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Le treizième congrès de l'IRPA (International Radiation Protection Association) a eu lieu à Glasgow du 13 au 18 mai 2012.
Ce numéro 3 du Volume 37 des Annales de l'Association belge de Radioprotection reprend des articles d'auteurs belges.

Van 13 tot 18 mei 2012 vond te Glasgow het dertiende congres van de IRPA (International Radiation Protection Association) plaats.
Dit nummer, n° 3 van Volume 37 van de Annalen van de Belgische Vereniging voor Stralingsbescherming, herneemt de artikels met Belgische auteurs.

SOMMAIRE **INHOUD**

IRPA 13

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PARTICIPATION BELGE

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CHARACTERIZATION OF THE NEUTRON FIELDS AROUND CERNAVODA NPP

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In the environment near a nuclear reactor, a fuel container or a particle accelerator, mixed neutron/gamma fields are very common, necessitating routine neutron dosimetry. Accurate neutron dosimetry is complicated by the fact that the neutron effective dose E and neutron personal dose equivalent $H_p(10)$ is strongly dependent both on the neutron energy and the direction distribution of the neutron fluence. Therefore, neutron field characterization is indispensable if one wants to obtain a reliable estimate for the neutron dose. A measurement campaign in CANDU NPP in Cernavoda, Romania, was set up in November 2010 to characterize the neutron fields in four different locations and to investigate the behavior of different personal neutron dosemeters. Neutron field characteristics, such as energy and angular distributions, were determined using different neutron monitors. The energy distribution was measured using a BTI Mycrospec and Nprobe combination, the angular distribution was measured by placing personal dosemeters on five faces of a slab phantom. The results were combined together to obtain a reference value for the personal dose equivalent $H_p(10)$. The obtained values were compared to the readings of the personal monitors in order to choose a suitable neutron dosimetry system at Cernavoda nuclear power plant.

1. Introduction

When individuals are exposed in mixed neutron/gamma environments it is necessary, in addition to routine gamma dosimetry, to perform accurate routine neutron dosimetry. It would be optimal to have neutron dosemeters capable of measuring the dose equivalent with the same accuracy as the existing dosemeters for gamma radiation. But the fact that the neutron equivalent dose is strongly dependent on the neutron energy implies extra features to the neutron detectors. Most ambient and personal neutron dosemeters lack the requirement of providing a combined standard uncertainty of less than 50% (Garcia-Alves et al 2009).

In addition to the energy dependence of neutron dose measurements, the directional distribution of the neutron fluence strongly affects neutron dose measurements as well; the personal dose equivalent $H_p(10,\theta)$ and the effective dose E depend strongly on the direction of the incident radiation field (ICRP 74 1996). To make accurate estimations of the ambient and personal dose equivalent, neutron field characterization, taking into account both the energy and angular distribution, is indispensable.

In this work neutron field characterization was performed at four different locations in Cernavoda Nuclear Power Plant (NPP), which is a CANDU type reactor. The main goal of this collaboration was to characterize the neutron fields and to derive a reference value for the neutron ambient and personal dose equivalent, $H^*(10)$ and $H_p(10)$. This allowed us to investigate the behavior of different personal monitors in the chosen measurement locations by comparing the measured values with the estimated reference values. This provided information for a well informed choice of a neutron dosimetry system at the power plant.

2. Materials and methods

2.1 Measurement locations

Measurements were performed at different locations, including locations inside and outside the containment structure of unit 1. The locations were chosen taking into account dose rate estimates and the occupancy level of workers.

Measurements inside the containment structure were performed in the heat transport auxiliary room (R-405) and in the boiler room (R-501). The boiler room is situated at the top level, near the heat exchanger. Outside the

containment structure, measurements were performed in the D_2O vapour recovery room (S-146).
In order to obtain a reliable value for the personal dose equivalent, several measurements were performed intended to:
- Derive the energy distribution of the neutron fluence
- Determine the directional distribution of the neutron fluence
- Estimate a reference value for the ambient and the personal dose equivalent rate $\mathrm{d}H^*(10)/\mathrm{d}t$ and $\mathrm{d}H_p(10)/\mathrm{d}t$

2.2 Energy distribution of the neutron fluence

The energy spectrum was determined using a Microspec-2 Nprobe, developed by BTI bubble Technologies. Thermal and epithermal neutrons are measured with a ^{3}He counter encased within a special ^{10}B shield, separated in two energy bins. Fast neutrons are measured and presented in 16 energy bins by using a liquid scintillator. (Ing 2007)

2.3 Directional distribution of the neutron fluence

The directional distribution of the neutron fluence was estimated using the readings of different active and passive personal dosemeters. The detectors were placed on five faces of a slab phantom, being front, left, right, back and top, as shown in Figure 1. The fluence incident in different directions $P(\vartheta, \phi)$ on the phantom, indicated in Figure 1, was estimated using linear interpolation techniques in steps of 15° in the perpendicular directions.

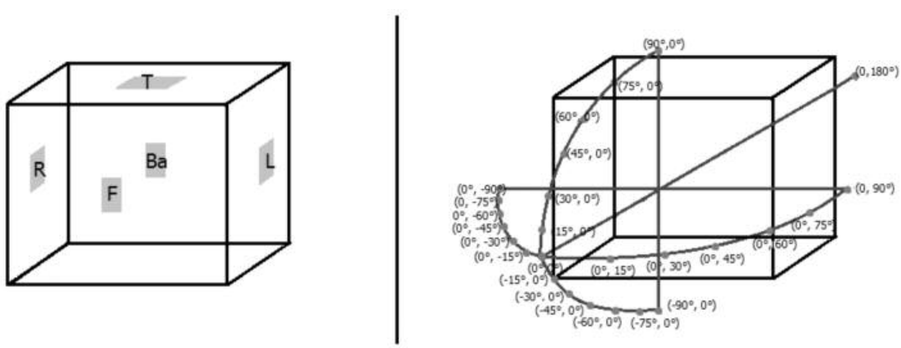

Figure 1: Both active and passive dosemeters were placed on all sides of a slab phantom (left figure) to estimate the angular distribution of the neutron fluence incident in different directions P(ϑ, ϕ) (right figure). This latter was done using linear interpolation techniques under the assumption that the energy distribution remains the same in all orientations.

2.4 Reference value for ambient dose equivalent rate d*H*(10)*/d*t*

A reference value for the ambient dose equivalent was determined using three different ambient monitors, Studsvik 2202D (Andersson and Braun 1964), Wendi II (Therom Scientific), and Eberline NRD ASP2. These detectors are all proportional counters based on the $^{3}He(n,p)^{3}H$ or $^{10}B(n,\alpha)^{7}Li$ reaction.

A reliable estimation for each monitor of the ambient dose equivalent rate d*H*(10)*/d*t* was obtained by taking into account the energy response of the monitors (shown in Figure 2) normalized to the proper calibration sources (Schumacher et al 2006), (IAEA 2001), (Tanner et al 2007) and the spectral information obtained with the Nprobe. The average of the energy corrected values was considered to be the reference value for d*H*(10)*/d*t*.

d*H*(10)*/d*t* was used to obtain the reference for the total neutron fluence $d\Phi_{total}/dt$, by dividing d*H*(10)*/d*t* with the site specific average neutron fluence to ambient dose equivalent conversion coefficient <*h*(10)*>. The latter was obtained by using the Nprobe data and the ICRP *h*(10)* values (ICRP 74 1996) in the following way:

$$< h^*(10) > = \frac{\sum_i h^*(10)_i \Phi_i}{\sum_i \Phi_i} \qquad \textbf{Eq1}$$

In this equation, Φ_i represents the fluence in the *i*th energy bin and $h^*(10)_i$ the average conversion coefficient for energy bin *i* taken from the ICRP/ICRU conversion factors (ICRP 74 1996; ICRU 1997).

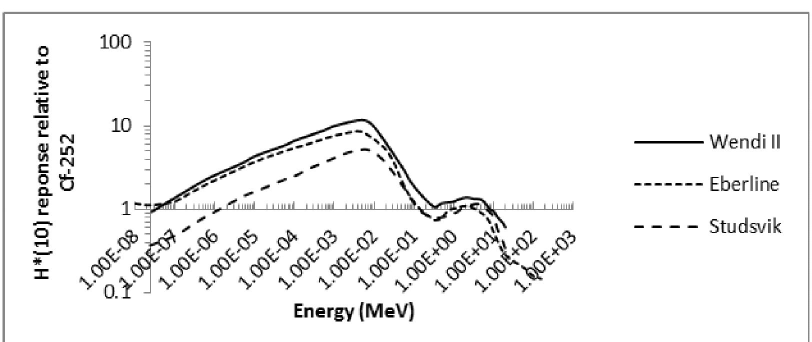

Figure 2: *H*(10)* response relative to Cf-252 of the ambient monitors used in the measurement campaign.

2.5 Reference value for personal dose equivalent rate dH_p*(10)*/d*t*

A reference value for personal dose equivalent rate was obtained by combining the information on the directional distribution of the neutron field and the reference value for the total neutron fluence dΦ_{total}/dt.

In a first approach a dose estimation was made under static conditions, meaning a person present in a certain location is not moving. The front of the phantom will therefore represent the front of the person. Partial dose rates were estimated by multiplying partial fluences d$\Phi(\vartheta, \phi)$/dt, derived from the directional distribution and the total neutron fluence, with an average personal dose equivalent conversion coefficient $<h_p(10, \theta)>$. The latter was calculated as explained previously in Eq1. For plane parallel irradiation from the front with an angle of incidence θ, $<h_p(10, \theta)>$ values were calculated from 0° to 90° in 15° increments using the data of (d'Errico et al 2007). A reference value for d$H_p(10)$/dt was obtained by summing together all partial dose rates.

$$\frac{\mathrm{d}H_p(10{,}0°)}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_{(0°,0°)}}{\mathrm{d}t} < h_p(10{,}0°) >$$

$$\frac{\mathrm{d}H_p(10,\theta)}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_{(0°,\theta°)} + \mathrm{d}\Phi_{(0°,-\theta°)} + \mathrm{d}\Phi_{(\theta°,0°)} + \mathrm{d}\Phi_{(-\theta°,0°)}}{\mathrm{d}t} < h_p(10,\theta) >$$

$$\text{where } \theta = (15°{,}30°{,}45°{,}60°{,}75°{,}90°) \qquad \textbf{Eq 2}$$

$$\frac{\mathrm{d}H_p(10{,}180°)}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_{(0°,180°)}}{\mathrm{d}t} < h_p(10{,}180°) >$$

$$\frac{\mathrm{d}H_p(10)}{\mathrm{d}t} = \sum \frac{\mathrm{d}H_p(10,\theta)}{\mathrm{d}t} \text{ where } \theta = (0°{,}15°{,}30°{,}45°{,}60°{,}75°{,}90°{,}180°)$$

The values obtained were compared to each other and to the readings of the personal monitors to evaluate the behavior of the monitors in the chosen locations.

3. Results

3.1 Energy distribution of the neutron fluence

In three out of four measurement locations, soft spectra were observed. In the boiler room a rather large contribution from neutrons spanning energies from 0.5 to 1 MeV were observed.

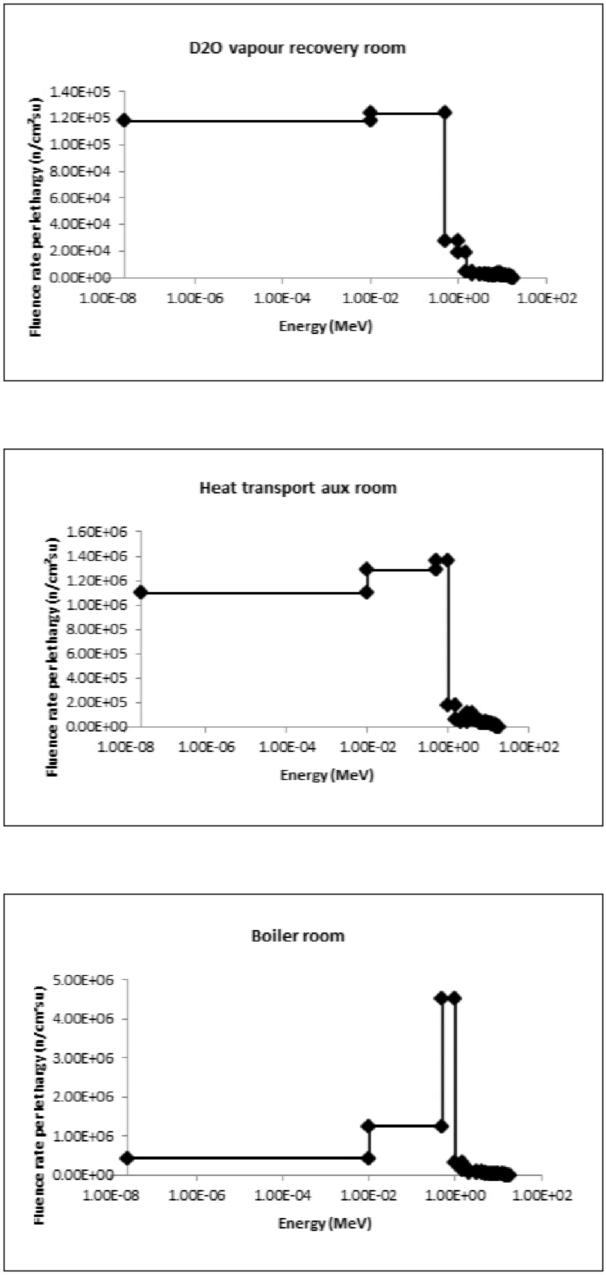

Figure 3: The spectra obtained with the Nprobe are in general soft spectra. An exception to this is the spectrum obtained in the boiler room, where there is a rather large contribution from neutrons having energy from 0.5 to 1 MeV.

3.2 Directional distribution of the neutron fluence

The directional distribution of the neutron fluence was estimated by placing different personal monitors on five faces of a slab phantom. The measured values from all detectors are presented in Table 1. These values were used to calculate the relative neutron fluence incident in different directions *P(ϑ; ϕ)* on the phantom using linear interpolation.

Table 1: Measured values from all the personal monitors in all the measurement locations.

Location		*Thermo EPDN2 (µSv/h)*	*DMC 2000 GN (µSv/h)*	*HPA PADC (µSv/h)*	*Landauer PADC (µSv/h)*	*Landauer FNTD (µSv/h)*
D2O vapour recovery room	**Front**	77 ± 11	46 ± 6	10 ± 2	13	11 ± 1
	Back	28 ± 4	19 ± 3	1 ± 1	5	2.6 ± 0.3
	Left	57 ± 11	67 ± 13	6 ± 2	3	4.4 ± 0.5
	Right	47 ± 9	31 ± 6	4 ± 1	7	1.9 ± 0.2
	Top	62 ± 12	34 ± 7		5	
Heat transport aux room	**Front**	383 ± 54	251 ± 36	76 ± 4	133	40 ± 5
	Back	66 ± 9	26 ± 4	4 ± 2	9	4.4 ± 0.5
	Left	160 ± 32	156 ± 31	12 ± 3	20	16 ± 2
	Right	164 ± 33	184 ± 37	10 ± 2	26	
	Top	160 ± 32	161 ± 32	18 ± 3	18	
Boiler room	**Front**	127 ± 18	101 ± 20	44 ± 3	80	17 ± 2
	Back	54 ± 8	36 ± 5	4 ± 1	14	
	Left	83 ± 17	69 ± 14	9 ± 2	19	
	Right	80 ± 16	81 ± 16	17 ± 2	33	
	Top	99 ± 20	57 ± 11	7 ± 2	20	

In the D_2O vapour recovery room the neutron fluence can be considered isotropic; in the boiler room and the heat transport aux room, the neutron fluence is mainly coming from the front of the phantom.

3.3 Reference value for ambient dose equivalent rate d*H*(10)*/d*t*

As explained in the "Materials and Methods" section of this paper, the ambient dose equivalent rate was measured using ambient monitors. The spectral information of the Nprobe was used together with the energy response of the monitors to obtain energy corrected values. The values are presented in Table 2. The average of the energy corrected values was considered the reference value for the ambient dose equivalent rate d*H*(10)*/d*t*.

Table 2: Measured values for the ambient dose equivalent rate, together with the corrected values, taking into account the energy response of the monitors. The average value of the energy corrected values is considered the reference value for the ambient dose equivalent rate.

	Ambient monitor	*Measured dose rate (µSv/h)*	*Energy corrected dose rate (µSv/h)*	*Average dose rate (reference dose rate) (µSv/h)*
D_2O vapour recovery room	*Wendi II*	41 ± 8	17 ± 3	16 ± 2
	EberlineASP2	44 ±9	17 ± 3	
	Studsvik2202D	23 ± 1	14 ± 1	
Heat transport aux room	*Wendi II*	150 ± 30	78 ± 16	97 ± 9
	EberlineASP2	218 ± 44	105 ± 21	
	Studsvik2202D	154 ± 4	107 ± 3	
Boiler room	*Wendi II*	126 ± 25	97 ± 19	92 ± 9
	EberlineASP2	139 ± 28	103 ± 21	
	Studsvik2202D	86 ± 2	77 ± 2	

As explained in section 2.4, the ambient dose equivalent rate was used to estimate the total neutron fluence $d\Phi/dt$, by dividing $dH^*(10)/dt$ with the site specific average neutron fluence to ambient dose equivalent conversion coefficient $h^*(10)$. The latter was obtained by using the Nprobe data and the ICRP $h^*(10)$ values (ICRP 74 1996). The values are presented in Table 3.

Table 3: Reference value for the ambient dose equivalent rates, average fluence to ambient dose equivalent conversion coefficient and reference value for the total fluence rate, calculated for every measurement location.

	dH(10)/dt (µSv/h)*	*<h*(10)> (µSvcm²)*	*dΦ/dt (n/cm²h)*
D_2O vapour recovery room	16 ± 2	4.02E-05	(4.0 ± 0.4) E+05
Heat transport aux room	97 ± 9	5.57E-05	(1.7 ± 0.2) E+06
Boiler room	92 ± 9	1.37E-04	(6.8 ± 0.7) E+05

3.4 Reference value for personal dose equivalent rate $dH_p(10)/dt$

Reference values for personal dose equivalent rate were estimated using a static approach, meaning a person present in a certain location is not moving. Partial dose rates were estimated by multiplying partial fluences $d\Phi(\vartheta,\phi)/dt$, derived from the directional distribution and the total neutron fluence, with an average personal dose equivalent conversion coefficient $\langle h_p(10, \theta)\rangle$.

Table 4 represents the average $<h_p(10, \theta)>$ conversion coefficients calculated using the Nprobe data and the ICRP $h_p(10)$ values (ICRP 74 1996).

Table 4: average $<hp(10, \theta)>$ conversion **coefficients**, obtained using the Nprobe data, and the ICRP **$h_p(10)$ values.**

	D_2O vapour recovery room	*Heat transport aux room*	*Boiler room*
$<h_p(10,0°)>$ pSvcm²	42.3	58.2	141.4
$<h_p(10,15°)>$ pSvcm²	40.5	53.7	122.5
$<h_p(10,30°)>$ pSvcm²	39.2	55.1	137.7
$<h_p(10,45°)>$ pSvcm²	33.5	48.1	123.5
$<h_p(10,60°)>$ pSvcm²	24.4	36.4	97.6
$<h_p(10,75°)>$ pSvcm²	10.7	17.1	48.0
$<h_p(10,90°)>$ pSvcm²	0.9	1.4	2.7
$<h_p(10,180°)>$ pSvcm²	2.1	2.9	5.4

Table 5 summarizes the values for the total personal dose equivalent rate estimations, calculated using a static approach.

Table 5: Personal dose rate estimations, under a static approach. The front of the phantom is considered the front of a person.

	D2O vapour recovery room		*Heat transport aux room*		*Boiler room*	
	Hp(10, x)	**u**	**Hp(10, x)**	**u**	**Hp(10, x)**	**u**
$H_p(10)$	11.3	1.2	73	11	65	9

As a final step, the calculated values for personal dose equivalent rate were compared with the readings of different detectors. Site specific correction factors for each detectortype were proposed and presented in in Table 6.

For proper evaluation, the readings of the monitors in the front of the phantom were compared to the calculated values of the personal dose equivalent rates.

Table 6: Comparison between the calculated static dose equivalent rates and the readings from the front detectors.

	D_2O vapour recovery room		*Heat transport aux room*		*Boiler room*	
	$H_p(10)$ (µSv/h)	**Site specific correction factor**	**$H_p(10)$ (µSv/h)**	**Site specific correction factor**	**$H_p(10)$ (µSv/h)**	**Site specific correction factor**
Reference	11.3 ± 1.2		73 ± 11		65 ± 9	
Thermo EPD N2 - Front	77 ± 11	6.8 ± 1.2	383 ± 54	5.2 ± 1.1	127 ± 18	2.0 ± 0.4
DMC 2000 GN - Front	46 ± 6	4.0 ±0.7	251 ± 36	3.4 ± 0.7	135 ± 20	2.1 ± 0.4
HPA CR 39 - Front	10.5 ± 2.0	0.9 ± 0.2	76 ± 4	1.0 ± 0.2	44 ± 3	0.7 ± 0.1
Landauer CR 39 - Front	13.1	1.2 ± 0.1	133	1.8 ± 0.3	80	1.2 ± 0.2
Landauer FNTD - Front	11.3 ± 1.4	1.0 ± 0.2	40 ± 5	0.6 ± 0.1	17 ± 2	0.27 ± 0.05

4. Conclusion

The measurements conducted in this project were intended to estimate reference values for $dH_p(10)/dt$ and $dH^*(10)/dt$. In order to obtain reliable reference values, information on energy and direction distribution is of great importance in the case of neutron dosimetry. Measurements were performed with an Nprobe to determine the energy distribution of the neutron fluence.

Information on the directional distribution was obtained by placing personal dosemeters in 5 faces of a slab phantom. It is clear that the neutrons do not come from one direction. In one location, most neutrons come from the top, which can give rise to underestimations of the effective dose.

A reliable value for $\mathrm{d}H^*(10)/\mathrm{d}t$ was estimated using different ambient monitors. After energy dependency corrections, consistent values for $\mathrm{d}H^*(10)/\mathrm{d}t$ were obtained in every location, with an exception for the basement perimeter. The reference values for ambient dose equivalent rate were used to determine reference values for the total neutron fluences $\mathrm{d}\Phi/\mathrm{d}t$ in each of the considered locations.

Using $h_p(10,\theta)$conversion coefficients (for every 15° in perpendicular directions, up to 90°), partial fluences, obtained using the information about the total fluence and the direction distribution, are converted into partial dose rates and combined together to a reference value for $\mathrm{d}H_p(10)/\mathrm{d}t$. The obtained values are compared with the readings of the personal monitors involved in the measurement campaign in order to propose site specific correction factors.

When comparing the calculated values with the detector readings, the PADC detectors perform relatively well in all considered locations. In general, Landauer PADC detectors have to tendency to overestimate the dose with an average of 20%, while HPA PADC detectors underestimate the dose with an average of 20%, meaning an overall correction coefficient could be used for this detector type.

The performance of the other detectors seem to differ depending on the location, which necessitates the use of different correction factors that are quite substantial. This limits the use of the passive Landauer FNTD detectors, but is relatively easy to overcome with active detectors.

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20 YEARS OF ALARA MANAGEMENT, RESEARCH AND DEVELOPMENT AT THE BELGIAN NUCLEAR RESEARCH CENTRE SCK•CEN

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Abstract

The Belgian Nuclear Research Centre SCK•CEN performs research and offers services in the domains of nuclear safety and radiation protection. It operates major large facilities such as research reactors and hot laboratories, it develops innovative nuclear infrastructures and decommissions and dismantles old facilities. After a reorganisation in 1991, an enhanced safety management was implemented, including a systematic ALARA approach. Staff was trained in the ALARA approach. A case study was developed: the dismantling of BR3, the first PWR reactor at the European continent. An ALARA management system including an ALARA-committee, an ALARA-procedure and an ALARA database was put into place, taking into account the complex mixture of routine tasks linked to the operation of larger facilities, and many unique, innovative tasks characteristic of a research environment.

To support the ALARA policy, a dedicated tool called "VISIPLAN 3D ALARA planning tool" to assess doses prior to an operation in a radiation environment was developed. Technological developments such as improved electronic dosimeters were implemented. Conceptual work has led to a holistic approach of radiation protection, nuclear and industrial safety, including waste management and cultural aspects. At present, an extension towards enhancing an adequate security culture is being made.

The design of a new research reactor MYRRHA creates a new challenge for our ALARA approach. Due attention must be given to dose reducing measures already embedded in the design. The experience gained in radiation protection in the past 20 years at the research centres is a valuable asset in the design process.

Keywords: ALARA management, ALARA tools, ALARA in dismantling, ALARA in design

1. Introduction

The Belgian Nuclear Research Centre SCK•CEN, www.sckcen.be, was created in the fifties to support the introduction of nuclear electricity production in Belgium. Several research reactors were constructed and a range of laboratories was designed and commissioned: hot laboratories for post-irradiation examination of nuclear fuels and materials, for radiochemical analyses, waste management and research, medical isotope production, radiation protection research including radioecology and radiobiology etc. In the seventies, when the first Belgian nuclear reactors in Doel and Tihange were connected to the grid, the need for nuclear research diminished and an exercise of diversification was started (energy in general, studies of materials in a non-nuclear context etc.). The isotope production was handed over to a subsidiary company located elsewhere. At the end of the eighties, it was decided to diminish the activities, leading to an important reduction in staff. The BR3 reactor, the first PWR nuclear power reactor on the European continent, was shut-down. The operational waste department was transferred to another company (Belgoprocess), and the non-nuclear activities were moved from the SCK•CEN to a newly created Flemish institute (VITO) in 1991. In parallel, a new management was nominated, a new organisation was put into place and many young people were recruited to fill the gaps in the organisation. This exercise included also a re-enforcement of the Health and Safety department. This resulted into the development of important efforts for education and training, initially mainly of in-house staff, later also for other nuclear actors feeling the need. The need to strengthen the management of radiation protection and ALARA was also identified and put into operation.

2. Implementation of an ALARA policy

2.1. Preparation

At the end of the eighties, at the moment ALARA management became an issue (e.g. Radiation Protection 44, 1988), SCK•CEN was in reorganisation, not actively introducing it within the organisation. From 1991 on however, efforts were made to implement an ALARA policy at the SCK•CEN. This took the following steps: i) decision by the management; ii) nomination of staff at the Health Physics Department to get specific training and to follow-up international guidance and developments; iii) selection of key persons in each facility and provide an adequate training; iv) campaigns of information and dissemination of information; v) formal approval of the ALARA procedure. CEPN, the ‘Centre d’Etude sur l’Evaluation de la Protection dans le domaine Nucléaire’, (France, www.cepn.asso.fr), was strongly involved in the training of the staff and in the dissemination efforts (CEPN, 1992), and also supported the first real case studies on site. Exchange was established with the Doel nuclear power plant (Segers, 1991). The book “ALARA from Theory towards Practice” (Stokell et al., 1991) was a valuable reference document used frequently and in all major facilities. Simultaneously, a constraint of 10 mSv maximal annual individual dose was approved.

2.2. ALARA Procedure

This paragraph shows the present status of ALARA at SCK•CEN. A particularity for a research centre is the large variety of facilities and projects, generating a large diversity of circumstances. This leads to many unique operations, though the maintenance of the major facilities also includes a number of routine tasks. Further information can be found in (Antoine 2007; Antoine 2010).

2.2.1. Scope

The ALARA procedure is applicable for all works involving a risk of external exposure or contamination.

2.2.2. The actors involved

The *applicant* is the person responsible for the execution of some particular project or task involving a risk of contamination or exposure.

The *Local ALARA Coordinator* is a person nominated within each major facility of the SCK•CEN, who performs the following tasks:

- Assistance to the applicants in correctly applying the procedure;
- Introduction of the ALARA demand in the ALARA database, launching the application officially;
- Follow-up of the outcome;
- Contact person with the Health Physics Department.

The *Radiation Control Agent* belongs to the Health Physics Department. This person provides the necessary data (radiation and contamination maps etc.) in the preparation stage, supervises the work if levels are high, and makes sure the right steps are followed and followed-up afterwards.

The *SCK•CEN ALARA Coordinator* is a high level staff member of the Health Physics Department, who is responsible for the analysis of the ALARA procedures submitted, and who gives the final approval to launch the work. He also reports results to the management of SCK•CEN, the Committee for Prevention and Protection at Work (a committee composed of employers and employees, the latter being appointed after social elections involving the trade unions), and the supervision authorities. For complex procedures, supplementary approvals by the authorities may be needed, e.g. if the operations involve modifications to the installations etc.

In the major facilities, a *Local ALARA committee* may be meeting, playing a role mainly in the preparation stage (defining the options, the planning etc.). It is composed of the major actors: the applicant, the radiation control agent, the local ALARA Coordinator and supplementary staff if considered useful.

At the level of SCK•CEN, the *ALARA Committee* meets monthly. It is composed of high level representatives of various departments: the Safety department, the Health Physics unit, the Medical Service, the head of the Waste Management Department, the Local ALARA Coordinators. The SCK•CEN ALARA coordinator acts as a secretary, and the meeting reports are distributed up to the top management of SCK•CEN.

Its roles are:
- The follow-up of on-going and past ‘ALARA procedures’;
- Advice and exchange and feedback of experience;
- Approval in case of larger doses involved (see below);
- Discussion of practical issues (waste, dosimetry, database development).

2.2.3. The major steps in the procedure

The ALARA procedure foresees the use of three forms:
Form A is used in case the operation it covers is to be executed for the first time (or is a unique operation). It has to be supplemented by a detailed working procedure for the particular operation.

The first part contains the dose estimates, the number of staff involved, the indication of non-radiological risks, data on waste generation and management etc. and is filled-in by the local ALARA Committee. The second part contains the remarks and conditions to be respected during execution (e.g. use of protective equipment, need for supervision by a Radiation Control Agent etc.)

Form B is a simplified version for operations that have been performed in the past without operational difficulties and without serious underestimations of the dose. Its objective is to make sure the operational and radiation environments have not changed in a negative sense, e.g. due to a change in radiation levels at the spot or the mounting of other equipment in the time lapse between previous and present execution.

Form C is used for the follow-up of the doses, based on electronic personal dosimeters, their parameters of importance, and the feedback of experience.

For dose estimations *below 0,5 man.mSv of collective dose*, and if the operation is executed for the first time (form A), an approval for execution by the SCK•CEN ALARA coordinator is needed; if it is a repetition of previous operations (form B), a check of form C is made, and the operation may be executed immediately.

For dose estimations between 0,5 and 5 *man.mSv of collective dose*, whether it is a first execution or not, the approval always has to be at the level of the ALARA coordinator at the level of SCK•CEN.

If the dose estimations trespass *5 man.mSv of collective dose and/or a maximal individual of 1 mSv of individual dose* is at stake, the approval by the ALARA committee is necessary.

Of course, depending on other risks present, whether industrial (fire, toxic products, …) or nuclear (interventions changing the facilities, or nuclear materials) or environmental (waste generation), other authorisations may be needed as well, either in-house or at the level of authorities.

2.3. Development and evolution

2.3.1. Improvements as regards dosimetry

Within SCK•CEN, the legal dosimetry is based upon TLD dosimeters. They show all the requirements imposed as regards stability, sensitivity, reproducibility, linearity as a function of energy, dose range etc. but they do not allow direct read-out nor provide alerting possibilities.

At the moment the ALARA became an organisational process, only electrostatic dosimeters were available, allowing direct read-out; yet, they were certainly not very reliable (very sensitive to shock), they did not allow to generate alerts and the dose records were made on paper, limiting future use for analysis. A major improvement was the introduction of electronic dosimeters for major projects from 1992 on, the test case being the BR3 dismantling project, solving the major issues of dose follow-up: alerting to assist reducing the doses during operations (as radiation fields may drastically change from one spot to another in the facilities), and to have at least a daily overview of individual doses.

In 2002, a new system was implemented, first stand-alone in the various facilities, and from 2003 on all systems were linked. This approach allows:

- Coupling authorisations in the ALARA procedure to tasks in the electronic personal dosimeter system allow defining dose constraints per task, combining the doses incurred with predictions etc. Tasks not being approved yet in the ALARA-procedure do not get a dosimeter task number, and as such do not allow starting the operations.
- The coupling of the various systems allows keeping daily track of all individual doses of all staff, also the ones working in several facilities.
- The coupling of the system to other systems allows limiting access to controlled areas for staff or subcontractors not having the adequate training, medical control, assessment of internal contamination,….

2.3.2. ALARA Database

The decision was made to develop an electronic tool to support the ALARA procedure; at present, the tool is programmed in Access®. It allows managing the ALARA-process electronically: authorisations, follow-up, dose records etc. The main advantage of electronic management is the guarantee that anyone involved has access to the most recent information and to identical versions; furthermore, delays are avoided: no forms have to circulate between several parties located in different buildings.

The Database also allows performing statistical analyses comparing tasks, doses, dose predictions, etc. Feedback to the staff, the ALARA Committee and reporting to the management, the committee for prevention and protection at work and the authorities is very convenient.

2.3.3. Non-radiological risks

For many operations, the radiation risks are but one of the inherent risks. Very often other risks are present. Heavy loads (shielding, use of containers), working at height or in closed environments (e.g. in dismantling projects) are part of daily experience. On rare occasions, other risks show up, such as the presence of asbestos (dismantling of old loops operating at high temperature).

The introduction of the ALARA procedure and the ALARA database also allow better identifying these risks on beforehand, supporting their prevention in a systematic way and following-up the outcome via the feedback foreseen on form C.

2.4. Major benefits

The formal introduction about 20 years ago of an ALARA policy, with supporting tools as explained above, has led to a considerable improvement of the protection against ionising radiation.

- Awareness was raised at all levels (workers, responsible of carrying out, management,...) of the importance of adequate management of the doses.
- Proposals to reduce the doses are debated inside the local ALARA committee, stimulating creativity, accountability and knowledge about practical radiation protection issues.
- The development of an ALARA database has enabled to centralise all information about ALARA, leading to a consistent approach within all facilities of SCK•CEN and for all types of tasks.
- The circulation of information concerning ALARA was strongly improved (among others via reports ALARA Committee).

3. A few illustrations

3.1. A major test-case: ALARA in the dismantling and decommissioning of the BR3 reactor

This paper is limited to some illustrations of the ALARA procedure; in the past, several papers and presentations have been made on the subject. We refer to (Antoine et al., 2009), (Govaerts and Zeevaert, 1993), (Massaut et al., 2002). This illustration deals a mixed risk case: radiation and asbestos.

The context:

The BR3 reactor was the first PWR (pressurised water reactor) in Western Europe and also the first one being decommissioned. Within the framework of the European five-year programme for research and technological development for the decommissioning of nuclear installations, BR3 was chosen, next to three other European installations, as a pilot project for the demonstration of the decommissioning of PWR plants. A second objective of this programme was to address the issue of the implementation of the ALARA principle in decommissioning operations.

The problem:

As required by the Belgian regulations the welfare on the workplace has to be guaranteed, including quality of the air. In this case, thermal insulation was present containing asbestos. This compound is a proven initiator of lung cancer, and air strict concentration limits have been set by law. During the BR3 decommissioning project, measurements indicated that this limit was reached on some workplaces located in controlled areas. Actions were undertaken in order to remove asbestos. The removal of asbestos is to be performed under stringent conditions fixed in Belgian legislation; only accredited companies are allowed proceeding to such removal operations. The main challenge faced with was to optimize the whole process, bearing in mind both requirements: radiation protection and asbestos.

Methodology:

The Health Physics department, in close co-operation with the BR3 management, decided:

- to invite the external company for a visit to the workplace and to inform them on the radiation protection measures to be followed by all workers in controlled areas;
- to require a detailed procedure describing the removal operations as well as the protective measures against the risk of asbestos;
- to develop, in addition to the daily monitoring of the workers, special monitoring of internal contamination of the external workforce; this was done for psychological reasons but also to detect, a potential internal contamination from asbestos;
- to inform all Belgian regulatory authorities concerned by radiological and non-radiological protection of workers – about this methodology.

Main results:

Due to this approach involving both the external workers and the BR3 workers, it has been possible:

- to reduce the number of required working days from 50 to 35;
- to reduce the number of external workers required for the removal operations;
- to avoid any air contamination with asbestos;
- to remove twice as much insulation material than planned.

As a consequence, the total collective dose for the whole operation was a factor 4.5 lower than the expected dose (19.2 man.mSv instead of 88.9 man.mSv).

Lessons learned:

Many valuable lessons have been collected during this removal project: examples are:

- Optimization doesn't prevent to comply with other requirements concerning other industrial risks; on the contrary, an ALARA approach contributes to a higher level of awareness and individual commitment to safety;
- An open minded approach with respect to all regulatory requirements and with adequate interactions with all authorities allows time-, dose- and cost savings;
- In such yards, time has to be made available for the initial information of external workforce and different ways of behaving have to be kept in mind;
- Detailed procedures need to be discussed between all the involved stakeholders and operators;
- Flexibility has to be allowed in order to cope with the technical, human and regulatory requirements.

3.2. A decontamination procedure of an experimental loop in the BR2 materials testing reactor

Context:

The BR2 reactor is a material testing reactor used for the production of medical isotopes, for the doping of high quality Si, for testing the behaviour of reactor materials and fuels etc. One of the major experimental loops within the BR2 reactor is the so-called Callisto loop. This loop simulates PWR temperature, pressure and water conditions, and allows the irradiation of materials for use in reactors in very high neutron fluxes for qualification and for prediction of their behaviour.

The problem:

The Callisto loop was installed in the early '90s, and due to deposition of activated materials at various positions, the dose rate around the loop has been rising throughout its operation. This had a negative impact on the dose to the workforce performing the maintenance of major components of this loop. The maintenance and inspection activities in the so-called Sub Pile Room (underneath the BR2 reactor and containing the major components of the loop such as the primary pumps) lead to a collective dose of 18.34 man.mSv in 2008.

Methodology:

As a topic within the periodic safety review of the BR2 facility, it was decided to investigate the possibility to decontaminate the loop. Decontamination has the advantage of reducing forthcoming exposures if further maintenance operations are performed. It has the disadvantage that the operation itself leads to exposure of the people performing it, to radiochemical wastes and maybe to damage to the loop if a sub-optimal chemical cocktail is used or if technical problems occur during the decontamination. After some test experiments, it was decided to proceed with the decontamination that was performed in 2011. Actors were: in-house staff specialised in this domain, in co-operation with the BR2 staff and the Health Physics department.

Main results:

- The decontamination of a major part of the Callisto loop lead to a collective dose of 5.5 man.mSv, with a maximal individual dose of around 0.8 mSv. (One part of the loop was not decontaminated because of some uncertainty of chemical compatibility between these components and the cocktail optimal to decontaminate the other parts);
- The operation took place without incidents (neither radiological nor chemical);
- The dose estimations were very comparable to the real doses;

- Predictions made indicate that in future in service inspections will lead to doses 4-5 times lower than in the past.

Lessons learned:

Many valuable lessons have been collected during this project: examples are:

- Optimisation includes an adequate balance between process control (sampling and subsequent radio-activity analysis), dose and effectiveness of the operations: very frequent sampling allows adjusting technical parameters adequately, yet leads to higher doses (due to the more frequent interventions and sample manipulations).
- An adequate cooperation between specialists (in decontamination in this case), operators within the facilities and the Health Physics department leads to reliable dose predictions and to successful elaboration of complex processes avoiding incidents. Involvement of all stakeholders and operators is vital.
- Optimisation includes the balance between a gain in dose reduction on the one hand, and the risk of future operational difficulties that might lead in their turn to higher doses. That's why a part of the loop has not been decontaminated.

<u>Remark</u>: Major decontamination operations have been adopted during the BR3 decontamination process as well, at the level of the primary circuit (Klein and Valenduc, 2002).

4. Development of tools: VISIPLAN 3D-ALARA planning tool

During the decommissioning of the BR3 reactor a need was identified for a tool to support the ALARA-analyst in the evaluation of dose reducing options. In order to perform a good ALARA-study for a planned work, information has to be gathered concerning the site geometry, the distribution of the sources, the work planning, the shielding options, the costs,... All these aspects have to be considered and integrated to arrive at an adequate ALARA-decision. The information has to be organised, structured and analysed to determine the best approach for the planned work. Evaluating the potential effectiveness of the dose reduction options is a large and time consuming part of the work. The need to dispose of a fast 3D - calculation tool became apparent due to the geometrical complexity and the distribution of source in the BR3 decommissioning work environment.

Therefore SCK•CEN started with the development of the VISIPLAN 3D-ALARA planning tool to assist the ALARA analyst in the ALARA pre-job studies, in the dose calculations but also in the communication between the stakeholders during the ALARA process (Vermeersch and Van Bosstraeten, 1998), (Vermeersch, 2003), (Vermeersch, 2004). The tool is based on a point-kernel dose calculation in a 3D environment with build-up correction. Dose accounts can be evaluated for different work scenarios investigated in the ALARA process taking into account the worker position, work duration and subsequent geometry and source distribution changes.

Its capabilities were proven in the decommissioning of the BR3 reactor especially in the optimisation of the work under the operating deck. Scenarios could not only be assessed in a shorter time; the communication of the results was also facilitated by the 3D representation. Soon external interest for the use of the VISIPLAN grew in the field of decommissioning and resulted in the creation of commercially available software. The field of application was extended to ALARA in routine operation and design of new installations and experiments. The use of VISIPLAN has stimulated a more rigorous implementation of ALARA and has facilitated the communication with stakeholders.

5. ALARA in Research

5.1. Support of policy by Research activities

Though working in a research centre leads on the one hand to complications due to the large variety of applications (routine versus experiments; very innovative experiments in old installations; design of prototypes versus dismantling), it also allows reflection on both the conceptual and managerial levels, as well as on practical implementation. In this paragraph, we briefly mention some examples of study subjects that have been tackled in the past without detailing them, just to stimulate the reader to be creative and open minded. Applications in the medical domain or legal aspects have been studied as well, but are not explained here.

5.1.1. The value of the man.Sievert

In the nineties, a lot of attention was paid to formal decision making based on cost-benefit analysis or cost-effectiveness analysis. Some references are (Lefaure et al., 1993), (Lefaure, 1995). Our centre has contributed in the clarification of conditions for application, the costs to include or not in the assessment etc. as published in (Hardeman et al., 1998).

5.1.2. Extending the scope

The scope of application was extended from external exposure in an occupational context to non-radiological risks (EAN 2000), management of radioactive waste as a contributing factor (conceptually, waste generation may lead to a transfer of professional exposure to long term public exposure), and potential exposures as aspects of a major refurbishment operation in the BR2 research reactor. The preparatory stage is given in (Hardeman, 1993).

5.1.3. Emergency conditions

The intervention levels applicable for early countermeasures in emergency conditions have been generically optimised in the nineties (ICRP 63), (IAEA SS 109); though some of the visions have been recently modified/superseded, the exercise of generic optimisation remains valid. Our centre has contributed in assessing whether higher intervention levels were justified and could be optimised for particular actors, such as people active in industrial facilities in the vicinity of a major nuclear power station in accidental conditions (Pauwels et al., 1999).

Further research has been performed in the domain of the selection of management options, using much more advanced mathematical methodologies besides the cost benefit analysis, and including methodologies for stakeholder involvement. This work has been published a.o. in (Turcanu 2007), (Turcanu et al., 2010).

5.2. Future developments

At present, much effort is made in supporting the integration of optimisation of the radiation protection risk from a cultural approach, not only focussing on optimisation, but also taking into account justification, and human and organisational factors. The management of culture is furthermore broader than radiation protection culture: it also needs attention to nuclear safety culture, safety culture with regards to non-nuclear related risks and environmental impact, security culture and safeguards culture. Reflections are still on-going and not yet to full maturity. Yet we refer to (Hardeman and Vermeersch, 2009) and (SSRAOC 2012) for further information.

6. ALARA in design

Nuclear safety plays a major role in the design and construction of new installations such as Myrrha, the new research reactor currently in design at the SCK•CEN. In the past occupational radiation protection and ALARA were addressed to a lesser extent in the design phase. However, it is clear from experience feedback that occupational radiation protection (ORP) and ALARA need to be included from the beginning in the design in order to avoid doses due to a bad design or architecture of the installation (OECD 2010).

Design and architectural changes in order to reduce dose can become very expensive once the design is fixed or the facility is under construction. Therefore we included ORP and ALARA from the beginning in the Myrrha design process, and anticipate exposure situations in all phases of the life cycle of the installation. The design will be regularly reviewed by an ALARA review committee in order to give feedback on the design. The review will be based on past experience in construction, operation and decommissioning, and on the critical evaluation of the different manipulations leading to exposure situations that are to be performed in the future installation. This calls for a multidisciplinary approach in which radiation exposure is seen as one of the risks among others.

7. Conclusions

The present paper has given an overview of the major evolutions in ALARA management at the level of the Belgian Nuclear Research Centre SCK•CEN, illustrated from a managerial, an implementation and a conceptual point of view. It is obvious that optimisation is and remains a vital cornerstone of risk and dose management in a nuclear setting, though the scope is and has to be widened:

- Including other risks (non-nuclear industrial risks, environmental risks, security issues, safeguards issues);
- Including cultural issues, taking into consideration organisational and human factors;
- Using advanced tools for risk prediction (such as VISIPLAN for radiation related issues; other methodologies for more complex problems);

- Including stakeholder involvement processes, communication issues.

A research centre is a good environment to explore the possibilities and needs and to test methodologies and tools, as it is a rapidly changing environment, tackling many issues from dismantling to design of innovation.

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ONGOING EFFORTS OF HERCA ON THE HARMONISATION OF THE RADIOLOGICAL MONITORING SYSTEMS FOR OUTSIDE WORKERS

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Abstract

HERCA[1] is an association which brings together the Heads of 47 European Radiological protection Competent Authorities from 29 countries, in order to build and maintain a network of chief radiation safety regulators in Europe. A working group was created in 2007 to investigate on the practical implementation of the Directive 90/641/Euratom[2] and on how a better harmonisation of the radioprotection systems for outside workers

could be achieved. In 2008, a survey was lead about the practical transposition of the Directive within the Member Countries. It allowed to derive the commonalities and variations of the radiological monitoring systems for outside workers and to compare the content registered in the radiation passbooks to the required information in the Directive. A model of radiological passbook was proposed by this working group, including the harmonisation of terminology and of the requirements on data content, with a distinction between mandatory fields and optional fields. The Radiation Passbook can be a paper based system but countries could also opt to use an electronic (possibly web-based) system instead of the paper based system (or parts of it). The radiation passbook is one of the first major achievements of HERCA, in its aim of harmonisation at the European level. The proposal was sent to the European Commission for its inclusion in the Basic Safety Standards (BSS) recast. Additionally, HERCA invited all European national competent authorities and stakeholders to express their comments. Furthermore, a guidance document on how to implement and use the passbook is being developed.
In 2010, the working group has been given the new mandate to carry out a feasibility study for the transition to an electronic information exchange between countries for the radiological protection of workers.

Key words : HERCA, outside worker, radiation passbook, radiological monitoring system, BSS

1. Introduction

In the beginning of the 1980ies, the problem of outside workers' radiation protection within the nuclear facilities was raised. Those workers received 80% (and even more) of the collective dose from most nuclear facilities and most of the time higher individual doses than the workers of the nuclear undertakings. Outside workers' radiation protection was not explicitly taken into account into the 1980 Basic Safety Standards[3]. In 1990, the European Commission issued the Directive 90/641/Euratom in order to ensure that outside workers would benefit from the same level of protection as permanently employed workers. Nevertheless, the practical implementation of these requirements varies considerably among the different European countries.

2. HERCA

HERCA is an association which brings together the Heads of European Radiological protection Competent Authorities. It was created in 2007 at the initiative of the French Nuclear Safety Authority (ASN). It currently brings together 47 Radiation Protection Authorities (RPA) from 29 European countries. HERCA consists of a Board of Heads and topical working groups. The highest decision-making body of HERCA, the Board of Heads, is composed of national representatives at managerial level appointed by the corresponding radiation protection authority. The topical working groups are composed of senior experts from the different national RPAs. Currently, there are working groups in the following domains : Outside workers & Radiation Passbook, Non-medical sources and practices, Medical Applications, Emergencies and Surveillance of collective doses from medical exposures.

The objectives of HERCA are to build and maintain a network of chief radiation safety regulators in Europe; to promote exchange of experience and learning from each other's best practices; to discuss and where appropriate, express its consensus opinion on significant regulatory issues; to develop, by consensus whenever possible, a common approach to radiological protection issues and to have an impact on the practice of radiological protection, within the Countries of HERCA members.

The association involves, as appropriate, the European Commission and other relevant stakeholders in its activities. At the occasion of the first meeting of the Heads of European Radiological protection Competent Authorities (HERCA), which took place in Paris on 29 May 2007, it was decided to create a working group to investigate on the practical implementation of the Directive 90/641/Euratom within the Member Countries and on how a better harmonisation of the radioprotection systems for outside workers amongst the Member Countries could be achieved.

3. Methodology

The working group Outside Workers and Radiation Passbook met for the first time in January 2008. Its basic objective was to ensure in an efficient way the radiological protection of both permanently employed and outside workers. For a given level of risk, radiological protection of outside workers should not be less than that of permanently employed workers.

The working group decided, as a first step, to lead a survey for the transposition of the 90/641 Euratom Directive within the Member Countries covering a series of aspects : local terminology, rights, responsibilities and obligations of the various parties, radiological monitoring system for outside workers, contents of dose register and radiation passbook, approval of dosimetry services. 23 countries participated in the survey.

In this way the commonalities and variations of the radiation monitoring systems for outside workers within the countries could be derived and compared to the required information in the Council Directive 90/641/Euratom. In addition, the national legislative difficulties in providing the information required from the directive could be identified. The results of the survey were presented in a report[2].

Based on the answers to the survey, further steps towards harmonization of the systems amongst the different countries were proposed : a common terminology, a set of good practices, the data contents of a Radiation passbook and a model of Radiation passbook.

4. Good practices used in developing a national radiation passbook and in its practical use

Good practices were identified for creating a radiation passbook and its subsequent practical use by the employer and the undertaking. These “good practices” were derived from the answers to the questionnaire, the examples of existing radiation passbooks, single use documents and experience from countries using an electronic system.

4.1 Application of the 90/641 Euratom Directive

The Directive stipulates that Member states shall establish a centralized national network or the issuing of an individual radiological monitoring document for all outside workers of category A (category B is optional), including employees, self-employed workers, students, apprentices and trainees.

On a transitional basis to a uniform system on Community level for the radiological protection of outside workers, the issuing of individual radiological monitoring documents or radiation passbooks must in any case be established by the Member States for cross-frontier outside workers of category A.

4.2 Selected definitions

The definitions should be taken from or in accordance with the definitions in the Directive, in particular for Outside worker, which should include mention of self-employed workers, students, apprentices and trainees, Employer and Undertaking.

4.3 Rights and responsibilities

The radiation passbook (or single issue document) or electronic system must enable the undertaking to

- o check the dosimetric data (in order to verify the respect of the dose limits and to apply the ALARA principle), the medical fitness, and whether the outside worker needs a training specific to the activities to be carried out in the controlled areas, prior to allowing the outside worker to enter the undertaking's controlled areas.
- o enter in the passbook an estimate of the radiation dose received by the outside worker in the undertaking's controlled area

The employer should have made arrangements for

- o official dosimetry (the dosimeters may be actually provided by the undertaking by arrangement)
- o medical surveillance (possibly using the medical surveillance system of the undertaking by arrangement)
- o basic training (the basic training may actually be provided by the undertaking by arrangement)
- o any specific training needed by his employees for the work activities to be carried out in the undertaking's controlled areas. This training would normally be provided by the undertaking.
- o keeping the **radiological data** of the individual exposure monitoring and the data of medical surveillance (medical fitness, date of next medical examination) of each of their workers **up to date** in the radiation passbook;
- o authorization/notification of their activities as required by national regulations.

4.4 Practical use of the passbook

- o The content and the issuing procedure should follow the requirements of the regulator/issuing authority.
- o The owner of the data should be the home country (of the employer). The decision of who keeps the data is up to the Member Country: (authority, employer or approved dosimetry)
- o It is up the Members States to decide who can issue the passbook;
- o The passbook can be composed of different parts issued by different bodies (e.g. in some countries, parts about dosimetric and medical

surveillance are issued by 2 different entities);

- o It could either be **official bodies or approved dosimetry services**.
- o The employer is responsible for obtaining a radiation passbook for each of his/her outside workers.
- o Non-transferability between Outside Workers should be ensured by unique identification of the worker in the passbook.
- o Non-plurality can be checked by use of a register of the issued radiation passbooks (with unique serial number) coupled to a unique number identifying the worker. If each issued document has a unique number and if it can be linked to its holder in the database, it is easy to see how much documents correspond to an individual worker. If the expiration date as well as the status (in circulation/returned) of the issued documents are also recorded in the database, one can check that a worker is not in possession of several documents. An Outside worker should only have one radiation passbook even if he has more than one employer. Consequently the passbook should allow to enter more than one employer.

- o Language : either national language(s) + English or national language(s) with code
- o The media used for the radiation passbook is up to the Member States. It can either be **electronic or paper-based**
- o The passbook can be composed of **one document of several documents**. If it is composed of several documents, each document should not necessarily be issued by the same issuing body.
- o Validity period : the document must mention its validity period if it is reusable.
- o Reusability : the document should mention whether it is single use or multi-use
- o The employer keeps a register of who has been authorised, on behalf of the employer, to write information into specified parts of the radiation passbook e.g. details of the current employer,date of medical review, details of official dosimetry for the current year.
- o The undertaking keeps a register of who has been authorised, on behalf of the undertaking, to write information into specified parts of the radiation passbook e.g. estimated doses for activities in the undertaking's controlled areas

5. Data to include in the radiation passbook and passbook model

The content of the document (passbook or single use document) should provide all the information required by the Directive.

In order to fulfil these requirements, a list of mandatory and optional data fields were proposed by the working group. A model of radiological passbook (figure 1) has been elaborated as a tool in order to better visualize these mandatory (in black) and optional (in grey) fields. It is not obliged to use the model exactly as it is. Countries can use their own model as far as it meets the good practices given in and it contains the minimal data content (black fields).

FRONT COVER (Identification of Radiation Worker)

Window to allow to see picture on next page

Radiation worker
[SURNAME] [2nd SURNAME]
[First name] [Middle names]
[Unique identification number of the worker]

Ref. of domestic Legislation under which Radiation Passbook is issued

RADIATION PASSBOOK
BELGIUM
[Country code (ISO3166) - Passbook number – Passbook sequence number]]
[bar code or RFID]

If found, please return to last named employer (see section ..)

SECTION 1 – Details of the radiation worker
(Normally to be completed by the company or institution designated by the competent authority to issue the radiation passbook)

Surname(s)	[SURNAME]	[2nd SURNAME]
First name	[First name]	Middle name(s) [Middle names]
Sex	[M/F]	
Date of birth	[date of birth]	*Picture*
Place of birth	[Place of birth]	
Nationality	[Nationality]	
Signature	[Signature]	

Unique identification number
(unique number in the worker's employer's country, for example :

National number	[National number]
Social security number	[Social security number]
Fiscal number	[Fiscal number]

Relevant dose limits in country of issuance:

Effective dose	[Effective dose/period]
Eyes	[Equivalent dose/period]
Skin	[Equivalent dose/period]
Extremities	[Equivalent dose/period]
Other	[]

SECTION 2 – Issuing details of the radiation passbook
(to be completed by the entity issuing the radiation passbook)

Radiation passbook number	[Radiation Passbook number]	
Issuing date	[issuing date]	Valid until [expiry date]
Issuing body	[body issuing passbook]	
Address	[address]	Web address [Web address]
Tel number	[tel number]	Mark of endorsement
Fax number	[fax number]	
E-mail	[e-mail address]	

SECTION 3 – General information
(any information needed by foreign undertaking to interpret the conditions applying to this worker, depending on the nationality of his employer)

3.1. Contents
(to be completed by the Member States)

3.2. Guidelines to fill in the radiation passbook
(to be completed by the Member States)

3.3. General information
(to be completed by the Member States – including :
- purpose of the passbook
- conditions of use
- scope of application
- temporality
- conditions of issue/renewal
- loss of the radiation passbook/damage to the radiation passbook
- pursuit in case of fraudulent use/entries/amendments
- summary of the legal provisions relative to the operational protection of outside workers, including the definition or clarification of the following concepts :
    - undertaking
    - employer (outside undertaking)
    - outside worker
    - official dosimetry
    - operational dosimetry
    - responsible party
    - issuing entity/responsible entity
    - responsible person
    - under apron/above apron
    - national dose limits (explanation)
- national requirements regarding health surveillance of outside workers

SECTION 4 - Current employer

(To be completed by the employer of the outside worker)

Employer (Name, Identification number, Employer number, Address, Tel, Fax, e-mail address)	**Employment** (Start date/ End date)	Occupational category (see guidance)	**Classification** (A or B)	**Stamp and/or signature or identification number of the responsible party**

SECTION 5 – Health surveillance

(To be completed by the approved medical practitioner or approved occupational health service acting for the employer).

Date	Type of Examination	**Result** (fit, not fit, fit subject to special conditions as shown)	**Restrictions to work with radiations**	**Validation of result** (name, signature and stamp or identification number of the approved medical practitioner, approved occupational health service or other designated instance/person)	**Period of validity of the result**

SECTION 6 – Official dose record up to the radiation passbook issue date

(To be completed by the entity issuing the radiation passbook).

6.1. Occupational life time dose (mSv)

External dose						
Uniform			Non-uniform : equivalent dose to specific body location (extremities/other area's)			
ph/b * $H_p(10)$ [a]	n ** $H_p(10)$ [b]	Skin dose $H_p(0.07)$	Lens dose $H_p(3)$	Extremity dose [...]	Extremity dose [...]	Extremity dose [...]

Internal dose						Effective dose (sum of [a], [b] and [c])	Authorized signature/ stamp of the issuing entity and date
Committed effective dose from internally deposited radionuclides [c]	Radio-nuclide	Dose assess-ment method ***	Committed equivalent dose to specific individual organs or tissues				
			[...]	[...]	[...]		

6.2. Official doses (mSv) for the last 5 calendar years *(not including the current year – mandatory for persons having a 5 year dose limit.)*

Year	External dose						
	Uniform			Non-uniform : equivalent dose to specific body location (extremities/other area's)			
	ph/b $H_p(10)$ [a]	n $H_p(10)$ [b]	Skin dose $H_p(0.07)$	Lens dose $H_p(3)$	Extre-mity dose [...]	Extre-mity dose [...]	Extre-mity dose [...]

Internal dose						**Effective dose (sum of [a], [b] and [c])**	Authorized signature/ stamp of the issuing entity and date
Committed effective dose from internally deposited radionuclides [c]	Radio-nuclide	Dose assess-ment method ***	Committed equivalent dose to specific individual organs or tissues				
			[...]	[...]	[...]		

* photon/beta - ** neutron - *** body counter, urine, faeces, air sampling,...

Signature/stamp of the issuing entity and date	

6.3. Details concerning the entity responsible for the record of the official dosimetry *(To be completed by the entity(ies) responsible for the record of the official dosimetry : approved dosimetry service, National Dose Register or other. Only if different from the entity issuing the passbook.)*

Date	**[Date]**
Responsible entity	**[name of the responsible entity]**
Address	**[Address of the responsible entity]**
Contact person	**[name and job title of contact person]**
Tel number	**[tel number]**
Fax number	**[fax number]**
E-mail	**[e-mail address]**

Date	[Date]
Responsible entity	[name of the responsible entity]
Address	[Address of the responsible entity]
Contact person	[name and job title of contact person]
Tel number	[tel number]
Fax number	[fax number]
E-mail	[e-mail address]

Date	[Date]
Responsible entity	[name of the responsible entity]
Address	[Address of the responsible entity]
Contact person	[name and job title of contact person]
Tel number	[tel number]
Fax number	[fax number]
E-mail	[e-mail address]

6.4. Official dose record for current year …. (mSv) *(To be completed by the employer or the health physics service or other person acting for him).*

Period (ddmm yyyy-ddmm yyyy)	External dose							
	Uniform					Non-uniform : equivalent dose to specific body location (extremities/other area's)		
	ph/e * $H_p(10)$ [a]	n ** $H_p(10)$ [b]	Skin dose $H_p(0.07)$	Above apron	Under apron	Lens dose $H_p(3)$	Extremity dose [...]	Extremity dose [...]
TOTAL								

Internal dose						Effective dose (sum of [a], [b] and [c])	Signature of the responsible person and identification number of the employer
Committed effective dose from internally deposited radionuclides [c]	Radionuclide	Dose assessment method ***	Committed equivalent dose to specific individual organs or tissues				
			[...]	[...]	[...]		

* photon/beta - ** neutron - *** body counter, urine, faeces, air sampling,...

SECTION 7 – Operational dose in the undertaking's controlled area(s) (mSv) *(An estimate of any dose received by the outside worker, to be filled by the undertaking after the end of any activity in the undertaking's controlled area)*

Period (ddmm yyyy-ddmm yyyy)	External dose							
	Uniform					Non-uniform : equivalent dose to specific body location (extremities/ other area's)		
	ph/b* $H_p(10)$ [a]	n ** $H_p(10)$ [b]	Skin dose $H_p(0.07)$	above apron	Under apron	Lens dose $H_p(3)$	Extremity dose [...]	Extremity dose [...]
Name and address undertaking :								
Name and address undertaking :								
Name and address undertaking :								
Name and address undertaking :								
Name and address undertaking :								
Name and address undertaking :								
Name and address undertaking :								

Internal dose						Effective dose [sum of [a], [b] and [c])	Signature/ stamp of the responsible person for the undertaking and date
Committed effective dose from internally deposited radionuclides [c]	Radionuclide	Dose assessment method ***	Committed equivalent dose to specific individual organs or tissues				
			[...]	[...]	[...]		

* photon/beta - ** neutron - *** body counter, urine, faeces, air sampling,...

SECTION 8 – Information regarding training in radiological protection *(To be filled by the person or entity responsible for the course)*

8.1. Basic training in radiological protection *(obligation of the employer)*

Date	Number of hours	Description of the contents	Centre or training company	Signature and stamp of the responsible for the entity or delegated person	Valid until	Observations

8.2. Specific training in radiological protection *(obligation of the undertaking)*

Date	Number of hours	Description of the contents	Centre or training company	Signature and stamp of the responsible for the entity or delegated person	Valid until	Observations

Figure 1 : radiation passbook model

6. Stakeholder involvement and inclusion of the HERCA radiation passbook in the draft BSS recast

At the 5th meeting of HERCA in 2010, the Board of Heads approved the content for a harmonised European Radiation Passbook. This represents a milestone for the work of the association in its aim to develop a common approach to radiation safety and regulation in particular within the

European Union. Such harmonisation might also be useful for non-EU European or worldwide “neighbouring” countries. HERCA considers the work as its first major achievement.

Following the approval of the harmonised European Radiation Passbook, it was sent to the European Commission proposing to include it in the last version of the BSS recast. A task group consisting of a representative of the European Commission and the Chairman of the working group included the requirements for the data content of the dose passbook for outside workers based on the work of the HERCA WG on outside workers & dose passbook in the Basic Safety Standards (version 29/09/2011).

Additionally, HERCA invited all European national competent authorities and stakeholders to express their comments on its implementation at national level. Comments from stakeholders have been integrated in a new version of the dosimetric passbook approved at the occasion of the 8 th HERCA meeting held in Bern, in December 2011.

7. Future work

Transnational (and transcontinental) workforce is increasing, and therefore the number of nationalities working in one undertaking increases as well. This complexity can be partially coped with by the paper passbook system, if implemented well. However, the system has some weaknesses. It is always implemented as a means to exchange information between the undertaking and the employer (and other actors), on top of the basic data that are available in more or less fragmented ways, for example in dosimetry services, national authorities,… This increases the risk on errors or misuse. One worker could be issued with more than one passbook, for instance in two or more countries, or when they work for two or more employers. Data on one worker are kept in the national register of the country of his employer. However, when he starts a new carreer in another country, there is no guarantee that his history of doses is passed on.

In December 2010, the Board of Heads has given a new mandate to WG1. According to this mandate WG1 should carry out, in close collaboration with the EC and using the experience of ESOREX, a feasibility study for the transition from a radiation passbook to an electronic information exchange between countries. This study should define the general principles and user specifications of this electronic information exchange. Then, starting from 2012, the EC will have the possibility to take this feasibility study as a starting point to look more closely at the technical solutions for such an electronic information exchange system.

Several possibilities were identified:

1. A full electronic exchange of data, in a network, could solve the problems observed with the paper passbook. Indeed, in such a way, all data concerning one worker can be brought together. However, a fully electronic system, preferably web-based to provide access to all actors involved, implies a considerable cost and effort to implement. Data privacy and encryption are important issues. To deal with business processes distributed over a large landscape of existing and heterogeneous systems that are under the control of different owners, an Enterprise Service Bus (ESB) technology in a Service Oriented Architecture (SOA) could be used.

2. Depending on the cost-benefit and risks, other possible options can be distinguished, that will however only solve part of the problems observed : instead of bringing together the data, a magnetic card containing his dose data could be kept by the worker. This would be a somewhat more elegant form of a paper passbook but would probably have the same deficiencies if not completed by an "issuing database", linking a unique issued passbook/magnetic card to a unique worker.

3. Limiting the centralization of data to solely an issuing database, coupling 1 uniquely identified worker to 1 uniquely identified passbook, is a limitative but also viable option. In this way, Member Countries are free to stick to a paper passbook or to move on to an electronic system, but multiple issuing could be prevented. It is clear that such an "issuing database" is a minimalistic solution. It could be used as a first step, but evolving to a complete electronic exchange is advisable.

Data security is a major issue. Some other issues can also be identified, such as the need for a unique identifier of the worker and privacy-related issues like identification and authentication. A magnetic card (possibly electronic ID-card) could be used as a key for identification purposes.

HERCA also intends to develop a guidance document on implementation and use of the radiation passbook.

8. Conclusions

A model of radiological passbook was proposed by a working group of HERCA on Outside workers and radiation passbook. It includes the harmonisation of terminology and of the requirements on data content, with a distinction between mandatory fields and optional fields. The Radiation Passbook can be a paper based system but countries could also opt to use an electronic (possibly web-based) system instead of the paper based system (or parts of it). The radiation passbook is one of the first major achievements of HERCA, in its aim of harmonisation at the European level. The mandatory data fields are integrated in the draft BSS recast.

The HERCA working group on Outside workers and radiation passbook is currently working on the feasibility of the transition to an electronic data exchange.

9. References

[1] HERCA, http://www.herca.org

[2] Council Directive 90/641/Euratom of 4 December 1990 on the operational protection of outside workers exposed to the risk of ionizing radiation during their activities in controlled areas

[3] Council Directive 80/836/Euratom of 15 July 1980 amending the Directives laying down the basic safety standards for the health protection of the general public and workers against the dangers of ionizing radiation

[4] Report on the progress to draft a European Radiation Passbook for Outside Workers to meet the requirements of Council Directive 90/641 Euratom, http://www.herca.org/documents/WG1_OutsideWorkers_report_01_12_2010.pdf

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PUBLIC PARTICIPATION IN DECISION-MAKING ON NUCLEAR RESEARCH INSTALLATIONS

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Abstract

The aim of this paper was to determine predictors for the intended level of involvement in decision making concerning new installations for nuclear research. The research is based on empirical data from a large-scale public opinion survey in Belgium. Results show that attitudes towards participation and moral norms are the strongest predictors for the intention to take part in public involvement activities, other influential predictors being subjective norms, descriptive norms and time constraints. At the same time, the analysis reveals that financial benefits from participation do not seem to influence people's intention to participate in decision processes related to new nuclear installations.

Keywords: participation, nuclear research, predictors

Introduction

Public participation is nowadays an imperative for the formulation and implementation of good policies in the environmental and health domains. It has also become a key determinant in decision making processes related to the development of science and technology in general, in the framework of "responsible research and innovation" (Sutcliffe 2011, pp.9; European Commission 2011, pp.31).

Higher forms of public and/or stakeholder involvement are more and more called for in the framework of participatory risk governance related to nuclear technologies, not only because they contribute to democratizations of decisions, but also because they increase the overall efficiency of the process and result in more sustainable decisions (Rick Jones 2008; OECD 2006 pp.9).

However, motivating stakeholders remains a challenge and previous studies show that, when offered the opportunity to participate, the public frequently refrains from active participation (Dijkstra *et al* 2010).

Results from past public opinion surveys in Belgium (Perko *et al* 2010; Van Aeken *et al* 2006) highlighted a decrease in people's willingness to invest time in getting informed about installations with risks (in general) or participating in related decision-making processes. The percentage of people in Belgium who would not spend any time in getting informed about such installations increased from 25% in 2002 to 34% in 2009. With regards to participating in decision–making processes, 40% said that they had no time at all for such activities in 2002, with a slight increase to 44% in 2009. These studies showed that (self-assessed) cautious people, younger respondents, those who read scientific magazines regularly or have interest in science and technology, as well as those with lower confidence in authorities (for the actions they take to protect against chemical/nuclear accidents and environmental pollution) are more willing to spend some time in getting informed or participating in decision-making processes concerning industrial installations with risks.

The goal of this study was to determine predictors for the intention to participate in decision making processes related to new nuclear research installations. The predictors studied were derived from the social psychology theory of planned behaviour (Ajzen, 1991) and related literature.

Although extensively used in health studies, only few applications of the theory of planned behaviour can be found in the literature that deal with science related issues (or new technologies). Some examples shall be mentioned here. Poliakoff and Webb (2007) have looked into scientists' participation in public engagement activities. Their study highlighted four important predictors: past behaviour, attitude, perceived behavioural control and descriptive norms. Dijkstra *et al* (2010) found that the strongest predictors for the level of public engagement were the self-reported knowledge about genomics research, the information-seeking behaviour and the level of education. Other, weaker predictors, contributing to a lesser extent to their model were the interest in genomics issues, age, gender, social involvement and trust-confidence. Miller *et al* (2007) investigated socio-demographic predictors for public engagement in the assessment of carbon dioxide capture and storage (CCS) technology. They found small effect sizes showing that men were more prepared to take part in public discussions; at the same time, women were more likely to believe in the importance of public consultation by the government. This study also revealed that a higher education was a significant contributor to the willingness to participate in public discussions on CCS.

In the next section, we detail on the theoretical background underlying this study. In section 3 we elaborate on the methodology used and in section 4 we present and briefly discuss the results. A more detailed analysis will be reported elsewhere. In section 5 we take a closer look at the actor organising the involvement process and its influence on people's willingness to get involved. In the final section we summarise the conclusions of this study.

Theoretical background

2.1 The theory of planned behaviour

One of the leading theories used for the prediction of human behaviour is the so-called "theory of planned behaviour" (Ajzen, 1991). This theory argues that actual behaviour is determined by the person's behavioural intention, which is, in turn, influenced by three independent predictors: specific attitudes towards the behaviour in question, the person's subjective norms and the perceived behavioural control.

An attitude is understood in this context as a "*disposition to respond with some degree of favorableness or unfavorableness*" (Ajzen and Gilbert Cote 2008) to the behaviour in focus, in our case participation. Subjective norms refer to beliefs about whether a "*specific referent group* [for instance relatives or friends] *would approve or disapprove of one engaging in the focal behaviour*" (Poliakoff and Webb 2007). Perceived behavioural control refers to one's perception about whether she/he has the resources, abilities and other prerequisites required to perform the behaviour successfully, for instance the ability to participate in public engagement. A high level of perceived control "*should strengthen a person's intention to perform the behavior, and increase effort and perseverance*" (Ajzen 2002b).

2.2 Extensions of the theory of planned behaviour

Several studies in the literature have suggested adding to the predictors derived from the theory of planned behaviour the following: descriptive norms, i.e. what others actually do in a similar situation (Chassin *et al* 1984); moral norms, i.e. the individual's perception of the moral correctness or incorrectness of performing a behaviour (Beck and Ajzen 1991); past behaviour (Ajzen 2002a); and environmental constraints (e.g. financial or time-related, see Poliakoff and Webb 2007). The latter are considered in some other studies as part of the perceived behavioural control, since they are resources or obstacles that are perceived as impeding or facilitating the behaviour (Ajzen 2002b).

In some cases, moral norms were shown to be strongest predictors of intention and behaviour than the three factors suggested by the theory of planned behaviour (Beck and Ajzen 1991).

In the study reported here we applied the extended theory of planned behaviour in order to determine predictors for the intended level of involvement in decision making concerning new installations for nuclear research. For this purpose we analysed the following potential predictors: socio-demographic variables (age and gender), specific attitudes, subjective norms, descriptive norms, moral norms, past participation behaviour, environmental constraints. In order to tackle the specifics of the nuclear domain we added to these the attitude towards nuclear, the risk perception of an accident in a nuclear installation and the confidence in authorities for the actions undertaken to protect the population against risks from nuclear installations. The study is based on empirical data from a large scale opinion survey in Belgium (Turcanu *et al* 2011)

3. Methodology

3.1 Data collection and sample

The survey data were collected using CAPI ("Computer Assisted Personal Interviews"). The population sample consisted of 1020 respondents and is representative for Belgium adult population (18+) with respect to sex, age, region, province, habitat and social class.

Most questions in the survey were formulated as statements, to which the respondent could answer using a five point Likert-scale (e.g. <strong disagreement, disagreement, undecided, agreement, strong agreement>), plus a sixth category (<no answer/don't know>). The latter answering

option was allowed, but not encouraged. To avoid question-order effects, randomization or rotation was applied whenever deemed appropriate.
For the in-depth analysis of the relation between the dependent and the independent variables, multiple item constructs were used whenever possible, in order to increase the reliability of the measurement and to enhance the measurement scale. The formal test for the reliability of the scales constructed with multiple items was the calculation of Cronbach's alpha. When this coefficient exceeds 0.70, it indicates a reliable scale. Factor analysis was employed to improve the measurement of a latent variable and to determine the extent to which the various items are components of a one-dimensional construct.

3.2 The level of involvement

The dependent variable investigated was peoples' intention to take part in public involvement activities *regarding new installations for nuclear research"* (see figure 1). The answering scale was derived from the theory of stakeholder participation (Health Canada 2000), and ranged from no involvement at all to active partnership in decision making process.

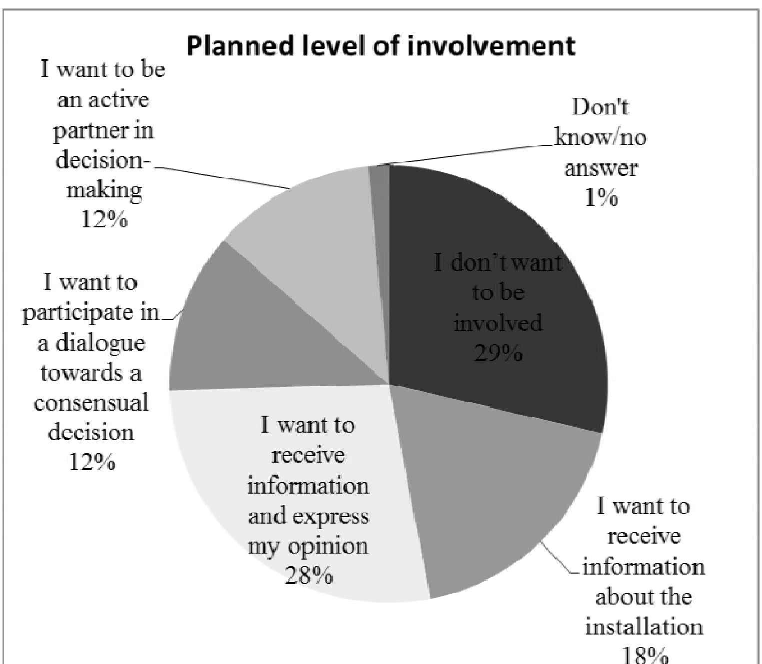

Fig. 1 Intended level of involvement regarding new installations for nuclear research

Results show that almost one third of the respondents does not wish to be involved in any way. Among the people who would like to be involved most of them prefer to receive the information and express their opinion (28%). From the 1020 respondents interviewed, 24% would like to be involved to a larger extent, either as an active partner in decision-making or as a participant in a dialogue towards a consensual decision.

3.3 Potential predictors

3.3.1 Attitude towards participation

We measured both specific attitudes related to the studied behaviour, as well as general attitudes, namely the attitude towards nuclear energy.
The attitude towards participation in public involvement activities concerning new nuclear installations in their municipality was measured by three questions with a common root assessing whether participation was regarded as a positive behaviour. The participants were asked to give their opinion about participation in such a process using the scales: pointless - worthwhile, useless - useful and disappointing – rewarding, using a score from one to seven (see figure 2).

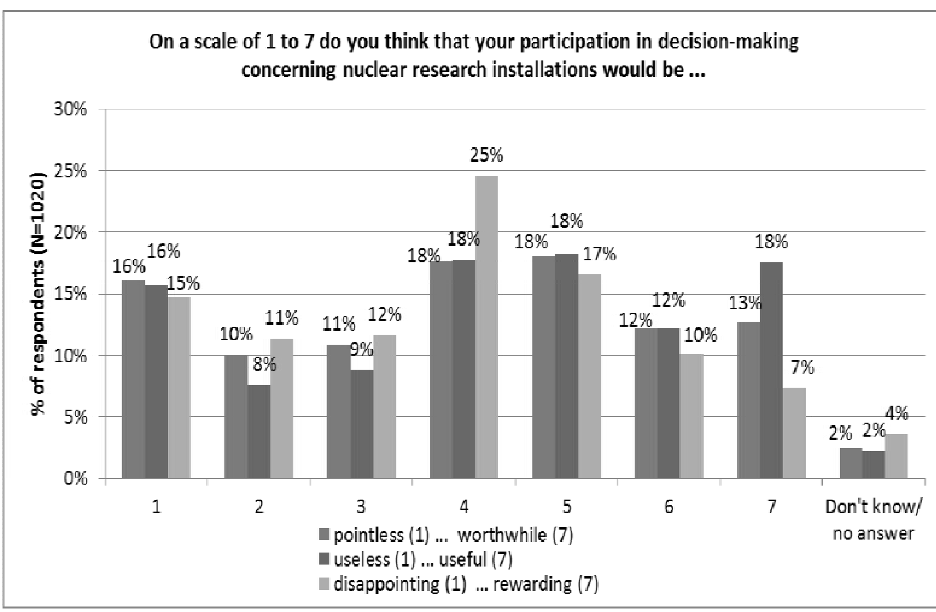

Fig. 2 Three dimensions of the attitude towards participation (N=1020)

The results show that the attitude towards participation is somewhat sceptical, with average scores near to the middle point of the scale for all three dimensions investigated. Most people take a neutral, a neutral-positive or an extreme negative stand. The usefulness of participation seems to be somewhat more appreciated than the other two dimensions which are more related to the expected outcome.

A factor analysis performed on these three items revealed one factor accounting for 73% of the variance in the data, a higher value on this scale implying a more positive attitude towards participation. The reliability of the scale constructed with these three items is α=0.82.

3.3.2 Descriptive, subjective and moral norms, environmental constraints

Subjective norms were measured with the statement: *"Most people who are important to me (family, friends) would support my participation"*. Almost half of the respondents felt that their close environment would support such activities: 44% agreed vs. 32% disagreed.

The item referring to moral norms was expressed as "*I have a duty as a citizen to participate in such activities"*. More than 40% of the respondents agreed or strongly agreed that participating in public involvement activities is a citizen's duty, while a similar percentage (36%) disagreed or strongly disagreed.

Descriptive norms captured the (lack of) social pressure of performing the behaviour: "*Of the people I know, nobody would participate in such activities*. Almost half of the respondents disagreed or strongly disagreed with this statement, while 25% agreed or strongly agreed.

We also measured the influence of time and financial constraints, respectively, by the following items: i) *"I do not have enough spare time to participate in such activities*" and ii) *" I would participate only if this activity would be remunerated"*.

About 30% of the respondents stated that they do not have enough spare time for public involvement activities regarding new nuclear research installations, compared to 47% who think time constraints are not an issue.

Expected financial benefits did not seem important to the respondents: almost 70% of the respondents disagreed that remuneration is a necessary condition for participation.

3.3.3 Past involvement

Past involvement was assessed in a general context, with no reference to the nuclear domain. The respondents were asked if they participated in the past in a public involvement activity concerning decisions about their environment: "*Citizens can become involved – participate- to decisions concerning their environment in various ways, for instance a citizens panel, a meeting in the town hall, an internet forum. Have you participated in the past in any public involvement activity?*" The possible answers to this question were "yes" / "no".

Almost one out of ten respondents (9%) said that they have participated in the past in some form of public involvement activity related to their environment.

3.3.4 Attitude towards nuclear energy

The attitude towards nuclear energy was assessed through three general statements. These enquired whether the respondent believed that "*the benefits/ advantages of nuclear energy outweigh the disadvantages"*, whether "*the reduction of the number of nuclear power plants in Europe is a good cause*" and, respectively, if they thought that "*nuclear power plants endanger the future of our children".* The respondents had to state their degree of agreement or disagreement with these statements on a 5-point Likert scale ranging from "*strongly disagree"* to *"strongly agree"*.

A factor analysis performed on the three items (with first item inverted) resulted in one factor with eigenvalue larger than 1, which accounts for 64% of the variance in the data. The reliability of the scale is $\alpha=0.72$. A higher value on this scale represents a more negative attitude towards nuclear energy.

3.3.4 Risk perception and confidence in authorities

Risk perception of an accident in a nuclear installation was measured with the following question: *"How do you evaluate the risks from an accident in a nuclear installation for an ordinary citizen of Belgium"*. Confidence in authorities was measured with respect to the actions undertaken to protect the population against nuclear accidents: *"How much confidence do you have in the authorities for the actions they undertake to protect the population against risks from an accident in a nuclear installation?"* For both items, a 5-point Likert answering scale was used ranging from “very low” to “very high”.

About 34% of the respondents evaluated an accident in a nuclear installation as a high or very high risk, while 39% expressed a low or very low risk perception. When it comes to confidence in authorities for the actions undertaken to protect the population, 42% of the respondents expressed high or very high confidence, while 28% expressed a low or very low confidence.

4. What influences peoples’ intended level of involvement?

4.1. No involvement vs. some degree of involvement

We first tested a model in which the dependent variable was recoded as a binary variable, with “0“ coding the case when the respondent is not willing to be involved at all, and “1“ meaning that the respondent is willing to be involved to a certain degree.

Binary logistic regression was performed to study the influence of the potential predictors discussed above (see Table 1, second and third columns). Results show that the attitude towards participation and the moral norms are the strongest predictors for the intention to take part in public involvement activities. For instance, the more one believes that participation is a citizen’s duty the more likely he/she is to be taking part in public involvement activities. Only two other predictors came out as statistically significant in the model: subjective norms and time constraints. The more support one feels from its close environment, the more likely he/she is to be involved. While time constraints play an important rol, it is interesting to notice that financial benefits from participation do not seem to influence people’s intention to participate in decision processes related to new nuclear installations. Neither do risk perception of an accident in a nuclear installation, or the confidence in authorities as regards the actions undertaken to protect the population against such risks, play any role.

The age (year of birth) and the descriptive norms were just below the 95% confidence level ($p=0.08$ and $p=0.07$, respectively). Younger respondents could be slightly more inclined towards getting involved in decision-making processes concerning new nuclear research installations. The involvement of the people one knows could also increase the respondent‘s level of involvement.

Table 1 Summary of results from explanatory models

Dependent variable / Predictor	Participation (binary: yes/no)		Level of involvement (4 levels: receive inform., receive inform.and give opinion, participate in dialog towards consensus, active partnership)	
	B	**Sig.**	**Stand. Beta**	**Sig.**
Constant	-22.595	.074		.216
Gender of the respondent (male)	.063	.760	-.071	.032
Year of birth	.011	.081	-.011	.747
Subjective norms	.342	<.001	.083	.031
Moral norms	.717	<.001	.168	<.001
Descriptive norms	-.170	.072	-.140	<.001
Time constraints	-.239	.004	-.148	<.001
Financial constrains	-.071	.451	.042	.229
Attitude towards participation	.989	<.001	.249	<.001
Attitude towards nuclear energy	.137	.320	.154	<.001
Past behaviour (yes)	-.322	.431	-.079	.022
Risk perception of a nuclear accident	-.010	.907	.004	.910
Confidence in authorities	.046	.627	-.066	.061
	Logistic regression. Nagelkerke's R^2 = 0.51. N=841 (out of N=1020)		Linear regression. Adj. R^2 = 0.33 N = 624 (out of N=713)	

4.2. Predictors for the degree of involvement

Next we looked at which variables can act as predictors for the level of involvement. We retained from the total population (N = 1020) only the people who would like to be involved to a certain extent (N = 713). A second regression model was thus constructed (Table 1, last two columns). The most influential predictors were again the attitude towards participation, moral norms and time constraints, and, differently from the previous model, descriptive norms and the general attitude towards nuclear energy. A more positive attitude towards nuclear energy leads to less (intended) involvement. At the same time, the higher the belief that most people (known to the respondent) would participate in decision-making processes, the more likely it is that one intends to commit to a higher level of involvement.

Time constraints come out again as influential, whereas financial constraints are inconsequential. Opposite to the study of (Poliakoff and Webb, 2007), in which both constraints of time and money did not predict scientists' intentions to participate in public engagement activities, time limitations seem to play an important role in our study with regards to the intention of citizens to participate in public involvement activities.

Past participation and gender have but a weak influence: men are likely to be more involved than women in decision-making processes related to new nuclear research installations (which confirms e.g. Perko *et al* 2010 and Dijkstra *et al* 2010); and those who have participated in the past are more likely to have a higher involvement. Confidence in authorities for the actions undertaken to protect the people against accidents from nuclear installations is just below the 95% confidence level, but it looks like people who are have higher confidence will be less involved than people with low confidence, which confirms the past results mentioned in section 1.

5. Who organises the process: does it matter?

Finally, we investigated the willingness to participate depending on the actor organising the process: the controlling authority, the company managing the project, a non-governmental organisation, an independent institution (e.g. a university) or a local action group. The scale used was from 1="not at all", to 7="very much".

In general, for those who would not like to be involved at all in decision-making processes concerning new nuclear research installations, the organiser of the process did have a significant influence on their planned behaviour.

Among the respondents who would like to get involved to a certain extent in decision-making processes (N=713), the preferred organising actors an independent institution (mean = 5, std.dev=1.8) followed by local action groups (mean=4.75, std.dev=1.8), as illustrated in figure 3.

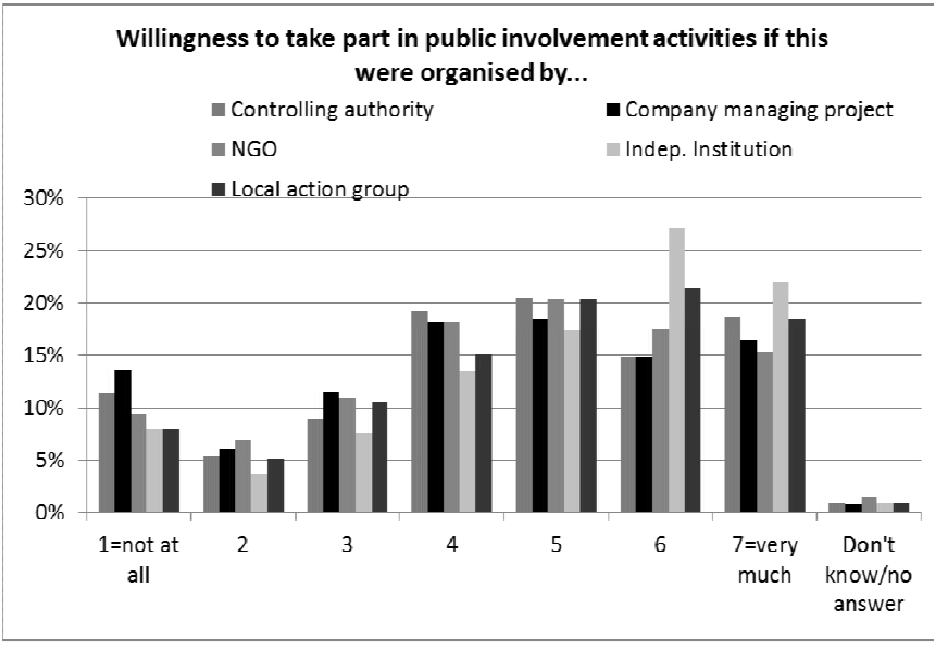

Fig. 3 Involvement depending on the actor organising the process (N=713)

The least preferred is the company managing the project (mean=4.3, std.dev=1.9). The controlling authority (mean=4.5, std.dev=1.9) and an NGO (mean=4.5, std.dev=1.8) score in between the previously mentioned actors.

6. Conclusions

Results clearly show that most people (70%) would like to get involved in decision-processes related to new nuclear installations and to be able to at least express their opinion (52%). For higher degrees of involvement however, people have to be convinced that their participation is worthwhile and brings benefits to the decision-making process. It is also worth noting that while time constraints are recognized as a challenge, financial benefits are inconsequential as regards the planned degree of involvement.

Citizen’s culture associated to participation, as well as the support of the close environment, plays an important role. Long term programmes of stakeholder involvement, with early involvement at the outset of the process are therefore necessary. It is important to allow divergent views to be expressed from the very beginning and to create the premises for a constructive dialogue.

Finally, it also came out that the actor organising of the process bears some influence on people's willingness to be involved, independent institutions (e.g. a university) being the preferred actors.

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MODELLING RADIATION DOSE EFFECTS TO WILDLIFE POPULATIONS

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Abstract

A continuous, dual life stage, logistic model for generic populations of wildlife is presented in order to assess the non-stochastic effects of radiation on repairable radiation damage, reproductive ability and mortality. Population change is modelled as a function of survival, fecundity, natural mortality and small density 'Allee' effects. Radiation-induced damages in young and adult life stages are modelled by means of a recovery compartment representing the organism's repairing system. Direct effect of radiation on fecundity is also incorporated in the model.

The model is tested against radiation effects data for freshwater fish and small mammal populations, predicting approximately the observed mortality, morbidity and reproductive changes for fish and mice populations at various doses of γ-radiation. Experimental doses at which effects were observed and those for which the model predicts the same effect are well correlated and observed no-effect doses tend to coincide with doses at which model predictions are in the order of a few percent. Limited data for low-energy β-exposures in mammals suggests that the same model may also be applicable in that situation.

Taken together, the results suggest that for small mammal and fish populations, dose rates less than 2×10^{-2} Gy d^{-1} are not generally predicted to be fatal to the population. Model tests carried out for large mammals indicate that chronic exposure at this level is predicted to be harmful. The long-term effects on the survivability of populations are predicted to be negligible for exposure rates similar to the ERICA screening value for non-human biota (2.4×10^{-4} Gy d^{-1}), supporting the appropriateness of this value for use in environmental assessments.

Keywords: Logistic model, Population Model, Radiation Effects, Repair Mechanism

1. Introduction

Assessing the degree of environmental protection from radiation requires the evaluation of exposure in relation to effects. The ERICA methodology has proposed a benchmark at the ecosystem level of 2.4×10^{-4} Gy d^{-1} (Beresford et al. 2007; Brown et al. 2008), further endorsed by the EU PROTECT project (Andersson et al. 2009), with expectation that the earliest effects are observed no less than one order of magnitude above this level. However, it is impossible to treat all biota species in a radiological assessment using a single benchmark level. Responses to radiation exposure are highly variable depending on the biological species, since the 50% lethal dose ($LD_{50/30}$) varies greatly from ~ 10^3 Gy for simple unicellular organisms to ~ 1 Gy for large mammals (Bytwerk 2006; Garnier-Laplace et al. 2004; Garnier-Laplace et al. 2006; UNSCEAR 2008).

In order to assess the level of protection for the population (rather than the individual of the species), models are necessary to predict the actual population dynamics of a generic species. There are many examples of these models in the literature, e.g. Leslie Matrix or logistic approaches, both of which have been applied in an ecotoxicology context (Chandler et al. 2004; Doi et al. 2005). These models cover the range from 1 to more than 10 age classes. However, the available genomics data indicates that, in most cases, it is sufficient to consider the population as composed of two age classes. Our approach therefore adopts a system of first-order differential equation with self-limiting growth according to the logistic equation (Verhulst 1838, 1845).

The effect of radiation can be incorporated into a population model and there are many ways to deal with this. The simplest is to assume that the mortality rate is proportional to the dose rate. More sophisticated models include the effect of radiation on reproduction. Even more advanced models consider a variable effect of radiation in the range from chronic to acute exposures, as the natural radiation damage mechanisms of the body are depleted and the balance between ‘healthy’ and ‘damaged’ organisms becomes altered (Kryshev et al. 2006; Kryshev et al. 2008). Lastly, more sophisticated approaches that include the effect of radiation on the dynamic energy budgets of living organisms (DEBTox models) have also been successfully developed to deal with toxicity data (Massarin et al. 2010; Alonzo et al. 2008).

In this study we present the most recent results of a project that has successfully developed a simple, 12-parameter generic model of the observed radiation effects (mortality, fecundity and degree of organism damage) over a range of non-human biota, by considering the action of radiation on the repair mechanism, bridging the gap between chronic and acute effects.

2. Materials and methods

The population model used is based on our previous logistic approach for the European lobster (Vives i Batlle et al. 2009), adapted to a population formed of two age-classes including an independent fecundity function and low-density 'Allee' effect, as represented by the following system of 7 first-order differential equations:

$$\frac{dN_0}{dt} = rF\left(1-\frac{N_0+Y_0}{K_0}\right)\left(1-\frac{W}{N_1}\right)+\kappa_0 Y_0 R_0 - (\alpha_0 d_r + s + d_0)N_0$$

$$\frac{dY_0}{dt} = \alpha_0 d_r N_0 - (\kappa_0 R_0 + \varepsilon)Y_0 - (s+d_0)Y_0$$

$$\frac{dR_0}{dt} = r_0 R_0\left(1-\frac{R_0}{M_0}\right) - \left(k_R^0 Y_0 + \alpha_R^0 d_r\right)R_0$$

$$\frac{dN_1}{dt} = sN_0 + \kappa_1 Y_1 R_1 - (\alpha_1 d_r + d_1)N_1$$

$$\frac{dY_1}{dt} = \alpha_1 d_r N_1 - (\kappa_1 R_1 + \varepsilon)Y_1 + sY_0 - d_1 Y_1$$

$$\frac{dR_1}{dt} = r_1 R_1\left(1-\frac{R_1}{M_1}\right) - \left(k_R^1 Y_1 + \alpha_R^1 d_r\right)R_1$$

$$\frac{dF}{dt} = fF\left(1-\frac{F}{L}\right) - rF\left(1-\frac{N_1}{K_1}\right) - \alpha_f^1 d_r F$$

Where the dynamic variables are the abundances of healthy (N_i) and damaged (Y_i) individuals at time t ($i = 0$ for young and 1 for adult) and the fecundity F, which represents the number of individuals capable of reproducing. The following rate constants underpin the model:

- s, the growth rate from young to adult;
- d_i, the intrinsic rates of population loss for young and adult;

- R, the reproduction rate (number of females produced by each fertile female);
- $K_0 = K_1 \frac{d_1}{s}\left(1 - \frac{s+d_0}{s}\frac{d_1}{r}\right)$ and K_1, the carrying capacities for juveniles and adults;
- W, the Allee constant indicating how reproduction reduces at low population density ($W \geq 2$).

The effect of radiation manifests itself as repairable radiation damage, reproduction effects and lethal damage (mortality). This is incorporated as the repairing functions R_i for young and adult, an approach grounded on previous literature (Laurie et al. 1972) where $\alpha_i, \alpha_R^i, \alpha_f^i, \varepsilon, \kappa_i, k_R^i, r_i, f$ are parameters for the radiation model described elsewhere (Kryshev et al. 2006; Kryshev et al. 2008; Vives i Batlle in press; Vives i Batlle et al. 2009). For example, The lethality parameter ε is designed such that at a dose equal to the $LD_{50/30}$ over 30 days 50% of the organisms suffer lethal damages, hence $\varepsilon = 2.3 \times 10^{-2}\ d^{-1}$. M_0 and M_1 are logistic constants for the recovery pool, made equal to K for symmetry reasons, and d_r is the radiation dose rate.

This system of equations was solved numerically by the Gear method, using the modelling software *ModelMaker*® version 4 (Citra 1997; Rigas 2000). The characteristic physiological parameters for the species were taken from the Animal Ageing and Longevity Database (AnAge 2012) and other online resources such as Arkive (www.Arkive.org) and the Fishbase (www.fishbase.org), as described previously (Vives i Batlle in press). To cover for lack of information on the adult mortality rate we interpreted lifespan as the age of the 10% oldest survivors, and an average mortality rate of ln(10)/lifespan was thus derived. Observing that the adult death rate follows an allometric law with mass, we adapted this law to fit the mortality rate for juveniles. The basic model parameters for the various species studied are given in Table 1.

The model was calibrated for various species with $LD_{50/30}$s of 3 Gy for fish eggs (Gorodilov 1971), 5.78 gy for adult fish (Kryshev et al. 2008) and 11.1 (Gambino et al. 1968; Golley et al. 1965), 10.2 (Pryor et al. 1967), 2.6 Gy (Norris et al. 1968) and 2.3 Gy (Sasser et al. 1971; Von Zallinger and Tempel 1998) for mouse, rabbit, dog and deer (cattle), respectively (assumed to be the same for adult and young due to data unavailability).

A key feature of the model calibration is the equation for the reversibly damaged population which contains the terms $\alpha_i d_r N_i - (\varepsilon + \kappa_i R_i) Y_i$ factorising loss due to lethal damages plus repaired damages (for chronic doses of radiation, R can be approximated to R_{max}). If the ratio "lethal damages / total (lethal + repaired) damages" expressed as $\rho = \frac{\varepsilon}{\varepsilon + \kappa R_{\max}}$ is known, then a certain relationship exists between k and R_{max}: $\kappa = \frac{\varepsilon}{R_{\max}}\left(\frac{1}{\rho} - 1\right)$. For low-LET irradiation f is low, no more than 2% (Kryshev et al. 2006; Kryshev et al. 2008) which for ε = 2.3 x 10^{-2} d^{-1} gives $\kappa \approx \frac{1}{R_{\max}}$. For high-LET irradiation the ratio of lethal to total damages is high, no less than 90% (Vives i Batlle et al. 2009) giving $\kappa \approx \frac{1}{400 R_{\max}}$. In both cases $\kappa_R \approx 1.5\kappa$. For low-energy beta radiation, we adopted an intermediate f value of 0.25 (chosen by judgment to be closer to the low-LET than the high-LET case), which gives $\kappa \approx \frac{1}{15 R_{\max}}$.

In this paper we tested for the first time the applicability of both high- and low-LET approximations to a combined dataset of radiation effects (mortality, morbidity, reproduction) in mammals and fish derived from the ERICA (Brown et al. 2008) and the EPIC (Sazykina and Kryshev 2003) radiation effects databases. The mortality, morbidity and reproduction effect endpoints assessed were modeled as changes in the adult (or, in the case of fish eggs, juvenile) age classes at the indicated post-exposure time, expressed mathematically as $1 - \frac{N_0 + Y_0}{K_1}$, $1 - \frac{R}{K_1}$ and $1 - \frac{F}{K_1}$, respectively.

3. Results and discussion

3.1. Fish and small mammals - Low LET radiation

We consulted the information on the effects of chronic radiation in fish and fish eggs established by other authors (Kryshev et al. 2008; Kryshev et al. 2006). For small mammals (mouse/vole) we used the effects data from the ERICA tool (Copplestone et al. 2008), which also contained additional data for fish. Not all the data could be used - a limitation of our study is that the radiation repair approach is not mechanistic, and therefore cannot cover the whole range of teratogenic, genetic, developmental and behavioral effects observed in biota, such as hormetic effects, specific genetic, blood composition effects or changes in size or lifespan.

In general, the model was found to predict successfully most of the experimental observations for loss of fecundity/survival/repair. The mean absolute differences between prediction and observation for fish and mice were 13% (77% of the data within ±20%) and 22% (75% of the data closer than ±30%), respectively. We then calculated the dose rates at which the model predicts the same effects on mortality, morbidity or reproduction as observed experimentally for the reported observation periods. The 49 theoretical versus model-predicted dose rates for fish and mammals were combined in order to obtain a larger dataset, and the results were graphically analyzed, as shown in figure 1. The two sets of data were found to be linearly correlated: Modelled dose rate = 0.98 × Experimental dose rate; close to a 1:1 relationship with a coefficient of determination $R^2 = 0.88$ over a wide dose rate interval from 10^{-4} to 1 Gy d^{-1}. The data subsets for fish (EPIC), fish (ERICA) and mice (ERICA) are similarly correlated.

There are some limitations to our validation. For fish egg there was a single anomaly in that practically total mortality of eggs is predicted for a dose rate of 9.4×10^{-1} Gy d^{-1} applied over 14 days. With a $LD_{50/30}$ of 3 Gy d^{-1} the model cannot reproduce this result because it implies a higher $LD_{50/30}$ for acute doses). Likewise, for mice a single data point corresponding to an acute dose of 7.7 Gy applied over a 20-minute period could not be modelled for the same reason. These problems can nevertheless be avoided by optimizing the radio-sensitivity parameters to values somewhat different from the actual $LD_{50/30}$.

We verified mathematically that survival, fecundity and repairing pool have a quasi-sigmoidal dose-response relationship with an initial low-effect region followed by large variation over a narrow interval around a tipping value, whereupon the dose-response curve decreases to 0% effect (Figure 2). The most sensitive endpoint seems to be morbidity, followed by fecundity and effect on survival. At a population (rather than individual) level, the mouse appears more radiosensitive than fish despite the lower

$LD_{50/30}$ for the latter, with an earlier onset of fecundity loss for the former organism. We attribute this to the combined effect of greater longevity and reproduction rates for freshwater fish compared with mice. A general effects threshold value in the order of $(2 – 3) \times 10^{-2}$ Gy d^{-1} can be deduced for both species. We also found that for fish and small mammals the adult mortality fraction f_m correlates approximately with the cumulative dose D_c as in $f_m = 1 - e^{-kD_c}$. The parameter k is species-dependent, being 3.5×10^{-2} Gy^{-1} (modelled data) vs. 3.1×10^{-2} Gy^{-1} (experimental data) for mammals, and 5×10^{-2} Gy^{-1} (modelled data) vs. 1.1×10^{-1} Gy^{-1} (experimental data) for fish.

3.2. Higher LET radiation

We studied the relative difference in effect of adopting a "lethal damages / total damages" ratio of 0.02 (γ-radiation) or 0.90 (α-radiation). Whilst for small mammals (mice) a low-LET radiation dose rate of 10^{-2} Gy d^{-1} induces a 2.1% loss of survival (mortality) after 10^3 days, an equivalent α-radiation dose rate of 7×10^{-4} Gy d^{-1} is required to generate the same effect in the model. This suggests a radiation quality factor of 14 for high-LET α-radiation, resembling the factor of 10 - 20 often adopted in non-human biota dose assessments (Brown et al. 2008; Vives i Batlle et al. 2004). With ρ = 25% (the intermediate < 10 keV β-radiation case) the equivalent dose rate is 2.2×10^{-3} Gy d^{-1} which gives a radiation quality factor of 4.5, resembling the factor of 3 for low-energy β-radiation adopted in non-human biota dose assessments by analogy to ^3H dosimetry. For fish, the model-predicted radiation quality factors are 25 for α - similar to the value of 30 calculated in our previous work (Vives i Batlle et al. 2009) - and 7.5 for < 10 keV β-radiation. These higher values result from an asymmetric population effect on species that have a very high fecundity but a very low survival from egg to adult.

The ERICA database contains only 5 records of quantifiable effects (mainly fecundity) of < 10 keV β-radiation to small mammals which can be interpreted on the basis of our model (Table 2). Some of the records are for rat rather than mice species; hence model runs for those data were adapted for the different $LD_{50/30}$ of 7.5 Gy for the rat (Casarett 1968; Hall 1973) to avoid reducing the dataset.

The model tends to give somewhat lower estimates of loss of survival and fecundity (differences < 20%), but successfully predicts zero-to-moderate effects on fecundity at doses < 5×10^{-3} Gy d^{-1} and significant effects at doses in the order of 2×10^{-2} Gy d^{-1}, a factor of ~ 3 below the doses at which low-energy β-radiation produces significant effect on reproduction. Without adjusting the $LD_{50/30}$, a single acute effect in mice fecundity at 1.7×10^{-2} Gy d^{-1} in 30 d (equivalent to a dose of 0.5 Gy) cannot be reproduced by the model – a similar problem as that encountered previously for acute doses. However, the remaining results show an acceptable linear correlation between experimental dose and 'same effect' modelled dose (y = 1.6731x; $R^2 = 0.97$). This provisional result needs to be revisited when further effects data for low-energy β radiation on mammals and other species becomes available.

3.3. Predictions for larger mammals

Theoretical 5-year model predictions for larger mammals (mouse, rabbit, wolf and deer) exposed to chronic low-LET radiation with dose rates of 0 to 5×10^{-2} Gy d^{-1} suggest that whilst for small mammals exposed to dose rates ≤ 0.02 Gy d^{-1} populations reach a stable level some 10% below controls, while for larger animals (dog, deer) populations become extinct at lower dose rates. Overall, these results tend to confirm the ERICA benchmark value of 2.4×10^{-4} Gy d^{-1} being a dose rate below which adverse effects are not expected, with the first observable effects on mammals occurring typically one order of magnitude above. A potential relationship: bigger animals = more longevity = slower reproduction rate = more radiation effect can be hypothesized from this analysis (Vives i Batlle in press).

4. Conclusions

A logistic population model was calibrated with life history data for dual age-class populations representing fish and mammals. Radiation effects were modeled using the concept of a recovery pool representing the effect of radiation on the repair system, as well as direct effect on fecundity. The key radiation parameters driving the model are the $LD_{50/30}$'s for young and adult, to which the model calibration is connected for acute effects.

In most cases, the model gives reasonable results in predicting the observed mortality, morbidity and reproductive changes for fish and mice populations at various doses of γ-radiation (differences typically within ± 20%). Experimental doses at which effects were observed and those for which the model predicts the same effect are well correlated and observed no-effect doses tend to coincide with doses at which model predictions are in the order of a few percent. Limited data for low-energy β-exposures in mammals suggests that the same model may also be applicable by recalibrating a single parameter (ρ).

Our modeling results cannot be interpreted as final model validation because an independent extensive set of data for chronic irradiation in natural conditions is not yet available. However, our approach offers a practical way to approach the problem, suggesting a way to treat more complex situations at the foodweb/ecosystem level with a relatively simple formalism.

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Table 1: Population model parameters

Symbol	Description	Freshwater fish[1]	Mouse	Hare/rabbit	Wolf/dog	Deer
d_0	Juvenile death rate (d^{-1})	1.23E+00	2.74E-05	*1.34E-05*	*9.68E-06*	*5.80E-06*
m_0	Mass for juvenile (kg)	1.78E-06	1.90E-03	8.25E-02	4.50E-01	6.71E+00
d_1	Adult death rate (d^{-1})	8.85E-04	1.42E-03	6.40E-04	3.15E-04	2.93E-04
m_1	Mass for adult (kg)	4.94E+00	2.32E-02	3.00E+00	3.33E+01	1.49E+02
s	Growth rate(d^{-1})	1.14E-04	4.12E-02	2.10E-02	2.11E-02	4.87E-03
r	Reproduction rate (d^{-1})	7.53E+02	2.98E-02	1.99E-02	7.39E-03	1.60E-03

[1] Average of data for Common carp, Grass carp, Loach, Tilapia, Siberian roach, Goldfish, Silver carp and Pike

Table 2: Effects of low energy (< 10 keV) β-radiation to small mammals interpreted as % loss of survival/fecundity.

Endpoint	Species	Dose rate (Gy d^{-1})	Time (d)	Effect	Survival/fecund. loss		Dose for same effect
					Observed	Predicted	
Mortality	Mice	3.6E-03	7.2E+02	No effect on lifespan	0%	2.9%	1.3E-03
Fecundity	Rats	4.8E-03	4.1E+01	Moderate effect in female reproductive organs (oocytes)	30%	11%	1.4E-02
Fecundity	Mice	1.7E-02	3.0E+01	Severe effect in female reproductive organs (oocytes)	93%	20%	N/A
Fecundity	Rats	3.0E-02	4.3E+01	Reduction in sperm content. No effects in females	77%	56%	5.0E-02
Fecundity	Rats	3.0E-02	2.3E+01	Major decrease of fecundity	60%	40%	5.0E-02

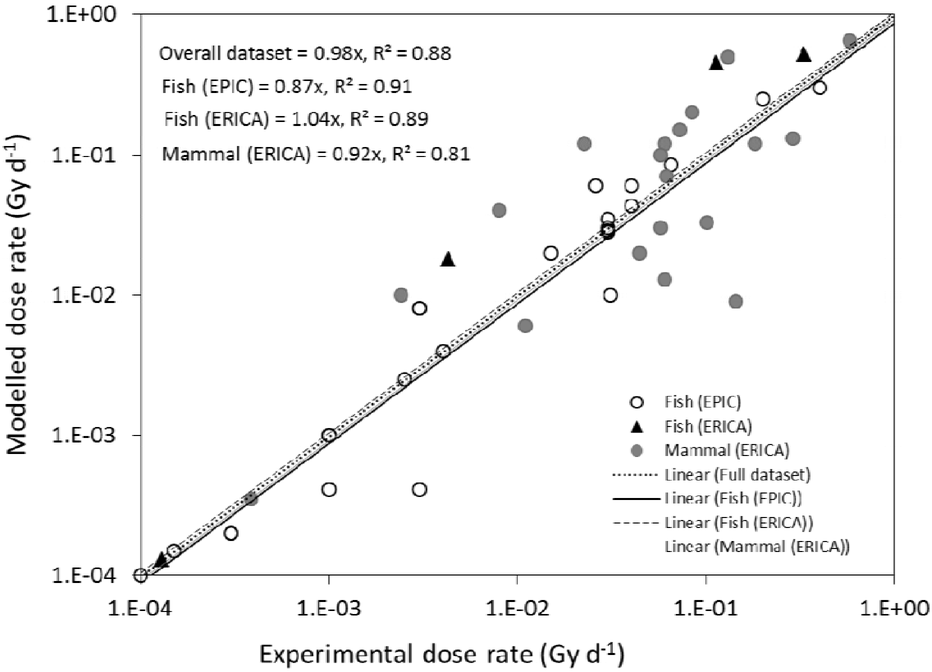

Figure 1: Comparison of experimental dose rates for different effects with model-predicted dose rate needed to obtain the same observed effect in (combined data for mice, fish and fish eggs from EPIC and ERICA).

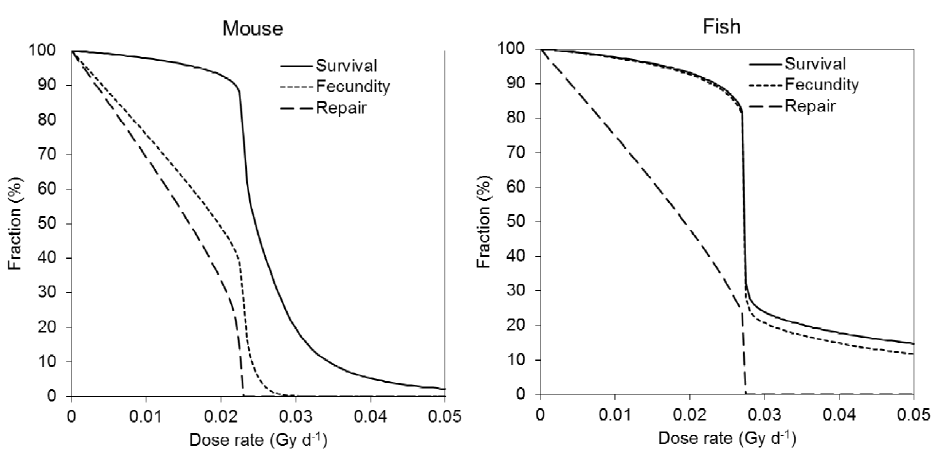

Figure 2: Survival, fecundity and repair pool of the adult mouse (left) and fish (right) as a function of dose rate.