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Proposal of a quantitative approach integrating radioactive and chemical risks

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Abstract – A number of situations lead to risks associated with both radionuclides and chemicals exposures: management of contaminated sites, NORM industries, management of indoor air quality, occupational risks, etc. Risk assessment and risk management associated with chemical and radioactive substances are based on different approaches and risk metrics, making it possibly hard to compare those risks and to manage risks in a commensurate way. This article presents a method to express health risk using a common metric, the DALY (Disability-Adjusted Life Year), which is used among others by WHO to guide public health policies. The proposed approach, allowing for comparison, hierarchy and aggregation of risks associated with exposure to ionizing radiations and chemical substances, can support communication and dialog between stakeholders on complex situations.

Keywords: risk / detriment / toxicological reference value / DALY / combined risk

1 Introduction

The OECD Nuclear Energy Agency (OECD NEA) recently published a report on the management of sites contaminated by radionuclides and other pollutants (NEA, 2019). In this report, the Agency notably states that "*The development of a common set of protection objectives and, hence assessment endpoints and methods* [...] *would prove to be very beneficial. In parallel, regulatory development that helps to ensure the process for managing chemical and radiological hazards and risks in a consistent and commensurate manner is worth further consideration.*" This raises the question of quantifying the risk arising from the exposure of an individual to a mixture of chemical and radioactive substances and, more generally, the management of exposure to multiple pollutants. The question of a holistic approach to risk management is also a subject of debate in the field of occupational exposure management in the nuclear industry. Equally, in its review of the 2016–2018 French National Plan for the Management of Radioactive Waste (PNGMDR, 2016), the French Environmental Authority stated that "*the concept of harmfulness cannot be reduced to the hazard arising from the radioactivity of radioactive waste alone and should fully take into account their chemical impacts* [...]" (Environmental Authority, 2016). Within this context and in line with the Environmental Authority's demand, the French Nuclear Safety Authority (ASN) and the French General Directorate for Energy and the Climate (DGEC) commissioned the Institute for Radiological Protection and Nuclear Safety (IRSN) to develop a method for evaluating the potential risk associated with radioactive material and waste (IRSN, 2018). In parallel, the French National Agency for Radioactive Waste Management (Andra), in conjunction with the Nuclear Protection Evaluation Centre (CEPN), developed an exploratory approach to radioactive waste potential risk assessment, making use of a metric, which combines both chemical and radiological risks via the DALY concept (Disability-Adjusted Life Year). To date, the 2022–2026 French National Plan for the Management of Radioactive Waste recommends in its ENV.2 action (PNGMDR, 2022) to continue the proposed approach review, by seeking to "*evaluate the potential complementarity of the exploratory approach to the health damage metric expressed in DALY with the approach presented by IRSN*".

The adequate management of a situation causing human exposure to pollutants of various types (radionuclides, heavy metals, etc.), requires a method for quantifying the risks arising from exposure to these substances, comparing and ranking them in order to propose management plans or procedures commensurate with the challenges (Hoorelbeke, 2018). As a contribution to the review process on this topic, this article discusses the approach developed by Andra and the CEPN to quantify the risk arising from exposure to a mixture of

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chemical and radioactive substances, based on the DALY concept. As a first step, the procedures for evaluating the radiological risk are presented, with emphasis on the radiological detriment concept as defined by the International Commission on Radiological Protection (ICRP). Then the procedures for quantifying the risk arising from exposure to chemical substances are described. On this basis and after introducing the DALY measurement, an approach for quantifying the risk arising from a mixture of chemical and radioactive substances, based upon the DALY concept, is detailed. The last part discusses the benefits and limits of the proposed approach.

2 Quantification of the radiological risk

The radiological protection system aims at preventing the incidence of tissue reactions (relying mainly on the principle of dose limitation) and reducing the risk of stochastic effects though the implementation of the ALARA (As Low As Reasonably Achievable) approach (or principle of optimisation of radiological protection).

Quantification of the radiological risk at low doses and low dose rates is one of the pillars of the radiological protection system built by the ICRP. It is based on the assumption of a no-threshold linear relationship between exposure and risk: any dose increment induces a proportional risk increment. The detriment concept was introduced by the ICRP to establish a quantified relationship between exposure and risk, and a first detriment quantification was proposed in 1977 (ICRP, 1977). In 1990, in its Publication 60 (ICRP, 1991), the ICRP revised the detriment quantification method on the basis of new scientific data produced in particular by epidemiology and follow-up of the cohort of survivors of the Hiroshima and Nagasaki atomic bombs (Life Span Study, LSS). The ICRP also introduced the DDREF (Dose and Dose Rate Reduction Factor) which accounts for the extrapolation to low doses and dose rates of observations made for high doses and dose rates. In 2007, the ICRP published new general recommendations (ICRP, 2007), which are the basis for international radiological protection standards. In this publication, the radiological detriment was revised and is expressed as follows:

$$D = \sum_{T} R_T \times (1 - k_T) \times [(1 - q_{min}) \times k_T + q_{min}] + R_T \times k_T,$$

where,

- D: radiological detriment;
- T: organ or tissue;
- R_T: nominal risk of cancer incidence of organ T;
- k_T: lethality fraction of cancer T;
- q_{min}: 0.1.

The first component of the expression of detriment $R_T \times (1 - k_T) \times [(1 - q_{min}) \times k_T + q_{min}]$ refers to the non-lethal component of the detriment (morbidity), the second component $R_T \times k_T$ to the lethal component of the detriment.

The nominal risks (R_T) are mostly calculated by applying mathematical models produced from epidemiological studies, particularly the follow-up of the LSS. They reflect the excess cancer incidence for a population exposed to ionizing radiation. An article by Cléro *et al.* (2019) and the ICRP Publication 152 (ICRP, 2022) detail the calculations made in ICRP Publication 103 (calculation of nominal risks and quantification of detriment). Table 1 presents the values of R_T and k_T, as well as the detriment value (per organ and whole body), derived from ICRP Publication 103.

Accordingly, detriment is equal to $5.7 \cdot 10^{-2}\,Sv^{-1}$ for a member of the public and $4.2 \cdot 10^{-2}\,Sv^{-1}$ for workers. On this basis, ICRP Publication 103 states "*It is therefore the recommendation of the Commission that the approximated overall fatal risk coefficient of 5% per Sv on which current international radiation safety standards are based continues to be appropriate for the purposes of radiological protection.*"

3 Quantification of the chemical risk

The quantification of the health risk caused by exposure to chemical substances (in particular) relies upon the following approach:

- exposure assessment ("dose") of individuals;
- quantification of the risk on the basis of a ratio between the received dose and a reference value named Toxicological Reference Value (TRV) for chemical substances.

Quantification of the risk arising from exposure to chemical substances relies upon TRVs obtained after analysis of dose-effect relationships. In most cases, these relationships are established from experimental data from animals and rely upon cautious assumptions (specifically, use of a safety factor for the extrapolation of the experimental data to humans, along with risk transfer between populations) (INERIS, 2016). A variety of exposure routes (inhalation, ingestion and more rarely cutaneous absorption) and exposure modalities (chronic and/or acute) are taken into account. Exposure is generally expressed as mass (mg) of substance per unit body mass (kgbm) or per unit volume (m^3) and per day (d) ($mg.kgbm^{-1}.d^{-1}$) and two types of dose-effect relationships are distinguished:

- linear no-threshold relationship, where the probability of disease induction increases with exposure to the relevant substance;
- threshold relationship: absence of expected effect below an exposure value.

For chronic exposure to low doses, the toxic effects considered for humans are varied: carcinogenic, mutagenic, reprotoxic, etc. The objective of protection from exposure to chemical substances is to prevent the occurrence of threshold effects and to minimise as much as possible the probability of occurrence of no-threshold effects (As Low As Reasonably Practicable, ALARP). To do this, exposure to substances should be compared with TRVs.

Unlike radiological risk, no international organisation equivalent to the ICRP exists for providing international recommendations for the evaluation and the management of the risk arising from exposure to chemical substances. The TRVs used by national agencies in charge of managing chemical risk are based on the values proposed by reference organisations such as the United States Environmental

Table 1. Evaluation of the radiological detriment caused by exposure to ionizing radiation for a member of the public (for 10^4 persons per Sv) (ICRP, 2007).

Organs/Tissues	Number of incident cases (R_T, for 10^4 persons per Sv)	Lethality fraction k_T	Detriment (for 10^4 persons per Sv)
Oesophagus	15	0.93	13.1 (2.3%)
Stomach	79	0.83	67.7 (11.8%)
Colon	65	0.48	47.9 (8.3%)
Liver	30	0.95	26.6 (4.6%)
Lung	114	0.89	90.3 (15.7%)
Bone	7	0.45	5.1 (0.8%)
Skin	1000	0.002	4 (0.7%)
Breast	112	0.29	79.8 (13.9%)
Ovary	11	0.57	9.9 (1.7%)
Bladder	43	0.29	16.7 (2.9%)
Thyroid	33	0.07	12.7 (2.2%)
Bone marrow	42	0.67	61.5 (10.7%)
Other	144	0.49	113.5 (19.8%)
Gonads	20	0.8	25.4 (4.4%)
Total	1715		574.2 (100%)

The percentage given in brackets in column 4 corresponds to the contribution of the organ/tissue to the total detriment.

Table 2. Example TRVs adopted by the INERIS for chronic exposure to chemical substances through inhalation.

	Threshold TRV $\mu g.m^{-3}$	Critical effect considered	No-threshold TRV $(\mu g.m^{-3})^{-1}$	Critical effect considered
Pb (lead)	–	–	1.20E-05	Renal tumours
Hg (mercury)	0.03	Neurological effects	–	
As (arsenic)	0.015	Diminished intellectual capacity	0.0043	Pulmonary cancers
Ni (nickel)	0.09	Nasal and pulmonary lesions	2.60E-04	Pulmonary cancers
Cd (cadmium)	0.3	Pulmonary tumours	–	–

Protection Agency (US EPA) or the Agency for Toxic Substances and Disease Registry (ATSDR). In France, the INERIS (French National Institute for Industrial Environment and Risks) along with the ANSES (French Agency for Food, Environmental and Occupational Health & Safety) are defining (only by ANSES) and validating TRVs for a range of toxics on the basis of their own expert appraisal work. These data are available free of access *via* the INERIS portal (https://substances.ineris.fr) or the ANSES database (https://www.anses.fr/fr/content/liste-des-valeurs-toxicologiques-de-référence-vtr-de-l'anses).

The thresholds TRVs are expressed in the form of reference dose (RfD) or reference concentration (RfC). The threshold TRV then corresponds to "*the quantity of a product, or its airborne concentration, to which an individual may be exposed without any adverse effect being observed over a set period*" (INERIS, 2016). For no-threshold substances, the TRV is defined as "*unit risk factor (URF) and corresponds to the slope of the straight line of the dose-effect relationship*" (INERIS, 2016). For illustrative purposes, Tables 2 and 3 present several TRVs proposed by the INERIS (https://substances.ineris.fr) and the critical effects considered when deriving these values.

To quantify the health risk induced by chemical substances, the TRV values are linked to mean exposure to the evaluated substance. The average daily dose of an individual to a substance i (ADD_i) is evaluated by distinguishing between inhalation and ingestion and on the basis of assumptions regarding the exposure period from the calculation of the substance i concentration in the medium compartments. Taking this value and the TRV_i for substance i, a hazard quotient $HQ_{i,v}$ (threshold effect) or Cancer Risk $CR_{i,v}$ (linear no-threshold relationship) is calculated, where v denotes the exposure route.

For a threshold substance:

$$HQ_{i,v} = ADD_{i,v}/RfD_{i,v},$$

- if $HQ_{i,v}$ is less than 1, there is no risk of occurrence of the effect;
- if $HQ_{i,v}$ is greater than or equal to 1, the effect may occur.

Table 3. Example TRVs adopted by the INERIS for chronic exposure to chemical substances through ingestion.

	Threshold TRV μg. (kgbm.d)$^{-1}$	Critical effect considered	No-threshold TRV (μg. (kgbm.d)$^{-1}$)$^{-1}$	Critical effect considered
Pb (lead)	–	–	8.50	Renal tumours
Hg (mercury)	0.66	Renal effects	–	–
As (arsenic)	0.45	Cutaneous lesions	1.50E+03	Cutaneous cancers
Ni (nickel)	2.8	Reprotoxic effects	–	–
Cd (Cadmium)	0.36	Urinary beta2 microglobin	–	–

For a no-threshold substance:

$$CR_{i,v} = ADD_{i,v} \times URF_{i,v}.$$

For no-threshold effects, a quantitative protection goal should be defined, *i.e.* a risk level deemed acceptable given that 0 risk (*e.g.*, null concentration of the relevant substance in the environment) cannot be guaranteed. The lifetime risk values for the occurrence of effects, which are deemed acceptable for anthropic environmental exposure, vary between 10^{-6} and 10^{-4} (BIOPROTA, 2017).

To quantify the hazard potential of a mixture of chemical substances, a simple approach is to combine the calculated risk indices for each substance. Note however that for the particular case of the HQs, only those inducing the same effect on the same target organ may be added together. This default approach, recommended in France by the INERIS, rules out synergistic or antagonistic effects between substances.

4 DALY concept

In the early 1990's, the World Health Organization (WHO), in collaboration with Harvard University, developed an evaluation method for quantifying the health state of a population, in order to prioritise public health actions. This method relies upon a synthetic measurement of the state of health of the population: DALY (Disability-Adjusted Life Year). The DALY is "*a health gap measure that extends the concept of potential years of life lost due to premature death to include equivalent years of healthy life lost by virtue of individuals being in states of poor health or disability. One DALY can be thought of as one lost year of healthy life and the burden of disease as a measure of the gap between current health status and an ideal situation where everyone lives into old age free from disease and disability.*" (Lopez *et al.*, 2006). Broadly, the DALY metric was set up to meet the need for objective, comparable and worldwide health evaluation data.

To date, in the environmental health field, the DALY concept is used, for example, in life cycle analyses (LCA) or for the WHO's preparation of drinking water quality standards. For each of its member states, the WHO is also in charge of periodically evaluating the DALY values assigned to a number of pathologies. The DALY metric is calculated by combining the number of Years of Life Lost (YLL), caused by early death (mortality) and the number of equivalent years of life lost because of deterioration in health (morbidity) (Years Lost due to Disability, YLD): DALY = YLL + YLD (Fig. 1).

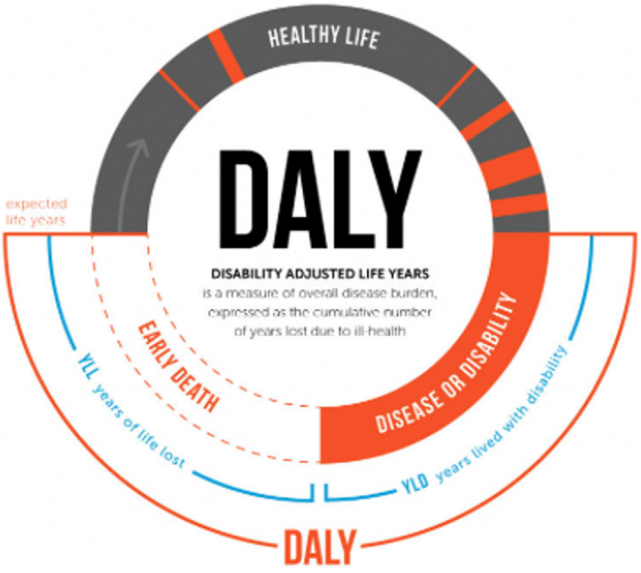

Fig. 1. DALY concept.

The YLL term is evaluated from the standard life expectancy at the age of death and the mortality rate of the considered disease. The YLD term corresponds to the average duration of the disease before cure or death, adjusted for a disability rate. Standard life expectancy and disability rates are important parameters whose evaluation relies upon mathematical models (life expectancy) or expert opinion (disability rate).

A number of studies published in the literature give an estimate of the DALY number for a wide spectrum of pathologies. For illustrative purposes, extracts from the Huijbregts publication (Huijbregts *et al.*, 2005) are given in Table 4. This article describes the development of a method for evaluating health impact within the framework of LCAs, using DALY to express the health effects. These data are taken from the 1990 Global Burden of Disease and Injury study and give an average disability-free life expectancy expressed in DALY, for a wide spectrum of pathologies.

These data allow to assign a DALY number to the diseases associated with exposure to radioactive or chemical substances. The risk of occurrence of a disease can then be expressed as a probability of loss of life years in good health calculated by multiplying the risk of occurrence of the disease

Table 4. Examples of DALY for a variety of pathologies (source: Huijbregts *et al.*, 2005).

Disease	DALY
Oesophageal cancer	17.9
Stomach cancer	13.6
Colon cancer	8.8
Liver cancer	22.5
Lung cancer	16.5
Thyroid cancer	13.3
Skin cancer	6.3
Breast cancer	7.6
Ovarian cancer	13.3
Bladder cancer	5.0
Leukaemia	28.3
Other cancers	11.5
Nephrosis	12.4
Non-cancer disease	2.7
Congenital abnormality	6.2–80
Chronic pulmonary disease	8.2
Cataract	1.1

The incidence of oesophageal cancer corresponds on average to the loss of 17.9 years of life in good health.

per unit exposure by the DALY for this disease. This means that a risk of occurrence of a disease is replaced by a risk of loss of years of life in good health (DALY).

5 Expressing radiological and chemical risks with DALY

Although the procedures for evaluating the risk arising from exposure to ionizing radiation or exposure to a chemical substance as presented in the above sections are not so far apart, the risk metrics used remain specific. This means that, because of differing expressions, it is no simple matter to compare the radiological and chemical risks in the case of exposure to a mixture of radioactive and chemical substances. The joint work carried out by the IRSN and the INERIS (Cléro *et al.*, 2021) also identified several disparities in the approaches to building the TRVs and the radiological detriment. In particular, it was highlighted that:

- the input data are mostly experimental in one case (TRV) and result from epidemiological studies in the other (detriment);
- detriment is evaluated from absorbed dose via biokinetic models, while the TRVs are evaluated on the basis of exposure concentration – behaviour in the organism cannot be known for each of the chemical toxics;
- a whole body approach is applied in the detriment calculation, while the TRVs are obtained from the lowest observed effect on the most sensitive organ;
- radiological detriment is estimated by weighting probabilities of occurrence of radiation induced fatal cancer according to their severity, while the TRVs are determined from the probability of occurrence of a disease.

Despite these limits, this section proposes to adopt DALY as the common metric, in order to express radiological and chemical risks on a consistent basis.

5.1 Expressing radiological detriment in DALY

For ionizing radiation, the detriment calculation relies upon nominal risks, which reflect excess cancer incidence for an exposed population. For each cancer under consideration, it is possible to assign a DALY to express radiological detriment in DALY.Sv^{-1}. In order to illustrate this method on the basis of the nominal risks outlined in ICRP Publication 103, the following assumptions are made:

- the incidence of skin cancer is not considered. The nominal risk for skin cancer corresponds to a very high incidence, but its contribution to radiological detriment is near null (lethality fraction set at 0.002). Further, the data for this cancer have not been updated recently[1].
- in the absence of precise information for a type of cancer in Huijbregts *et al.* (2005), the incidence of this cancer is assigned 11.5 DALY, or the value corresponding to "Other cancers" in Table 4;
- the incidence of a hereditary effect is assigned 43.1 DALY, corresponding to the median value of the DALY range proposed in Table 3 for a congenital abnormality.

For a given organ or tissue, Table 5 gives:

- the nominal risk or number of cancer incident cases for 10^{+4} persons.Sv (column 2) taken from ICRP Publication 103 (Tab. 1);
- the DALY for cancer of the organ or tissue (column 3) (Tab. 4);
- the product of the nominal risk and the DALY number (column 4).

Combining the values in column 4 for the relevant organs and tissues gives an estimate of the radiological detriment as follows: $D_{DALY} = 1$ DALY.Sv^{-1} (9928.625 DALY for 10^{+4} persons per Sv): for an average individual, a whole body exposure of 1 Sv leads to the loss of one year of life in good health. As a reminder, expressing the detriment in DALY does not change the nature of the detriment: it is a quantitative metric for assessing a risk level corresponding to an exposure for an average individual and not a quantitative evaluation of

[1] "*Regarding non-melanoma skin cancer, the nominal risk estimate was taken from Publication 59 because models derived from LSS were judged to be not adequate for a general population due to differences between countries in risk related to skin pigmentation. The risks of skin cancer have been estimated using an absolute and constant relative risk model, with no modifying effects of age or time since exposure, using both mortality and incidence data, based on the epidemiological and experimental results published before 1990. The radiation effect has been seen mainly for basal cell carcinomas, which are essentially non-fatal. Publication 59 estimated the risks assuming 0.01% mortality for basal cell carcinomas and 1% mortality for squamous cell carcinomas)*" (Cléro *et al.*, 2019).

Table 5. Expressing radiological detriment in DALY.

Organ	Number of incident cases (for 10^{+4} persons.Sv)[A]	DALY	Detriment (for 10^{+4} persons.Sv) expressed in DALY
Oesophagus	15	17.9	277.45 (3%)[B]
Stomach	79	13.6	1081.2 (11%)
Colon	65	8.8	576.4 (6%)
Liver	30	22.5	675 (7%)
Lung	114	16.5	1889.25 (19%)
Bone	7	11.5	80.5 (1%)
Breast	112	7.6	851.2 (9%)
Ovary	11	13.3	139.65 (1%)
Bladder	43	5	217.5 (2%)
Thyroid	33	13.35	433.875 (4%)
Leukaemia	42	28.3	1188.6 (12%)
Other solid	144	11.5	1656 (17%)
Gonads (Heritable)	20	43.1	862 (9%)
Total	716		9928.625 (100%)

[A] Or 10^{+4} people exposed to 1 Sv.
[B] The percentage given in brackets in the fourth column corresponds to the contribution of the organ/tissue to the total detriment expressed in DALY.

Table 6. Contributions of the organs/tissues to radiological detriment according to the calculation method.

Organs/Tissues (T)	Number of incident cases (for 10^{+4} persons per Sv)	T contribution to D^{ICRP}	T contribution to D_{DALY}	Ratio
Oesophagus	15	13.1 (2%)	277.4 (3%)	1.22
Stomach	79	67.7 (12%)	1081.2 (11%)	0.92
Colon	65	47.9 (8%)	576.4 (6%)	0.70
Liver	30	26.6 (5%)	675 (7%)	1.47
Lung	114	90.3 (16%)	1889.2 (19%)	1.21
Bone	7	5.1 (1%)	80.5 (1%)	0.91
Skin	1000	4 (1%)	NA	NA
Breast	112	79.8 (14%)	851.2 (9%)	0.62
Ovary	11	9.9 (2%)	139.6 (1%)	0.82
Bladder	43	16.7 (3%)	217.5 (2%)	0.75
Thyroid	33	12.7 (2%)	433.9 (4%)	1.98
Bone marrow	42	61.5 (11%)	1188.6 (12%)	1.12
Other solid	144	113.5 (20%)	1656 (17%)	0.84
Gonads (heritable)	20	25.4 (4%)	862 (9%)	1.96
Total	1715	574.2 (100%)	9928.6 (100%)	

the risk of an exposed individual. Note that results in DALY cannot be interpreted as time life effectively lost. It is an indicative value allowing to express different risks in the same metric.

This result is supported by several factors, as follows:

– an article published in 2015 on the use of DALY for measuring the excess cancer risk after exposure to ionizing radiation proposes a value of 1.14 DALY.Gy^{-1} for the Japanese population (Shimada and Kai, 2015). This value confirms the approach adopted as part of the method presented in this article;
– note also that the contributions of the organs/tissues to the total detriment are similar between Tables 1 and 4, which emphasises the similarity of the proposed approach to the one adopted by the ICRP for quantifying the radiological detriment (Tab. 6). The ratio of the contributions for each of the organs/tissues varies from 0.6 (breast) to 2 (hereditary effects and thyroid cancer);

– with the data used by the ICRP for quantifying the detriment, it is estimated that a radiation-induced cancer leads on average to a loss of life expectancy on the order of 15 years (ICRP, 2007). On this basis, with a radiological detriment value of $5.7 \cdot 10^{-2}\,Sv^{-1}$ in ICRP Publication 103, the expression of the detriment in year of life lost is $15 \times 0.057 = 0.9$ years of life lost. This value matches the value of $1\,DALY.Sv^{-1}$ in this article.

5.2 Example

Take the case of a worker involved in remediation work on a building. He operates for 800 h in an environment with an ambient dose rate of $1\,\mu Sv.h^{-1}$ and an atmospheric contamination of $1\,Bq.m^{-3}$ of ^{137}Cs. The worker does not put on any respiratory protection equipment.

The worker is exposed to a dose D calculated as follows:

$$D = 1{\cdot}10^{-6} \times 800 + 1.2 \times 800 \times 1 \times 6.7{\cdot}10^{-9} = 0.8{\cdot}10^{-3} + 0.6{\cdot}10^{-5} \approx 0.8{\cdot}10^{-3}\,Sv.$$

The first component ($1.10^{-6} \times 800$) is associated with external exposure (dose rate fold duration of exposure), while the second is associated with internal exposure, considering a breathing rate of $1{,}2\,m^3.h^{-1}$ and a dose factor of $6.7 \cdot 10^{-9}\,Sv.Bq^{-1}$ for ^{137}Cs (and a duration of exposure of 800 h).

The risk expressed in DALY arising from this exposure situation is $0.8 \cdot 10^{-3}$ DALY. The main risk component is external exposure. In the case of exposure to several radionuclides, the received doses are combined before being converted to DALY.

5.3 Expressing chemical risk in DALY

To express the chemical risk in DALY, the critical effect considered when evaluating the TRV for each chemical toxic is matched with a corresponding DALY value referenced in the literature. Table 4 gives examples of DALY values chosen for each chemical toxic, for each envisaged exposure scenario.

For no-threshold effects, for an exposure route v, the risk of developing a disease P caused by exposure to a substance i is expressed as follows:

$$CR_{i,v,P} = URF_{i,v,P} \times ADD_{i,v,P}.$$

With $DALY_P$ denotes the number of years of life in good health lost for disease P, cancer risk can be expressed in DALY:

$$CR_{i,v,P} = URF_{i,v,P} \times ADD_{i,v,P} \times DALY_P.$$

For example, for lead inhalation in chronic exposure (P: renal cancer), the following formula is obtained from the data in Tables 2 and 4:

$$CR_{Pb,\,inh.} = 1.2 \times 10^{-5} \times ADD_{Pb,\,inh.} \times DALY_{renal\ cancer} = 1.2 \times 10^{-5} \times 11.5 \times ADD_{Pb,\,inh.} = 1.38 \times 10^{-4} \times ADD_{Pb,\,inh.},$$

where $DALY_{renal\ cancer} = 11.5$ DALY and $ADD_{Pb,inh.}$ is the average daily dose to lead in $\mu g.m^{-3}$.

For threshold effects, for an exposure route v, the risk of developing a disease P caused by exposure to a substance i is expressed as follows:

$$HQ_{i,v,P} = ADD_{i,v,P}/RfD_{i,v,P}.$$

If $HQ_{i,v,P}$ is less than 1, the risk of developing disease P is considered null. Otherwise, it is considered as equal to 1, irrespective of the actually calculated value. Within the approach proposed in this article, it was decided to express as follows the risk of developing a disease for threshold effects:

– if $HQ_{i,v,P} < 1$ then $R = 0$;
– if $HQ_{i,v,P} \geq 1$ then $R = DALY_P$, where $DALY_P$ is the DALY number corresponding to the occurrence of disease P.

For chronic exposure to cadmium through inhalation, Table 2 gives a threshold TRV of $0.3\,\mu g.m^{-3}$ (pulmonary tumours). Where $ADD_{Cd,inh.}$ denotes chronic exposure to cadmium through inhalation of an individual (in $\mu g.m^{-3}$) and based on Table 4:

– if $ADD_{Cd,inh.} < 0.3$ then $HQ_{Cd,inh.} < 1$ and therefore $R = 0$;
– if $0.3 \leq ADD_{Cd,inh.}$ then $HQ_{Cd,inh.} \geq 1$ and therefore $R = 16.5$ DALY.

Note that for a cocktail of chemical substances, interaction mechanisms (synergy, additivity, antagonism) have rarely been described and are difficult to quantify. For threshold substances, it is commonly accepted that risk coefficients can be summed if the substances have critical effects on the same target organs. Whereas, for no-threshold substances, risk coefficients can be freely added (INERIS, 2021). Therefore, as a first approach, and to simplify the process, it is proposed to consider only the maximum obtained value for both threshold and no-threshold substances. Note that this assumption marks an important limit to the current approach.

6 Discussion

The radiological protection system was built and consolidated through the 20th century with support, among other factors, from the increasing scientific evidence on the health risk associated with exposure to ionizing radiation and the adoption of a precautionary approach. On this basis, radiological detriment, constructed on the basis of assumed no-threshold linearity between risk and dose, supplies a quantitative risk metric for guiding protective actions at the low doses and dose rates characterising most environmental and occupational exposure situations. In parallel with the radiological protection system, the research work on the toxicity of chemical substances has made it possible to build exposure-risk relationships for a large number of substances, even if one should mention that this number is still limited compared to the total number of substances people are actually exposed to. This knowledge was used to prevent occupational risks in the environmental health field and to guide public health policies. With the TRVs, the probability of occurrence

of a wide spectrum of pathologies is quantified according to the relevant pollutant and the exposure routes.

The procedure for managing radiological and chemical risks is based on separate regulatory frameworks, approaches and risk expression modalities. These approaches should, however, be increasingly merged. Indeed, preventers are today facing a large number of situations involving the simultaneous management of the radiological and chemical risks: evaluation of the potential risk associated with radioactive materials and waste, dismantling of nuclear installations, management of contaminated sites, industries using naturally occurring radioactive material (NORM), etc. The development of an approach for quantifying the risk arising from exposure to a variety of substances, both chemical and radiological, with the same metric (unit), may be a contributor to this.

The procedure for evaluating the risks arising from exposure to radioactive or no-threshold chemical substances exhibits similarities and primarily relies upon reference values for a lifetime risk, a single no-threshold linear relationship system and unit risk factor (URF), as well as nominal risk coefficients relating to the general population case (Cléro *et al.*, 2021). For ionizing radiation, the nominal risks calculated for tissues and organs are aggregated by the ICRP to form the radiation detriment (D), a single mortality metric, which includes both the morbidity and the mortality of cancers and incidental hereditary effects. For chemical substances, an excess risk of a disease (CR) or hazard quotient (HQ) is calculated. As mentioned here above (Sect. 5), several disparities remain between the two approaches, and cannot be dismissed.

The approach proposed in this article does not aim to establish a risk quantification method for an individual exposed to multiple pollutants. The aim is rather to apply a method based on quantification of potential exposures to assess the risk levels for several pollutants, with reliance upon homogeneous expression of risks through the DALY concept, at the population level. In this sense, the results provided in DALYs do not express an absolute value of life lost in good health, but an indicative and comparative value, allowing the comparison of several risks usually expressed in different metrics. Thus, with this homogeneous quantitative metric, the proposed approach enables graduated, customised multiple risk assessment. Moreover, in a context of increasing involvement of non-institutional actors in the management of some risk situations, the proposed approach may contribute to a better understanding of the challenges by avoiding the use of multiple risk metrics and enabling better risk comparison and aggregation.

By homogeneously expressing the risks arising from exposure to different substances, the proposed approach may also lead to the questioning and comparison of the numerical values and expert judgements adopted to derive some exposure limit values. However, the approach proposed in this article has a number of limitations, which should subsequently be given greater consideration. Among these limits, particular emphasis may be placed on the fact that:

- the 1 DALY/Sv conversion factor is obtained without taking into account the case of skin cancer. Note that taking into account this type of cancer would lead to the determination of a conversion factor of 1.6 DALY/Sv. The ICRP has undertaken a process of revision of its general recommendations, which will include a new value for detriment and the nominal risk coefficients (Clement *et al.*, 2022). When available, these new data will therefore benefit from being integrated into the DALY/Sv conversion factor calculation;
- the 1 DALY/Sv conversion factor, obtained from the radiological detriment evaluation, is only valid in the low dose domain. The case of deterministic effects is not considered for the time being. However, the impact of threshold substances can be expressed in DALY for chemical substances. For an overall evaluation of chemical and radiological impacts, the deterministic effects of exposure to ionizing radiation should therefore be translated into DALY;
- the matching of the critical effects used to determine the TRVs with DALY values would benefit from being refined with aid from toxicologists and statisticians.

The case of particular substances such as uranium, exhibiting both chemical and radiological toxicity, is for now evaluated by considering the two types of toxicity independently of each other, without finding out whether one outweighs the other.

Finally, it should be noted that for the time being, the proposed approach does not go as far as summing up the DALYs assessed from chemical and radiological exposures. This can be done to the extent that both types of risk are expressed in the same metric, but any limitations associated with this aggregation would need to be specified (Cléro *et al.*, 2021).

7 Conclusion and outlook

This article proposes an approach for quantifying the risk arising from exposure to chemical and radioactive substances by means of a new metric, DALY, with support from the risk exposure models derived from the literature. The approach can be further refined, particularly to make sure that there is more similarity between the two risk assessment approaches (organ-based approach for the two types of risk for example, see Cléro *et al.*, 2021). However, the work detailed in this paper can contribute to current reflections related to an holistic approach to the management of multiple exposures. It is also an asset in terms of the information communicated to the general public, allowing a risk level to be expressed in a unit (years of life in good health lost) which is perhaps easier to grasp than those currently used (Sv, μg.(kgbm.d)$^{-1}$). Lastly, this approach could also serve to compare standards (limits, guide values, etc.) established for human protection and explicit the rationale.

The approach outlined in this article could be usefully supported by updating the input data used to quantify radiological detriment, along with the DALY values by disease given in Table 3. There is notably a need to update the data used for the quantification of the radiological detriment: incidence rate of cancers, risk models, etc. In the same way, and depending on the evolution of the scientific knowledge, new pathologies could be integrated into the detriment

calculation in the medium term. The average DALY values used within this article date back to the 1990s and could also be updated on the basis of the data provided by the Institute for Health Metrics and Evaluation (IHME).

Conflict of interest

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Authors contributions

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