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Algorithm to assess neutron $H_P(10)$ with estimation of uncertainties using Alnor albedo dosemeters: application in Brazilian nuclear power plants

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ABSTRACT

The *Instituto de Radioproteção e Dosimetria* (IRD) is implementing an automatic neutron individual monitoring system, which uses albedo dosemeters from the Alnor manufacturer. For practical purposes, the occupational neutron fields have been divided into four application areas, named N1, N2, N3 and N4, as recommended in the German standard DIN 6802-4. For each area, specific Workplace Correction Factors (WCF), as a function of the ratio between photon dose responses measured in the incident and albedo component of the albedo dosemeter (D_i/D_a), must be used. This study proposes an algorithm for evaluating the photon and neutron personal dose equivalent, $H_P(10)$, values for the Alnor albedo system. It uses WCF × D_i/D_a curves previously defined by the authors, using MCNPX code simulations of the neutron dosemeter response for several occupational neutron fields. The methodology for calculating all uncertainties involved in the photon and neutron $H_P(10)$ assessment is also shown. Before the routine use of this system at IRD, several tests and calibrations are being carried out. This manuscript presents a case study carried out at the Angra I and Angra II power plants in 14 different fields (N1 application area). The results of the Alnor system are compared with those from the albedo system currently in routine use at the IRD. The average value of the ratio between the measurements with the Alnor system and the IRD system was 0.97 for photon $H_P(10)$, and 0.84 for neutron $H_P(10)$. Considering an expanded uncertainty to 95% confidence level, all results agree with each other.

Keywords: **neutron and photon $H_P(10)$, uncertainty, Angra PWR.**

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1. INTRODUCTION

The neutron individual monitoring system of the *Instituto de Radioproteção e Dosimetria* (IRD) is one of the few that assess the neutron personal dose equivalent, $H_P(10)$, of Brazilian workers, and it uses currently an in-house albedo dosemeter [1]. This system has already participated in several international interlaboratory comparisons, always with good results, but its procedures need many manual steps, which limits the capacity to increase the number of monitored workers. Therefore, IRD is implementing an automatic neutron individual monitoring system to meet the Brazilian demand.

This new neutron individual monitoring system of IRD is an albedo dosemeter used worldwide from the Alnor manufacturer, whose prototype was developed in Germany in the 80's by Piesch and Burgkhardt [2,3]. This dosemeter is used in different facility types for several neutron fields. Because of the high energy dependence of its response to neutrons, which is true for all types of albedo dosemeters, the dosimetric system that uses the Alnor albedo dosemeter considers four application areas to facilitate the choice of the most suitable calibration factor for each workplace neutron field. They are named N1, N2, N3 and N4 in the German standard DIN 6802-4 [4] and are presented in Table 1, with their reference spectrum and typical neutron field for each of the areas.

Before the implementation of the Alnor albedo system in the IRD, this dosemeter was tested, calibrated and its response was simulated using the Monte Carlo code MCNPX for different workplace neutron fields. This simulation is used in order to obtain curves of neutron calibration workplace correction factor *(WCF)* as function of the ratio between incident and albedo component readings (D_i/D_a), used to correct the neutron $H_P(10)$ [5]. In this study, an algorithm is proposed for the calculation of photon and neutron $H_P(10)$ using the Alnor albedo dosemeter. This algorithm includes $WCF \times D_i/D_a$ curves and estimation of uncertainties. To validate the proposed algorithm and the applied operational procedures, comparisons between measurements with this Alnor albedo system and the current IRD system were carried out in two Brazilian nuclear power plants, Angra I and Angra II (application area N1).

Table 1 : Neutron application areas with examples of typical occupational neutron fields and neutron reference spectrum [4].

Application areas	Reference Field	Typical Neutron Fields
N1 - Reactors and accelerators, heavy shielding	$^{252}Cf(D_2O)$	Research reactors (near beam) Betatron, Linacs Therapy particle accelerators Nuclear power stations
N2 - Fuel element cycle, criticality, low shielding	^{252}Cf with shadow cone	Experimental reactors Criticality, handling fissile materials Fuel element cycle, including transportation, storage, reprocessing
N3 - Radionuclide neutron sources	Am-Be and ^{252}Cf	Am-Be, Pu-Be, Ra-Be, ^{252}Cf
N4 - Accelerators for research and technology	Not yet defined	Cyclotron: variation in targets, particles Accelerators for electrons > 50 MeV Accelerators for protons, deuterons, etc.

2. ALNOR ALBEDO DOSEMETER SYSTEM

The Figure 1 shows the Alnor albedo dosemeter with its components. This dosemeter consists of a case made of boron-loaded plastic, with an incident free window on its front side and an albedo window, without boron, on its back side. Inside the case, there is one TLD card with four TLD crystals: two ^{6}LiF:Mg,Ti (named MTS-6) and two ^{7}LiF:Mg,Ti (named MTS-7); one pair of MTS-6 and MTS-7 being located in the front window and the other in the albedo window. Both types of TLD, MTS-6 and MTS-7, detect photons, while only the MTS-6 also detects neutrons, mainly thermal neutrons [3,6].

The TLD pair under the incident free window on the dosemeter detects the incident radiation (incident component). The TLD pair under the albedo window of the dosemeter's backside detects the backscattered radiation by the worker's body (albedo component). The frontal boron-loaded plastic cuts off the incident thermal neutrons that cannot be detected by the TLD positioned on the albedo window. On the other hand, the TLD crystals under the incident free window do not detect the albedo neutrons due to the boron shield of the dosemeter's backside.

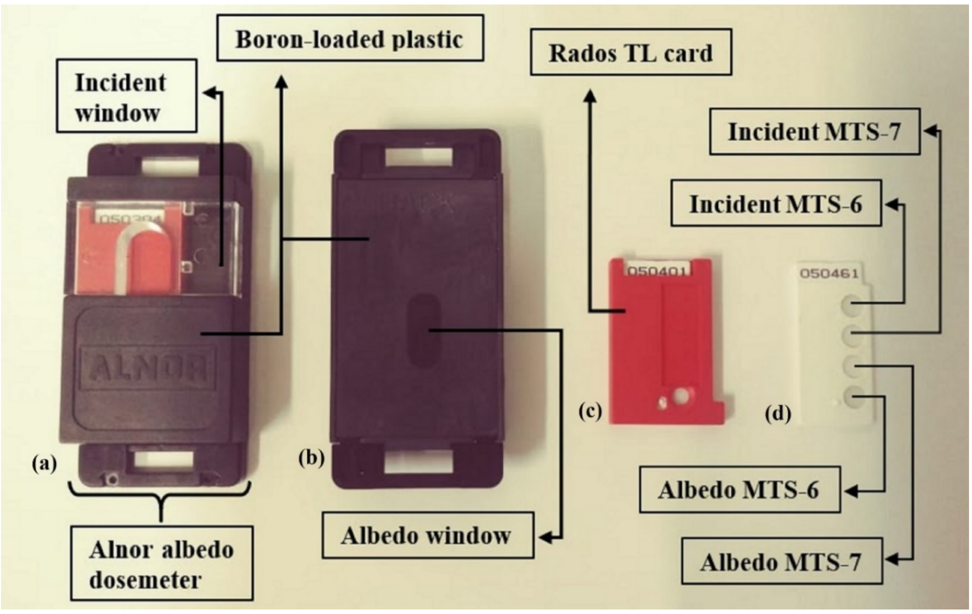

Figure 1: *Alnor albedo dosemeter with the description of its components. View from the front (a) and the back (b). The TLD card (c) with TLDs in the holder (d).*

All readings are made on Mirion Technologies's automatic TLD reader model RA-2000, using nitrogen gas heated to 300 ºC for 13.5 s. After the readings and before use, the TLDs are annealed in the reader itself at 300 ºC for another 13.5 s. Before the readings, another thermal treatment is performed on the same reader at 150 ºC for 13.5 s. To test the reader's stability over time, quality control (CQ) dosemeters are used. Each day, five dosemeters irradiated in the RADOS automatic ^{90}Sr irradiator are evaluated before the TLD readings.

3. DOSE EVALUATION WITH UNCERTAINTIES

3.1. TLD responses

For the dose evaluation, the net response for each TLD must be calculated considering the readings of TLD in non-irradiated albedo dosemeters (background dosemeters). Individual sensitivity factors (*fs*) for each TLD are used to homogenize the TLD batch response. Equation 1 calculates the corrected net response of a TLD *j* of the type of TLD *f*.

$$R_{MTSf,j} = L_{MTSf,j} \times fs_{MTSf,j} - \bar{L}_{MTSf,Bkg} \quad (1)$$

where L_{MTSf} is the gross readings of MTS-6 and MTS-7 and $\bar{L}_{MTSf,Bkg}$ is the mean value of the readings of MTS-6 and MTS-7 used in background dosemeters.

The empirical Equation 2 calculates the uncertainty, u, of each TLD reading (L).

$$u(L) = \sqrt{\sigma_0^2 + (\sigma_{batch} \times L)^2} \quad (2)$$

where σ_0 is the standard deviation of non-irradiated TLD, in counts; and σ_{batch} is the relative standard deviation of the TLD batch irradiated for calibration purposes (doses at least ten times higher than the lower detection limit). For the TLD batches used in this study, σ_{batch} is 6.12% for MTS-6 and 1.32% for MTS-7 TLD batch.

The standard uncertainty of the individual sensitive calibration factor for both types of TLD is estimated at 2%. The uncertainty of the mean value of the background dosemeters is calculated by the standard deviation of the non-irradiated dosemeters that followed the dosemeters to be irradiated.

The combined uncertainty (U) of $R_{MTS6,j}$ and $R_{MTS7,j}$ was calculated by the ISOGUM method [7], using Equation 3.

$$U(R_{MTSf,j}) = \sqrt{\left\{(L_{MTSf,j} \times fs_{MTSf,j})^2 \times \left[\left(\frac{u_{L_{MTSf,j}}}{L_{MTSf,j}}\right)^2 + \left(\frac{u_{fs_{MTSf,j}}}{fs_{MTSf,j}}\right)^2\right] + u^2_{\bar{L}_{MTSf,Bkg}}\right\}} \quad (3)$$

3.2. Photon $H_P(10)$

The photon dose (D) of TLD j is obtained by multiplying its TLD's reading by the photon $H_P(10)$ calibration factor as shown in Equation 4, for MTS-6 and MTS-7.

$$D_{MTSf,j} = R_{MTSf,j} \times FC\gamma_{MTSf} \quad (4)$$

where $FC\gamma_{MTSf}$ is the $H_P(10)$ photon calibration factor for the MTS-6 batch and MTS-7 batch (mSv/counts). The $H_P(10)$ photon calibration standard uncertainty was calculated as 8% for MTS-6 and 5% for MTS-7 in this study.

If the mean value of the readings of TLDs used for Quality Control (QC) on the evaluation day differs by more than 5% from that obtained on the day of the $H_P(10)$ photon calibration, a unique daily correction factor (f_{dc}) must be applied to the value of D_{MTSf}, for both types of TLD. Quality Control dosemeters are used to assess the stability of the TLD reader. Before starting any TLD reading in the laboratory, five dosimeters (ten MTS-6 and ten MTS-7) are irradiated 10 times in the ^{90}Sr irradiator (10 laps: 3 mGy). This daily correction factor is obtained by the ratio between the mean value of the readings of all TLDs of the QC dosemeters on the calibration day and the mean value of their readings on the evaluation day. The corrected dose values (D'_{MTSf}) are calculated by Equation 5.

$$D'_{MTSf,j} = D_{MTSf,j} \times f_{dc} \quad (5)$$

In the measurements of this study, f_{dc} value was 1.10, with an uncertainty of 1%, applied to both types of TLD. The combined uncertainty of $D'_{MTSf,j}$ are given by Equation 6.

$$U_{D'_{MTSf,j}} = D'_{MTSf,j} \times \sqrt{\left(\frac{U(R_{MTSf,j})}{R_{MTSf,j}}\right)^2 + \left(\frac{u_{FC\gamma_{MTSf}}}{FC\gamma_{MTSf}}\right)^2 + \left(\frac{u_{f_{dc}}}{f_{dc}}\right)^2} \quad (6)$$

The photon $H_P(10)$ is calculated by the mean value of the corrected doses measured by the MTS-7 TLDs in the incident and in the albedo positions (Equation 7).

$$H_\gamma = \frac{D_{MTS7,incident} + D_{MTS7,albedo}}{2} \quad (7)$$

It is estimated that other sources of uncertainty, such as energy and angular dependence of the photon response of the dosemeter, contribute to the combined uncertainty of the photon $H_P(10)$ value with an additional 10%. The combined uncertainty of the H_γ is given, then, by Equation 8.

$$U(H_\gamma) = \sqrt{\frac{1}{4} \times \left[\left(\frac{u_{D_{MTS7,incident}}}{D_{MTS7,incident}}\right)^2 + \left(\frac{u_{D_{MTS7,albedo}}}{D_{MTS7,albedo}}\right)^2\right] + 0{,}1^2} \tag{8}$$

3.3. Neutron $H_P(10)$

For evaluation of the neutron $H_P(10)$, an apparent neutron dose for the albedo component (D_a) must be calculated using the difference between the corrected photon dose of MTS-6 and MTS-7, at albedo position (Equation 9). Equation 10 gives the expanded uncertainty U of D_a.

$$D_a = \left(D'_{MTS6,albedo} - D'_{MTS7,albedo}\right) \tag{9}$$

where $D'_{MTS6.albedo}$ and $D'_{MTS7.albedo}$ are calculated by Equation 5 on the albedo window.

$$U(D_a) = \sqrt{U_{D'_{MTS6,albedo}}{}^2 + U_{D'_{MTS7,albedo}}{}^2} \tag{10}$$

The neutron $H_P(10)$ is calculated using the Equation 11, where the NCF_{ref} is the neutron calibration factor for a reference neutron field. In this study, the bare ^{252}Cf spectrum was used as the neutron reference field and its uncertainty is 10,3%. *WCF* is the workplace correction factor associated with the actual neutron workplace field where the dosemeter was used. Its value is calculated by the equations presented in the Table 2. The standard uncertainty of the N1 curve fit is estimated at 10%.

$$H_P(10)_{neutron} = H_n = D_a \times NCF_{ref} \times WCF \tag{11}$$

The equations of Table 2 were obtained from $WCF \times D_i/D_a$ curves obtained previously by Monte Carlo simulations [5] for the four application areas N1 to N4. Figure 2 shows the results for N1 area. The responses of Alnor albedo dosemeter for the incident and the albedo components were simulated using the MCNPX Monte Carlo transport code, version 2.5.0. For the simulations, the Alnor albedo dosemeter was positioned on the center of the front face of an ISO water slab phantom and were irradiated with several parallel neutron beams striking perpendicularly its face. The tool Tally + F6 of the MCNPX, which provides the energy deposited in the TLDs, was used to calculate the TLD responses. For each application area, the values obtained were used to plot $WCF \times D_i/D_a$ curves.

Table 2. Proposed WCF × D_i/D_a for N1 to N4 application areas [5].

Application area	D_i/D_a range	WCF
N1	$D_i/D_a < 1.3$	0.10
	$1.3 \leq D_i/D_a \geq 10$	$0.1167\times D_i/D_a^{-0.512}$
	$D_i/D_a > 10$	0.04
N2	$D_i/D_a < 0.4$	0.57
	$0.4 \leq D_i/D_a \geq 2.3$	$0.3299\times D_i/D_a^{-0.6}$
	$D_i/D_a > 2.3$	0.20
N3	$D_i/D_a < 0.3$	1.60
	$0.3 \leq D_i/D_a \geq 10$	$0.856\times D_i/D_a^{-0.536}$
	$D_i/D_a > 10$	0.25
N4	$D_i/D_a < 0.3$	1.14
	$0.3 \leq D_i/D_a \geq 10$	$0.4099\times D_i/D_a^{-0.851}$
	$D_i/D_a > 10$	0.10

The neutron spectra used in the simulations for N1 application area was the reference $^{252}Cf(D_2O)$ ISO neutron field and several other power reactor, particle accelerators, neutron generators and interim storage place neutron spectra.

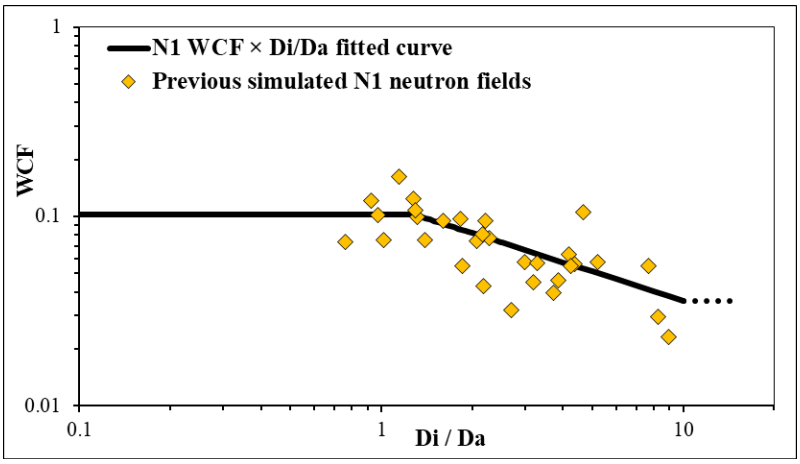

Figure 2: *WCF* × D_i/D_a *curve for the application area N1 (normalized by the* ^{252}Cf*).*

To calculated the WCF by the proposed curves of Table 2, it is necessary to calculated the D_i/D_a ratio and put it in the equation of Table 2. The combined uncertainty of WCF depends on the confidence interval of the projected WCF value for the confidence interval of D_i/D_a, in addition to the uncertainty of the curve fit itself.

The neutron dose normalized to photons $H_P(10)$ for incident component (D_i) is calculated similarly to the apparent neutron dose, but considering the readings of the MTS-6 and MTS-7 at incident position (Equation 12). Its uncertainty is calculated by Equation 13.

$$\mathrm{D_i} = \left(D'_{MTS6,incident} - D'_{MTS7,incident}\right) \tag{12}$$

$$U(D_i) = \sqrt{{U_{D'_{MTS6,incident}}}^2 + {U_{D'_{MTS7,incident}}}^2} \tag{13}$$

The uncertainty of D_i/D_a ratio is given by Equation 14.

$$U(\mathrm{D_i}/\mathrm{D_a}) = \frac{\mathrm{D_i}}{\mathrm{D}_a} \times \sqrt{\left(\frac{U_{\mathrm{D_i}}}{\mathrm{D_i}}\right)^2 + \left(\frac{U_{\mathrm{D}a}}{\mathrm{D}_a}\right)^2} \tag{14}$$

Then, the combined uncertainty of the H_n is given by Equation 15.

$$U(H_n) = H_n \times \sqrt{\left(\frac{U_{\mathrm{D}a}}{\mathrm{D}_a}\right)^2 + \left(\frac{u_{NCF_{ref}}}{NCF_{ref}}\right)^2 + \left(\frac{U_{\mathrm{WCF}}}{\mathrm{WCF}}\right)^2} \tag{15}$$

Including other sources of uncertainty not considered in the above calculations, such as angular dependence of the dosemeter response, an additional uncertainty of 10% should be considered and the final combined uncertainty, $U'(H_n)$ is given by equation 16.

$$U'(H_n) = H_n \times \sqrt{\left(\frac{U_{Hn}}{H_n}\right)^2 + 0.1^2} \tag{16}$$

The proposed algorithm for calculating the neutron $H_P(10)$ using the IRD's Alnor albedo system is shown in Figure 3.

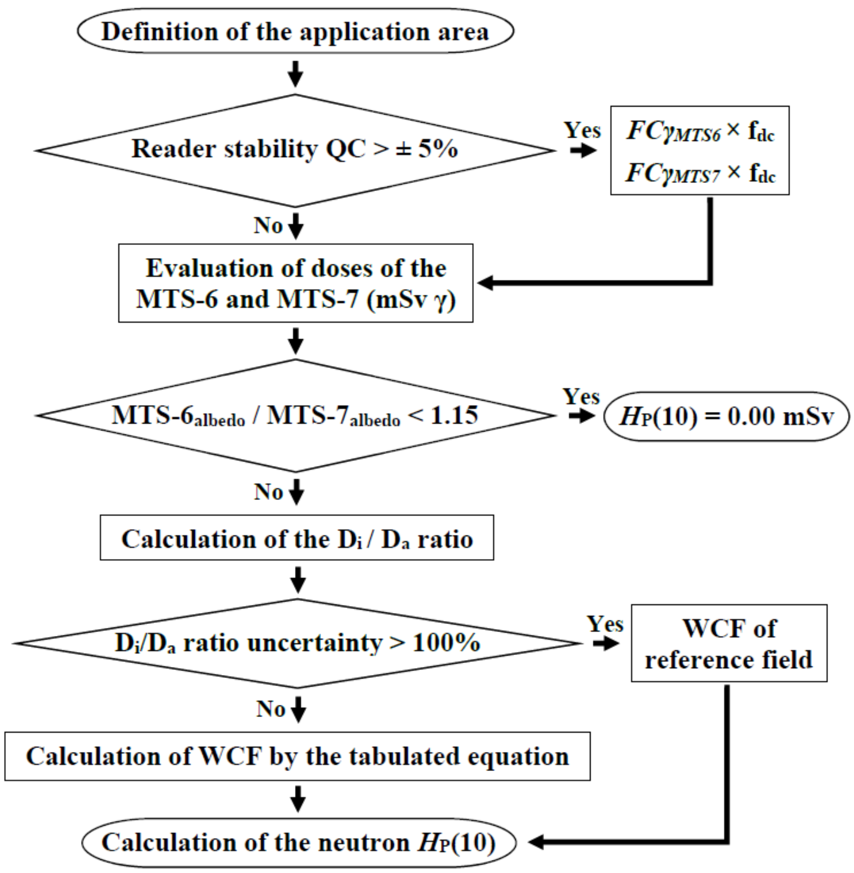

Figure 3: *Neutron* $H_P(10)$ *calculation algorithm flowchart*

4. APPLICATION OF THE PROPOSED ALGORITHM: ANGRA NUCLEAR POWER PLANTS

For this study, measurements were performed with 14 Alnor albedo dosemeters and 14 reference albedo dosemeters [1] irradiated in different neutron fields of pressurized water reactors (PWR) of two nuclear power plants, Angra I and Angra II, managed by the *Eletrobras Eletronuclear,* a governmental Brazilian Company. These irradiations were carried out using an ISO slab phantom positioned in different locations of the facilities with different exposure times. Alnor albedo dosemeters were measured using the apparatus and operational procedures of the automatic neutron individual monitoring system, which is being implemented at the IRD. The algorithm presented in this study was used for $H_P(10)$ evaluation. The reference albedo dosemeters were evaluated by the current IRD neutron individual monitoring system according to its routine procedures. The uncertainties of IRD reference system are calculated following the same methodology used for Alnor system.

Table 3 presents a comparison of photon $H_P(10)$ measured using the Alnor dosemeters and the reference IRD albedo dosemeters, with expanded uncertainties calculated for 95% confidence level.

Table 3: Comparison of photon $H_P(10)$, in mSv, measured by Alnor and by the IRD systems with expanded uncertainties calculated using k = 2.

#Field	#Alnor	$H_P(10) \pm U(95\%)$	#Reference	$H_P(10) \pm U(95\%)$	Alnor/Reference dosemeter
1	50447	0.29 ± 0.07	3	0.29 ± 0.09	1.02
2	50449	0.44 ± 0.10	5	0.49 ± 0.12	0.89
3	50456	0.16 ± 0.05	11	0.19 ± 0.07	0.84
4	50455	0.19 ± 0.06	10	0.21 ± 0.08	0.90
5	50446	1.06 ± 0.22	2	1.16 ± 0.27	0.91
6	50448	0.34 ± 0.08	4	0.29 ± 0.09	1.17
7	50450	1.13 ± 0.24	6	1.10 ± 0.25	1.03
8	50453	0.18 ± 0.05	8	0.19 ± 0.07	0.94
9	50452	0.73 ± 0.16	7	0.80 ± 0.19	0.92
10	50454	0.26 ± 0.07	9	0.26 ± 0.08	1.00
11	50442	57.70 ± 11.86	12	63.10 ± 14.11	0.91
12	50444	21.09 ± 4.34	14	21.10 ± 4.72	1.00
13	50443	28.74 ± 1.06	13	27.43 ± 6.13	1.05
14	50445	9.88 ± 0.37	15	10.69 ± 2.39	0.92
				Average:	0.97

Table 4 shows a comparison of the neutron $H_P(10)$ evaluated by Alnor dosemeter applying the developed algorithm and the neutron $H_P(10)$ assessed by the validated reference IRD albedo system, both with expanded uncertainties calculated for 95% confidence level.

The results show good agreement between the measurements with the Alnor albedo system and the current routine albedo system of IRD.

Table 4: Comparison of neutron $H_P(10)$, in mSv, measured by Alnor and by the IRD system, with expanded uncertainties calculated using k = 2.

#Field	#Alnor	$H_P(10) \pm U(95\%)$	#Reference	$H_P(10) \pm U(95\%)$	Alnor/Reference dosemeter
1	50447	1.06 ± 0.47	3	0.92 ± 0.42	1.15
2	50449	1.88 ± 0.83	5	2.53 ± 1.14	0.75
3	50456	0.51 ± 0.23	11	0.60 ± 0.27	0.85
4	50455	0.84 ± 0.38	10	0.75 ± 0.34	1.11
5	50446	1.47 ± 0.68	2	1.22 ± 0.56	1.20
6	50448	0.23 ± 0.12	4	0.32 ± 0.15	0.73
7	50450	0.95 ± 0.44	6	1.96 ± 0.89	0.49
8	50453	0.41 ± 0.19	8	0.53 ± 0.24	0.77
9	50452	2.19 ± 0.97	7	2.52 ± 1.14	0.87
10	50454	0.20 ± 0.10	9	0.40 ± 0.18	0.50
11	50442	< 3.6 ± 1.80	12	< 6.00 ± 2.70	
12	50444	< 1.2 ± 0.60	14	< 2.00 ± 0.90	
13	50443	< 1.6 ± 0.80	13	0.59 ± 0.74	
14	50445	< 0.6 ± 0.30	15	< 1.00 ± 0.42	
				Average:	0.84

5. CONCLUSIONS

The results show, within the uncertainties for a 95% confidence level (k = 2), a good agreement between measurements with the Alnor albedo system and the current IRD albedo system, used as reference dosemeter, for both photon $H_P(10)$ and neutron $H_P(10)$ measurements, at Angra I and Angra II power plant occupational fields. This validates the *WCF × Di/Da* simulated curves and the algorithm proposed in this study for use with Alnor albedo dosemeter in power reactors (N1 application area). It was also seen that the results indicate that the Alnor system is also capable of measuring photon doses. However, for neutrons, other real fields still need to be tested, including workplaces of the other application areas.

As with any measurement, quality control points and the correct use of correction factors are critical for a reliable result, as well as the system calibration. The proposed algorithm, for neutron dose calculation, highlights the main control points:

1. Choice of application area,
2. Check of the reader stability,
3. Evaluation of the reliability of *Da* neutron apparent dose, and
4. Evaluation of the reliability of the *Di/Da* ratio value.
5.

The first step of the dose calculation algorithm, which is the choice of the application, is one of the key points of the algorithm for neutron dose evaluation. The selection of a wrong area may overestimate or underestimate the neutron $H_P(10)$ by more than 100%. Hence, there is a need to obtain information about the real neutron field before starting the neutron dose calculations. In the case study of this paper, there is no doubt that the field is N1. However, sometimes the choice of the corrected application area is not a trivial task.

As the TLD reader may change its sensitivity over time, it is important to check and to correct its calibration factor, if necessary. When the photon dose is much higher than the neutron dose, the difference between the albedo TLD responses (MTS6-MTS7) is smaller than the value of its uncertainty, making the neutron dose calculation impossible. Nevertheless, this is not relevant, because, in terms of radiation protection, for the occupational worker, what matters is the total dose (photons + neutrons).

Last, but not least, it is only possible to use $WCF \times D_i/D_a$ curves when the value of D_i/D_a ratio is reliable, that is, when its uncertainty is not greater than 100%. For unreliable ratio values, the WCF of the reference field of the application area should be used, which can lead to a large overestimation of the dose. In this case, in the normal routine of an individual neutron monitoring service, if the value of the measured occupational dose of neutrons is close to the value of the investigation level, a specific study of the correct WCF in the real neutron radiation field must be carried out to reduce the overestimation of the dose value.

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