Benchmark test results for validation of the Basic Point Kernel and the Extended Point Kernel dosimetric code units of the Halden Planner

by

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In this document, we describe the results and conclusions obtained during a process towards validation of the dosimetric calculation units of the Halden Planner, the “Basic Point Kernel” (basic PK) and “Extended Point Kernel” (extended PK) models. This benchmarking exercise has been approached by performing calculations for two simple problems reported and solved in the literature (Sample problem 1 and 2 below), and by executing calculations for a series of simple irradiation situations (Sample problem package 3). For the series of situations, calculations have been made using the dosimetric tools of the Halden Planner and a sample of de-facto industry standard tools, generally considered reliable, in order to compare results.

Sample problem 1 [1]: A ^{60}Co source of A = 3.7×10^{13} Bq (1,000 Ci) is treated in a room enclosed by concrete wall of 100 cm thickness. Calculate the ambient dose equivalent rate at a point P on the outside wall. The calculation model is illustrated in Figure 1, where the distance r between the source and the front of the concrete wall is 500 cm.

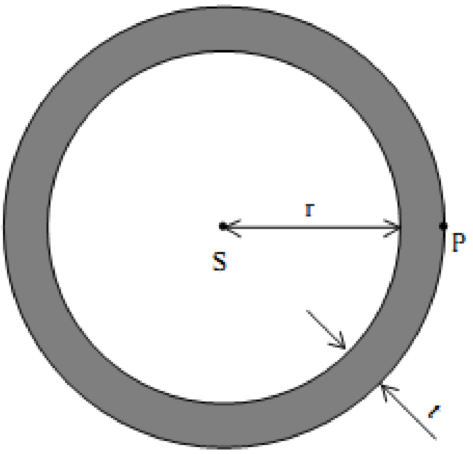


Figure 1.

Solution	Exposure rate X in R/h	Kerma (free-in-air) rate Ka in Gy/h	Ambient dose equivalent rate H*(10) in µSv/h
In [1], technique 1	4.689×10^{-3}	4.117×10^{-5}	52.7
In [1], technique 2			56.4
Basic PK model*			8.32
Extended PK model**	4.22×10^{-3}	3.7×10^{-5}	45.83

* The hardwired default density for concrete (2.4 g/cm^3) has been used.
**A 2.1 g/cm^3 density was used for concrete in these calculations.

[1] Becker, D., et al., Radiological Protection. Landolt-Börnstein - Group VIII Advanced Materials and Technologies - Numerical Data and Functional Relationships in Science and Technology ed. W. Martienssen. Vol. 4. 2005: Springer.

Sample problem 2 (reference problem I.1 in [2]): A point isotropic source of ^{16}N gamma rays (6.2 MeV) with a source strength of 1 photon/sec (A = 1 Bq). The point source is positioned at a height of 18.3 m above the air-ground interfaces. The detector is positioned at various distances from the normal-to-the-ground surface through the point source and at a height of 0.91m above the ground. In this problem, exposure (roentgens), dose equivalent (rem), and absorbed dose (rad) are considered numerically equivalent and reported as rads/yr. One year is assumed to be 8766 hours.

The calculation model is illustrated in Figure 2.

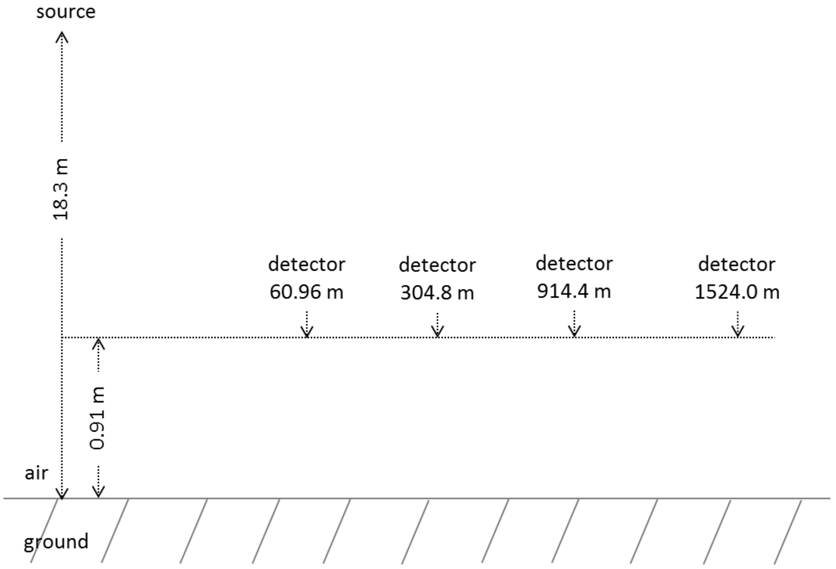
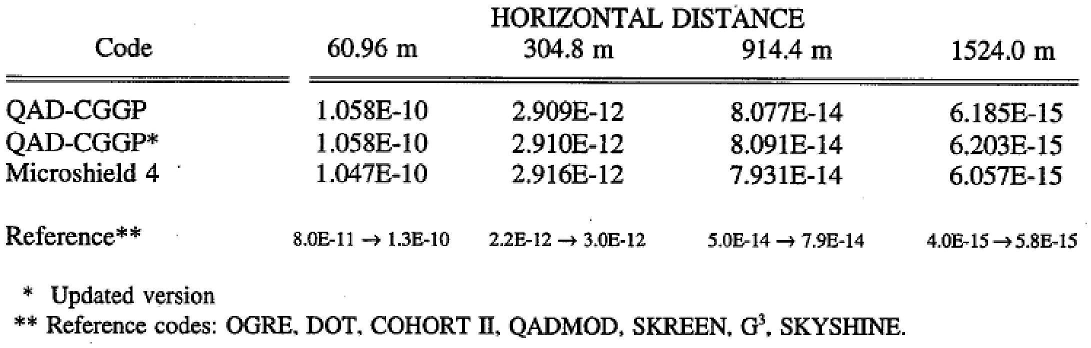


Figure 2.

Solution in [2]&[3]:



Code	HORIZONTAL DISTANCE 60.96 m	304.8 m	914.4 m	1524.0 m
QAD-CGGP	1.058E-10	2.909E-12	8.077E-14	6.185E-15
QAD-CGGP*	1.058E-10	2.910E-12	8.091E-14	6.203E-15
Microshield 4	1.047E-10	2.916E-12	7.931E-14	6.057E-15
Reference**	8.0E-11 → 1.3E-10	2.2E-12 → 3.0E-12	5.0E-14 → 7.9E-14	4.0E-15 → 5.8E-15

* Updated version

** Reference codes: OGRE, DOT, COHORT II, QADMOD, SKREEN, G^3, SKYSHINE.

Our solution:

Code	HORIZONTAL DISTANCE 60.96 m	304.8 m	914.4 m	1524.0 m
Extended PK model***	1.057E-10	2.92E-12	8.24E-14	6.4E-15

*** The basic PK model was not included here, as it does not support ^{16}N.

[2] ANS, *Calculation and measurement of direct and scattered gamma radiation from LWR nuclear power plants, an American National Standard,* ANSI/ANS-6.6.1-1987, American Nuclear Society, June 1987

[3] Oak Ridge National Laboratory, In documentation for *CCC-645/QAD-CGGP-A: Point Kernel Code System for Neutron and Gamma-Ray Shielding Calculations Using the GP Buildup Factor*, Oak Ridge National Laboratory, December 1995.

Sample Problem Package 3:

This package includes a series of calculations with common parameters but varying parameter values for source geometry, source to detector distance, shield (slab shield) thickness, and shield material. Dosimetric calculations have been performed using MicroShield (v. 5 and v.6), Rad Pro Calculator, and the two dosimetric units of the Halden Planner to calculate absorbed dose rate in air.

MicroShield® is a comprehensive photon/gamma ray shielding and dose assessment program that is widely used for designing shields, estimating source strength from radiation measurements, minimising exposure to people, and teaching shielding principles. The dosimetric techniques adopted by this software are similar to those applied by the two dosimetric methods of the Halden Planner. For more information, see http://www.radiationsoftware.com/mshield.html.

Rad Pro Calculator is a calculator with a web-based user interface for determining dose absorbed in air from radiation emitted by mono-isotopic gamma sources behind monolayer (homogeneous) shield. Rad Pro Calculator is a very simple free online tool, based on similar principles implemented in the dosimetric units of the Halden Planner. For more information, see http://www.radprocalculator.com/Gamma.aspx.

The common parameters of the exposure situation are described below:

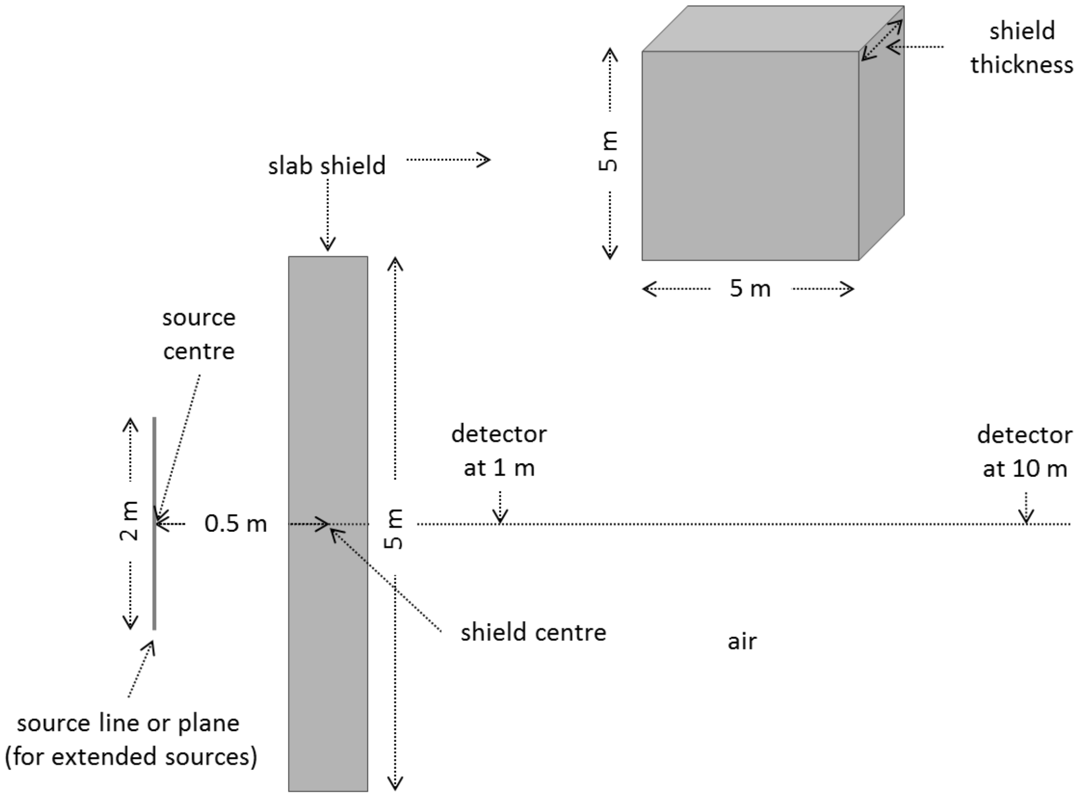


Figure 3.

The source is a multi-isotopic source containing 500 GBq of ^{60}Co, and 4 TBq of ^{137}Cs (^{137m}Ba, the radioactive daughter generated by nuclear decay of the ^{137}Cs, has naturally been included). A 5×5 m slab shield is positioned, with its centre at 0.5 meters from the source, and perpendicular to the source to detector line. Calculations have been performed for various shield materials and thicknesses (including no shielding), source to detector distances, and source geometries. In the case of extended sources (line and rectangular plane), the source is always centred relative to the shield, and orthogonal to the source-to-detector line. The calculation model is illustrated in Figure 3.

The irradiation situation in Sample Problem Package 3 has been designed with the following points taken in to account:

- Halden Planner currently supports three radiation source geometry shapes: point, line (segment), and rectangular plane.
- The default buildup factors applied in the Halden Planner estimate photon buildup from a parallel beam orthogonally incident on monolayer infinite slab shields. That is:
    - buildup in multilayers is simply summed up,
    - the pathway of the beam through the shield is applied to calculate the optical thickness of the shield, in case penetration is slanted,
    - radiation reflected (“back scattered”) from nearby objects is neglected.
- Interaction with air is taken into account in the extended PK model.
- Halden Planner currently supports the three shielding materials applied in this problem package.
- The isotopes applied are relevant for many common situations in a nuclear power plant, and are also supported by the basic PK model of the Halden Planner.

Additionally, a series of different shield materials and shield thicknesses have been applied to provide a more comprehensive overview of the agreement/disagreement of the results calculated by the Halden Planner with the two reference applications presented above.

Note that the output quantity, selected for comparison of the results of the extended PK model of the Halden Planner to the rate of dose absorbed in air, calculated by the MicroShield and the Rad Pro Calculator, was the *kerma* rate. In the irradiation situation demonstrated in Figure 3, kerma is a very good approximation of dose absorbed in air. For a more complete description of this quantity and its connection to other quantities, please see Halden Work Report 1030 (HWR-1030).

The results calculated using MicroShield v.5, the Rad Pro Calculator, and the two dosimetric tools of the Halden Planner, are listed below, sorted by input parameters. Note that the last row, labelled “combined”, is the sum of all rows, corresponding to an irradiation condition combining all the simple situations investigated.

Table 1 Absorbed dose rates in air (in mGy/h), calculated by the basic (HP basic) and the extended (HP extended) PK models of the Halden Planner, MicroShield v5 (MicroSh.), and the Rad Pro Calculator (RadPro), for Sample Problem Package 3, for various shield materials and thicknesses, at 1 m from the source centre.

	point source				line source			plane source		
	HP basic	**HP ext**	**MicroSh.**	**RadPro**	**HP basic**	**HP ext**	**MicroSh.**	**HP basic**	**HP ext**	**MicroSh.**
Unshielded	4,55E+02	4,55E+02	4,61E+02	4,58E+02	3,57E+02	3,57E+02	3,62E+02	2,91E+02	2,91E+02	2,95E+02
0,5m WATER	7,94E+01	8,05E+01	8,12E+01	7,91E+01	4,74E+01	4,80E+01	4,83E+01	2,93E+01	2,97E+01	2,98E+01
1,0m WATER	5,00E+00	5,16E+00	4,98E+00	5,95E+00	2,35E+00	2,42E+00	2,35E+00	1,13E+00	1,17E+00	1,14E+00
30cm CONCRETE	2,59E+01	2,92E+01	3,13E+01	2,58E+01	1,41E+01	1,60E+01	1,72E+01	7,93E+00	9,04E+00	9,79E+00
0,5m CONCRETE	2,09E+00	2,52E+00	2,84E+00	2,69E+00	9,45E-01	1,15E+00	1,30E+00	4,40E-01	5,40E-01	6,17E-01
1,0m CONCRETE	3,78E-03	5,25E-03	6,48E-03	4,79E-03	1,27E-03	1,78E-03	2,25E-03	4,36E-04	6,17E-04	7,92E-04
2mm IRON	4,44E+02	4,43E+02	4,42E+02	4,09E+02	3,48E+02	3,47E+02	3,46E+02	2,82E+02	2,82E+02	2,81E+02
5mm IRON	4,23E+02	4,24E+02	4,23E+02	3,49E+02	3,29E+02	3,30E+02	3,29E+02	2,66E+02	2,66E+02	2,66E+02
1cm IRON	3,86E+02	3,87E+02	3,91E+02	3,71E+02	2,96E+02	2,97E+02	2,99E+02	2,35E+02	2,36E+02	2,38E+02
5cm IRON	1,21E+02	1,23E+02	1,25E+02	1,13E+02	7,83E+01	7,99E+01	8,10E+01	5,26E+01	5,37E+01	5,45E+01
10cm IRON	1,94E+01	2,01E+01	2,08E+01	1,92E+01	9,67E+00	1,08E+01	1,13E+01	5,01E+00	6,06E+00	6,31E+00
0,5m IRON	6,29E-07	4,77E-06	5,43E-06	6,69E-06	1,68E-07	1,32E-06	1,50E-06	4,56E-08	3,67E-07	4,21E-07
1,0m IRON	7,02E-16	1,41E-14	1,80E-14	2,24E-13	1,35E-16	2,77E-15	3,57E-15	2,62E-17	5,45E-16	7,13E-16
1mm LEAD	4,22E+02	4,25E+02	4,24E+02	4,09E+02	3,29E+02	3,31E+02	3,30E+02	2,65E+02	2,67E+02	2,66E+02
2mm LEAD	3,92E+02	3,95E+02	3,96E+02	3,68E+02	3,02E+02	3,05E+02	3,06E+02	2,42E+02	2,44E+02	2,45E+02
5mm LEAD	3,12E+02	3,15E+02	3,22E+02	3,01E+02	2,33E+02	2,36E+02	2,42E+02	1,81E+02	1,84E+02	1,89E+02
1cm LEAD	2,08E+02	2,13E+02	2,23E+02	2,20E+02	1,49E+02	1,53E+02	1,61E+02	1,11E+02	1,14E+02	1,20E+02
5cm LEAD	1,19E+01	1,26E+01	1,43E+01	1,22E+01	6,79E+00	7,18E+00	8,17E+00	4,03E+00	4,27E+00	4,87E+00
10cm LEAD	5,63E-01	6,05E-01	7,40E-01	6,35E-01	2,50E-01	2,78E-01	3,44E-01	1,14E-01	1,32E-01	1,65E-01
0,5m LEAD	2,76E-12	1,06E-11	2,80E-11	1,27E-11	5,98E-13	2,33E-12	6,25E-12	1,31E-13	5,15E-13*	1,40E-12
1,0m LEAD	3,01E-26*	2,65E-25*	3,18E-23	1,10E-24	4,66E-27*	4,16E-26*	2,51E-23	7,25E-28*	6,55E-27*	2,05E-23
Combined**	3,31E+03	3,33E+03	3,36E+03	3,14E+03	2,50E+03	2,52E+03	2,54E+03	1,97E+03	1,99E+03	2,01E+03

* These calculations required extrapolation of the adopted buildup factors above the upper limit of confidence reported.

** The last row is the sum of all preceding rows.

The initial output of HP basic (corresponding to dose absorbed in tissue) was converted to dose absorbed in air by multiplication by 8.7/9.7.

Table 2 Absorbed dose rates in air (in mGy/h), calculated by the basic (HP basic) and the extended (HP extended) PK models of the Halden Planner, MicroShield v5 (MicroSh.), and the Rad Pro Calculator (RadPro), for Sample Problem Package 3, for various shield materials and thicknesses, at 10 m from the source centre.

	point source				line source			plane source		
	HP basic	**HP ext**	**MicroSh.**	**RadPro**	**HP basic**	**HP ext**	**MicroSh.**	**HP basic**	**HP ext**	**MicroSh.**
Unshielded	4,55E+00	4,50E+00	4,55E+00	4,42E+00	4,53E+00	4,49E+00	4,54E+00	4,52E+00	4,474121	4,52E+00
0,5m WATER	7,94E-01	7,96E-01	7,72E-01	7,65E-01	7,88E-01	7,91E-01	7,66E-01	7,82E-01	7,87E-01	7,60E-01
1,0m WATER	5,00E-02	0,051031	4,80E-02	5,76E-02	4,94E-02	0,050541	4,74E-02	4,87E-02	5,01E-02	4,68E-02
2,0m WATER	1,56E-04	1,62E-04	1,51E-04	1,73E-04	1,52E-04	1,59E-04	1,48E-04	1,49E-04	1,57E-04	1,45E-04
5,0m WATER	4,10E-12	4,50E-12	4,12E-12	6,13E-12	3,90E-12	4,32E-12	3,91E-12	3,71E-12	4,16E-12	3,72E-12
0,5m CONCRETE	0,020904	0,024933	2,69E-02	2,61E-02	2,06E-02	0,024679	2,65E-02	2,03E-02	0,024427	2,62E-02
1,0m CONCRETE	3,78E-05	5,18E-05	6,25E-05	4,65E-05	3,69E-05	5,09E-05	6,10E-05	3,60E-05	5,00E-05	5,96E-05
2,0m CONCRETE	1,04E-10	1,90E-10	2,95E-10	2,40E-10	9,95E-11	1,84E-10	2,82E-10	9,49E-11	1,77E-10	2,70E-10
0,5m IRON	6,29E-09	4,71E-08	5,12E-08	6,49E-08	6,06E-09	4,58E-08	4,95E-08	5,84E-09	4,46E-08	4,78E-08
1,0m IRON	7,02E-18	1,40E-16	1,73E-16	2,17E-15	6,55E-18	1,33E-16	1,62E-16	6,11E-18	1,26E-16	1,51E-16
0,5m LEAD	2,76E-14	1,05E-13	2,64E-13	1,24E-13	2,61E-14	1,01E-13	2,51E-13	2,47E-14	9,65E-14	2,38E-13
1,0m LEAD	3,01E-28*	2,62E-27*	3,25E-25	1,07E-26	2,71E-28*	2,42E-27*	3,24E-25	2,44E-28*	2,23E-27*	3,23E-25
Combined**	5,41E+00	5,37E+00	5,40E+00	5,27E+00	5,39E+00	5,35E+00	5,38E+00	5,37E+00	5,34E+00	5,35E+00

* These calculations required extrapolation of the adopted buildup factors above the upper limit of confidence reported.

** The last row is the sum of all preceding rows.

The initial output of HP basic (corresponding to dose absorbed in tissue) was converted to dose absorbed in air by multiplication by 8.7/9.7.

Note that for shield thicknesses above 1m, the centre of the shield (initially at 0.5 m from the source) was moved closer to the detector, to avoid overlap between the source and the shield.

1. Note that the basic PK model of the Halden Planner initially calculates dose absorbed in tissue, as the only output quantity. In order to obtain dose absorbed in air, the initial values were multiplied by 8.7/9.7 = 0.097. Detailed explanation of this can be found in HWR-1030.

2. Note that in the Halden Planner, buildup of photons, that is the contribution of scattered radian to the detector response, is estimated based on buildup factors. In the current version, standard buildup factors from [4] are adopted. Some calculations (marked by an * in the tables) require buildup factors for optical thicknesses higher than those supported by [4]. In this case, constant extrapolation has been utilised in the basic PK model, and extrapolation applying the geometric progression fitting formula has been utilised in the extended PK model to obtain a value. Thus, these values inherit a huge inaccuracy. Values for high optical thicknesses (thick and heavy shields) inherit a high level of imprecision from simplification of the description of photon scatter by the application of a buildup factor. Accurate modelling of these situations requires, in general, more sophisticated (Monte Carlo) radiation transport modelling, and the precision of deterministic (Point Kernel) model is determined by the applied buildup factors.

The first conclusions that can be drawn for the two tables above are:

- For all situations, dose decreases, replacing the point source to a line and a plane sources. This is natural, and follows from the activity being more and more spread, which (a) causes some of the activity to gain greater distance from the detector, and (b) improves shielding, due to the slanted pathway of the radiation from the distal parts of the extended source.
- As expected, since the above-mentioned phenomena have a lower role if the detector is further away, the decrease in dose is less evident if the detector is at 10 meters form the source.

Table 3 Agreement (in %) to MicroShield v.5 results, at 1 m from the source (centre).
A "-" sign indicates underestimation.

	point source			line source		plane source	
	HP basic	HP ext	RadPro	HP basic	HP ext	HP basic	HP ext
Unshielded	-99	-99	-99	-99	-99	-99	-99
0,5m WATER	-98	-99	-97	-98	-99	-98	-100
1,0m WATER	100	96	84	-100	97	-99	97
30cm CONCRETE	-83	-93	-82	-82	-93	-81	-92
0,5m CONCRETE	-74	-89	-95	-73	-88	-71	-87
1,0m CONCRETE	-58	-81	-74	-57	-79	-55	-78
2mm IRON	100	100	-93	100	100	100	100
5mm IRON	-100	100	-83	100	100	-100	-100
1cm IRON	-99	-99	-95	-99	-99	-99	-99
5cm IRON	-97	-99	-90	-97	-99	-96	-99
10cm IRON	-93	-96	-92	-86	-96	-79	-96
0,5m IRON	-12	-88	81	-11	-88	-11	-87
1,0m IRON	-4	-79	8	-4	-78	-4	-76
1mm LEAD	-100	100	-96	-100	100	-100	100
2mm LEAD	-99	-100	-93	-99	-100	-99	-100
5mm LEAD	-97	-98	-94	-96	-98	-96	-97
1cm LEAD	-93	-96	-99	-93	-95	-92	-95
5cm LEAD	-83	-88	-85	-83	-88	-83	-88
10cm LEAD	-76	-82	-86	-73	-81	-69	-80
0,5m LEAD	-10	-38	-45	-10	-37	-9	-37
1,0m LEAD	0	-1	-3	0	0	0	0
Combined	-98,3	-99,0	-93,4	-98,4	-99,0	-98,3	-99,1

In order to investigate the agreement of the results obtained by the different tools, additional tables, quantifying the harmony/deviance of the results, were prepared. Table 3 quantifies the agreement of the Halden Planner and Rad Pro Calculator results with those obtained by the Micro Shield v5. More specifically, the table applies the following formula to compare the results:

$$Agreement\ of value\ with\ standard = \begin{cases} \frac{value}{standard} * 100 \quad if\ value\ > standard \\ -\frac{standard}{value} * 100 \quad if\ value\ < standard \end{cases}$$

where the results calculated by MicroShield were taken as standard.

As opposed to Table 3, the values in Table 4 show the deviance of the results from MicroShield. In Table 4 the following formula has been used, to quantify the difference between the results:

$$Deviance\ of value\ from\ standard = \begin{cases} \left(\frac{value}{standard} - 1\right) * 100\ \ if\ value\ > standard \\ -\left(\frac{standard}{value} + 1\right) * 100 \quad if\ value\ < standard \end{cases}$$

Table 4 Discrepancy (in %) from MicroShield v.5 results, at 1 m from the source (centre).
A “-“ sign indicates underestimation.

	point source			line source		plane source	
	HP basic	HP ext	RadPro	HP basic	HP ext	HP basic	HP ext
Unshielded	-1	-1	-1	-1	-1	-1	-1
0,5m WATER	-2	-1	-3	-2	-1	-2	0
1,0m WATER	0	4	19	0	3	-1	3
30cm CONCRETE	-21	-7	-21	-22	-8	-24	-8
0,5m CONCRETE	-36	-13	-5	-38	-13	-40	-14
1,0m CONCRETE	-72	-24	-35	-77	-26	-81	-28
2mm IRON	0	0	-8	0	0	0	0
5mm IRON	0	0	-21	0	0	0	0
1cm IRON	-1	-1	-6	-1	-1	-1	-1
5cm IRON	-3	-1	-11	-3	-1	-4	-1
10cm IRON	-7	-4	-8	-17	-4	-26	-4
0,5m IRON	-763	-14	23	-791	-14	-823	-15
1,0m IRON	-2464	-27	1146	-2539	-29	-2618	-31
1mm LEAD	0	0	-4	0	0	0	0
2mm LEAD	-1	0	-8	-1	0	-1	0
5mm LEAD	-3	-2	-7	-4	-2	-4	-3
1cm LEAD	-7	-5	-1	-8	-5	-8	-6
5cm LEAD	-20	-14	-17	-20	-14	-21	-14
10cm LEAD	-31	-22	-17	-38	-24	-44	-25
0,5m LEAD	-914	-164	-120	-944	-168	-971	-172
1,0m LEAD	-1,1E+05	-1,2E+04	-2,8E+03	-5,4E+05	-6,0E+04	-2,8E+06	-3,1E+05
Combined	-1,7	-1,0	-7,0	-1,7	-1,0	-1,7	-0,9

Similarly, Table 5 and Table 6 investigate results obtained at 10 m distance from the radiation source.

Table 5 Agreement (in %) to MicroShield v.5 results, at 10 m from the source (centre). A "-" sign indicates underestimation.

	point source			line source		plane source	
	HP basic	HP ext	RadPro	HP basic	HP ext	HP basic	HP ext
Unshielded	-100	-99	-97	-100	-99	-100	-99
0,5m WATER	97	97	-99	97	97	97	97
1,0m WATER	96	94	83	96	94	96	93
2,0m WATER	97	93	87	97	93	97	92
5,0m WATER	-100	92	67	-100	90	-100	89
0,5m CONCRETE	-78	-93	-97	-78	-93	-78	-93
1,0m CONCRETE	-60	-83	-74	-60	-83	-60	-84
2,0m CONCRETE	-35	-64	-81	-35	-65	-35	-66
0,5m IRON	-12	-92	79	-12	-93	-12	-93
1,0m IRON	-4	-81	8	-4	-82	-4	-83
0,5m LEAD	-10	-40	-47	-10	-40	-10	-41
1,0m LEAD	0	-1	-3	0	-1	0	-1
Combined	99,7	-99,5	-97,7	99,8	-99,5	99,7	-99,7

Table 6 Discrepancy (in %) from MicroShield v.5 results, at 10 m from the source (centre). A "-" sign indicates underestimation.

	point source			line source		plane source	
	HP basic	HP ext	RadPro	HP basic	HP ext	HP basic	HP ext
Unshielded	0	-1	-3	0	-1	0	-1
0,5m WATER	3	3	-1	3	3	3	4
1,0m WATER	4	6	20	4	7	4	7
2,0m WATER	3	7	15	3	8	3	8
5,0m WATER	0	9	49	0	11	0	12
0,5m CONCRETE	-29	-8	-3	-29	-7	-29	-7
1,0m CONCRETE	-65	-21	-35	-65	-20	-66	-19
2,0m CONCRETE	-183	-55	-23	-183	-54	-185	-52
0,5m IRON	-714	-9	27	-716	-8	-718	-7
1,0m IRON	-2364	-24	1157	-2373	-22	-2371	-20
0,5m LEAD	-856	-152	-114	-861	-149	-863	-147
1,0m LEAD	-1,1E+05	-1,2E+04	-2,9E+03	-1,2E+05	-1,3E+04	-1,3E+05	-1,4E+04
Combined	0,3	-0,5	-2,3	0,2	-0,5	0,3	-0,3

Investigation of Table 3, Table 4, Table 5 and Table 6 reveals that there is very good agreement between the results obtained by the different calculation tools for low optical thicknesses. For high shield thicknesses, however, the deviance strongly increases with shield thickness, and reaches great proportions for extreme optical thicknesses. The deviance of the results from MicroShield is apparent for the Rad Pro Calculator as well as the two calculators of the Halden Planner. Nevertheless, as mentioned earlier, the simplified methods applied in the dosimetric tools used are not designed for general application to extreme situations, where radiation dose mainly arises from photons scattered in the shields. These situations usually call for more sophisticated Monte Carlo simulations if an accurate answer is required. In most cases of this kind, however, the dose (detector response) is very low, and thus the overall inaccuracy of the model is acceptable. The last rows of the comparison tables show the agreement (Table 3 and Table 5) and the discrepancy (Table 4 and Table 6) of the sum of the results for all the simple cases, that is, the sum of the preceding rows. The combined cases correspond to exposure situations combining multiple sources shielded by different shields (including one unshielded case). The last rows of the tables show that the result calculated by the Halden Planner in such a more complex scenario is in very good agreement with the results provided by the MicroShield v5. This indicates that use of the Halden Planner is indeed valid for general (common) situations in typical nuclear installations.

The results also show that for more specialised situations, involving only shields of great optical thickness, the variation of the results provided by deterministic models is very high, and more sophisticated radiation transport simulation is required for accurate modelling. In these situations, the resulting detector response mainly depends on how scatter of photons in the shield is accounted for, that is, what kind of buildup factors, and how they are applied. Since buildup factors reported in the literature inherit a great uncertainty for high optical thicknesses, and values reported vary from report to report, the deviance between the results is neither surprising nor unexpected. Users of these radiation transport tools must recognise the inaccuracy inherent from the simplified methodology applied and resort to more sophisticated Monte Carlo radiation transport tools for more precise simulation.

Note that for the most common tasks requiring radiation protection in nuclear installations (e.g. NPP), such as maintenance tasks, these simple tools are able to provide fast but adequately accurate information.

Similar equations were applied to quantify the harmony and deviance of the detector responses at 1m (Table 7) and 10m (Table 8) from the source, calculated by Halden Planner and MicroShield, to those obtained by the Rad Pro Calculator, for point sources. The values calculated by the Rad Pro Calculator were obtained by summing up the two separate values, calculated for the two isotopes, relevant for the radiation source(s) applied in this task.

Based on all the tables comparing the results obtained by different tools, we can conclude that the extended PK model of Halden Planner has a better agreement to both the MicroShield and Rad Pro Calculator than the basic PK model, especially for high optical thicknesses. However, recall that while the extended PK model is in much better agreement with MicroShield (and the Rad Pro Calculator) at extreme shield thicknesses, all of the models used give a very inaccurate assessment in these situations.

Table 7 Agreement (left panel) and discrepancy (right panel) in % from Rad Pro Calculator results, at 1 m from the source (centre). A "-" sign indicates underestimation.

	point source				point source		
	HP basic	HP ext	MicroSh.		HP basic	HP ext	MicroSh.
Unshielded	-99	-99	99	Unshielded	-1	-1	1
0,5m WATER	100	98	97	0,5m WATER	0	2	3
1,0m WATER	-84	-87	-84	1,0m WATER	-19	-15	-19
30cm CONCRETE	99	88	82	30cm CONCRETE	1	13	21
0,5m CONCRETE	-78	-94	95	0,5m CONCRETE	-29	-7	5
1,0m CONCRETE	-79	91	74	1,0m CONCRETE	-27	9	35
2mm IRON	92	92	93	2mm IRON	9	8	8
5mm IRON	83	82	83	5mm IRON	21	21	21
1cm IRON	96	96	95	1cm IRON	4	5	6
5cm IRON	93	91	90	5cm IRON	7	9	11
10cm IRON	99	96	92	10cm IRON	1	5	8
0,5m IRON	-9	-71	-81	0,5m IRON	-964	-40	-23
1,0m IRON	0	-6	-8	1,0m IRON	-31835	-1486	-1146
1mm LEAD	97	96	96	1mm LEAD	3	4	4
2mm LEAD	94	93	93	2mm LEAD	6	7	8
5mm LEAD	97	96	94	5mm LEAD	3	5	7
1cm LEAD	-95	-97	99	1cm LEAD	-5	-3	1
5cm LEAD	-98	97	85	5cm LEAD	-2	3	17
10cm LEAD	-89	-95	86	10cm LEAD	-13	-5	17
0,5m LEAD	-22	-83	45	0,5m LEAD	-361	-20	120
1,0m LEAD	-3	-24	3	1,0m LEAD	-3556	-315	2,8E+03
Combined	95,0	94,3	93,4	Combined	5,2	6,0	7,0

Table 8 Agreement (left panel) and discrepancy (right panel) in % from Rad Pro Calculator results, at 10 m from the source (centre). A "-" sign indicates underestimation.

	point source				point source		
	HP basic	HP ext	MicroSh.		HP basic	HP ext	MicroSh.
Unshielded	97	98	97	Unshielded	3	2	3
0,5m WATER	96	96	99	0,5m WATER	4	4	1
1,0m WATER	-87	-89	-83	1,0m WATER	-15	-13	-20
2,0m WATER	-90	-94	-87	2,0m WATER	-11	-7	-15
5,0m WATER	-67	-73	-67	5,0m WATER	-49	-36	-49
0,5m CONCRETE	-80	-95	97	0,5m CONCRETE	-25	-5	3
1,0m CONCRETE	-81	90	74	1,0m CONCRETE	-23	12	35
2,0m CONCRETE	-43	-79	81	2,0m CONCRETE	-130	-26	23
0,5m IRON	-10	-73	-79	0,5m IRON	-932	-38	-27
1,0m IRON	0	-6	-8	1,0m IRON	-30875	-1457	-1157
0,5m LEAD	-22	-85	47	0,5m LEAD	-347	-18	114
1,0m LEAD	-3	-25	3	1,0m LEAD	-3446	-308	2,9E+03
Combined	97,4	98,2	97,7	Combined	2,6	1,8	2,3

A similar investigation has been performed using MicroShield v.6. Table 9 lists the results calculated for the exposure situations described above using the newer version of MicroShield.

Table 9 Absorbed dose rates in air (in mGy/h), calculated by the MicroShield v.6, for sample problem package 3, for various shield materials and thicknesses, at 1 and 10 meters from the source centre.

1 m from the source

	point	**line**	**plane**
Unshielded	4,61E+02	3,62E+02	2,95E+02
0,5m WATER	8,12E+01	4,83E+01	2,98E+01
1,0m WATER	4,98E+00	2,35E+00	1,14E+00
30cm CONCRETE	3,13E+01	1,72E+01	9,79E+00
0,5m CONCRETE	2,84E+00	1,30E+00	6,17E-01
1,0m CONCRETE	6,48E-03	2,25E-03	7,92E-04
2mm IRON	4,42E+02	3,46E+02	2,81E+02
5mm IRON	4,23E+02	3,29E+02	2,66E+02
1cm IRON	3,91E+02	2,99E+02	2,38E+02
5cm IRON	1,25E+02	8,10E+01	5,45E+01
10cm IRON	2,08E+01	1,13E+01	6,31E+00
0,5m IRON	5,43E-06	1,50E-06	4,21E-07
1,0m IRON	1,80E-14	3,57E-15	7,13E-16
1mm LEAD	4,24E+02	3,30E+02	2,66E+02
2mm LEAD	3,96E+02	3,06E+02	2,45E+02
5mm LEAD	3,22E+02	2,42E+02	1,89E+02
1cm LEAD	2,23E+02	1,61E+02	1,20E+02
5cm LEAD	1,43E+01	8,17E+00	4,87E+00
10cm LEAD	7,40E-01	3,44E-01	1,65E-01
0,5m LEAD	2,80E-11	6,25E-12	1,40E-12
1,0m LEAD	3,18E-23	2,51E-23	2,05E-23
Combined*	3,36E+03	2,54E+03	2,01E+03

10 m from the source

	point	line	plane
Unshielded	4,55E+00	4,54E+00	4,52E+00
0,5m WATER	7,72E-01	7,66E-01	7,60E-01
1,0m WATER	4,80E-02	4,74E-02	4,68E-02
2,0m WATER	1,51E-04	1,48E-04	1,45E-04
5,0m WATER	4,12E-12	3,91E-12	3,72E-12
0,5m CONCRETE	2,69E-02	2,65E-02	2,62E-02
1,0m CONCRETE	6,25E-05	6,10E-05	5,96E-05
2,0m CONCRETE	2,95E-10	2,82E-10	2,70E-10
0,5m IRON	5,12E-08	4,95E-08	4,78E-08
1,0m IRON	1,73E-16	1,62E-16	1,51E-16
0,5m LEAD	2,64E-13	2,51E-13	2,38E-13
1,0m LEAD	3,25E-25	3,24E-25	3,23E-25
Combined*	5,40E+00	5,38E+00	5,35E+00

* The last row is the sum of all preceding rows.

The same methodology applied to compare the other calculators with MicroShield v.5 has been used to compare results calculated by the Halden Planner to those obtained by the MicroShield v.6. Table 10 and Table 11 show the deviance of the results calculated by the basic and the extended PK models of the Halden Planner and the Rad Pro Calculator compared to the results yielded by the MicroShield v.6, for 1m and 10m from the centre of the source respectively.

Table 10 Discrepancy (in %) from MicroShield v.6 results, at 1 m from the source (centre). A "-" sign indicates underestimation.

	point source			line source		plane source	
	HP basic	HP ext	RadPro	HP basic	HP ext	HP basic	HP ext
Unshielded	-1	-1	-1	-1	-1	-1	-1
0,5m WATER	-1	1	-1	0	1	0	1
1,0m WATER	0	3	19	0	3	0	4
30cm CONCRETE	-40	-24	-40	-40	-24	-41	-24
0,5m CONCRETE	-48	-23	-15	-49	-23	-50	-22
1,0m CONCRETE	-62	-17	-28	-64	-17	-65	-17
2mm IRON	-1	-1	-10	-1	-1	-1	-1
5mm IRON	-3	-3	-25	-3	-3	-4	-4
1cm IRON	-7	-7	-12	-9	-8	-10	-9
5cm IRON	-47	-44	-58	-49	-46	-53	-50
10cm IRON	-71	-65	-73	-86	-67	-102	-67
0,5m IRON	-1182	-69	-21	-1233	-70	-1275	-71
1,0m IRON	-3789	-93	721	-3878	-94	-3946	-94
1mm LEAD	-6	-5	-10	-7	-7	-8	-7
2mm LEAD	-13	-12	-20	-16	-14	-16	-15
5mm LEAD	-34	-32	-39	-44	-42	-44	-41
1cm LEAD	-76	-72	-67	-106	-101	-95	-89
5cm LEAD	-286	-265	-276	-293	-272	-300	-277
10cm LEAD	-322	-293	-275	-440	-386	-487	-407
0,5m LEAD	-8665	-2178	-1806	-8997	-2235	-9289	-2288
1,0m LEAD	-9,7E+06	-1,1E+06	-2,6E+05	-4,9E+07	-5,5E+06	-2,6E+08	-2,8E+07
Combined	-15,4	-14,6	-21,4	-18,0	-17,1	-16,8	-15,9

Table 11 Discrepancy (in %) from MicroShield v.6 results, at 10 m from the source (centre).
A “-“ sign indicates underestimation.

	point source			line source		plane source	
	HP basic	HP ext	RadPro	HP basic	HP ext	HP basic	HP ext
Unshielded	0	-1	-3	0	-1	0	-1
0,5m WATER	4	5	1	5	5	4	5
1,0m WATER	6	8	22	6	8	6	9
2,0m WATER	4	8	15	3	8	4	10
5,0m WATER	1	10	50	1	11	1	13
0,5m CONCRETE	-40	-18	-12	-40	-17	-40	-17
1,0m CONCRETE	-53	-12	-25	-53	-11	-53	-10
2,0m CONCRETE	-98	-9	16	-99	-8	-99	-7
0,5m IRON	-1111	-62	-17	-1115	-61	-1117	-59
1,0m IRON	-3575	-85	741	-3579	-81	-3582	-79
0,5m LEAD	-8158	-2074	-1739	-8214	-2049	-8240	-2035
1,0m LEAD	-9,7E+06	-1,1E+06	-2,7E+05	-1,1E+07	-1,2E+06	-1,2E+07	-1,3E+06
Combined	0,5	-0,3	-2,1	0,4	-0,3	0,5	-0,1

Comparing Table 10 and Table 11 to Table 4 and Table 6, their counterparts for the earlier MicroShield version, we can see that the tendency of the deviance is very similar; the deviance strongly increases at high optical thicknesses, but for more common shield thicknesses the agreement is, in general, good. It is apparent that at 1 m from the source, the deviance is reaching considerable limits at lower optical thicknesses than it did in the comparison to MicroShield v.5. This can also be observed in the difference for the combined case. Even with this stronger deviance for thicker shields, the difference at the combined case, characterising more general situations, is still acceptable, as it is definitely still below the levels of uncertainty of the methods adopted in the tools applied in this study. Users of deterministic models should always take into account that these simple deterministic models should be used mainly for common situations with a high conservatism, and acknowledge that these models should not be utilised as alternatives to Monte Carlo radiation transport models for complex specialised situations such as scatter in thick and heavy shields.

[4] American Nuclear Society - Working Group ANS-6.4.3, *American national standard for gamma-ray attenuation coefficients and buildup factors for engineering materials*. (ANSI/ANS-6.4.3) 1992, La Grange Park, Illinois: American Nuclear Society.