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REFLECTION ON THE PROPOSED CHANGES TO DOSE QUANTITIES - AN INDUSTRIAL PERSPECTIVE

M. Lips[1], E. Anderson[2], K. Nishida[3], G. Schneider[4], J. Zic[5], C. Sanders[6], J. Owen[7], J. Hondros[8], A. de Ruvo[9]

[1] Kernkraftwerk Gösgen-Däniken, Postfach, CH-4658 Däniken, Switzerland
[2] Radiation Safety & Control Services, Seabrook, NH, USA
[3] Kansai Electric Power Co., Inc, Mihama, Fukui-prefecture, Japan
[4] Namibian Uranium Institute, Swakopmund, Namibia
[5] Mc Master University, Hamilton, Canada
[6] University of Nevada, Las Vegas (UNLV), Las Vegas, NV, USA
[7] BHP – Olympic Dam, Adelaide, Australia
[8,9] World Nuclear Association, London, UK

E-mail: alexandre.deruvo@world-nuclear.org

Abstract

In 2021, the ICRP initiated the revision of the general recommendations of the system of Radiation Protection, and part of it will focus on dose quantities. The recently published ICRP Publication 147 and ICRU Report 95 have described the extent of the proposed modifications and paved the way for the strategy to be adopted. These revisions would seek to simplify, improve the accuracy and extend the field of use of dose quantities. While the Radiological Protection Working Group (RPWG) of the World Nuclear Association (WNA) recognises the notable improvement in the estimation of the protection quantities and the usefulness of such changes for the medical and research sector, the benefits of the proposed new system seem very limited for the nuclear industry and industries involving naturally occurring radioactive materials (NORM). The complexity associated with changing a long standing and robust system and the risk incurred by the human factor seem unjustified bearing in mind the likely cost.

Keywords: Dose quantities, ICRU Report 95, ICRP Publication 147, Nuclear industry

1. Introduction

The World Nuclear Association (WNA) is the international organisation that represents the global nuclear industry. Its mission is to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions and contributing to the energy debate. The WNA is also the global nuclear industry's interface with the established international institutions (IAEA, ICRP, NEA-OECD, IRPA, etc).

The Radiation Protection Working Group (RPWG) is a committee of the WNA and consists of experienced radiation protection professionals from a range of organisations involved in the nuclear industry. Areas of activity include uranium mining, fuel fabrication, electricity generation, education, research, plant construction, decommissioning and waste disposal. The RPWG, created in 2002, promotes worker, public and environmental protection through implementing robust radiation protection practices and develops and advocates scientific policy and practice.

2020 and 2021 have seen the publication of two important documents from the ICRP (ICRP Publication 147: *Use of Dose Quantities in Radiological Protection*) [ICRP 2021] and the ICRU/ICRP (ICRU Report 95: *Operational Quantities for External Radiation Exposure*) [ICRU 2020] proposing to change the existing radiological protection dose quantities. Because of the recent publication of these documents, assessments of the potential impact of these changes are few and far between. The WNA has however gathered the analysis of several industry practitioners and committee members from the ICRP and ICRU to understand the pros and cons this new system might bring to the nuclear industry. As of today, the initial assessment from the WNA notes that the change in dose quantities proposed by the ICRP and the ICRU will not bring any significant health or safety improvement to the nuclear industry, but will entail additional costs and complexities.

2. Existing system of dose quantities

The concept of dose applied to radiological protection is defined by three sets of quantities tightly linked together: the physical quantities, the protection quantities and the operational quantities.

2.1 Physical quantities

The physical quantities, defined by the ICRU, are used by both the ICRP and the ICRU for the definition of their dose quantities. These quantities are directly measurable and are used for the characterisation of radiation fields and can be defined as follow:

- Φ: fluence,
- K: kerma,
- D: absorbed dose

2.2 Protection quantities

ICRP 60 [ICRP 1991] , and later ICRP 103 [ICRP 2007], defined the protection quantities, as the summation of doses received from external sources and from intakes of radionuclides for comparison with dose limits and constraints, set to limit the risk of cancer and hereditary effects . Their calculations derive from the use of biokinetic and dosimetric models, including the use of reference phantoms representing the human body.

The protection quantities defined by the ICRP through calculation in anthropomorphic phantoms are not measurable and are supplemented by the operational quantities developed by the ICRU. These operational quantities are based on a concept of equivalent doses and are both calculated and measured through geometric phantoms. The role of the operational quantities is to provide the RP specialist with a reasonable approximation of the protection quantities for the purpose of optimisation, reporting routine monitoring but also to comply with regulatory dose limits. To remain conservative, the operational quantities will generally overestimate the protection quantities [ICRP 1996 and 2010].

The protection quantities currently in use are as follows:

The absorbed dose to the tissue or organ (D_T) is the amount of energy deposited by radiation in the tissue or organ. It is defined as the deposition of energy (Joule) in a mass (kilogram) and is expressed in gray (1 Gy = 1 J/kg). Nevertheless, the observed biological effects of ionising radiation are not linked to thermal effects, but rather to the type of particle and radiosensitivity of the tissues causing stochastic effects at low doses, expressed through the use of radiation weighting factors in two different protection quantities: the equivalent dose and the effective dose.

The equivalent dose ($H_T = \sum_R w_R D_{T,R}$) is the absorbed dose to a tissue or organ, taking into account the effectiveness of the type of radiation. The equivalent dose is expressed in sieverts (Sv) to a tissue or organ.

The effective dose ($E = \sum_T w_T H_T$) is calculated for the whole body and is the sum of the equivalent doses to all tissues and organs, adjusted to account for the sensitivity of the tissue or organ to radiation. The effective dose is expressed in sieverts (Sv).

2.3 Operational quantities

The operational quantities in use today were initially been defined in ICRU Report 39 [ICRU 1985] and later in ICRU Reports 43 [ICRU 1988], 51 [ICRU 1993] and 57 [ICRU 1998]. These operational quantities are measurable and represent a conservative approximation of the protection quantities for external irradiation fields. They are based on the dose equivalent *H*, at a certain point in a tissue equivalent material. Depending on the considered particle, *H* can be defined as the product of a physical quantity (absorbed dose) with a quality factor that is quantified by reference to the linear energy transfer of charged particles contributing to that absorbed dose.

The operational quantities currently in use are summarised in Table 1. When using a handheld monitor or a static monitor, the area monitoring quantities will be measured and subdivided into 3 protection quantities: the ambient dose equivalent $H^*(10)$ used for assessing the effective dose (*E*), the directional dose equivalent $H'(3,\Omega)$ and $H'(0.07,\Omega)$ respectively used for the assessment of the equivalent dose to the lens of the eye ($H_{T\ lens}$) and the skin ($H_{T\ local\ skin}$).

When a passive or operational personal dosimeter is used, the personal dose equivalent will be measured respectively at 10mm for the effective dose (Hp(10)), 3mm for the lens of the eye (Hp(3)) and 0.07mm for the skin (Hp(0.07)).

Table 1: Summary of the existing protection quantities as per ICRU Report 57

	Whole body	Lens of the eye	Local skin
	Effective dose	Equivalent dose to the lens of the eye	Equivalent dose to local skin
Protection quantity	*E*	$H_{T\ lens}$	$H_{T\ local\ skin}$
Area monitoring	Ambient dose equivalent **$H^*(10)$**	Directional dose equivalent **$H'(3,\Omega)$**	Directional dose equivalent **$H'(0.07,\Omega)$**
Individual monitoring	Personal dose equivalent ***H*p(10)**	Personal dose equivalent ***H*p(3)**	Personal dose equivalent ***H*p(0.07)**

3. Suggested changes to the current system

3.1 ICRP Publication 147

ICRP Publication 147: *Use of Dose Quantities in Radiological Protection* aims to provide guidance for the control of ionising radiation using the dose quantities for occupational, public and medical applications. ICRP publication 147 draws several important conclusions. One of them outlines that despite the fact that low doses can be accurately measured, the associated risks are increasingly uncertain at lower dose. The effective dose can therefore only be considered as an approximate indicator of possible risk, varying with different human factors. Another important conclusion of this publication, which this present article will focus on, is the proposal to discontinue the use of the equivalent dose (H_T) as a protection quantity and to set the dose limits to the skin, hands, feet, and lens of the eye in terms of absorbed dose (D_T).

As seen in the definition of the ICRP units above, the dimensionless particle weighting factor w_R is aimed at comparing the RBEs (Relative Biological Effectiveness) of various ionising radiations and their ability to develop cancer on specific tissues and organs. It derives from the evaluation of clinical and epidemiological surveys. The use of w_R and the use of the equivalent dose is only relevant at low doses to estimate the stochastic effects.

Although the equivalent dose (H_T) is still expected to be used as a step in the calculation of the effective dose, future dose limits to the tissue or organ (such as eye and skin dose) will use the absorbed dose (Gy). The absorbed dose does not incorporate a correction factor that would account for the different types of ionising radiations and their corresponding RBEs, (e.g. weighting factor w_R), making it a poor indicator of the likely biological effects. As such, the use of the absorbed dose without any indication of radiation weighting for tissue reaction would result in considering an exposure to low LET radiation and high LET radiation equal, even though a difference of up to an order of magnitude could exist between the two. The RPWG would seek greater clarity as to how the differences of biological effects from different radiation types would be reflected when calculating the tissue or organ dose with the newly proposed system.

3.2 ICRU Report 95

ICRU/ICRP Report 95 suggests redefining the operational quantities previously developed by the ICRU Reports 39, 43, 51 and 57 and will replace the dose estimate at a specific point in geometric phantoms (e.g., ICRU sphere) to relates measurements of particle fluence directly to measurements of the protection quantities in anthropomorphic phantoms , thus better aligning the measured dose quantities with the protection quantities as defined in ICRP 103. The overarching goal of these changes are to better estimate the protection quantities, to provide acceptable estimates of the protection quantities outside of the 70 keV - 3 MeV energy range and to provide new conversion coefficients to extend the type of measurable particles, namely: positrons, protons, positive and negative pions, positive and negative muons and helium ions. Earlier ICRU publications only provide conversion coefficient for photons, electrons and neutrons.

The directional dose equivalent ($H'(3,\Omega)$, $H'(0.07,\Omega)$) and the personal dose equivalent ($Hp(3)$, $Hp(0.07)$) at 3 and 0.07 mm will respectively be redefined as the directional absorbed dose in the lens of the eye ($D'_{\text{lens}}(\Omega)$) and in the skin ($D'_{\text{local skin}}(\Omega)$), and as the personal absorbed dose in the lens of the eye ($D_{\text{p,lens}}$) and the skin ($D_{\text{p local skin}}$). These changes (summarised in table 2) of the dose quantities will be accompanied by a change of unit from sievert to gray.

These proposals anticipate the changes desired by the ICRP with Publication 147, which recommends the discontinuation of the use of the tissue or organ equivalent dose (H_T) expressed in sievert, and its replacement with the tissue or organ absorbed dose (D_T) expressed in gray. The modality of application of these changes is set to be decided during the next revision of the general recommendations. Meanwhile, current dose limits will continue to be applied.

Table 2: Summary of the suggested changes in dose quantities and units between the current system and the newly proposed system by ICRU Report 95

	Whole body		Lens of the eye		Local skin	
	Effective dose		Equivalent dose to the lens of the eye		Equivalent dose to local skin	
Protection quantity	E		$H_{\text{T lens}}$		$H_{\text{T local skin}}$	
ICRU report	ICRU 57	ICRU 95	ICRU 57	ICRU 95	ICRU 57	ICRU 95
Area monitoring	Ambient dose equivalent **$H^*(10)$**	Ambient dose **H^***	Directional dose equivalent **$H'(3,\Omega)$**	Directional absorbed dose in the lens of the eye **$D'_{\text{lens}}(\Omega)$**	Directional dose equivalent **$H'(0.07,\Omega)$**	Directional absorbed dose in local skin **$D'_{\text{local skin}}(\Omega)$**
Individual monitoring	Personal dose equivalent **$Hp(10)$**	Personal dose **Hp**	Personal dose equivalent **$Hp(3)$**	Personal absorbed dose in the lens of the eye **$D_{\text{p,lens}}$**	Personal dose equivalent **$Hp(0.07)$**	Personal absorbed dose in local skin **$D_{\text{p local skin}}$**
Units	Sv	Sv	Sv	Gy	Sv	Gy

4. Impact assessment

4.1 ICRP Publication 147

Publication 147 explains proposals for future changes to the protection quantities. The details on the implementation and the extent will be decided during the revision of the general recommendations. Thus, the methods for assessing the absorbed dose using new correction factors, correlated to the RBEs, have not been defined yet. As seen previously, some of the suggested changes incorporate the need for new correction factors (e.g., Stochastic vs Deterministic effects), or increased effectiveness of the radiation per gray (high LET radiation) and will have to be thoroughly explained to the RP community.

The aim of the ICRP with these changes is twofold: sievert as a unit was intended to be used as an exposure and risk management tool in relation to stochastic effects, but is in practice sometimes (wrongly) used by professionals to describe deterministic effects.

The corrective radiation and tissue weighting factors (w_R and w_T) used for the calculation of the equivalent dose and effective dose, both in sievert, were based on RBE data and epidemiological studies relating to stochastic effects (cancer), and therefore are only suitable for long term risk assessment. This situation was reported to engender communication issues with people unfamiliar with the system of radiological protection, particularly members of the public. The communication of risk to the general public for two different dose quantities assessing two different types of risk with a same unit was reported to be challenging by the ICRP. The Fukushima Daichii incident was mentioned to be one such case, where communication to the public of the equivalent dose to the thyroid versus the (whole body) effective dose, both in sievert and with different dose criteria created a confusing situation. The RPWG's experience towards communication of dose and risk to the general public during and after radiation emergencies is that it needs to be achieved through simple comparisons (long haul flights, CT scan etc) instead of trying to explain the technicalities of the radiological protection system.

The RPWG has also noted that because of the discontinuation of the equivalent dose, any system, or software currently incorporating it, will have to be modified, or updated. Similarly, any procedure or legal document mentioning the equivalent dose will have to be amended to reflect the new system.

Moreover, the new system of dose quantities will need to be thoroughly explained to RP specialists through a dedicated course or through their mandatory "refresher course". In France alone, the number of Radiation Protection Officers (PCR) is estimated to be between 8000 to 15,000 people [IRSN n.d.]. RP professionals with a greater degree of specialism (metrologists, dosimetry specialists, health physicists…) will need to go through a more comprehensive training course to familiarise themselves with the new system.

4.2 ICRU Report 95

4.2.1 Change of units

As seen in Table 2, four out of the six new operational dose quantities will see their units change from sievert to gray. The nuclear industry evolves in a highly regulated environment, and any change to its operating system is usually followed by a lengthy and burdensome implementation. Discontinuing a dose quantity (ICRP Publication 147) and changing units which have been in use for decades for the expression of a dose to a tissue or organ is a significant difference from the established system and is estimated to have repercussions on several levels. Training programs for staff, revision of procedures and materials, control room computers and software, proprietary or not, and instrumentation in general could bear significant cost and complexity in its implementation. A comparable situation occurred in the 1980's with the replacement of the rad and the rem (roentgen equivalent man) with the gray and sievert. An internal business case conducted by Ontario Power Generation in 2011 revealed that the cost associated with a change to the International System of Units (SI) dose units, would bear a cost estimated to be above 2 million USD across the organisation. Because of the risk of human error incurred in changing a critical protection unit, potentially leading to risks of overexposure, but also because of the high cost associated with such changes, many organisations in countries such as the United States and Canada decided not to transition to the new system of units. It is worth noting that the roentgen, rad and rem are not accepted as international units by the International Committee for Weights and Measures (CIPM), but are still in use regardless.

As for the instrumentation, digital instruments using these dose quantities will have to go through the necessary changes by updating their programme and display. Analog instruments could also be adapted to the new units, however this would be more challenging. Many of them might need a new certification.

4.2.2 Instrument response

The current operational quantities (ICRU Report 57) provide a conservative estimate of the protection quantities and generally tend to overestimate them. ICRU Report 95 aims at better estimating the protection quantities as defined in ICRP Publication 103. The initial results seem to confirm that, to a large extent, that objective has been achieved [Bordy 2021]. However, the change of dose quantities will also induce an important modification of the interpretation of the instruments' response to a particular radiation field. For example, many instruments used in the nuclear industry are designed to indicate a quantity in $H^*(10)$ and will overestimate by about 15 to 20% the new operational quantities in H^* in a photon energy range between 70 keV to 3 MeV, and up to 5 times lower for the low energy range (below 70 keV). The monitoring instruments currently in use will have to be recalibrated to reflect the change of dose quantities. As for the low dose range, depending on the technology used, the instruments will either need an update of the algorithm, or the redesign of the instrument to account for the low energy photons [Otto 2021].

Aligning the operational quantities with the protection quantities will also mean a decrease in the recorded value of the dose. A practical example taken from the nuclear industry would be for a standard maintenance operation. Assuming similar exposure conditions, the worker accomplishing the same task as the previous year and wearing a dosimeter calibrated with the ICRU Report 95 values will have a lower recorded dose when compared with the previous year's (estimated to be about 20% lower than the dose recorded using the current calibration for a standard gamma spectrum found in an operating NPP). By extension the recorded average occupational exposure in the nuclear industry should significantly decrease after the implementation of the ICRU Report 95. RP professionals will therefore have to be cognizant that any apparent lowering of doses is consequence of the new measurement protocols and not an actual improvement in working conditions.

As mentioned above, the adoption of the recommendations from ICRU Report 95 would mean a better approximation of the effective dose and the dose to the extremities. An exception to that rule would be the representativity of the absorbed dose to the local skin ($D_{\mathrm{p\ local\ skin}}$) for photons and neutrons which differ significantly from the value given by the

ICRP Publication 103 [Bordy 2021]. This is explained by the lack of representativity of ICRP Phantom with the measurement conditions undertaken by ICRU for the finger and wrist at the torso level. This leads to a large overestimation of the photon absorbed dose to the skin below 200 keV and an underestimation above the same value. A similar issue has been reported for the neutron dose to the skin which underestimates the absorbed dose to the skin for neutrons below 20 keV [Bordy, 2021]. The practical consequences, and the ways to remediate these inconsistencies will need to be clarified.

4.2.3 Implementation time

ICRP and ICRU recommend that international and national authorities recognize the need for a gradual and prudent period of adoption to balance the costs of implementation of the changes of doses quantities. This implementation time is estimated to fall between 10 to 20 years, which is considered to be a reasonable timespan for a successful implementation across the board. Nevertheless, the RPWG would like to raise awareness of the fact that the implementation time will need to take into account the time required for the incorporation of all the conception and testing standards (by ISO, IEC) for radiation protection instrumentation. The practical implementation of these norms and their translation to all the methods and procedures used by the implementers will also need to be encompassed.

Finally, the RPWG would like to point out that large nuclear facilities or government agencies will likely not be able to make the necessary changes to their fleet of instruments and procedures all at once. The resulting consequence will be the coexistence of monitoring instruments calibrated with both the current system (ICRU Report 57) and the newly proposed system (ICRU Report 95). As such, certain dose quantities will keep the same unit from one system to another (e.g. mSv), increasing the risk of confusion from the users. It will therefore be necessary to proceed with caution, as human error and communication issues over critical protection units could result in dose reporting issues of classified workers.

5. Conclusion

The purpose of the ambitious programme set by the ICRP Publication 147 and the ICRU Report 95 were:

- To simplify the system of protection quantities and to make it more understandable
- To express the dose to the tissues and organs in terms of absorbed dose (Gy)
- To align the operational quantities to the protection quantities (currently related to anthropomorphic phantoms) as endorsed by the new recommendations
- To provide conversion coefficients from physical field quantities for a larger subset of particles (positrons, protons, pions etc) and energy ranges.

The initial assessment undertaken by the RPWG seems to confirm that most of the objectives listed above have been fulfilled. The added benefits of the new dose quantities will be particularly felt in sectors where less common particles and energy ranges were needed (e.g. research, medical sector etc). However, for the nuclear industry or industries with NORM, the drawbacks brought by these changes will predominantly outweigh its benefits . The types of particle and energy range encountered in the industry are already covered by the current system, and the greater accuracy offered by the ICRU Report 95 will not necessarily be helpful to the practitioners. Radiation protection as practised by the nuclear industry consists mostly of “field measurements” which encompass an acceptable degree of error (10-20%). The overestimation of the effective dose by the operational quantities, as defined by the ICRU Report 57, was also used by industry professionals as a conservative approach to stochastic effects in line with the ALARA principle. Finally, the expected global reduction of the registered personal dose to the workers will need to be carefully explained to RP professionals, as it could be misused or misunderstood as an actual reduction of the exposure, leading to complacency in the application of the ALARA principle.

The current system for assessing worker and public doses is adequate, simple and generally well understood and the nuclear industry has worked hard to represent radiation dose impacts in a simple and repeatable method. Implementation of the proposed changes will be a costly endeavour, with minimal or no improvement to the radiological safety of workers, the public and the environment.

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