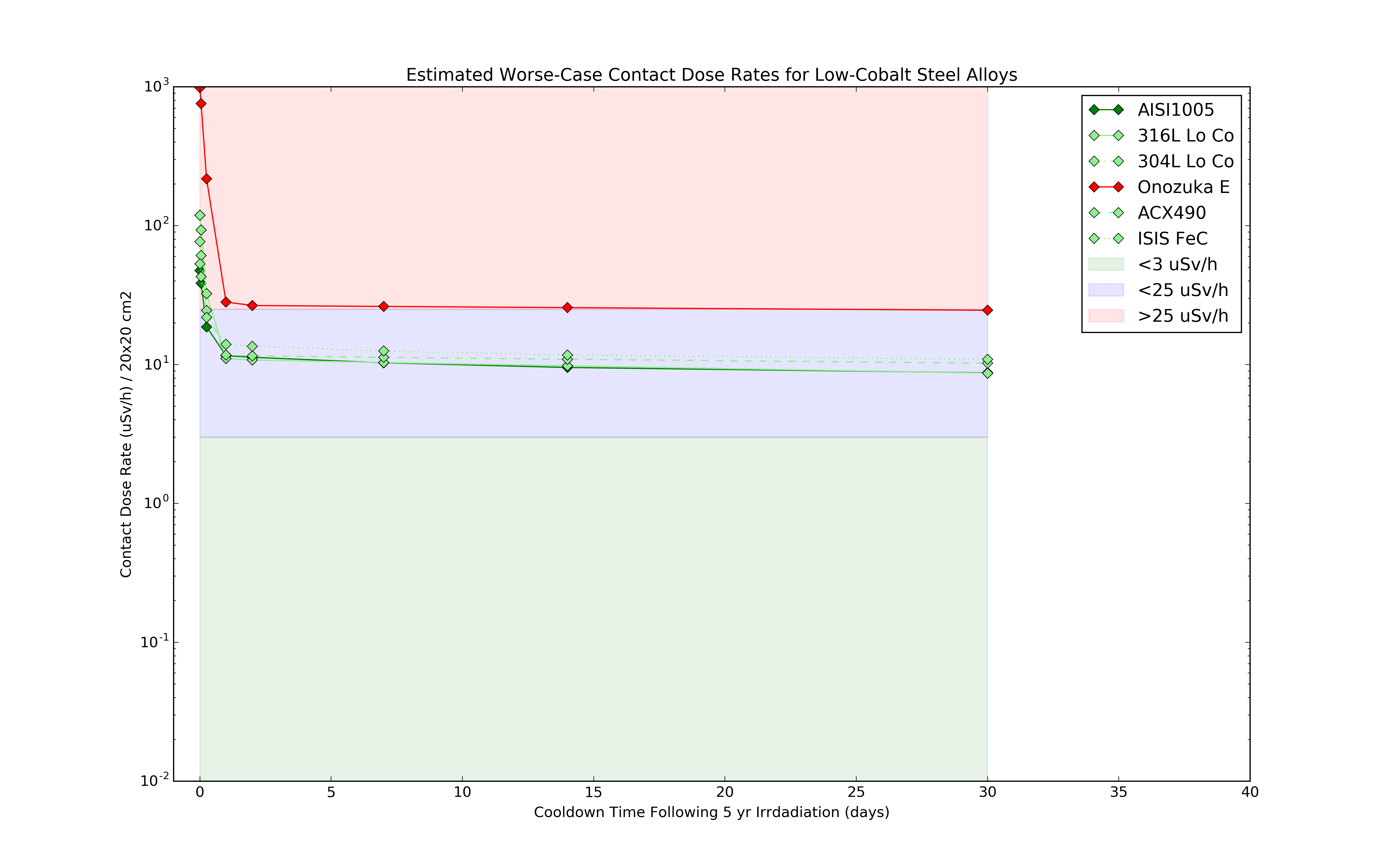


Figure 5: Simulated contact dose rates for different steel alloys in the bunker area.

Only use this where their use is essential, and cannot be fulfilled by approved aluminium, copper, or bronzes. All of these materials allow rad-worker maintenance only:

### Allowed Mild Steels

* AISI 1005-1025
* EN10025 S275JR /1.0044
* ASTM A36
* EN 10025 S235JR /1.0037
* ASTM A570 Grade 33

### Allowed Low cobalt stainless steels

* ACX490
* 304L low cobalt
* 316L low cobalt

## Allowed Antimony-Free Lead Alloys

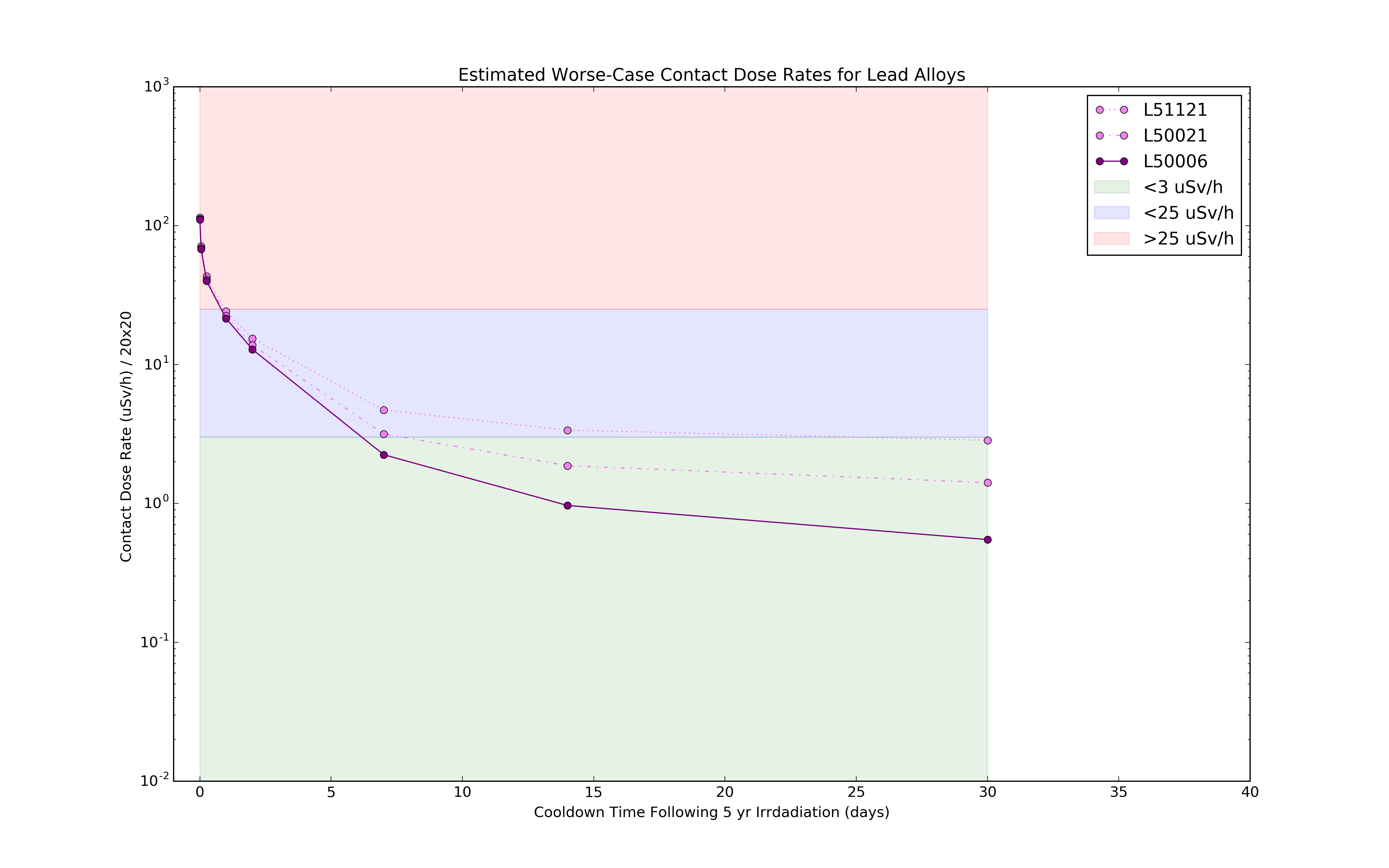


Figure 6: Simulated contact dose rates for different lead alloys in the bunker area.

Antimony and silver content will be measured as part of site acceptance testing. Bordeline cases (L51121 that needs 30 days cooldown) are to be avoided.

* L50006 - hands-on access after 1 week
* L50021 - hands-on access after 2 weeks

# Material Definition Files

The materials definitions are based on the data in the following tables.  
Raw PHITS input files are available on request and/or in NOSG repositories.  
Note that due to a bug in PHITS v3.0, carbon is entered as C-12 rather than C.  
This is not considered to be a significant problem, since the isotopes of carbon are not dominant contributors to contact dose compared to the other materials in the inventory.

## acx490.mat

Table 1: Material definition of acx490.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Fe | 79.875 |
| C12 | 0.04 |
| Si | 1.0 |
| Mn | 1.0 |
| P | 0.04 |
| S | 0.015 |
| Cr | 18.0 |
| N | 0.03 |

## aisi1005.mat

Table 2: Material definition of aisi1005.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Fe | 99.5 |
| C12 | 0.06 |
| Mn | 0.35 |
| P | 0.04 |
| S | 0.05 |

## al5083.mat

Table 3: Material definition of al5083.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Al | 92.55 |
| Cr | 0.25 |
| Cu | 0.1 |
| Fe | 0.4 |
| Mg | 4.9 |
| Mn | 1.0 |
| Si | 0.4 |
| Ti | 0.15 |
| Zn | 0.25 |

## al5754.mat

Table 4: Material definition of al5754.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Al | 94.35 |
| Cr | 0.3 |
| Cu | 0.1 |
| Fe | 0.4 |
| Mg | 3.6 |
| Mn | 0.5 |
| Si | 0.4 |
| Ti | 0.15 |
| Zn | 0.2 |

## al6061.mat

Table 5: Material definition of al6061.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Al | 96.15 |
| Mg | 1.2 |
| Ti | 0.15 |
| Si | 0.8 |
| Fe | 0.7 |
| Cu | 0.4 |
| Cr | 0.35 |
| Zn | 0.25 |
| Mn | 0.15 |

## al6065t6.mat

Table 6: Material definition of al6065t6.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Al | 94.7 |
| Bi | 1.5 |
| Mg | 1.2 |
| Ti | 0.1 |
| Si | 0.8 |
| Fe | 0.7 |
| Cu | 0.4 |
| Cr | 0.15 |
| Zn | 0.25 |
| Mn | 0.15 |
| Pb | 0.05 |

## al6082.mat

Table 7: Material definition of al6082.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Al | 95.35 |
| Si | 1.3 |
| Fe | 0.5 |
| Cu | 0.1 |
| Mn | 1.0 |
| Mg | 1.2 |
| Cr | 0.25 |
| Zn | 0.2 |
| Ti | 0.1 |

## al7075.mat

Table 8: Material definition of al7075.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Al | 87.32 |
| Cr | 0.28 |
| Cu | 2.0 |
| Fe | 0.5 |
| Mg | 2.9 |
| Mn | 0.3 |
| Si | 0.4 |
| Ti | 0.2 |
| Zn | 6.1 |

## alMgSiCu.mat

Table 9: Material definition of alMgSiCu.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Al | 98.5 |
| Mg | 1.0 |
| Ti | 0.75 |
| Si | 0.6 |
| Fe | 0.35 |
| Cu | 0.325 |
| Cr | 0.195 |
| Y | 0.125 |
| Mn | 0.075 |

## borofloat.mat

Table 10: Material definition of borofloat.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Si | 82.0\*28/60.0 |
| O | 82.0\*32/60.0 |
| Al | 1.5\*27/75.0 |
| O | 1.5\*48.0/75.0 |
| Na | 4.0\*23.0/55.0 |
| O | 4.0\*32.0/55.0 |
| K | 0.5\*78.0/94.0 |
| O | 0.5\*16.0/94.0 |
| B | 12.0\*22.0/70.0 |

## c87500.mat

Table 11: Material definition of c87500.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Cu | 79.0 |
| Pb | 0.09 |
| Zn | 16.0 |
| Al | 0.5 |
| Si | 5.0 |

## c87600.mat

Table 12: Material definition of c87600.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Cu | 88.0 |
| Pb | 0.09 |
| Zn | 7.0 |
| Fe | 0.2 |
| Mn | 0.25 |
| Si | 5.5 |

## c91300.mat

Table 13: Material definition of c91300.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Cu | 78.49 |
| Sn | 19.0 |
| Pb | 0.25 |
| Zn | 0.25 |
| Fe | 0.25 |
| Ni | 0.5 |
| Sb | 0.2 |
| P | 1.0 |
| S | 0.05 |
| Al | 0.005 |
| Si | 0.005 |

## c95300.mat

Table 14: Material definition of c95300.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Cu | 87.5 |
| Fe | 1.5 |
| Al | 11.0 |

## isisMildSteel.mat

Table 15: Material definition of isisMildSteel.mat

|  |  |
| --- | --- |
| Element | Weight % |
| B | 3.99E-05 |
| C12 | 1.20E-03 |
| N | 8.99E-05 |
| Al | 1.25E-03 |
| Si | 9.96E-04 |
| Mn | 4.00E-03 |
| P | 5.00E-04 |
| Si | 4.00E-04 |
| Fe | 9.86E-01 |
| Co | 2.00E-04 |
| Cu | 1.50E-03 |
| Ni | 1.00E-03 |
| Cr | 1.14E-03 |
| Mo | 1.00E-03 |
| Nb | 1.00E-04 |
| V | 1.00E-04 |
| Ti | 1.00E-04 |

## naFloat.mat

Table 16: Material definition of naFloat.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Si | 73.0\*28/60.0 |
| O | 73.0\*32/60.0 |
| Al | 0.15\*27/75.0 |
| O | 0.15\*48.0/75.0 |
| Ca | 9.0\*40.0/56.0 |
| O | 9.0\*16.0/56.0 |
| Mg | 4.0\*24.0/16.0 |
| O | 4.0\*16.0/16.0 |
| Na | 14.0\*23.0/55.0 |
| O | 14.0\*32.0/55.0 |
| K | 0.03\*78.0/94.0 |
| O | 0.03\*16.0/94.0 |
| Ti | 0.02\*22.0/54.0 |
| O | 0.02\*32.0/54.0 |
| Fe | 0.1\*112/160.0 |

## nbk7.mat

Table 17: Material definition of nbk7.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Si | 73.0\*28/60.0 |
| O | 73.0\*32/60.0 |
| B | 10.0\*22.0/70.0 |
| O | 10.0\*48.0/70.0 |
| Al | 0.25\*27/75.0 |
| O | 0.25\*48.0/75.0 |
| Mg | 1.25\*24.0/40.0 |
| O | 1.25\*16.0/40.0 |
| Na | 10.0\*23.0/55.0 |
| O | 10.0\*32.0/55.0 |
| K | 5.0\*78.0/94.0 |
| O | 5.0\*16.0/94.0 |
| Ca | 0.25\*40.0/56.0 |
| O | 0.25\*16.0/56.0 |
| Ba | 0.25\*137.0/153.0 |
| O | 0.25\*16.0/153.0 |

## onozukaE.mat

Table 18: Material definition of onozukaE.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Fe | 61.161 |
| C12 | 0.025 |
| Si | 0.51 |
| Mn | 24.6 |
| P | 0.025 |
| S | 0.007 |
| Ni | 0.03 |
| Cr | 13.4 |
| Mo | 0.01 |
| V | 0.01 |
| N | 0.219 |
| Co | 0.003 |

## pb50006.mat

Table 19: Material definition of pb50006.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Pb | 99.9807 |
| Sb | 0.0005 |
| As | 0.0005 |
| Sn | 0.0005 |
| Cu | 0.001 |
| Ag | 0.001 |
| Bi | 0.015 |
| Zn | 0.0005 |
| Te | 0.0001 |
| Ni | 0.0002 |

## pb50021.mat

Table 20: Material definition of pb50021.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Pb | 99.97 |
| Sb | 0.0005 |
| As | 0.0005 |
| Sn | 0.0005 |
| Cu | 0.001 |
| Ag | 0.0075 |
| Bi | 0.025 |
| Zn | 0.001 |
| Te | 0.0001 |
| Ni | 0.0002 |
| Fe | 0.001 |

## pb51121.mat

Table 21: Material definition of pb51121.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Pb | 99.896 |
| Sb | 0.001 |
| As | 0.001 |
| Sn | 0.001 |
| Cu | 0.08 |
| Ag | 0.02 |
| Bi | 0.025 |
| Zn | 0.001 |
| Ni | 0.002 |

## ss304l.mat

Table 22: Material definition of ss304l.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Fe | 65.045 |
| C12 | 0.03 |
| Mn | 2.0 |
| P | 0.045 |
| S | 0.03 |
| Si | 0.75 |
| Cr | 20.0 |
| Ni | 11.8 |
| Co | 0.2 |
| N | 0.1 |

## ss316l.mat

Table 23: Material definition of ss316l.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Fe | 65.645 |
| Cr | 17.0 |
| Ni | 11.8 |
| Co | 0.2 |
| Mo | 2.5 |
| Mn | 2.0 |
| Si | 0.75 |
| P | 0.045 |
| C12 | 0.03 |
| S | 0.03 |

## zircaloy4.mat

Table 24: Material definition of zircaloy4.mat

|  |  |
| --- | --- |
| Element | Weight % |
| Zr | 98.24 |
| Sn | 1.45 |
| Fe | 0.21 |
| Cr | 0.1 |

# Activation Tables After 30 Day Cooldown

## ACX-490

Table 25: Main contributors to contact dose in alloy / material ‘ACX-490’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 9.2972 | 90.92 |
| Cr | 51 | 0.47188 | 4.61 |
| Fe | 59 | 0.45672 | 4.47 |

## AISI-1005

Table 26: Main contributors to contact dose in alloy / material ‘AISI-1005’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 8.0852 | 92.66 |
| Fe | 59 | 0.58372 | 6.69 |
| Mn | 52 | 0.054864 | 0.63 |

## Al-5083

Table 27: Main contributors to contact dose in alloy / material ‘Al-5083’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 0.315668 | 83.08 |
| Mn | 54 | 0.05368 | 14.13 |
| Cr | 51 | 0.006872 | 1.81 |

## Al-5754

Table 28: Main contributors to contact dose in alloy / material ‘Al-5754’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 0.260356 | 86.09 |
| Mn | 54 | 0.0298136 | 9.86 |
| Cr | 51 | 0.0084552 | 2.80 |

## Al-6061

Table 29: Main contributors to contact dose in alloy / material ‘Al-6061’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 0.332348 | 90.63 |
| Mn | 54 | 0.0177492 | 4.84 |
| Cr | 51 | 0.0100564 | 2.74 |

## Al-6065-T6

Table 30: Main contributors to contact dose in alloy / material ‘Al-6065-T6’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 0.332984 | 91.92 |
| Mn | 54 | 0.0178852 | 4.94 |
| Cr | 51 | 0.0043328 | 1.20 |

## Al-6082

Table 31: Main contributors to contact dose in alloy / material ‘Al-6082’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 0.263572 | 79.79 |
| Mn | 54 | 0.055688 | 16.86 |
| Cr | 51 | 0.0071432 | 2.16 |

## Al-7075

Table 32: Main contributors to contact dose in alloy / material ‘Al-7075’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 8.0192 | 99.47 |
| Mn | 54 | 0.0227216 | 0.28 |
| Cr | 51 | 0.0080444 | 0.10 |

## Al

Table 33: Main contributors to contact dose in alloy / material ‘Al’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Al | 26 | 3.33936e-05 | 99.99 |
| Na | 22 | 4.7964e-09 | 0.01 |
| Na | 24 | 3.1982e-14 | 0.00 |

## AlMgSiCu

Table 34: Main contributors to contact dose in alloy / material ‘AlMgSiCu’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 0.0087176 | 29.89 |
| Sc | 46 | 0.0059476 | 20.39 |
| Y | 88 | 0.005854 | 20.07 |

## Borofloat

Table 35: Main contributors to contact dose in alloy / material ‘Borofloat’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Be | 7 | 0.00787 | 67.57 |
| Na | 22 | 0.00377768 | 32.43 |
| K | 40 | 4.4816e-08 | 0.00 |

## C87500

Table 36: Main contributors to contact dose in alloy / material ‘C87500’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 32.0532 | 97.32 |
| Co | 60 | 0.88372 | 2.68 |
| Fe | 59 | 6.6652e-06 | 0.00 |

## C87600

Table 37: Main contributors to contact dose in alloy / material ‘C87600’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Zn | 65 | 10.1768 | 91.58 |
| Co | 60 | 0.90364 | 8.13 |
| Mn | 54 | 0.0305824 | 0.28 |

## C91300

Table 38: Main contributors to contact dose in alloy / material ‘C91300’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Sb | 125 | 5.7608 | 30.20 |
| Sb | 124 | 5.726 | 30.02 |
| Sn | 113 | 4.4352 | 23.25 |

## C95300

Table 39: Main contributors to contact dose in alloy / material ‘C95300’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Co | 60 | 0.9318 | 93.07 |
| Mn | 54 | 0.059656 | 5.96 |
| Fe | 59 | 0.0094664 | 0.95 |

## Cu

Table 40: Main contributors to contact dose in alloy / material ‘Cu’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Co | 60 | 1.00424 | 99.98 |
| Zn | 65 | 0.000197116 | 0.02 |
| Fe | 59 | 6.3968e-06 | 0.00 |

## Fe

Table 41: Main contributors to contact dose in alloy / material ‘Fe’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 41.712 | 95.27 |
| Fe | 59 | 1.45964 | 3.33 |
| Mn | 52 | 0.357452 | 0.82 |

## Mild-steel

Table 42: Main contributors to contact dose in alloy / material ‘Mild-steel’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 8.0892 | 74.09 |
| Co | 60 | 2.18172 | 19.98 |
| Fe | 59 | 0.5474 | 5.01 |

## Na-Float

Table 43: Main contributors to contact dose in alloy / material ‘Na-Float’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Na | 22 | 0.0351968 | 80.86 |
| Be | 7 | 0.0069076 | 15.87 |
| Mn | 54 | 0.00112828 | 2.59 |

## NBK-7

Table 44: Main contributors to contact dose in alloy / material ‘NBK-7’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Na | 22 | 0.0265244 | 76.64 |
| Be | 7 | 0.0074824 | 21.62 |
| Ba | 131 | 0.00044112 | 1.27 |

## Onozuka-E

Table 45: Main contributors to contact dose in alloy / material ‘Onozuka-E’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 23.6912 | 96.30 |
| Cr | 51 | 0.314112 | 1.28 |
| Co | 60 | 0.294936 | 1.20 |

## L-50006

Table 46: Main contributors to contact dose in alloy / material ‘L-50006’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Tl | 202 | 0.160564 | 29.23 |
| Ag | 110m | 0.142428 | 25.93 |
| Au | 195 | 0.139156 | 25.33 |

## L-50021

Table 47: Main contributors to contact dose in alloy / material ‘L-50021’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Ag | 110m | 1.00432 | 71.06 |
| Tl | 202 | 0.160564 | 11.36 |
| Au | 195 | 0.139156 | 9.85 |

## L-51121

Table 48: Main contributors to contact dose in alloy / material ‘L-51121’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Ag | 110m | 2.42536 | 85.12 |
| Tl | 202 | 0.160564 | 5.64 |
| Au | 195 | 0.139156 | 4.88 |

## SS-304L

Table 49: Main contributors to contact dose in alloy / material ‘SS-304L’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 4.11 | 47.35 |
| Co | 58 | 3.59612 | 41.43 |
| Cr | 51 | 0.51084 | 5.89 |

## SS-316L

Table 50: Main contributors to contact dose in alloy / material ‘SS-316L’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Mn | 54 | 4.11 | 47.35 |
| Co | 58 | 3.59612 | 41.43 |
| Cr | 51 | 0.51084 | 5.89 |

## W

Table 51: Main contributors to contact dose in alloy / material ‘W’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Hf | 175 | 2.79904 | 68.12 |
| Ta | 182 | 1.29932 | 31.62 |
| W | 181 | 0.0069512 | 0.17 |

## Zircaloy4

Table 52: Main contributors to contact dose in alloy / material ‘Zircaloy4’ after 30 days of cooldown, assuming 20x20 cm2 illumination.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | A | Contact Dose (uSv/h) | % Contrib |
| Y | 88 | 11.5416 | 50.70 |
| Nb | 95 | 4.5476 | 19.98 |
| Zr | 95 | 3.4162 | 15.01 |

# References

1. T. Sato, K. Niita, N. Matsuda, S. Hashimoto, Y. Iwamoto, S. Noda, T. Ogawa, H. Iwase, H. Nakashima, T. Fukahori, K. Okumura, T. Kai, S. Chiba, T. Furuta, & L. Sihver, Particle and heavy ion transport code system phits. *J. Nucl. Sci. Technol.*, **50** (2013) 913–923.

# Glossary

| Term | Definition |
| --- | --- |
| PHITS | Particle and Heavy Ion Transport Code System |
| ALARA | As Low As Reasonably Achievable |
|  |  |

Document Revision history

| Revision | Reason for and description of change | Author | Date |
| --- | --- | --- | --- |
| 1 | First issue | P M Bentley | 2017-11-17 |
|  |  |  |  |
|  |  |  |  |