IAEA
International Atomic Energy Agency

IAEA TECDOC SERIES

No. 2132

Implications of ICRU Report 95: Operational Quantities for External Radiation Exposure

IMPLICATIONS OF ICRU REPORT 95: OPERATIONAL QUANTITIES FOR EXTERNAL RADIATION EXPOSURE

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ANTIGUA AND BARBUDA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS, THE
BAHRAIN
BANGLADESH
BARBADOS
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CABO VERDE
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
COMOROS
CONGO
COOK ISLANDS
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ESWATINI
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GAMBIA, THE
GEORGIA
GERMANY
GHANA
GREECE
GRENADA
GUATEMALA
GUINEA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALDIVES
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS, KINGDOM OF THE
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORTH MACEDONIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAINT KITTS AND NEVIS
SAINT LUCIA
SAINT VINCENT AND THE GRENADINES
SAMOA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOMALIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
TOGO
TONGA
TRINIDAD AND TOBAGO
TUNISIA
TÜRKİYE
TURKMENISTAN
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VANUATU
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA-TECDOC-2132

IMPLICATIONS OF ICRU REPORT 95: OPERATIONAL QUANTITIES FOR EXTERNAL RADIATION EXPOSURE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2026

For further information on this publication, please contact:

Radiation Safety and Monitoring Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

Printed by the IAEA in Austria
July 2026
https://doi.org/10.61092/iaea.frnd-rgwx

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Implications of ICRU report 95: operational quantities for external radiation exposure / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2026. | Series: IAEA-TECDOC series, ISSN 1011-4289 ; no. 2132 | Includes bibliographical references.
Identifiers: IAEAL 26-01847 | ISBN 978-92-0-700014-3 (paperback : alk. paper) | ISBN 978-92-0-700015-0 (pdf)
Subjects: LCSH: Radiation — Safety measures. | Radiation dosimetry. | Ionizing radiation.

FOREWORD

In radiological protection, operational quantities are designed for use in assessing external exposure to ionizing radiation in order to provide acceptable estimates of protection quantities. These estimates in turn enable the optimization of individual exposures. In 2020, the International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection (ICRP) published ICRU Report 95, which proposes an alternative approach to the current definition of operational quantities, aligning them with the phantoms currently used for calculating protection quantities. This new approach is intended to improve the accuracy and reliability of radiation protection measures.

Although the ICRU has communicated the conceptual changes and definitions of the proposed quantities, Member States and interested parties from the nuclear industry have expressed concerns that insufficient information is available about the potential impact on existing radiation protection practices. In addition, several important issues have been raised regarding the practical implementation and financial implications of the new approach. Addressing these issues is essential to facilitate the adoption of this approach and to maintain confidence in the radiological protection system.

In accordance with the IAEA's mandate to support radiation protection and safety in Member States, this publication provides technical information and practical insights to assist in enhancing the knowledge, resources and processes needed to assess the implications for radiological protection of the redefined operational quantities proposed in ICRU Report 95 and to mitigate any potential negative impacts. The publication aims to inform discussions on monitoring system redesign, calibration, standardization and regulation, as well as the associated training needs. It is intended to engage interested parties, including monitoring services, instrument manufacturers, metrology laboratories, standardization bodies, international organizations, legislators, regulators, licensees, qualified experts and occupationally exposed workers. The information presented is expected to facilitate an objective analysis of costs and benefits and to enable a balanced decision on the adoption of the proposed paradigm shift.

This publication was developed on the basis of input from four IAEA consultancy meetings held between 2023 and 2025, together with the Technical Meeting on the Implications of the International Commission on Radiation Units and Measurements Report 95 on Operational Quantities for External Radiation Exposure. These meetings brought together the experience and perspectives of the interested parties and provided the foundation for the insights, approaches and examples presented in this publication. The IAEA is grateful to all those who contributed their expertise. The IAEA officers responsible for this publication were R. Cruz Suárez and M. Hajek of the Division of Radiation, Transport and Waste Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Operational quantities are used in practical applications to measure and assess external exposure, aiming to provide conservative estimates of protection quantities for ionizing radiation fields. Recognizing the limitations in the current definitions [1−3], which can lead to protection quantities for specific radiation fields being either overestimated or underestimated, the International Commission on Radiation Units and Measurements (ICRU), in its Report 95 [4], published jointly with the International Commission on Radiological Protection (ICRP), recommends an alternative approach to the definitions of operational quantities, aligning them with the anthropomorphic phantom approach currently used to calculate protection quantities.

1.2. OBJECTIVE

This TECDOC aims to summarize current knowledge and identify gaps regarding the impact of adopting the proposed operational quantities on radiation protection practices across various occupational fields. It is intended to serve as a framework to foster discussion and encourage relevant interested parties to consider and document the potential implications of the proposed operational quantities on the existing radiation protection system. This includes, among other aspects, the adaptation of monitoring systems, calibration, standardization, legislation, radiation protection practices, and the needs for education and training.

1.3. SCOPE

After providing a brief overview of the shortcomings of the current operational quantities and the approach to alternative definitions, this TECDOC will concentrate on the potential practical implications of implementing the operational quantities defined in ICRU Report 95 [4] for occupational radiation protection.

1.4. STRUCTURE

This publication comprises six sections and three appendices. Section 2 reviews the fundamental quantities in radiological protection, outlines the limitations of the current operational quantities, and presents the scientific rationale for an alternative approach. Section 3 summarizes the current knowledge, standards, and practices in radiation monitoring, calibration and reference fields, and radiation protection, including education and training. To assist the interested parties in identifying the most relevant information, each subsection is preceded by a bullet pointed summary. Section 4 outlines the actions needed to implement the proposed operational quantities, addressing the implications for all relevant interested parties, including monitoring services, manufacturers, metrology laboratories, standardization bodies, technical and scientific support organizations, regulators, licensees, qualified experts, and occupationally exposed workers. Section 5 proposes a timeline for potential implementation, and Section 6 presents the conclusions. Appendix I compares the protection quantities from ICRP Publication 103 [5] with the operational quantities from ICRU Reports 39/51 [1−3] and ICRU Report 95 [4], highlighting key definitional differences. Appendix II provides illustrative cost estimates for medium and large sized dosimetry services. Appendix III lists international standards that might need revision.

For clarity, in this publication the term 'current operational quantities' refers to the operational quantities defined in ICRU Reports 39/51 [1−3], whereas the term 'proposed operational quantities' refers to those proposed in ICRU Report 95 [4]. Specific variables, such as $H_p(10)$ (current operational quantity for individual monitoring of penetrating radiation) or H_p (proposed operational quantity for individual monitoring), are used when referring to specific quantities.

2. SCIENTIFIC BASIS FOR NEW OPERATIONAL QUANTITIES

2.1. QUANTITIES IN RADIOLOGICAL PROTECTION

The system of radiological protection is built on three major principles: justification, optimization of protection, and dose limitation for individual exposure to ionizing radiation, as introduced in ICRP Publication 26 [6]. The practical implementation of the optimization and limitation principles necessitates a quantitative measure of radiation exposure.

Quantities in radiological protection can be categorized into three main types (Fig. 1). Physical quantities, such as fluence, Φ, kerma, K, and absorbed dose, D, describe the properties of a radiation field. Protection quantities, such as effective dose, E, and organ equivalent dose, H_T, are based on physical quantities but modified by risk related factors, w_R and w_T. These were defined by the ICRP to compare radiation detriment for stochastic effects with exposure limits and to estimate harmful tissue reactions (deterministic effects), such as those in the lens of the eye or local skin. Operational quantities, such as personal dose equivalent, $H_p(10)$, directional dose equivalent, $H'(10)$, and ambient dose equivalent, $H^*(10)$, were defined by the ICRU for practical use in radiological protection, since protection quantities are, by definition, not directly measurable.

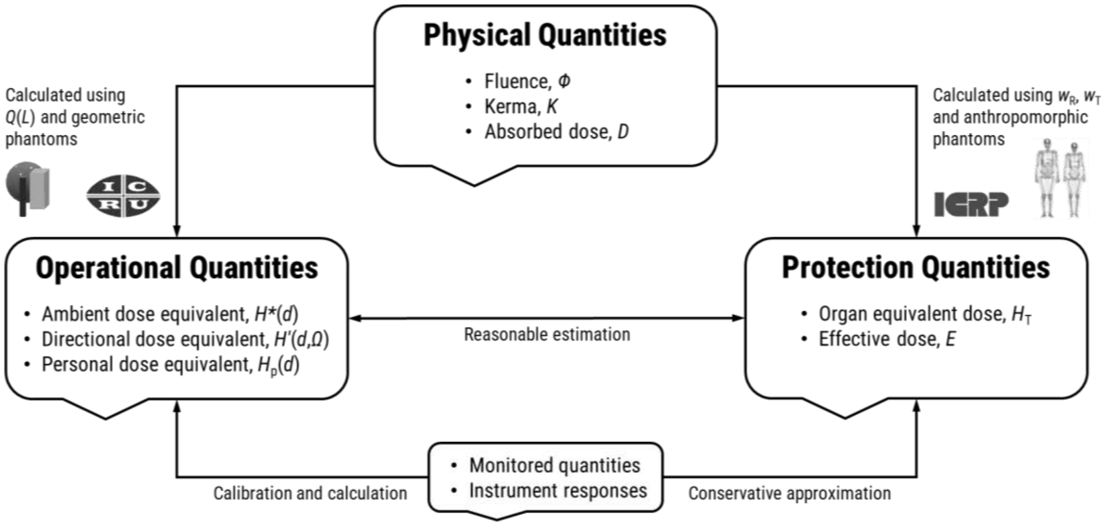

FIG. 1. Conceptual relationship between physical quantities, protection quantities and operational quantities used for radiological protection purposes (adapted from IAEA Safety Standards Series No. GSG-7, Occupational Radiation Protection [7]).

The role of operational quantities is to provide reasonable estimates of the protection quantities for prospective planning of control measures and optimization, and for retrospective assessment of compliance with legal limits. Operational quantities are related to instrument responses through calibration, ensuring that monitored quantities conservatively approximate the corresponding protection quantities for most radiation qualities to enable the optimization of individual exposure [8, 9]. Appendix I reproduces definitions of fundamental physical, protection, and operational quantities pertinent to individual and area monitoring, as provided in IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [10].

The current system of quantities has effectively served its purpose of protecting individuals from the harmful effects of ionizing radiation for nearly four decades. It has also played a central role in establishing radiological protection as a uniform, consistent, and coherent discipline. Few other fields have achieved a comparable degree of conceptual simplification in managing exposure to a detrimental agent, integrating numerous variables that describe the relationship between exposure, risk, and protection into a limited set of quantities [11].

The definition of protection quantities has evolved over time: from the 'dose equivalent' and 'effective dose equivalent' introduced in ICRP Publication 26 [6], to the 'equivalent dose' and 'effective dose' defined in ICRP Publication 60 [12]. In the aftermath of nuclear accidents, it became apparent that the increasing complexity of the quantity system posed significant challenges in communicating radiological information to non-specialists and the public [13]. These difficulties were further compounded by the use of the same unit – the sievert (Sv) – for both protection and operational quantities, despite their differing conceptual foundations.

2.2. OPERATIONAL QUANTITIES IN ICRU REPORTS 39/51

The current set of operational quantities for monitoring external radiation was introduced in ICRU Reports 39 [1], 43 [2], and 51 [3]. Conversion coefficients linking physical, operational, and protection quantities were provided in ICRU Report 57 [14], published jointly with ICRP Publication 74 [8]. These dose equivalent quantities, denoted as H, are point quantities derived by multiplying the absorbed dose, D, at a point by a quality factor, Q, which accounts for the biological effectiveness of the charged particles responsible for the absorbed dose: $H = D \times Q$ [3]. The functional dependence of the quality factor Q on the linear energy transfer, L, in water is detailed in ICRP Publication 60 [12].

The operational quantity for individual monitoring is the personal dose equivalent, $H_p(d)$. Its definition, being a point quantity at a fixed depth d, facilitates practical implementation using personal dosimeters worn on the body and covered with tissue equivalent material of appropriate thickness. However, this fixed depth approach might introduce slight over or underestimations across certain energy ranges. The measured value of $H_p(d)$ is influenced by individual body size, making it, in a strict sense, a personalized dose estimate.

For area monitoring, ambient and directional dose equivalents are used. These quantities are defined in a geometrical phantom, the ICRU sphere. For calibration purposes, a sphere is not ideal due to geometrical limitations. ICRU Report 47 [15] therefore recommends using standardized alternative phantoms, such as slabs, rods, or cylinders composed of ICRU tissue, rather than actual human tissue, to ensure reproducibility and comparability for calibration, performance and type testing. These phantoms approximate the backscatter characteristics of the human body and enable the derivation of conversion coefficients from fluence or kerma to personal dose equivalent.

2.2.1. Shortcomings of operational quantities in ICRU Reports 39/51

Due to inconsistencies arising from the differing definitions of protection and operational quantities, ICRU Report 95 [4] proposed a paradigm shift in the definition of operational quantities. Protection quantities are defined as doses averaged in anthropomorphic phantoms and weighted by radiation and tissue weighting factors. In contrast, current operational quantities for external radiation monitoring are based on dose equivalents at specific points within simplified geometrical models such as slabs, rods, or cylinders. Current operational quantities lead to significant overestimation of effective dose for low energy photons and underestimation for high energy neutrons. Consequently, ICRU Report 95 [4] advocates abandoning the point based definition of operational quantities.

ICRU Report 95 [4] highlights several limitations and inconsistencies in the current operational quantities.

- The ambient dose equivalent is defined in the ICRU sphere, which does not reflect the anthropomorphic phantom used for effective dose calculations.

- Conversion coefficients derived from simple geometries are used for instrument calibration, whereas personal dose equivalent is defined at a specific depth within the human body.

- Assessing dose at a single depth fails to capture the anatomical complexity of the human body, making it incompatible with the definition of effective dose.

- Using a 10 mm depth for ambient and personal dose equivalents leads to considerable overestimation of effective dose at low photon energies.

- The equivalent dose to the lens of the eye is underestimated for electrons with energies below 1 MeV.

- A conceptual discrepancy exists between the quality factor, $Q(L)$, and the radiation weighting factor, w_R, in representing radiation effectiveness.

2.3. OPERATIONAL QUANTITIES IN ICRU REPORT 95

ICRU Report 95 [4] states that:

“The recommendations in this Report on operational quantities are defined in terms of conversion coefficients to personal dose, personal absorbed dose to the lens of the eye, and personal absorbed dose to local skin; ambient dose, directional absorbed dose in the lens of the eye, and directional absorbed dose in local skin; that are related directly to the values of the protection quantities, and effective dose and absorbed dose in the lens of the eye and local skin”. [4]

The operational quantities are redefined as the product of radiometric (dosimetric) quantities, calculated using the same computational phantom employed for protection quantities, and appropriate conversion coefficients. Consequently, for identical particle energies and irradiation geometries, protection and operational quantities yield numerically equivalent values, except in cases involving high energy photons under non-charged particle equilibrium conditions. This alternative approach simplifies the relationship between operational quantities and protection quantities within the radiological protection framework.

Unlike the current operational quantities defined in ICRU Reports 39/51 [1−3], which rely on the ICRU sphere and the quality factor $Q(L)$, the approach proposed in ICRU Report 95 [4] eliminates the need for these elements. Furthermore, the report expands the range of radiation types and energies for which conversion coefficients are available.

The relationship between the operational quantities defined in ICRU Reports 39/51 [1−3] and those in ICRU Report 95 [4] is presented in Appendix I, along with a comparison of the phantoms used to calculate conversion coefficients from physical quantities to protection and operational quantities [4].

2.3.1. Charged particle equilibrium

Radiation transport calculations, such as those performed using Monte Carlo simulations, can be conducted under various assumptions. The most comprehensive approach – full particle transport – tracks all particles individually and is applicable under all conditions. However, this method is computationally intensive. When the current operational quantities were originally established, such computational resources were not available, and a simplified approach – the kerma approximation – was adopted.

The kerma approximation is a practical concept in radiation dosimetry. It allows the absorbed dose, used in defining operational quantities, to be approximated by the collisional kerma under conditions of charged particle equilibrium (CPE) and negligible radiative losses. However, CPE is not always assured, particularly at high photon energies or when dosimeters have thin entrance windows. In such cases, a buildup plate is needed during calibration and testing to ensure CPE.

In practical radiation protection scenarios, CPE cannot be universally assumed. Nonetheless, instrument design and air pathlengths typically generate sufficient secondary charged particles to establish CPE in most realistic situations.

Challenges might arise in space dosimetry, where CPE conditions are less predictable. In such environments, protection quantities are typically calculated directly from particle fluence using full particle transport methods, bypassing the use of operational quantities. Further details are provided in [16].

3. CURRENT KNOWLEDGE: BENEFITS AND GAPS

This section offers a comprehensive overview of the current understanding of the impact of the proposed operational quantities introduced by ICRU Report 95 [4]. It underscores the potential benefits of simplifying the measurement philosophy, as well as the practical implications for measurement systems. The section identifies knowledge gaps highlighting the need for further research or clarification to fully assess the implications of the proposed changes. It aims to inform and guide interested parties, including researchers, policymakers, and regulatory bodies, in making well informed decisions regarding the adoption or rejection of the proposed operational quantities.

3.1. SHIFT IN MEASUREMENT PARADIGM

The key considerations for metrology are summarized in the following bullet points:

- Shift in measurement paradigm: ICRU Report 95 introduces new operational quantities, personal dose (H_p) and ambient dose (H^*), that aim to more directly estimate effective dose (E), simplifying the radiation protection framework by removing legacy constructs like the quality factor (Q) and simplified geometric phantoms.

- Challenges in practical implementation: while the proposed operational quantities are conceptually aligned with protection quantities, they are not always directly measurable, especially for complex radiation types, and might need more sophisticated dosimeter designs and algorithms.

- Loss of independence between quantities: the proposed system eliminates the traditional separation between operational and protection quantities, potentially compromising stability and adaptability, as any future changes in protection quantity definitions would necessitate corresponding updates in operational measurement systems.

For the optimization and control of stochastic effects resulting from whole body exposure, the proposed operational quantities personal dose, H_p, and ambient dose, H^*, are considered more accurate estimators of protection quantities due to their direct relationship with the effective dose, E (see Section 2.3). In accordance with ICRU Report 95 [4], personal dosimeters used in individual monitoring need to provide readings numerically identical to E, while instruments used in area monitoring need to reflect the maximum expected value of E. Conversion coefficients are provided for a wider range of particle types and energies.

Organ doses are calculated using male and female reference computational phantoms, and the results are averaged to determine E. Consequently, the operational quantities H_p and H^* are not individual specific and do not depend on the characteristics of the exposed person.

Regarding operational quantities for the control of tissue effects to the lens of the eye and local skin, ICRP Publication 147 [17] followed the conceptual shift introduced in ICRU Report 95 [4] by adopting absorbed dose (in gray (Gy)) as the more appropriate quantity for establishing dose limits to prevent tissue reactions, in place of equivalent dose (in sievert (Sv)). For the lens of the eye, the operational quantity is defined using the same numerical phantom employed in the derivation of conversion coefficients for the current operational quantity, but with absorbed dose as the basis. For the skin, the proposed quantity is derived using the same numerical cylindrical phantoms for the trunk, wrist, and finger as those used in the current system.

Further contributing to the simplification of the radiation protection framework, the proposed operational quantities eliminate the use of the quality factor $Q(L)$, which is a function of the linear energy transfer, L, of each charged particle and remains part of the current operational quantity definitions. Additionally, the artificial representations of the human body, such as the ICRU sphere and slab phantom, used in the calculation of conversion coefficients from physical to operational quantities, are also discontinued.

Accordingly, the proposals set forth in ICRU Report 95 [4] represent a major shift in the measurement paradigm, giving rise to several crucial questions.

- To what extent can a 'point' detector or dosimetric device accurately quantify a parameter such as the effective dose, which, by definition, is not directly measurable?[1]

- How stable is the one to one correspondence between protection quantities and the proposed operational quantities, given that H_p and H^* are defined in terms of E, and that the weighting factors and computational phantoms used in the definition of E might be subject to future revision?

- Are the proposed operational quantities for tissue effects – based on absorbed dose rather than dose equivalent – sufficiently robust, considering that radiation induced cataracts are no longer recognized as typical tissue reactions with a clear threshold at relatively high dose?[2]

3.1.1. Operational quantities as measurable quantities

The protection quantity effective dose, E, is not defined at a single point but as an average over organs and the whole body, and across both adult male and female reference phantoms. As such, E is not directly measurable. To address this, the concept of operational quantities was introduced in ICRU Report 39 [1] as practical estimators of protection quantities. These were defined as "dose equivalents determined at appropriate locations in suitable receptors" [1]. For individual monitoring, the receptor is typically the trunk, with the measurement taken at a specified depth.

Most occupational exposures involve photons and low linear energy transfer particles, for which the radiation quality factor Q equals 1. In such cases, current operational quantities are directly proportional to a physical quantity (absorbed dose) at a point. These quantities are measurable, as detectors generate signals related to ionization within the detector material, which, although not necessarily identical to absorbed dose, provides a reasonable approximation. According to ICRU Report 51 [3], "$H_p(d)$ can be measured with a detector which is worn at the surface of the body and covered with an appropriate thickness of tissue equivalent material." This enabled the practical implementation of operational quantities, as $H_p(0.07)$ and $H_p(10)$ could be measured using a simple dosimeter (e.g. comprising two near tissue equivalent detectors positioned at the necessary depth using suitable absorber materials), without the need for complex algorithms. Achieving comparable simplicity with the operational quantities proposed in ICRU Report 95 [4] is unlikely, particularly without compromising measurement accuracy. These quantities necessitate additional detector elements or algorithmic processing to ensure that the dosimeter reading reflects the more complex energy and angular dependence of the proposed quantities. The minimum design specifications, such as the number of detector elements, necessary to adequately approximate the proposed operational quantities across various detector types have yet to be established.

[1] As an example, in posterior–anterior irradiation geometry, it is evident that the point in front of the trunk, where the dosimeter is typically worn, is not suitable for monitoring, as it provides an unacceptable estimate of the effective dose.

[2] The absence of a clear threshold and the influence of tumour related factors in cataract formation suggest a stochastic component to cataractogenesis [18]. Further research is warranted to clarify this issue.

For particles where $Q \neq 1$, such as neutrons, current operational quantities are already not directly measurable, as they are no longer proportional to a physical quantity like absorbed dose. Although still defined as point quantities, no physical measurement principle inherently reflects the complex processes involved (e.g. elastic and inelastic neutron scattering) weighted by committee defined factors (Q). This is evident in the current state of neutron dosimetry, where measurements remain challenging due to the lack of instruments with flat energy response relative to operational quantities. Nevertheless, only a small proportion of workers are exposed to neutrons and high linear energy transfer particles. ICRU Report 95 [4] eliminates the use of Q in defining operational quantities, simplifying the conceptual framework but rendering the quantities not directly measurable in all cases (including photons and low linear energy transfer particles).

3.1.2. Separation between operational and protection quantities

Despite the considerations outlined in the previous section, the operational quantities defined in ICRU Reports 39/51 [1−3] represent a clear separation between measured (operational) quantities and calculated (protection) quantities. While the effectiveness of $H_p(10)$ as an estimator of E for radiation protection might be debated, the operational quantities – and thus the design of dosimeters and instruments – are not directly dependent on the definition of protection quantities.

This separation is no longer maintained in the operational quantities proposed in ICRU Report 95 [4]. In this approach, the operational quantities are explicitly defined to match the numerical values of the protection quantities. However, the stability of this one to one correspondence remains uncertain, as the assumptions underlying the definition of protection quantities, such as reference phantoms and tissue weighting factors, might evolve. If operational quantities are defined to always align with protection quantities, then any revision to the latter would necessitate corresponding changes to the former, posing significant challenges for instrument design. Conversely, if the protection quantities change but the operational quantities remain fixed, the numerical equivalence is lost. For example, replacing voxel phantoms with mesh phantoms as the reference standard would introduce discrepancies between operational and protection quantities, potentially necessitating recalculation of fluence to dose conversion coefficients. Such changes could undermine confidence in the radiation protection system.

ICRU Report 39 [1] acknowledges that the existing operational quantities are not universally applicable. It states that “A single depth in the sphere is recommended for both photons and neutrons at which a useful estimate of the effective dose equivalent can be obtained.” [1] However, it also recognizes that:

“for some types of radiation and their energies or directions of incidence, the dose equivalent at a single depth may provide an unacceptable underestimate or overestimate of the effective dose equivalent received by a person exposed to that radiation field. In such cases, the dose equivalent at other depths, or with other geometries, may be considered.” [1]

For instance, for high energy photons, a depth of 10 mm might be inadequate for estimating E, and other depths might be more appropriate. Nonetheless, these are considered exceptions; in most cases, a 10 mm depth is adequate. The limitations of the operational quantities introduced in ICRU Reports 39/51 [1−3] were recognized from the outset, and a practical solution was adopted: point based, measurable quantities that are independent of the protection quantities. This separation ensured that updates to protection quantities based on new scientific knowledge do not necessitate changes to operational quantities. The performance of operational quantities as estimators of protection quantities can always be evaluated and, if needed, corrected, without directly affecting dosimeter or instrument design.

3.2. RADIATION PROTECTION

The key considerations for radiation protection are summarized in the following bullet points:

- Systemic and regulatory implications: the adoption of proposed operational quantities offers conceptual clarity and alignment with protection quantities but introduces challenges in harmonization, legal revisions, and communication with interested parties, potentially affecting trust in the radiation protection system.

- Practical and dosimetric impact: while the proposed operational quantities might reduce conservatism and improve dosimetric accuracy, especially for low energy photons, they also risk underestimating biological effects and complicating dose interpretation in medical, occupational, and high energy environments.

- Implementation and transition challenges: transitioning to the new system will necessitate updates to dosimetry systems, national dose registries, and training programmes, with careful management needed to avoid misinterpretation of lower recorded doses and ensure continued adherence to radiation protection principles.

3.2.1. General considerations

One advantage of the proposed operational quantities is their closer alignment with protection quantities. This eliminates the conservatism inherent in current operational quantities, such as the over response at low photon energies. This is beneficial, as conservatism is expected to be applied during implementation rather than embedded in the conceptual definitions or structure of the quantities. Incorporating conservatism at the definitional level can obscure the boundary between scientific evidence and strategic judgement. Instead, conservatism can be introduced through other mechanisms, such as dosimeter type testing criteria, and directed towards constraints, dose limits, and the optimization of radiation protection practices.

3.2.1.1. Impact on trust in the radiation protection system

Changes to quantities used in radiological protection can affect trust in the entire radiation protection system. The framework is complex, and many individuals, including professionals, do not fully understand its intricacies. Clear explanations of the practical implications of such changes help maintain transparency and understanding. Different interested parties might interpret these changes differently, and without sufficient clarity, modifications to units, dosimeters, or measured values might undermine confidence in the system as a whole. Altering the definitions or units of quantities risks further confusion, complicating communication with professionals and the public alike. This highlights the essential need for comprehensive training of radiation protection professionals.

The stability of the current system itself is a significant advantage and cannot be overlooked. There is no conclusive evidence that the proposed operational quantities will improve public or occupational health and safety in practice. Evaluating and testing planned changes plays a key role in maintaining high safety standards while considering factors such as efficiency, worker comfort, and operational effectiveness. Nonetheless, the operational quantities proposed by the ICRU offer the potential advantage of being, in principle, easier to explain, though certain caveats remain.

3.2.1.2. *Impact on harmonization*

Significant efforts have been made to harmonize quantities used in radiological protection. Despite this, some countries have yet to adopt the current operational quantities or have done so only recently. Interlaboratory comparisons continue to reveal substantial discrepancies in the performance of monitoring services [19−21].

These harmonization efforts risk being undermined by the introduction of the proposed operational quantities, particularly as the proposed quantities retain the same units and similar nomenclature (e.g. $H_p(d)$ vs H_p). Adoption rates vary across countries, and during the extended transition period, a loss of harmonization is inevitable as different systems operate in parallel. This challenge is compounded by the continued use of older quantities in some regions [16], raising the risk of further fragmentation and the concurrent use of different quantities.

Additional complications arise from the coexistence of legacy and new equipment. Instruments measuring different operational quantities are likely to be used simultaneously within facilities for some time, leading to difficulties in interpreting and recording measurement results.

3.2.1.3. *Revision of legislation and regulations*

The proposed operational quantities can only be introduced through amendments to national legislation. This is likely to necessitate revisions to existing regulations to ensure alignment with current scientific understanding and best practices. As a result, legal frameworks that define the current operational quantities are subject to updates. Such revisions typically follow a phased, multi institutional process, including scientific review to assess the implications of adopting the proposed quantities, consultations with interested parties (e.g. input from relevant organizations), and the drafting of regulatory updates. Moreover, these changes will need to be reflected across a wide range of related regulations and operational procedures.

3.2.1.4. *Tissue reactions in eye lens and skin*

The proposed use of the sievert (Sv) for stochastic effects on the whole body and the gray (Gy) for tissue reactions in the lens of the eye and provides a more direct alignment with the type of effect considered, compared with the current system in which all operational quantities are expressed in sievert (Sv).

At present, $H_p(3)$ is recommended for estimating eye lens dose [7]. However, in practice, whole body quantities such as $H_p(0.07)$ or $H_p(10)$ are often used as conservative proxies, due to the limited use of dedicated eye lens dosimeters.

Adoption of the proposed operational quantities will necessitate a re-evaluation of this approach. While the eye lens dose itself will not change significantly, since the proposed conversion coefficients are generally similar to those for $H_p(3)$, except at high photon energies, measured whole body doses are expected to decrease significantly in certain fields, such as diagnostic and interventional procedures in medical, veterinary, and dental settings. Consequently, under the new system, H_p might no longer serve as a reliably conservative estimator for $D_{p,\,\mathrm{lens}}$.

3.2.1.5. *Epidemiology*

Extensive epidemiological evidence has been gathered on the adverse effects of radiation exposure. Studies involving both the general population and occupational groups provide quantitative estimates of cancer risk associated with exposure. In research, the introduction of new operational quantities is expected to influence future epidemiological studies and, consequently, the established dose–response relationship. Caution is therefore needed in interpreting results.

Changes to radiological quantities have occurred in the past, and these continue to complicate epidemiological analyses. Identifying which quantities were used in historical datasets remains an important aspect of such research. The introduction of additional quantities might add another layer of complexity when interpreting and comparing results from such studies.

3.2.1.6. Records of occupational exposure

National dose registries maintain records of occupational radiation exposure. Some record operational quantities, while others register effective dose, E. If the proposed operational quantities are adopted, registries might need to be updated. Those that record E might not need structural changes; however, since operational quantities are often used as proxies for effective dose from external exposure, a shift in recorded values will occur once the new quantities are implemented. A transition period is likely, during which dosimeters measuring both current and proposed quantities will be in use. As a result, national dose registers might temporarily contain mixed data for different groups of workers. For individual workers, the recorded dose might shift from one quantity to another partway through a monitoring period. This means that cumulative doses over one or five years might comprise a combination of quantities. In principle, both sets of quantities aim to estimate effective dose, so their sum can still provide a sufficiently accurate (or conservative) basis for comparison with dose limits. However, clear communication with all interested parties will be essential to ensure understanding and maintain confidence in the system.

3.2.2. Photon fields

3.2.2.1. Biological effectiveness at low photon energies

One benefit of the proposed operational quantities is a more accurate estimation of effective dose, E, for low energy photons, as $H_p(10)$ can overestimate E by up to a factor of five for monoenergetic photon beams. However, this improved accuracy might be offset by the potentially higher relative biological effectiveness of low energy photons.

For practical purposes, a quality factor of 1 is typically assumed for all photon energies. Yet, several studies [22−25] indicate that the relative biological effectiveness of photons is not constant and can vary significantly with energy and other factors. Lower energy photons might exhibit higher RBEs, resulting in greater biological impact. For example, microdosimetric analyses [22] comparing low energy X-rays (20–40 kV) with higher energy sources such as ^{60}Co, ^{192}Ir, ^{125}I, and ^{90}Sr/^{90}Y found that low dose and clinically relevant RBEs were greater than unity. Additional studies [23−25] reported that low energy X-rays (20–50 kV) were 1.2−3.3 times more effective than high energy external beam or brachytherapy sources in irradiating various cell lines, including early stage breast cancer and Chinese hamster ovary cells. Furthermore, for dicentric chromosome formation, the maximum relative biological effectiveness of moderately filtered 200 kV X-rays is approximately 2–3 relative to gamma rays, while mammography X-rays (29 kV) show a maximum relative biological effectiveness exceeding 1.5 relative to the 200 kV X-rays [26]. These findings suggest that while the proposed quantities offer improved dosimetric accuracy, biological effectiveness at low photon energies remains an important factor in risk assessments and dose evaluations.

3.2.2.2. *Impact on occupational exposures in medical applications*

A recent study [27] used Monte Carlo simulations to determine the energy and angle of incidence of scattered photon distributions across a range of clinical interventional radiology configurations. These distributions were then used to calculate the ratio $H_p(10)/H_p$ for various X-ray beam settings. The ratio, which depended on the X-ray tube voltage, ranged from 1.5 to 2.2, indicating a significant reduction in measured doses with the proposed quantity H_p. This implies that, for the same clinical procedure, the operational dose recorded for medical staff is substantially lower under the proposed system, even though the legal dose limits (based on protection quantities) remain unchanged. This apparent reduction could lead to decreased vigilance and a more relaxed attitude toward radiation protection measures. It is therefore essential to communicate clearly to staff that the lower recorded doses do not reflect a reduced risk. This impact is most relevant in scenarios where no personal protective equipment, such as protective garments, is used. Personal protective equipment introduces inhomogeneity in exposure, which is addressed in Section 3.2.2.3.

3.2.2.3. *Effective dose estimation using two dosimeters*

An important issue not addressed in ICRU Report 95 [4] is the treatment of inhomogeneous exposure, an area also overlooked in the current system. A typical scenario involves workers wearing protective garments, such as lead aprons. In such cases, double dosimetry is recommended [28], with one dosimeter worn under and one over the apron. Effective dose is then estimated using an algorithm that combines both readings. Some approaches use a single dosimeter with a correction factor to estimate effective dose.

The introduction of dosimeters calibrated to the proposed operational quantities will result in lower indicated values, both above and beneath the apron. Nevertheless, algorithm based estimation will still be needed for both single and double dosimetry approaches. This will necessitate a revision of existing algorithms to ensure they continue to provide reliable estimates of effective dose. Without updated algorithms, recorded values will be lower than current readings; with revised algorithms, monitored doses need to remain broadly comparable to present values. However, estimating effective dose in such scenarios will continue to involve greater uncertainty than is typical in personal dosimetry.

An alternative approach to reduce discrepancies between actual effective dose and algorithm based estimates would be to define conversion coefficients for various protective garments, based on effective dose calculations across different photon energies and angles of incidence. This would effectively establish an additional operational quantity.

3.2.3. Electron fields

For radiation protection practices involving electron fields, no significant changes are expected with the introduction of the proposed operational quantities. The performance of dosimeters and monitors in electron fields is addressed in Sections 3.3.1.2 and 3.3.2.2.

3.2.4. Neutron fields

The values of the proposed operational quantities for neutrons differ from those currently in use. The extent of the change depends on the energy and angular distribution of the neutron field [29]. In general, these differences are expected to be moderate. The performance of dosimeters and monitors in neutron fields is presented in Sections 3.3.1.3 and 3.3.2.3.

3.2.5. High energy mixed fields

3.2.5.1. Impact on space and aircrew dosimetry

The proposed operational quantities have limited applicability in aircrew dosimetry, where dose assessments are typically based directly on effective dose. Currently, $H^*(10)$ is employed to validate computational codes through measurements. Given the demonstrated reliability of this approach, the tissue equivalent proportional counter might continue to serve as a reference instrument. Initial modelling suggests that the proposed quantity H^* overestimates $H^*(10)$ by approximately 10% and effective dose, E, by around 30% under aviation conditions [30]. Measurements obtained with a tissue equivalent proportional counter calibrated to $H^*(10)$ might therefore be converted to H^* using a correction factor of 1.1.

In space dosimetry, the ICRP does not recommend the use of operational quantities [31]. Instead, effective dose equivalent is currently calculated using conversion coefficients from particle fluence to mean absorbed dose in organs or tissues, combined with mean quality factors for protons, neutrons, charged pions, alpha particles, and heavy ions ($2 < Z \leq 28$), based on reference voxel phantoms representing both sexes [32]. However, it remains unclear whether the quality factor concept will be retained and revised accordingly.

3.2.5.2. Impact on dosimetry at high energy accelerators

In high energy environments such as particle accelerators and proton therapy facilities, the proposed operational quantities offer the potential for more consistent dose assessments and more efficient use of radiological protection resources. However, in practice, these benefits might have limited impact on radiation protection outcomes [33].

At many high energy accelerator facilities, occupational doses primarily result from exposure to activation products during maintenance activities conducted in shutdown periods. As such, the introduction of the proposed operational quantities is unlikely to significantly affect the recorded doses of exposed personnel. Moreover, other radiation protection challenges, such as pulsed radiation fields and neutron exposure, are of greater concern in these settings and might warrant higher priority in protection strategies.

3.2.6. Shielding considerations

Changes in assessed operational dose values might also influence the structural shielding design of facilities. While dose and dose rate limits (expressed in protection quantities) will remain unchanged, a significant reduction in recorded doses could lead to reduced protective measures, such as the installation of less shielding in new or modified facilities.

For example, in medical settings where staff are exposed to low energy X-rays, the use of dosimeters calibrated to the proposed operational quantities will result in lower recorded doses during interventional procedures. Ideally, this would support improved compliance with dose limits and potentially allow for lower operational limits. However, there is a risk that these lower readings could foster a false sense of safety, weakening the overall radiation protection culture. Reduced dose values might lead to diminished protective practices or reduced efforts by employers and licensees to minimize exposure.

To mitigate this risk, ongoing education and vocational training are essential to maintain awareness and ensure appropriate radiation protection measures are upheld. It is essential to adhere to the optimization principle and avoid reducing shielding solely based on lower dosimetric readings.

3.3. MONITORING SYSTEMS

The key considerations for monitoring services are summarized in the following bullet points:

- Significant adaptations needed for monitoring systems: the adoption of the proposed operational quantities will necessitate recalibration, algorithmic adjustments, or even physical redesign of dosimeters and monitoring instruments, particularly for low energy photon and neutron fields.

- Variable impact across radiation types and dosimetry applications: while some systems, such as those for electron and high energy photon dosimetry, might only necessitate minimal changes, others, especially those for low energy photon and neutron monitoring, face challenges due to altered energy and angular response characteristics.

- Implementation complexity and cost considerations: transitioning to the new system involves substantial logistical and financial implications, including equipment redesign, type testing, and potential delays in procurement and deployment.

If the operational quantities proposed in ICRU Report 95 [4] are adopted, modifications to existing monitoring systems will be necessary. Assuming that type testing performance requirements remain unchanged, the extent of these changes will depend on the specific design and performance characteristics of the systems currently in use. In some instances, minor adjustments, such as recalibration of instruments, might be sufficient. In others, more substantial changes might be necessary, potentially involving the complete redesign or replacement of monitoring equipment to ensure compliance with updated legal and technical requirements.

3.3.1. Individual monitoring

3.3.1.1. Whole body photon dosimetry

The most significant impact is observed in systems measuring low energy photons (effective energies ~20–40 keV) for whole body dosimetry. Current commercial passive personal dosimeters optimized for $H_p(10)$ tend to overestimate H_p by a factor of approximately 3.5−4.5 at photon energies around 20–40 keV (Fig. 2).

At higher energies (above ~100 keV), discrepancies fall below 20%. This has been demonstrated across various commercially available systems, including: single element thermoluminescence dosimeters [34−36]; multi element thermoluminescence dosimeters using non-linear three branch algorithms [36]; single and multi element optically stimulated luminescence dosimeters [35, 37, 38]; radiophotoluminescence dosimeters [39]; electronic dosimeters [40]; and direct ion storage dosimeters [36].

The impact of adopting the proposed operational quantities varies by dosimeter type and might necessitate either physical redesign or algorithmic adjustment. Transitioning from single to multi element systems might also necessitate modifications to reader hardware and throughput capacity.

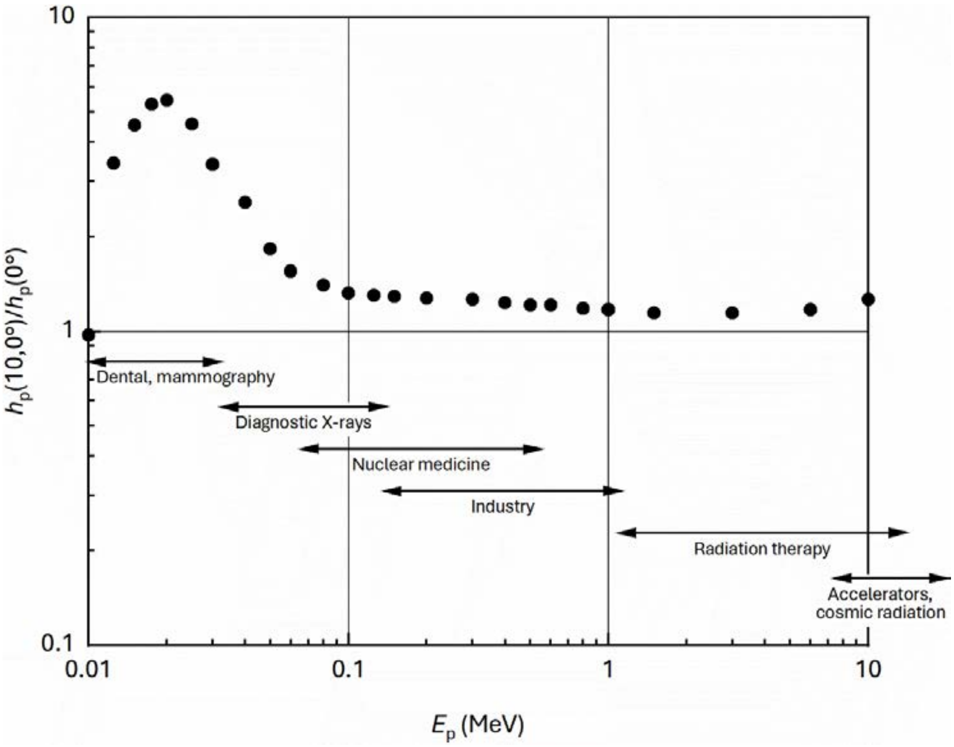

FIG. 2. Conceptual relationship between physical quantities, protection quantities and operational quantities used for radiological protection purposes (adapted from [4]).

(a) Physical redesign of dosimeters

Simple photon dosimetry systems using one or two detectors without energy compensation or correction algorithms will likely necessitate redesign, as they inadequately measure the proposed quantities [34−36]. In such cases, physical modification is necessary to correct the low energy response in accordance with current standards. Calibration factors or algorithmic adjustments alone are insufficient to achieve acceptable measurement uncertainty.

Ekendahl *et al.* [40] assessed the impact of H_p adoption on electronic dosimeters. Depending on the model, they observed: over response at all energies, especially low energies; uniform over response; or under response at low energies. This indicates that some models necessitate physical redesign (notably for ~33 keV), while others might only need to be recalibrated. However, the study was limited to photon fields; electron and mixed fields were not considered.

Redesigning dosimeters and monitoring instruments entails significant costs for development, type testing, and implementation. Although ICRU Report 95 [4] argues that these costs are mitigated by the typical 20 year commercial lifespan of dosimetry systems, this overlooks the limitations of simple, cost effective systems in meeting the new requirements.

(b) Algorithmic adjustments

For systems with multiple sensitive elements, various algorithms can be employed to estimate the operational quantity. In many cases, such systems can be adapted to meet the energy and angular response criteria for the proposed quantities without physical modification [37, 39, 41].

Hoedlmoser *et al.* [37] demonstrated improved H_p response using a two element BeO optically stimulated luminescence system, albeit with increased measurement uncertainty and the need for a non-linear algorithm. Similarly, Bossin *et al.* [39] showed that a five element radiophotoluminescence dosimeter algorithm yielded acceptable H_p response, though the study lacked comprehensive data on angular dependence and mixed fields. Rindhatayathon *et al.* [42] developed machine learning algorithms to enhance the energy and angular response of optically stimulated luminescence dosimeters in relation to the proposed operational quantities.

Reliable performance of algorithmic changes is influenced by their impact on dose response characteristics, including reproducibility at low doses, linearity, and angular dependence. To date, studies have focused solely on photon fields; the feasibility of simple algorithms for electron or mixed photon–beta fields remains untested. More complex, non-additive algorithms will also increase the complexity and cost of type testing.

3.3.1.2. Whole body electron dosimetry

The transition to the operational quantities proposed in ICRU Report 95 [4] is not expected to significantly affect the energy dependence of the response of whole body electron dosimeters currently used to assess $H_p(0.07,\Omega)$. These dosimeters might therefore continue to be used for determining $D_{p,\,\mathrm{local\,skin}}(\Omega)$ without needing hardware modifications. The difference between the conversion coefficients for $D_{p,\,\mathrm{local\,skin}}(\Omega)$ and $H_p(0.07,\Omega)$ remains within 5% across the energy range of 150 keV−2 MeV, except at the lowest energies. However, in the range of approximately 80–150 keV, significant discrepancies are observed, and poor response is expected below ~150 keV.

At higher electron energies (above ~3 MeV), an over response by a factor of 2–10 is typically observed. Conversely, at lower energies (~2 MeV), an under response by a factor of 10–100 might occur. This under response arises because only electrons with energies exceeding ~2 MeV have sufficient range to contribute to $H_p(10)$. In contrast, all electrons, regardless of energy, deposit energy in the voxel phantoms used to calculate personal dose and thus contribute to H_p [16].

3.3.1.3. Whole body neutron dosimetry

For neutrons, the ratios of conversion coefficients indicate that, in terms of H_p, an ideal, energy independent $H_p(10)$ dosimeter would exhibit an energy and angle dependent over response by a factor of 2–3 at approximately 0.2 MeV and in the low energy range of $\sim 10^{-9}$ MeV. This over response does not occur at large irradiation angles (e.g. 75°).

There is limited information on the angular and energy response of currently used commercial neutron dosimeters under the proposed operational quantities. Two studies [43, 44] evaluated dosimeters using poly(allyl diglycol carbonate) as the detector. The findings showed a more pronounced impact in anterior−posterior fields than in rotational fields, suggesting increased angular dependence under H_p. The implementation of H_p was found to reduce under response at intermediate energies, while increasing over response at thermal energies and around 1 MeV, the latter being particularly relevant for typical workplace exposures. Compared to $H_p(10)$, the energy response of whole body neutron dosimeters in terms of H_p shows overestimation at near thermal energies and around 0.1 MeV. The authors proposed that these issues might be mitigated through modifications to the shape, size, or material composition of the dosimeter holder, although no supporting data are currently available. At present, there is no published information on the response of albedo neutron dosimeters to the proposed operational quantities.

3.3.1.4. Eye lens, extremity and skin dosimetry

For photons and electrons, the transition to the operational quantities proposed in ICRU Report 95 [4] is expected to have negligible impact on passive individual monitoring for the eye lens, extremities, and whole body shallow (or skin) dosimetry. These are currently assessed using the operational quantities $H_p(3)$, $H_p(0.07)_{rod/pillar}$, and $H_p(0.07)_{slab}$, respectively. The conversion coefficients for the current and proposed quantities are essentially equivalent, except at very low energies that are not relevant under typical workplace conditions. Consequently, no changes to the physical design of existing dosimeters for these applications are anticipated. For electrons, while the proposed quantity $D_{p,lens}(\Omega)$ introduces significant changes in energy and angular dependence, these are not expected to affect practical dosimetry. This is because low energy electrons, which will be most affected, are generally not significant contributors in eye lens dose assessments. Therefore, adaptation of existing dosimeters is not considered necessary.

3.3.2. Area monitoring

3.3.2.1. Area monitoring for photons

Currently, the quantity $H^*(10)$ is predominantly employed for area monitoring, utilising both active and passive detector technologies. While the quantities $H'(0.07)$ and $H'(3)$ are defined, they are seldom applied in practice. Most photon survey meters operating in the intermediate energy range (typically above 50 keV) do not necessitate redesign or modification; recalibration is generally sufficient to meet the relevant standards.

A comparison of monoenergetic conversion coefficients from photon fluence to ambient dose equivalent $H^*(10)$ and ambient dose H^*, as presented in ICRU Report 95 [4], reveals that the overestimation of effective dose by $H^*(10)$ in the low energy range (<50 keV) is no longer evident for the proposed quantity H^*. This is due to H^* no longer being defined at a depth of 10 mm, resulting in significant differences in conversion coefficients at these energies. Such differences might necessitate physical redesign of the dosimeter.

Although ICRU Report 95 [4] initially proposed conversion coefficients based on full electron transport, leading to notable discrepancies above 3 MeV, it was later clarified that, in practice, only data derived using the kerma approximation will be applied [45]. Consequently, dosimeters optimized for $H^*(10)$ are expected to perform adequately for H^* above approximately 100 keV, with minor deviations depending on individual device characteristics. Findings from Behrens and Otto [45] suggest that, for the photon reference spectra examined, energy response remains consistent down to around 70 keV. Otto [35] further provides conversion coefficients from kerma to ambient and personal dose for reference X-ray spectra, enabling calculation of dosimeter response in terms of the proposed operational quantities.

Several studies have evaluated commonly used dosimeter types, including Geiger−Müller tube based, NaI(Tl) scintillation detectors, combinations thereof, TLDs [45], ionization chambers, and passive BeO optically stimulated luminescence dosimeters [35]. However, most investigations have not considered angular dependence, with measurements or simulations typically limited to normal incidence (0°). Notably, dedicated measurements are not needed for such assessments; existing relative response data can be converted to evaluate performance at other angles [16].

The impact of adopting H^* on current photon area dosimeters has been analysed by Čemusová *et al.* [46]. For high energy photons (65−1250 keV), recalibration or application of suitable correction factors is sufficient. However, for low energy applications (~30 keV), physical modifications are necessary due to overresponse at these energies.

Comparison of monoenergetic conversion coefficients for directional dose equivalent, $H'(3,\Omega)$, and directional absorbed dose to the lens of the eye, $D'_{\text{lens}}(\Omega)$, shows that current dosimeters perform poorly below ~100 keV and tend to overestimate $D'_{\text{lens}}(\Omega)$ above ~2 MeV. This overestimation arises from the use of the kerma approximation in calculating $H'(3,\Omega)$. Conversion coefficients from total air kerma to $D'_{\text{lens}}(\Omega)$ for standard photon reference spectra [45] indicate that above ~13 keV existing dosimeters and calibration factors remain compliant with IEC standards; below this threshold, design modifications might be necessary. Likewise, comparison of $H'(0.07,\Omega)$ and $D'_{\text{local skin}}(\Omega)$ suggests that current dosimeters overestimate $H'_{\text{local skin}}(\Omega)$ above ~300 keV. However, as these devices typically operate below this energy range, redesign is not needed. For reference X-ray spectra, conversion coefficients from air kerma to $D'_{\text{local skin}}(\Omega)$ show that above ~10 keV, no changes are needed. Below this energy, underestimation might occur, potentially needing adjustments.

3.3.2.2. Area monitoring for electrons

The changes to the operational quantities proposed in ICRU Report 95 [4] are not expected to significantly affect the energy dependence of area electron dosimeters currently used to assess $H'(0.07,\Omega)$. These dosimeters might therefore continue to be used for $D'_{\text{local skin}}(\Omega)$ without needing modification.

However, for eye lens dose measurements, existing dosimeters will need to be adapted, as the energy and angular dependence are substantially altered for the proposed operational quantity $D'_{\text{lens}}(\Omega)$ [47]. Since the revised operational quantity for area monitoring aligns closely with that for individual monitoring, the same considerations apply to the corresponding measuring instruments. To date, no studies have been published on the necessary adaptations of monitoring systems for assessing the new eye lens dose quantity.

3.3.2.3. Area monitoring for neutrons

Neutron area monitoring systems are typically designed to measure the ICRU Report 39/51 [1−3] operational quantities for whole body dose assessment, calibrated in terms of ambient dose equivalent, $H^*(10)$.

A comparison of monoenergetic conversion coefficients from neutron fluence to $H^*(10)$ and the ICRU Report 95 [4] operational quantity ambient dose, H^*, indicates that current neutron monitoring instruments optimized for $H^*(10)$ are likely to over respond at neutron energies below approximately 2 MeV and between 10 MeV and 40 MeV. Conversely, under response is expected between 2 MeV and 10 MeV, and above 40 MeV.

Studies have shown that the energy dependence of the response in both neutron personal dosimeters and survey instruments might worsen under the new quantities. However, this varies significantly by device model; some might need modification [48], while others might not [49]. Potential adaptations include adjusting air guides to enhance low energy neutron response [48], or modifying the moderating properties of materials, for example by altering hydrogen content. Materials such as ^{10}B and ^{6}Li, known for their neutron absorption characteristics, might also be incorporated or substituted.

Alternatively, renormalizing the energy response or selecting different calibration sources might help to meet type testing requirements. However, such measures do not alter the inherent energy dependence of the instrument's response.

3.4. CALIBRATION AND REFERENCE FIELDS

The key considerations related to calibration and reference fields are summarized in the following bullet points:

- Calibration and reference field adjustments: the adoption of the proposed operational quantities will necessitate updates to reference radiation fields, particularly for low energy photons, to reflect revised energy and angular dependencies.

- Standardization and traceability challenges: developing new secondary standards and updating ISO/IEC type testing protocols will be essential but time consuming, potentially taking decades due to the volume of affected standards and limited resources.

- Transition management and support needs: during the transition, dual systems might need to operate in parallel, needing revised guidance documents, broadened acceptance limits, and enhanced support for metrology labs and end users to maintain measurement reliability and regulatory compliance.

The operation of ionizing radiation metrology laboratories depends on the implementation of appropriate methods and procedures across all activities. These include equipment type testing, irradiation of passive dosimeters, and calibration in reference radiation fields, including in situ calibrations where applicable. The scope also encompasses the development of measurement techniques and ongoing metrological research.

3.4.1. Reference fields

The general standard applicable across all radiation fields is ISO 29661 [50]. Field specific requirements are detailed in ISO 4037 [51−54] for photons, ISO 6980 [55−57] for beta radiation, and ISO 8529 [58−60] for neutrons. Part 1 of each standard outlines the setup of reference radiation fields, Part 2 addresses dosimetry, and Part 3 specifies calibration procedures. For photons, Part 4 provides additional guidance for low energy photon reference fields.

3.4.1.1. Photon reference fields

The specification of reference field parameters, such as tube voltage and filtration, has been aligned to achieve an uncertainty of approximately 2% in the conversion coefficients for the current operational quantities. In light of the revised energy and angular dependence of the conversion coefficients proposed in ICRU Report 95 [4], corresponding adjustments to these specifications are anticipated.

While some energy ranges might allow for relaxed requirements, others might necessitate stricter controls. Analysis of the relative change (i.e. slope) in the current and proposed conversion coefficients across energy intervals indicates that, below 15 keV, tube voltage requirements might become less stringent than at present. Initial investigations into these aspects will be conducted under a research project coordinated by the European Association of National Metrology Institutes [61], which aims to harmonize, update and implement standards related to radiation protection dosimeters for photon radiation.

ISO 4037-1 [51] permits validation of radiation fields using two secondary standards: one for air kerma and one for the operational quantity, such as using a commercially available $H_p(10)$ chamber. However, this simplified validation approach will only be feasible once secondary standards for the proposed operational quantities become available. The same applies to supplementary intercomparisons needed for validating calibration and measurement capability entries in the key comparison data base, which demand instruments with sufficiently low measurement uncertainty.

General conversion coefficients, calculated without the kerma approximation (ICRU Report 95 [4], Sections A.1–A.4), and specific coefficients for calibration using the kerma approximation (ICRU Report 95 [4], Section A.5), have both been published. The coexistence of these two sets has led to confusion, underscoring the need for clear communication to ensure correct application. The kerma approximation assumes CPE and is necessary for calibrations in photon reference fields where separate contributions from photons and secondary electrons are not known (which is typically the case). In such scenarios, the use of a buildup plate remains standard practice, as described in ISO 4037-3 [53].

Conversion coefficients based on full electron transport, as in ICRP Publication 116 [9] (non-CPE conditions), are intended for dose calculations in high energy radiation fields. In these cases, the spectral and angular distributions of photon and electron fluence are determined separately and multiplied by their respective conversion coefficients. The total dose is the sum of both contributions.

Before a decision on the adoption of the proposed operational quantities has been reached, the necessity of reference fields based on full particle transport remains uncertain. The realization of such fields would be highly complex, as it would necessitate separate characterization of both photon and electron components.

3.4.1.2. Electron and neutron reference fields

For reference fields involving electrons/beta radiation [55−57] and neutrons [58−60], no significant impact is anticipated, as outlined in the European Radiation Dosimetry Group Report 2022-02 [16].

3.4.2. Calibration procedures

The procedures for calibrating radiation monitoring systems and irradiating personal dosimeters remain largely unchanged. Calibration laboratories continue to apply standardized methods and data as outlined in ISO 4037-3 [53], ISO 6980-3 [57], and ISO 8529-3 [60], using the recommended conversion coefficients to derive the relevant operational quantities. With the introduction of the proposed operational quantities, these recommended coefficients would need to be updated.

Although the current versions of ISO 4037-3 [53], ISO 6980-3 [57], and ISO 8529-3 [60] include conversion coefficients only for the existing operational quantities, coefficients for many relevant radiation fields based on the proposed quantities have already been published [45, 47, 62]. While the operational quantities in ICRU Report 95 [4] are defined using anthropomorphic voxel phantoms, there is no practical requirement to use these phantoms for measurements. The recommended phantoms for irradiating personal dosimeters remain unchanged [63, 64] from those used for the operational quantities defined in ICRU Reports 39 [1] and 51 [3].

For metrology institutes with traceability to $H_p(10)$, the development of new secondary standards for the proposed operational quantities is a priority. These standards are essential not only for maintaining traceability in metrology laboratories, such as for international key and supplementary comparisons supporting calibration and measurement capability entries, but also for measurements in unknown radiation fields. Their minimal dependence on radiation energy and angle of incidence enables lower measurement uncertainties than typically achievable with commercial instruments. However, the feasibility of developing secondary standards for the proposed operational quantities H_p and H^* remains uncertain. Currently, only chambers for $H_p(10)$ and $H^*(10)$ are available.

3.4.3. Standardization, traceability, performance and type testing

Performance requirements and calibration procedures for dosimetry systems are specified in several standards, primarily those issued by the International Organization for Standardization (ISO) and the International Electrotechnical Commission. An overview of the most relevant type testing[3] standards is presented in Table 1. A detailed list of international standards affected by ICRU Report 95 [4] is provided in Appendix III.

TABLE 1. INTERNATIONAL STANDARDS APPLICABLE TO DOSIMETERS (ADAPTED FROM [65])

Radiation type	Area dosimeters		Personal dosimeters	
	Active	Passive	Active	Passive
Photon	IEC 61017 (environmental) IEC 60532 (installed) IEC 60846-1 (portable) IEC 60846-2 (emergency)	IEC 62387 (all)	IEC 61526 (all)	IEC 62387 (all)
Electron	IEC 60846-1 (portable) IEC 60846-2 (emergency)	IEC 62387 (all)	IEC 61526 (all)	IEC 62387 (all)
Neutron	IEC 61005 (all) IEC 61322 (installed)		IEC 61526 (all)	ISO 21909-1 (all) ISO 21909-2 (workplaces)

[3] Type testing denotes the process of verifying that a representative product type conforms to the relevant normative requirements.

The ISO and IEC working groups have agreed to postpone the development of new requirements for the proposed operational quantities until formal adoption of the proposed operational quantities. Following adoption, the development of reference fields and type testing standards is expected to proceed in parallel. As the typical revision cycle for a standard is five years and given the large number of affected standards and the limited number of responsible working groups, a complete revision might take several decades. Simultaneous revision of all relevant standards is not feasible due to resource constraints.

Manufacturers need clarity on new type testing requirements during the development phase of instruments designed for the proposed quantities. In this context, the timing and availability of relevant standards and updated reference fields, particularly for low energy photon radiation, which represents the most significant change, play a key role in supporting testing activities.

International standards reflect the current state of science and technology but do not prescribe future requirements. Thus, understanding the achievable performance of instruments with respect to the proposed operational quantities is essential before standards can be revised. Some insight can be gained from intercomparison results, which reflect the performance of existing dosimeters not yet adapted to the new quantities. Based on these results, a temporary broadening of acceptance limits has been suggested to allow continued use of existing instruments during the transition. However, this would compromise the intended measurement uncertainty and reduce overall precision.

Due to the substantial modifications needed for dosimeter systems, type testing will be necessary for affected systems. In addition, changes in the permissible energy range and associated measurement uncertainties might prompt a re-evaluation of the scope of accreditation. Increased support for end users has to be anticipated, along with strategies for managing the transition period, during which two systems (corresponding to the current and proposed quantities) might need to be operated in parallel.

Implementation of the proposed quantities involves revisions to existing guidance publications. These publications are particularly important for smaller metrology laboratories and need to be updated shortly after the publication of revised standards, but well before the potential adoption of the proposed operational quantities.

3.5. EDUCATION AND TRAINING

The key considerations for education and training are summarized in the following bullet points:

- Need for comprehensive training: in order to shift to the proposed operational quantities, extensive education is needed to ensure professionals understand the new definitions, measurement techniques, and regulatory implications.

- Targeted and coordinated education: training programmes tailored to different groups of interested parties and aligned with broader transition efforts contribute to consistent and effective implementation.

- Clear communication to prevent complacency: as instrument readings might change under the proposed operational quantities, especially in low energy photon or neutron fields, it is essential to explain these changes clearly to prevent misinterpretation and maintain a strong safety culture.

Although the proposed operational quantities might be conceptually simpler, their implementation could still lead to confusion due to the inherent complexity of the radiological protection system [11, 13]. These quantities represent a significant shift in how radiation exposure is assessed and managed, presenting adaptation challenges for professionals in the field.

For effective implementation of the operational quantities outlined in ICRU Report 95 [4], comprehensive training is needed. This includes understanding the new definitions, adapting measurement techniques, interpreting data, and ensuring compliance with safety protocols and regulations. Tailored educational programmes need to be developed or updated for specific groups of interested parties and coordinated with other transition activities to address the associated challenges consistently.

Familiarity with the definitions, theoretical foundations, and practical applications of the new quantities plays an important role in professional practice. Understanding how they differ from current operational quantities is essential for correct usage. Interested parties need to grasp the implications for protection protocols and regulatory frameworks. Training in interpreting data from monitoring systems is crucial, particularly in explaining why instrument readings might change for the same activity, especially in environments with low energy X-rays, neutrons, or high energy charged particles. In some scenarios, apparent dose reductions might lead to complacency. It is vital to communicate clearly to workers why these changes occur and reinforce the continued importance of protective measures.

3.6. DECISION PROCESS AND COST ANALYSIS

The key considerations related to the decision process and cost analysis are summarized in the following bullet points:

- Lack of cost analysis and responsibility: no organization has taken responsibility for conducting a cost analysis of implementing the proposed operational quantities, creating uncertainty for manufacturers and monitoring services.

- Non-binding nature of recommendations: ICRU, ICRP, and related international standards are advisory, with legal enforcement only occurring through national or regional regulatory updates.

- Need for national and regional assessments: Member States as well as technical and scientific support organizations are encouraged to perform cost–benefit analyses to guide implementation decisions and provide early input to international bodies.

There is considerable uncertainty surrounding the decision making process, and, crucially, no organization has assumed responsibility for conducting a cost analysis on the implementation of the operational quantities proposed in ICRU Report 95 [4]. This lack of clarity hinders manufacturers and monitoring services from effectively planning for implementation.

ICRU Report 95 [4] is a recommendation. Similarly, ICRP Publications, GSR Part 3 [10], and international standards developed by ISO and IEC are non-binding. Legal implementation only occurs through revisions of regional or national regulations.

At present, no cost analysis has been undertaken. The ICRU does not assume responsibility for such assessments, and it is unlikely that other international organizations will do so. While individual countries might choose (or be required) to conduct cost analyses prior to legislative adoption, such efforts might lose relevance once international recommendations are in place.

Therefore, international as well as technical and scientific support organizations are encouraged to undertake cost analyses at national or regional levels. These are expected to outline the potential impacts, benefits, and costs associated with implementing the proposed operational quantities. Early feedback from these analyses is expected to be provided to international bodies to inform the process (see also Section 5).

4. ACTIONS FOR INTERESTED PARTIES

4.1. MONITORING SERVICES

Providers of monitoring services might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Assess the performance of existing monitoring systems against the proposed operational quantities and evaluate the overall impact on the monitoring service;

(b) Determine the need for adaptation or replacement of existing monitoring systems to ensure accurate assessment of the proposed operational quantities;

(c) Conduct or validate type testing of monitoring systems and evaluate measurement uncertainties in accordance with the proposed operational quantities;

(d) Coordinate with the regulatory body to develop a transition plan and timeline, including updates to documentation, databases, and processes, and to obtain necessary approvals or accreditations;

(e) Provide input to standardization bodies to support the revision of relevant standards;

(f) Develop and implement a training plan for personnel;

(g) Establish a communication strategy to inform and support customers during the transition;

(h) Secure the necessary resources to implement the above actions effectively.

4.2. MANUFACTURERS OF MONITORING EQUIPMENT

Manufacturers of monitoring equipment might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Assess the performance of existing monitoring systems against the proposed operational quantities;

(b) Determine the need to adapt existing systems or develop new ones to ensure accurate assessment of the proposed operational quantities;

(c) Perform type testing of monitoring systems and obtain type approval, where applicable;

(d) Develop a transition plan and timeline, considering the potential co-existence of production lines and the need to revise processes and documentation;

(e) Provide input to standardization bodies to support the revision of relevant standards;

(f) Establish a communication strategy to inform and support customers during the transition;

(g) Deliver training for both personnel and customers;

(h) Secure the necessary resources to implement the above actions effectively.

4.3. METROLOGY LABORATORIES

Metrology laboratories might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Develop secondary standards for the proposed operational quantities;

(b) Apply for new calibration and measurement capabilities, supported by relevant key or supplementary comparisons;

(c) Develop a transition plan and timeline, including updates to documentation, software, and reporting systems;

(d) Analyse the impact on quality management documentation, accreditation, and the scope of calibration services;

(e) Develop new reference fields, protocols, and equipment for measurements under non-CPE conditions;

(f) Assess potential increases in demand for irradiating monitoring systems using low energy photon reference fields;

(g) Provide input to standardization bodies to support the revision of relevant standards.

4.4. STANDARDIZATION BODIES

Standardization bodies might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Prioritize the revision of relevant standards to reflect the proposed operational quantities;

(b) Support and promote research that underpins standardization efforts related to the proposed operational quantities.

4.5. INTERNATIONAL, TECHNICAL AND SCIENTIFIC SUPPORT ORGANIZATIONS

International, technical and scientific support organizations might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Promote awareness and informed discussion on the benefits, costs, and implications of adopting the proposed operational quantities;

(b) Encourage Member States to conduct comprehensive cost–benefit analyses;

(c) Engage in the decision making process regarding adoption of the proposed operational quantities;

(d) Consult with legislators and regulators on the potential impact of adoption;

(e) Provide guidance on implementation, including updates to standards, documentation, and training materials;

(f) Support education of interested parties through the development of guidance documents and training courses;

(g) Organize interlaboratory comparisons to facilitate consistent implementation;

(h) Promote coordinated actions, identify research needs, and help secure funding to support implementation.

4.6. LEGISLATORS AND REGULATORS

Legislators and regulators might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Assess the benefits, costs, and impact of adopting the proposed operational quantities at national or regional level;

(b) Devise a roadmap and timeline for implementation, including a defined transition period;

(c) Revise relevant legislation and regulations to reflect the proposed operational quantities;

(d) Adapt national dose registries and associated systems to accommodate the changes;

(e) Coordinate actions among interested parties, including professional networks, to support a successful transition;

(f) Support interlaboratory comparisons to prepare for consistent implementation;

(g) Promote and fund research to facilitate effective adoption of the proposed operational quantities.

4.7. LICENSEES AND QUALIFIED EXPERTS

Licensees and qualified experts might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Maintain up to date knowledge of the proposed operational quantities and their implications;

(b) Evaluate the impact on work organization, operational procedures, and radiation protection practices;

(c) Plan for potential investments, including adaptation or replacement of monitoring systems and associated training;

(d) Consider the potential increase in workload during the transition period;

(e) Organize targeted training for specific audiences to maintain confidence in the radiation protection system;

(f) Continue to promote the optimization principle, particularly in light of potentially lower instrument readings.

4.8. OCCUPATIONALLY EXPOSED WORKERS

Occupationally exposed workers might need to undertake the following actions to facilitate the implementation of the proposed operational quantities:

(a) Participate in training opportunities to address questions and concerns related to the proposed operational quantities;

(b) Continue to apply the optimization principle, particularly in light of potentially lower instrument readings.

5. ESTIMATED TIMELINE FOR IMPLEMENTATION

The potential implementation of the ICRU Report 95 [4] operational quantities relies on well coordinated, time dependent actions among multiple interested parties. Fig. 3 illustrates the sequence of these actions, facilitating the transition between operational quantities. The time frame for implementation is highly dependent on individual Member States. In some developing countries, for example those using single element photon dosimeters for monitoring medical workers, significant delays might occur due to the need for substantial investment by monitoring services, as well as possible reliance on funding from international support organizations.

A roadmap for adopting the proposed operational quantities would need to consider:

- Uncertainty in timelines, as all relevant publications remain non-binding until national legislation is revised.
- Coexistence of different monitoring systems within the same monitoring service.

- Varied implementation timelines across services and Member States, posing challenges for manufacturers.

- The need for manufacturers to await revised guidance and standards before developing and marketing compliant products.

- Type testing of monitoring systems.

A prerequisite for the transition is the completion of the ICRP's revision of the system of radiological protection, updating the 2007 General Recommendations in ICRP Publication 103 [5]. ISO/IEC would need to update over 30 international standards, a process expected to take at least three to five years. Within European Union and associated states, the European Atomic Energy Community (EURATOM) would need to revise the Basic Safety Standards Directive [66], triggering a five year transition period for Member States to transpose the changes into national legislation.

The implementation process may be subdivided into four distinct phases:

(1) Decision phase – regulatory bodies formally decide to adopt the proposed operational quantities. This phase includes strategic planning, consultation with interested parties, as appropriate, and the establishment of an implementation timeline.

(2) Preparation phase – monitoring services and manufacturers undertake the necessary modifications to existing dosimetry systems or acquire new systems, including dosimeters and associated readout equipment.

(3) Transition period – regulatory bodies assess the capability of laboratories to accurately measure individual doses and to demonstrate compliance with applicable performance standards.

(4) Implementation phase – laboratories are authorized or accreditation. Quality management documentation is updated, regulations are enforced, and users are informed and trained. A formal transition date is established, with dose record consistency ensured through coordination with national dose registries.

A change in operational quantities constitutes a major shift, distinct from changes in units or technology. It entails a relatively abrupt modification within the framework of the International System of Units (SI), which underpins global consistency and comparability in measurements. This shift might render existing method approvals or accreditations invalid. Monitoring services are expected to undergo a short transition period. System upgrades over time are a natural part of dosimetry service evolution, typically pursued when improved dose assessment becomes achievable. Within a quality management framework, multiple dosimetric systems, such as film, thermoluminescence, optically stimulated luminescence, or radiophotoluminescence dosimeters, measuring the same operational quantity might operate concurrently under separate scopes of approval or accreditation.

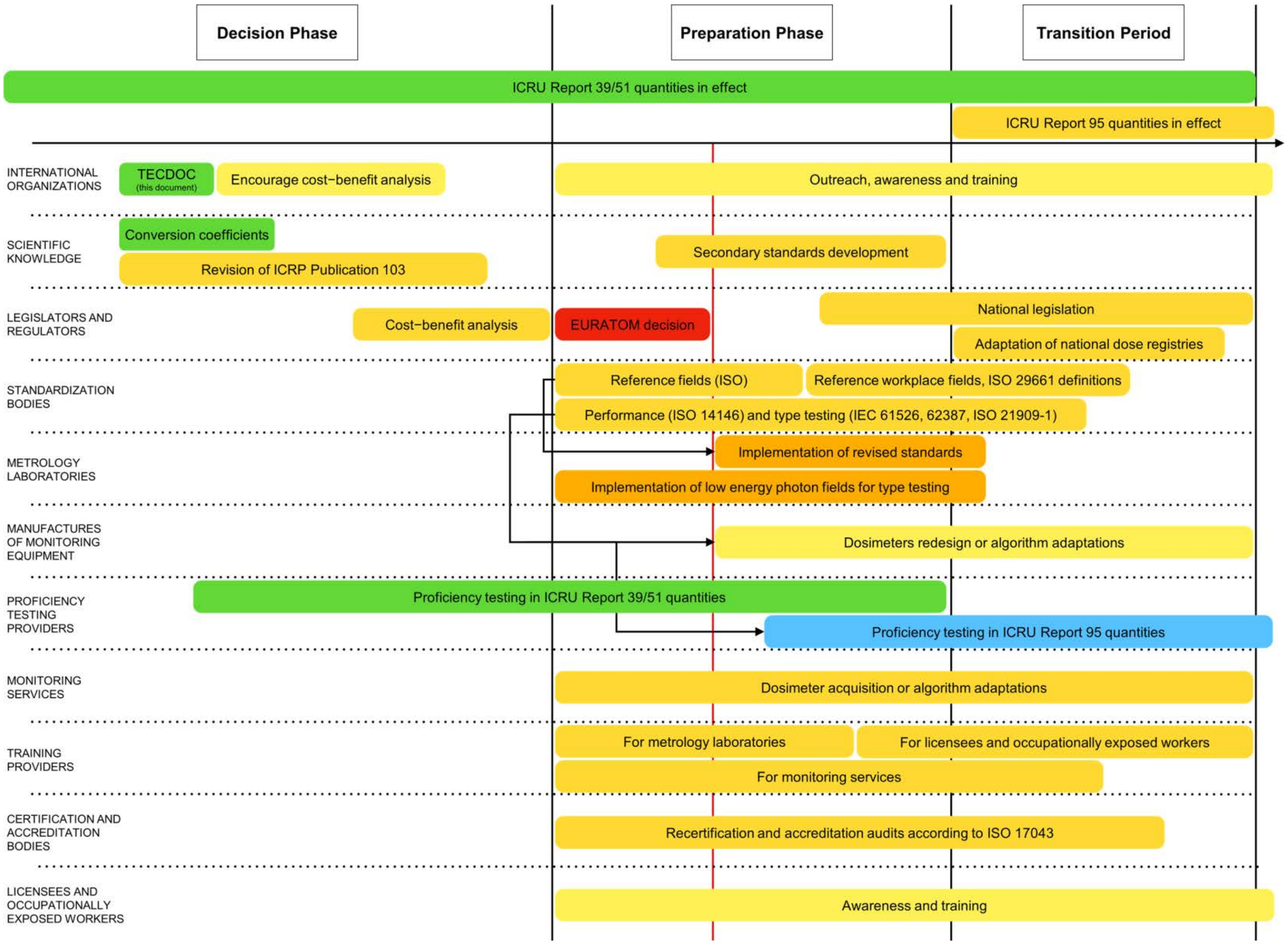

FIG. 3. Illustrative roadmap depicting the sequence of actions to facilitate the transition between operational quantities.

6. SUMMARY AND CONCLUSIONS

The introduction of the operational quantities proposed in ICRU Report 95 [4] presents both benefits and challenges for radiation protection practices.

Potential benefits include:

- The proposed operational quantities are, by definition, more accurate estimators of the protection quantities.
- Their definitions are conceptually simpler, using the same phantom as for protection quantities and eliminating the need for $Q(L)$ and the concept of expanded and aligned fields.
- The use of quantities based on absorbed dose for the control of tissue reactions in the lens of the eye and local skin aligns with ICRP Publication 147 [17] recommendations.

However, several challenges remain:

- It is unclear whether the practical benefits justify the associated costs, potential confusion, and possible erosion of trust in the radiological protection system.
- The financial implications of system redesign and implementation remain difficult to quantify, and no organization has yet assumed responsibility for estimating these costs.
- The minimum number of detector elements and the algorithmic requirements for whole body dosimeters to perform reliably in terms of H_p remain undefined.
- The coexistence of two sets of conversion coefficients – one with and one without the kerma approximation – might lead to confusion, particularly in calibration procedures.
- The feasibility of establishing secondary standards for H_p and H^* remains uncertain, with implications for traceability and standardization.
- $Q(L)$ will still be needed for space dosimetry applications.

In conclusion, while the proposed operational quantities offer conceptual and scientific improvements, their implementation involves a range of considerations that might affect various aspects of radiation protection practice. A coordinated approach involving monitoring services, manufacturers, metrology laboratories, standardization bodies, international organizations, technical and scientific support organizations, regulators, licensees, qualified experts, and occupationally exposed workers is essential to ensure a smooth and credible transition that maintains confidence in the system of radiological protection.

Appendix I

QUANTITIES IN RADIOLOGICAL PROTECTION

The following definitions of operational and protection dose quantities used throughout this report are based on the definitions given in IAEA Safety Standards Series No. GSR Part 3 [10], ICRU Report 39/51 [1-3], and ICRU Report 95 [4], respectively.

I.1. PHYSICAL QUANTITIES

The definitions of these physical quantities are based on GSR Part 3 [10].

Absorbed dose, D:

The fundamental dosimetric quantity D, defined as:

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m} \tag{1}$$

where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter in a volume element and $\mathrm{d}m$ is the mass of matter in the volume element.

- ⓘ The SI unit for absorbed dose is joule per kilogram (J/kg), termed the gray (Gy).
- ⓘ The energy can be averaged over any defined volume, the average dose being equal to the total energy imparted in the volume divided by the mass in the volume.
- ⓘ Absorbed dose is defined at a point; the mean absorbed dose in a specified tissue or organ of the human body is termed the organ dose.

Particle fluence, Φ:

A measure of the density of particles in a radiation field, defined as:

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a} \tag{2}$$

where $\mathrm{d}N$ is the number of particles incident on a sphere of cross-sectional area $\mathrm{d}a$.

- ⓘ See ICRP Publication 74 [8].

Kerma, K:

The quantity K, defined as:

$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m} \tag{3}$$

where $\mathrm{d}E_{\mathrm{tr}}$ is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged ionizing particles in a material of mass $\mathrm{d}m$.

- ⓘ The SI unit for kerma is joule per kilogram (J/kg), termed the gray (Gy).

Air kerma. The kerma value for air.

- ⓘ Under charged particle equilibrium conditions, the air kerma (in grays) is numerically approximately equal to the absorbed dose in air (in grays).

Reference air kerma rate. The kerma rate to air, in air, at a reference distance of 1 m, corrected for air attenuation and scattering.

ⓘ This quantity is expressed in μGy/h at 1 m.

I.2. PROTECTION QUANTITIES

The definitions of these protection quantities are based on GSR Part 3 [10].

Effective dose, $\boldsymbol{E}$:

The quantity E, defined as a summation of the tissue or organ equivalent doses, each multiplied by the appropriate tissue weighting factor:

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} \cdot H_{\mathrm{T}} \tag{4}$$

where H_{T} is the equivalent dose in tissue or organ T and w_{T} is the tissue weighting factor for tissue or organ T. From the definition of equivalent dose, it follows that:

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} \cdot \sum_{\mathrm{R}} w_{\mathrm{R}} \cdot D_{\mathrm{T,R}} \tag{5}$$

where w_{R} is the radiation weighting factor for radiation type R and $D_{\mathrm{T,R}}$ is the average absorbed dose in the tissue or organ T delivered by radiation type R.

ⓘ The SI unit for effective dose is joule per kilogram (J/kg), termed the sievert (Sv). An explanation of the quantity is given in Annex B of ICRP Publication 103 [5].

Equivalent dose, $\boldsymbol{H_{\mathrm{T}}}$:

The quantity $H_{\mathrm{T,R}}$, defined as:

$$H_{\mathrm{T,R}} = w_{\mathrm{R}} \cdot D_{\mathrm{T,R}} \tag{6}$$

where $D_{\mathrm{T,R}}$ is the absorbed dose delivered by radiation type R averaged over a tissue or organ T and w_{R} is the radiation weighting factor for radiation type R. When the radiation field is composed of different radiation types with different values of w_{R}, the equivalent dose is:

$$H_{\mathrm{T}} = \sum\nolimits_{\mathrm{R}} w_{\mathrm{R}} \cdot D_{\mathrm{T,R}} \tag{7}$$

ⓘ The SI unit for equivalent dose is joule per kilogram (J/kg), termed the sievert (Sv). An explanation of the quantity is given in Annex B of ICRP Publication 103 [5].

ⓘ Equivalent dose is a measure of the dose to a tissue or organ designed to reflect the amount of harm caused.

ⓘ Equivalent dose cannot be used to quantify higher doses or to make decisions on the need for any medical treatment relating to deterministic effects.

ⓘ Values of equivalent dose to a specified tissue or organ from any type(s) of radiation can be compared directly.

I.3. OPERATIONAL QUANTITIES

I.3.1. ICRU REPORT 39/51

These definitions of operational quantities are based on ICRU Report 39/51[1-3] and GSR Part 3 [10].

Ambient dose equivalent, $\boldsymbol{H^*(d)}$:

The dose equivalent that would be produced by the corresponding aligned and expanded field in the ICRU sphere at a depth d on the radius vector opposing the direction of the aligned field.

- ⓘ Parameter defined at a point in a radiation field. Used as a directly measurable proxy (i.e. substitute) for effective dose for use in monitoring of external exposure.
- ⓘ The recommended value of d for strongly penetrating radiation is 10 mm.

Directional dose equivalent, $\boldsymbol{H'(d)}$:

The dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth d on a radius in a specified direction Ω.

- ⓘ Parameter defined at a point in a radiation field. Used as a directly measurable proxy (i.e. substitute) for equivalent dose in the skin for use in monitoring of external exposure.
- ⓘ The recommended value of d for weakly penetrating radiation is 0.07 mm.

Personal dose equivalent, $\boldsymbol{H_p(d)}$:

The dose equivalent in soft tissue below a specified point on the body at an appropriate depth d.

- ⓘ Parameter used as a directly measurable proxy (i.e. substitute) for equivalent dose in tissues or organs or (with $d = 10$ mm) for effective dose, in individual monitoring of external exposure.
- ⓘ The recommended values of d are 10 mm for strongly penetrating radiation and 0.07 mm for weakly penetrating radiation for whole body monitoring.
- ⓘ $H_p(0.07)$ is used for monitoring for hands and feet for all radiation types.
- ⓘ $H_p(3)$ is used for monitoring exposure of the lens of the eye.
- ⓘ ‘Soft tissue’ is commonly interpreted as the ICRU sphere.

I.3.2. ICRU REPORT 95

These definitions of operational quantities are based ICRU REPORT 9 [4].

Ambient dose, $\boldsymbol{H^*}$:

The product of the particle fluence, Φ, at a point in a radiation field and the conversion coefficient, h^*, relating particle fluence to the maximum value of effective dose, E_{max}, for various irradiation conditions.

- ⓘ For a given particle type i with kinetic energy E_p, the conversion coefficient $h_i^*(E_p) = E_{max,i}(E_p)/\Phi_i(E_p)$ is calculated for exposure of the whole body ICRP/ICRU adult reference phantoms [32] for broad uniform parallel beams of the radiation field incident in irradiation geometries anterior–posterior, posterior–anterior, left lateral, right lateral, and for rotational, isotropic, superior hemisphere semi isotropic, and inferior hemisphere semi isotropic fields for photons and neutrons; anterior–posterior, posterior–anterior, isotropic, superior hemisphere semi isotropic, and inferior hemisphere semi isotropic fields for electrons, positrons, muons, and pions; and anterior–posterior, posterior–anterior, and isotropic, for He^{2+} ions.

ⓘ The SI unit for ambient dose is joule per kilogram (J/kg), termed the sievert (Sv).

Directional absorbed dose in the lens of the eye, $D'_{\mathrm{lens}}(\Omega)$:

The product of the particle fluence, $\Phi(\Omega)$, at a point in a radiation field with a specified direction of incidence, Ω, and the conversion coefficient, $d'_{\mathrm{lens}}(\Omega)$, relating particle fluence to the value of absorbed dose in the lens of the eye.

ⓘ For a given particle type i with kinetic energy E_{p}, the conversion coefficient $d'_{\mathrm{lens},i}(E_{\mathrm{p}},\Omega) = D'_{\mathrm{lens},i}(E_{\mathrm{p}},\Omega)/\Phi_i(E_{\mathrm{p}},\Omega)$ is calculated for exposure of the eye model and the whole body [8, 65] for broad uniform parallel beams of the radiation field incident in the direction Ω. For a given Ω, the maximum value of absorbed dose in the lens of the right or left eye is taken.

ⓘ The specification of the incident direction, Ω, requires a reference system for coordinates in which the direction of incidence is expressed. This reference system for an area monitoring quantity can be related to the radiation field in which the operational quantity is to be determined. In the particular case of a unidirectional field, the direction can be related to the angle, φ, between this direction and the direction of incidence, Ω_0, that is, antero posterior to the stylized eye model. When $\varphi = 0°$, the value of $D'_{\mathrm{lens}}(\Omega)$ at the point of interest for measurements using this specified direction shall be written D'_{lens}.

ⓘ The SI unit for absorbed dose is joule per kilogram (J/kg), termed the gray (Gy).

Directional absorbed dose in local skin, $D'_{\mathrm{local\ skin}}(\Omega)$:

The product of the particle fluence, $\Phi(\Omega)$, at a point in a radiation field with a specified direction of incidence, Ω, and the conversion coefficient, $d'_{\mathrm{local\ skin}}(\Omega)$, relating particle fluence to the value of absorbed dose in local skin.

ⓘ For a given particle type i with kinetic energy E_{p}, the conversion coefficient $d'_{\mathrm{local\ skin},i}(E_{\mathrm{p}},\Omega) = D'_{\mathrm{local\ skin},i}(E_{\mathrm{p}},\Omega)/\Phi_i(E_{\mathrm{p}},\Omega)$ is calculated for exposure to broad uniform parallel beams of the radiation field incident in the direction Ω. The conversion coefficient is calculated for exposure of a specified phantom, an ICRU 4-element tissue 300 mm × 300 mm × 148 mm slab (ρ = 1.0 g cm^{-3}), the front surface of which is covered with a 2 mm layer of skin of density 1.09 g cm^{-3} [32] of elemental composition given in ICRP Publication 89 [67]. The absorbed dose is averaged over the volume of a right circular cylinder with its axis perpendicular to the surface between the depths of 50 µm and 100 µm and a cross sectional area of 1 cm^2 below the centre of the front surface.

ⓘ The specification of the incident direction, Ω, requires a reference system for coordinates in which the direction of incidence is expressed. This reference system for an area monitoring quantity can be related to the radiation field in which the operational quantity is to be determined. In the particular case of a unidirectional field, the direction can be related to the angle, φ, between this direction and the direction of incidence, Ω_0, that is normal to the front surface of the slab phantom. When $\varphi = 0°$, that is for perpendicular incidence, the value of $D'_{\mathrm{local\ skin}}(\Omega)$ at the point of interest for measurements using this specified direction shall be written $D'_{\mathrm{local\ skin}}$.

ⓘ The SI unit for absorbed dose is joule per kilogram (J/kg), termed the gray (Gy).

Personal dose, H_p:

The product of the particle fluence, Φ, incident at a point on the body and the conversion coefficient, h_p, relating particle fluence to the value of effective dose, E.

- ⓘ For a given particle type i with kinetic energy E_p and direction of incidence Ω, the conversion coefficient $h_{\mathrm{p},i}(E_\mathrm{p},\Omega) = E_i(E_\mathrm{p},\Omega)/\Phi_i(E_\mathrm{p},\Omega)$ is calculated for broad uniform parallel beams, and for rotational and isotropic fields incident on the whole body ICRP/ICRU adult reference phantoms [28]. For a given Ω, other than those for 0°, 180°, rotational, isotropic, inferior hemisphere semi isotropic, and superior hemisphere semi isotropic, the conversion coefficient taken is that of effective dose as the average value for radiation incident from left and right.

- ⓘ A right handed orthogonal system centred at the midpoint of the body is adopted in which the *X* axis is from back to front, the *Y* axis from right to left, and the *Z* axis from toe to head. The irradiation directional angle Ω is defined in terms of the components θ and φ, with θ being the angle with respect to the *Z* axis (θ being equal to zero at the head) and φ being the projection on to the *XY* plane (positive φ pointing to the left).

- ⓘ The SI unit for absorbed dose is joule per kilogram (J/kg), termed the sievert (Sv).

Personal absorbed dose in the lens of the eye, $D_\mathrm{p,lens}$:

The product of the particle fluence, Φ, incident at a point on the head or body and the conversion coefficient, $d_\mathrm{p,lens}$, relating particle fluence to the value of absorbed dose in the lens of the eye.

- ⓘ For a given particle type i with kinetic energy E_p and direction of incidence Ω, the conversion coefficient $d_{\mathrm{p\,lens},i}(E_\mathrm{p},\Omega) = D_{\mathrm{p\,lens},i}(E_\mathrm{p},\Omega)/\Phi_i(E_\mathrm{p},\Omega)$ is calculated for broad uniform parallel beams incident on the whole body eye model [68]. For a given Ω, the conversion coefficient taken is that for the maximum value of the absorbed dose in the lens of the right or left eye.

- ⓘ The same right handed orthogonal system for the body is adopted as for the quantity H_p. It is different to that used for calculations for the Behrens−Dietze model in ICRP Publication 116 [9], but without consequence for the numerical results.

- ⓘ The SI unit for absorbed dose is joule per kilogram (J/kg), termed the gray (Gy).

Personal absorbed dose in local skin, $D_\mathrm{p,local\,skin}$:

The product of the particle fluence incident on the body or extremities, Φ, and the conversion coefficient, $d_\mathrm{p,local\,skin}$, relating particle fluence to the value of absorbed dose in local skin.

- ⓘ For a given particle type i with kinetic energy E_p and direction of incidence Ω, the conversion coefficient $d_{\mathrm{p\,local\,skin},i}(E_\mathrm{p},\Omega) = D_{\mathrm{p\,local\,skin},i}(E_\mathrm{p},\Omega)/\Phi_i(E_\mathrm{p},\Omega)$ is calculated for exposure of the specified phantoms to broad uniform parallel beams. For each phantom, of the dimensions shown below, there is a covering layer of 2 mm skin of density 1.09 g cm^{-3} [32] with the elemental composition given in ICRP Publication 89 [67]. The specific phantoms for local skin are as follows:

  - *For the trunk of the body*: below the centre of the front surface of a slab with dimensions 300 mm × 300 mm × 148 mm of ICRU 4 element tissue (ρ = 1.0 g cm^{-3}), the front surface of which is covered with a 2 mm layer of skin. The absorbed dose is averaged over the volume of a right circular cylinder with its axis perpendicular to the surface between the depths of 50 µm and 100 µm and a cross sectional area of 1 cm^2;

  - *For the extremities*: at the half length of the cylindrical surface of a pillar with dimensions 69 mm diameter and 300 mm length of ICRU 4 element tissue (with density in this instance taken to be equal to 1.11 g cm^{-3}), the cylindrical surface of which is covered with a 2 mm layer of skin. The absorbed dose is averaged over a volume between the radii 36.4 mm and 36.45 mm with a circle of area 1 cm^2 projected onto the upper and lower cylindrical surfaces, perpendicular to the radii;

- *For the finger*: at the half length of the cylindrical surface of a rod with dimensions 15 mm diameter and 300 mm length of ICRU 4 element tissue (with density in this instance taken to be equal to 1.11 g cm^{-3}), the cylindrical surface of which is covered with a 2 mm layer of skin. The absorbed dose is averaged over a volume between the radii 9.4 mm and 9.45 mm with a circle of area 1 cm^2 projected onto the upper and lower cylindrical surfaces, perpendicular to the radii.

ⓘ For the slab, θ is the angle of irradiation incidence with respect to the surface normal, and φ is the azimuthal angle. For the cylindrical geometries, the angles of incidence θ, φ, are with respect to the axis of the scoring cylinder.

ⓘ The SI unit for absorbed dose is joule per kilogram (J/kg), termed the gray (Gy).

I.4. RELATION OF OPERATIONAL QUANTITIES

Tables 2 and 3 present the relationship between the operational quantities defined in ICRU Reports 39/51 [1−3] and those in ICRU Report 95 [4], along with a comparison of the phantoms used to calculate conversion coefficients from physical quantities to protection and operational quantities.

TABLE 2. RELATION OF OPERATIONAL QUANTITIES DEFINED IN ICRU REPORTS 39/51 [1−3] AND ICRU REPORT 95 [4]

ICRU Report 39/51	Symbol	ICRU Report 95	Symbol
Ambient dose equivalent	$H^*(10)$	Ambient dose	H^*
Personal dose equivalent	$H_p(10)$	Personal dose	H_p
Personal dose equivalent	$H_p(3)$	Personal absorbed dose in the lens of the eye	$D_{p,lens}$
Personal dose equivalent	$H_p(0.07)$	Personal absorbed dose in local skin	$D_{p,local\ skin}$
Directional dose equivalent	$H'(3)$	Directional absorbed dose in the lens of the eye	$D'_{local\ skin}$
Directional dose equivalent	$H'(0.07)$	Directional absorbed dose in local skin	$D'_{local\ skin}$

TABLE 3. PHANTOMS EMPLOYED TO CALCULATE CONVERSION COEFFICIENTS FROM PHYSICAL QUANTITIES TO PROTECTION QUANTITIES AND OPERATIONAL QUANTITIES RECOMMENDED IN ICRU REPORT 95 [4]

Category	Whole body	Lens of the eye	Local skin
Protection quantities	Whole body ICRP/ICRU adult reference phantoms	Eye model embedded in whole body phantom	Skin tissue phantom
Operational quantities (area monitoring)	Whole body ICRP/ICRU adult reference phantoms	Eye model embedded in whole body phantom	Slab phantom, ICRU tissue
Operational quantities (individual monitoring)	Whole body ICRP/ICRU adult reference phantoms	Eye model embedded in whole body phantom	Slab, pillar or rod phantom, ICRU tissue

Appendix II

COST ESTIMATES FOR DOSIMETRY SERVICES

The transition to new operational quantities is a complex undertaking involving multiple interested parties and a coordinated sequence of activities. While associated costs might vary, the most substantial investments are expected within individual monitoring services, largely depending on the instrumentation employed. Planning for both financial and human resources is a relevant consideration in the context of implementing the proposed operational quantities.

Key cost considerations include:

- Testing and adaptation of existing dosimetry systems;
- Software and database development;
- Type testing and additional irradiation and calibrations;
- Accreditation, as well as possible approval processes;
- Participation in interlaboratory comparisons;
- Expansion of customer support and training;
- User support, dissemination, and outreach activities.

It is also essential to ensure access to calibration laboratories capable of performing irradiation with low energy photons.

To support cost identification and analysis, representative examples are provided in this appendix, based on current understanding.

Due to significant changes in conversion coefficients from photon fluence to the proposed operational quantities, some systems, particularly those with multiple sensitive elements, might be adapted via algorithm updates. However, it remains unproven whether single element dosimeters, commonly used in developing countries due to their lower cost, can be adapted accordingly. Where adaptation is not feasible, replacement of dosimeters and associated readers might be necessary. This is illustrated schematically in Fig. 4. The left branch (single element dosimeters) represents the most significant constraint in the transition.

Dosimeters might be procured from manufacturers or developed in house; in both cases, type testing is needed. Upgrading dosimetry systems (e.g. hardware, software, implementation, training) entails substantial direct investment. As such upgrades are typically achievable only over extended periods, the time frame presents an additional challenge. Operating two systems concurrently, each measuring different quantities, is not viable without compromising dose interpretation, user confidence, or accreditation. In this context, one time investments are typically associated with transitioning to a unified measurement approach.

For multi-element systems (Fig. 4, right branch) used in monitoring of whole body photon exposure, algorithm upgrades might suffice. However, due to their energy dependence, it has not yet been demonstrated that these systems fully meet type testing performance criteria.

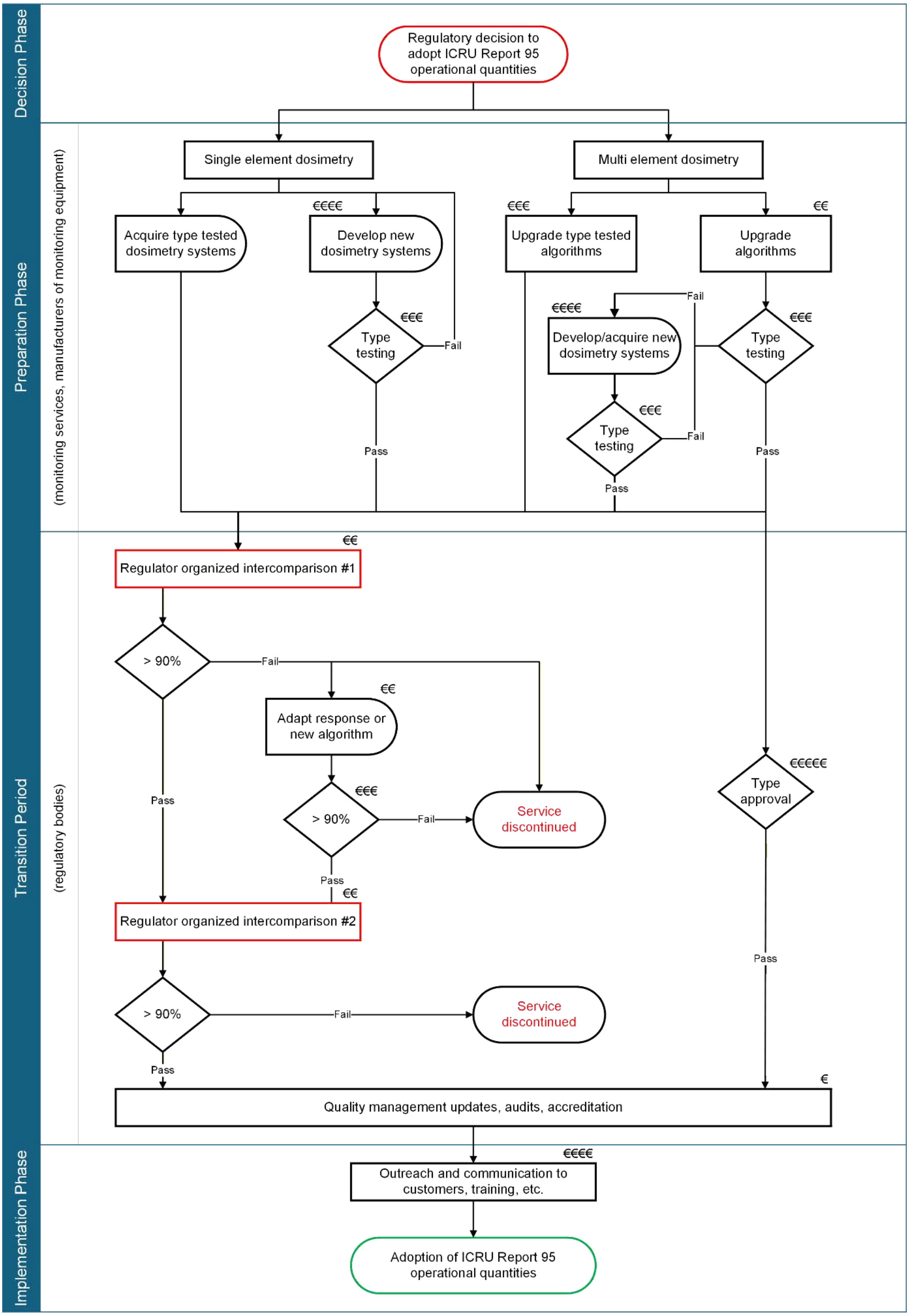

FIG. 4. Flowchart of actions by monitoring services using passive dosimetry systems and regulatory bodies during the transition to the operational quantities recommended in ICRU Report 95 [4]. Manufacturer actions are shown in blue, regulatory actions in red, with currency symbols qualitatively indicating associated costs.

New or significantly modified single or multi element systems will need type testing, representing a considerable cost. Additional costs related to performance testing, such as participation in interlaboratory comparisons, might be incurred by monitoring services when evaluating modified dosimeter responses to the proposed operational quantities. These blind tests assess laboratory capability and compliance with performance criteria, comparing results against acceptance limits. Test parameters are expected to align with national regulatory requirements, which might differ from those specified in type testing standards.

During implementation (illustrated in Fig. 4), individual monitoring services undertake revisions to quality management documentation, recalculate combined uncertainties, and update scopes of accreditation as well as possible approval. Once national regulations are enacted and a transition date is set, users are informed and trained accordingly. As terminology and units of operational quantities change, users might experience confusion regarding interpretation and application. This will likely need extensive follow-up and support, incurring additional costs.

II.1. EXAMPLE OF A MEDIUM SCALE DOSIMETRY SERVICE IN BRAZIL

Tables 4 and 5 present illustrative cost estimates for a dosimetry service in Brazil, monitoring approximately 10 000 occupationally exposed workers using single element dosimeters, which would need to be replaced by a multi-element system. The following assumptions apply:

- Brazilian regulations require that resource planning assumes an average issuance of three dosimeters per occupationally exposed worker.
- Prices reflect late 2024 rates for two element dosimeters; higher costs are expected for H_p dosimeters due to additional elements.
- Costs include governmental cross-border transaction duties, taxes, and fees (excluding shipping and brokerage).
- Costs associated with software/hardware modifications for readers and annealing furnace upgrades are not included.

Due to the increased number of readings needed per dosimeter to estimate H_p, throughput time might double or triple depending on whether two or three elements are used. Consequently, the number of automatic readers might need to be reassessed and potentially increased.

TABLE 4. ESTIMATED COSTS ASSOCIATED WITH THE REPLACEMENT OF TWO ELEMENT DOSIMETERS FOR A MEDIUM SCALE DOSIMETRY SERVICE

Description	Unit price (EUR)	Quantity	Total cost (EUR)
Two element dosimeters for 10 000 workers	20	30 000	600 000
Governmental cross border transaction duties, taxes and fees (shipping and brokers not included)	—	—	360 000

Note 1: It is essential to evaluate whether existing semi automatic readers, designed for single element dosimeters, can be adapted for multi element reading. If adaptation is not feasible, replacement of at least two readers, including software and annealing furnaces, might be needed. The estimated cost for such replacement is approximately EUR 220 000, based on current lower complexity single element systems.

TABLE 5. ESTIMATED COSTS FOR THE REPLACEMENT OF READERS AND ANNEALING FURNACES IN A MEDIUM SCALE DOSIMETRY SERVICE

Description	Unit price (EUR)	Quantity	Total cost (EUR)
Dosimeter readers	40 000	2	80 000
Annealing furnaces	30 000	2	60 000
Governmental cross border transaction duties, taxes and fees (shipping and brokers not included)	—	—	80 000

Note 2: Increasing the price of monitoring services to offset these costs might not be feasible, depending on market competition and the availability of alternative equipment within a country or region. Multi element dosimeters might be transitioned to the new operational quantities through algorithmic modifications, which entail different cost implications. As a result, high investment costs might need to be absorbed by the dosimetry service.

II.2. EXAMPLE OF A LARGE SCALE DOSIMETRY SERVICE IN GERMANY

A dosimetry service based in Germany has provided indicative cost estimates for implementing the proposed operational quantities, both domestically and for international clients. In Germany, assuming full replacement of all photon radiation dosimeters, approximately 1 million units would be needed, based on an estimated 400 000 monitored workers, each issued an average of 2.5 dosimeters. At an estimated unit cost of EUR 10, the direct replacement cost would be approximately EUR 10 million.

For international clients, assuming around 20 million monitored workers, the projected cost for full dosimeter replacement is estimated at EUR 500 million. These implementation costs are expected to be passed on to customers through service fees. These estimates do not include additional costs associated with necessary equipment and software upgrades.

Appendix III

AFFECTED INTERNATIONAL STANDARDS

The international standards listed by category in the following subsections have been identified as potentially affected by the conceptual and terminological changes arising from the implementation of the operational quantities recommended in ICRU Report 95 [4]. This list is not intended to refer to any particular edition of a standard. Rather, it serves to identify those standards that may need revision.

III.1. TERMINOLOGY

IEC 60050-395	International Electrotechnical Vocabulary (IEV) − Part 395: Nuclear instrumentation − Physical phenomena, basic concepts, instruments, systems, equipment and detectors
ISO 12749-2	Nuclear energy, nuclear technologies, and radiological protection – Vocabulary − Part 2: Radiological protection

III.2. CALIBRATION AND REFERENCE FIELDS

ISO 4037-1	Radiological protection – X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy – Part 1: Radiation characteristics and production methods
ISO 4037-2	Radiological protection – X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy – Part 2: Dosimetry for radiation protection over the energy ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV
ISO 4037-3	Radiological protection – X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy – Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence
ISO 4037-4	Radiological protection – X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy – Part 4: Calibration of area and personal dosemeters in low energy X reference radiation fields
ISO 6980-1	Nuclear energy – Reference beta-particle radiation – Part 1: Methods of production
ISO 6980-2	Nuclear energy – Reference beta-particle radiation – Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field
ISO 6980-3	Nuclear energy – Reference beta-particle radiation – Part 3: Calibration of area and personal dosemeters and the determination of their response as a function of beta radiation energy and angle of incidence

ISO 8529-1	Neutron reference radiations fields – Part 1: Characteristics and methods of production
ISO 8529-2	Neutron reference radiations fields – Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field
ISO 8529-3	Neutron reference radiations fields – Part 3: Calibration of area and personal dosemeters and determination of their response as a function of neutron energy and angle of incidence
ISO 12789-1	Reference radiation fields − Simulated workplace neutron fields – Part 1: Characteristics and methods of production
ISO 12789-2	Reference radiation fields − Simulated workplace neutron fields – Part 2: Calibration fundamentals related to the basic quantities
ISO 20956	Radiological protection − Low dose rate calibration of instruments for environmental and area monitoring
ISO 29661	Reference radiation fields for radiation protection – Definitions and fundamental concepts

III.3. INSTRUMENT DESIGN, PERFORMANCE AND TYPE TESTING

IEC 60846-1	Radiation protection instrumentation − Ambient and/or directional dose equivalent (rate) meters and/or monitors for beta, X and gamma radiation − Part 1: Portable workplace and environmental meters and monitors
IEC 60846-2	Radiation protection instrumentation − Ambient and/or directional dose equivalent (rate) meters and/or monitors for beta, X and gamma radiation − Part 2: High range beta and photon dose and dose rate portable instruments for emergency radiation protection purposes
IEC 60325	Radiation protection instrumentation − Alpha, beta and alpha/beta (beta energy > 60 keV) contamination meters and monitors
IEC 60532	Radiation protection instrumentation − Installed dose rate meters, warning assemblies and monitors − X and gamma radiation of energy between 50 keV and 7 MeV
IEC 61005	Radiation protection instrumentation − Neutron ambient dose equivalent (rate) meters
IEC 61017	Radiation protection instrumentation − Transportable, mobile or installed equipment to measure photon radiation for environmental monitoring
IEC 61322	Radiation protection instrumentation − Installed ambient dose equivalent rate meters, warning and monitoring assemblies for neutrons with energies from thermal to 20 MeV

IEC 61526	Radiation protection instrumentation − Measurement of personal dose equivalents for X, gamma, neutron and beta radiations − Active personal dosemeters
IEC 62327	Radiation protection instrumentation − Hand-held instruments for the detection and identification of radionuclides and for the estimation of ambient dose equivalent rate from photon radiation
IEC 62387	Radiation protection instrumentation − Dosimetry systems with integrating passive detectors for individual, workplace and environmental monitoring of photon and beta radiation
IEC 62438	Radiation protection instrumentation − Mobile instrumentation for the measurement of photon and neutron radiation in the environment
IEC 62463	Radiation protection instrumentation − X-ray systems for the security screening of persons
IEC 62694	Radiation protection instrumentation − Backpack-type radiation detector (BRD) for the detection of illicit trafficking of radioactive material
ISO 14146	Radiological protection – Criteria and performance limits for the periodic evaluation of dosimetry services for external radiation
ISO 21909-1	Passive neutron dosimetry systems – Part 1: Performance and test requirements for personal dosimetry
ISO 21909-2	Passive neutron dosimetry systems – Part 1: Methodology and criteria for the qualification of personal dosimetry systems in workplaces

III.4. UNCERTAINTIES AND DETECTION LIMITS

IEC TR 62461	Radiation protection instrumentation − Determination of uncertainty in measurement
ISO 11929-4	Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation − Fundamentals and application − Part 4: Guidelines to applications

III.5. METHODS AND PROCEDURES

IEC 62755	Radiation protection instrumentation − Data format for radiation instruments used in the detection of illicit trafficking of radioactive materials
ISO 14152	Neutron radiation protection shielding − Design principles and considerations for the choice of appropriate materials
ISO 15382	Radiological protection − Procedures for monitoring the dose to the lens of the eye, the skin and the extremities

ISO 15690	Radiological protection − Recommendations for dealing with discrepancies between personal dosimeter systems used in parallel
ISO 16645	Radiological protection − Medical electron accelerators − Requirements and recommendations for shielding design and evaluation
ISO 18310-1	Measurement and prediction of the ambient dose equivalent from patients receiving iodine 131 administration after thyroid ablation – Part 1: During the hospitalization
ISO 18310-2	Measurement and prediction of the ambient dose equivalent from patients receiving iodine 131 administration after thyroid ablation – Part 2: External effective dose of the caregivers after release from the hospital
ISO 18589-7	Measurement of radioactivity in the environment − Soil − Part 7: In situ measurement of gamma-emitting radionuclides
ISO 20043-1	Measurement of radioactivity in the environment − Guidelines for effective dose assessment using environmental monitoring data − Part 1: Planned and existing exposure situation
ISO 20043-2	Measurement of radioactivity in the environment − Guidelines for effective dose assessment using environmental monitoring data − Part 2: Emergency exposure situation
ISO 22188	Monitoring for inadvertent movement and illicit trafficking of radioactive material
ISO 24426	Radiological protection − Content of input data for the statistical analysis of dose records of individuals monitored for occupational exposure to ionizing radiation
ISO 24434	Radiological protection − Radiological monitoring for emergency workers and population following nuclear/radiological incidents − General principles

III.6. AIRCREW DOSIMETRY

ISO 20785-1	Dosimetry for exposures to cosmic radiation in civilian aircraft − Part 1: Conceptual basis for measurements
ISO 20785-2	Dosimetry for exposures to cosmic radiation in civilian aircraft − Part 2: Characterization of instrument response
ISO 20785-3	Dosimetry for exposures to cosmic radiation in civilian aircraft − Part 3: Measurements at aviation altitudes
ISO 20785-4	Dosimetry for exposures to cosmic radiation in civilian aircraft − Part 4: Validation of codes

III.7. PULSED RADIATION

IEC TS 62743	Radiation protection instrumentation − Electronic counting dosemeters for pulsed fields of ionizing radiation
IEC TS 63050	Radiation protection instrumentation − Dosemeters for pulsed fields of ionizing radiation
ISO/TS 18090-1	Radiological protection – Characteristics of reference pulsed radiation – Part 1: Photon radiation

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Determination of Dose Equivalents Resulting from External Radiation Sources, ICRU Report 39, ICRU, Bethesda, MD (1985).

[2] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Determination of Dose Equivalents from External Radiation Sources – Part 2, ICRU Report 43, ICRU, Bethesda, MD (1988).

[3] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Quantities and Units in Radiation Protection Dosimetry, ICRU Report 51, ICRU, Bethesda, MD (1993).

[4] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Operational Quantities for External Radiation Exposure, ICRU Report 95, J. ICRU 20, Sage Publications, Thousand Oaks, CA (1995).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Ann. ICRP 37, Elsevier, Amsterdam (2007).

[6] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the ICRP, Publication 26, Pergamon Press, Oxford (1977).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, Occupational Radiation Protection, IAEA Safety Standards Series No. GSG-7, IAEA, Vienna (2018).

[8] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Conversion Coefficients for Use in Radiological Protection Against External Radiation, Publication 74, Ann. ICRP 26, Pergamon Press, Oxford (1996).

[9] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures, Publication 116, Ann. ICRP 40, Elsevier, Amsterdam (2010), https://doi.org/10.1016/j.icrp.2011.10.001

[10] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014), https://doi.org/10.61092/iaea.u2pu-60vm

[11] GONZÁLEZ, A.J., VELOSO DE ALMEIDA, C.E., SPANO, F., "Radiation protection quantities and units: Desirable improvements", Ionizing Radiation Metrology (Proc. Braz. Congr. Metrol. Ioniz. Radiat., Rio de Janeiro, 2014), 1st edn (PEREIRA PEIXOTO, J.G., Ed.), CNEN, Institute of Radiation Protection and Dosimetry, Rio de Janeiro (2016) 71.

[12] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Ann. ICRP 21, Pergamon Press, Oxford (1991).

[13] GONZÁLEZ, A.J., "Emerging challenges for the international system of radiation protection quantities and units", Bridging Radiation Protection Culture and Science – Widening Public Empathy (Proc. 15th Int. Congr. Int. Radiat. Prot. Assoc., Seoul, 2021), IRPA, Seoul (2021) T2.1-P1254.

[14] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Conversion Coefficients for Use in Radiological Protection Against External Radiation, ICRU Report 57, ICRU, Bethesda, MD (1998).

[15] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Measurement of Dose Equivalents from External Photon and Electron Radiations, ICRU Report 47, ICRU, Bethesda, MD (1992).

[16] GILVIN, P., CARESANA, M., BOTTOLLIER-DEPOIS, J.-F., CHUMAK, V., CLAIRAND, I., EAKINS, J., FERRARI, P., HUPE, O., OLKO, P., RÖTTGER, A., TANNER, R.J., VANHAVERE, F., BAKHANOVA, E., BANDALO, V., EKENDAHL, D., HÖDLMOSER, H., MATTHIÄ, D., REITZ, G., LATOCHA, M., BECK, P., THOMAS, D., BEHRENS, R., Evaluation of the Impact of the New ICRU Operational Quantities and Recommendations for Their Practical Application, EURADOS Report 2022-02, EURADOS, Neuherberg (2022), https://doi.org/10.1093/rpd/ncac293

[17] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Use of Dose Quantities in Radiological Protection, Publication 147, Ann. ICRP 50, Sage Publications, Thousand Oaks, CA (2021), https://doi.org/10.1177/0146645320911864

[18] HAMADA, N., AZIZOVA, T.V., LITTLE, M.P., An update on effects of ionizing radiation exposure on the eye, Br. J. Radiol. **93** (2020) 20190829, https://doi.org/10.1259/bjr.20190829

[19] STADTMANN, H., MCWHAN, A.F., GRIMBERGEN, T.W.M., FIGEL, M., ROMERO, A.M., JANSEN, B.J., HRANITZKY, C., GÄRTNER, C., EURADOS Intercomparison 2016 for Whole Body Dosemeters in Photon and Mixed Radiation Fields, EURADOS Report 2020-03, EURADOS, Neuherberg (2020).

[20] MCWHAN, A.F., DOBRZYNSKA, W., STADTMANN, H., GRIMBERGEN, T.W.M., FIGEL, M., ROMERO, A.M., CLAIRAND, I., EURADOS Intercomparison 2019 for Extremity and Eye Lens Dosemeters – Summary of Procedures, Results and Conclusions, EURADOS Report 2021-05, EURADOS, Neuherberg (2021).

[21] MAYER, S., CHEVALLIER, M.-A., FANTUZZI, E., HAJEK, M., LUSZIK-BHADRA, M., TANNER, R., THOMAS, D.J., VANHAVERE, F., EURADOS Intercomparison IC2017n for Neutron Dosemeters, EURADOS Report 2021-06, EURADOS, Neuherberg (2021).

[22] BRENNER, D.J., LEU, C.-S., BEATTY, J.F., SHEFER, R.E., Clinical relative biological effectiveness of low-energy X-rays emitted by miniature X-ray devices, Phys. Med. Biol. **44** (1999) 323, https://doi.org/10.1088/0031-9155/44/2/002

[23] ASTOR, M.B., HILARIS, B.S., GRUERIO, A., VARRICCHIONE, T., SMITH, D., Preclinical studies with the photon radiosurgery system (PRS), Int. J. Radiat. Oncol. Biol. Phys. **47** (2000) 809, https://doi.org/10.1016/S0360-3016(00)00472-7

[24] HERSKIND, C., STEIL, V., KRAUS-TIEFENBACHER, U., WENZ, F., Radiobiological aspects of intraoperative radiotherapy (IORT) with isotropic low-energy X rays for early-stage breast cancer, Radiat. Res. **163** (2005) 208, https://doi.org/10.1667/RR3292

[25] MARTHINSEN, A.B.L., GISETSTAD, R., DANIELSEN, S., FRENGEN, J., STRICKERT, T., LUNDGREN, S. Relative biological effectiveness of photon energies used in brachytherapy and intraoperative radiotherapy techniques for two breast cancer cell lines, Acta Oncol. **49** (2010) 1261, https://doi.org/10.3109/0284186X.2010.504226

[26] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Relative Biological Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (w_R), Publication 92, Ann. ICRP 33, Pergamon Press, Oxford (2003), https://doi.org/10.1016/S0146-6453(03)00024-1

[27] ABDELRAHMAN, M., LOMBARDO, P., DABIN, J., STRUELENS, L., VANHAVERE, F., Impact of the implementation of the new radiation quantities recommended by ICRU/ICRP for practical use in interventional radiology: a Monte Carlo study, J. Radiol. Prot. **43** (2023) 011513, https://doi.org/10.1088/1361-6498/acb780

[28] BOETTICHER, H., LACHMUND, J., HOFFMANN, W., Effective dose estimation in diagnostic radiology with two dosimeters: impact of the 2007 recommendations of the ICRP, Health Phys. **95** (2008) 337, https://doi.org/10.1097/01.HP.0000318877.79131.08

[29] ENDO, A., Analysis of the relationship between ambient dose, ambient dose equivalent and effective dose in operational neutron spectra, Radiat. Prot. Dosim. **200** (2024) 1266, https://doi.org/10.1093/rpd/ncae157

[30] MATTHIÄ, D., MEIER, M.M., SCHENNETTEN, K., New operational dose quantity ambient dose H^* in the context of galactic cosmic radiation in aviation, J. Radiol. Prot. **42** (2022) 021520, https://doi.org/10.1088/1361-6498/ac5be0

[31] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Assessment of Radiation Exposure of Astronauts in Space, Publication 123, Ann. ICRP 42, Elsevier, Amsterdam (2013), https://doi.org/10.1016/j.icrp.2013.05.004

[32] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Adult Reference Computational Phantoms, Publication 110, Ann. ICRP 38, Elsevier, Amsterdam (2009).

[33] OTTO, T., WIDORSKI, M., "New operational quantities for radiation protection by ICRU and ICRP: Impact on workplaces at accelerators" (Proc. 12th Int. Particle Acc. Conf., Campinas, 2021), (LIU, L., BYRD, J., NEUENSCHWANDER, R., PICORETI, R., SCHAA, V.R.W., Eds), JACoW, Geneva (2021) 2231.

[34] EAKINS, J., TANNER, R., The effects of revised operational dose quantities on the response characteristics of a beta/gamma personal dosemeter, J. Radiol. Prot. **39** (2019) 399,
https://doi.org/10.1088/1361-6498/ab0443

[35] OTTO, T., Response of photon dosimeters and survey instruments to new operational quantities proposed by ICRU RC26, J. Instrum. **14** (2019) P01010,
https://doi.org/10.1088/1748-0221/14/01/P01010

[36] BOSSIN, L., CARBONEZ, P., CHRISTENSEN, J.B., FURLAN, M., FÜRHOLZ, F., MAYER, S., PITZSCHKE, A., YUKIHARA, E.G., Implications of the ICRU 95 quantities for various personal dosimetry techniques, Radiat. Meas. **176** (2024) 107207,
https://doi.org/10.1016/j.radmeas.2024.107207

[37] HOEDLMOSER, H., BANDALO, V., FIGEL, M., BeOSL dosemeters and new ICRU operational quantities: response of existing dosemeters and modification options, Radiat. Meas. **139** (2020) 106482,
https://doi.org/10.1016/j.radmeas.2020.106482

[38] BOSSIN, L., DAL BELLO, R., CHRISTENSEN, J.B., SCHISCHKE, S., MOTTA, S., TOGNO, M., YUKIHARA, E.G., Performance of a BeO-based dosimetry system for proton and electron beam dose measurements, Radiat. Meas. **179** (2024) 107310,
https://doi.org/10.1016/j.radmeas.2024.107310

[39] BOSSIN, L., CHRISTENSEN, J.B., PAKARI, O.V., MAYER, S., YUKIHARA, E.G., Performance of radiophotoluminescence personal dosimeters in terms of the ICRU Report 95's operational quantities, Radiat. Meas. **156** (2022) 106825,
https://doi.org/10.1016/j.radmeas.2022.106825

[40] EKENDAHL, D., ČEMUSOVÁ, Z., KURKOVÁ, D., KAPUCIÁNOVÁ, M., Response of current photon personal dosemeters to new operational quantities, Radiat. Prot. Dosim. **190** (2020) 45,
https://doi.org/10.1093/rpd/ncaa078

[41] MELO, G.T.P., KHOURY, H.J., ASFORA, V.K., FRANÇA, G.H.R.B., DE BARROS, V.S.M., Novel adaptation of the BeOSL whole-body dosimeter for the measurement of the ICRU 95 quantity H_p, Appl. Radiat. Isot. **222** (2025) 111839,
https://doi.org/10.1016/j.apradiso.2025.111839

[42] RINDHATAYATHON, P., SUKYAPROT, K., SUDCHAI, W., SANG-ONDEE, P., THEIRRATTANAKUL, S., RUNGSEESUMRAN, T., PUNGKUN, V., Machine learning approaches for improving dosimeter reading accuracy conform with new operational quantities recommended by the ICRU 95, Appl. Radiat. Isot. **225** (2025) 112013,
https://doi.org/10.1016/j.apradiso.2025.112013

[43] TANNER, R., HAGER, L., EAKINS, J., The response of the PHE neutron personal dosemeter in terms of the proposed ICRU personal dose equivalent, Radiat. Prot. Dosim. **180** (2018) 17,
https://doi.org/10.1093/rpd/ncx282

[44] MORENO, B., MILLION, M., THOMAS, D., TAYLOR, G., Assessment of the impact on a PADC neutron dosimetry system of the new operational dose quantities proposed in ICRU Report 95, Radiat. Prot. Dosim. **199** (2023) 1725,
https://doi.org/10.1093/rpd/ncac212

[45] BEHRENS, R., OTTO, T., Conversion coefficients from total air kerma to the newly proposed ICRU/ICRP operational quantities for radiation protection for photon reference radiation qualities, J. Radiol. Prot. **42** (2022) 011519,
https://doi.org/10.1088/1361-6498/abc860

[46] ČEMUSOVÁ, Z., EKENDAHL, D., JUDAS, L., KAPUCIÁNOVÁ, M., KUČA, P., VYKYDAL, Z., Response of current area dosemeters to new operational quantities, Radiat. Prot. Dosim. **198** (2022) 1313,
https://doi.org/10.1093/rpd/ncac154

[47] BEHRENS, R., Conversion coefficients from absorbed dose to tissue to the newly proposed ICRU/ICRP operational quantities for radiation protection for beta reference radiation qualities, J. Radiol. Prot. **41** (2021) 871,
https://doi.org/10.1088/1361-6498/abf94f

[48] EAKINS, J.S., TANNER, R.J., HAGER, L.G., The effects of a revised operational dose quantity on the response characteristics of neutron survey instruments, J. Radiol. Prot. **38** (2018) 688,
https://doi.org/10.1088/1361-6498/aaae1c

[49] POZZI, F., FERRARINI, M., FERRULLI, F., SILARI, M., Impact of the newly proposed ICRU/ICRP quantities on neutron calibration fields and extended range neutron rem-counters, J. Radiol. Prot. **39** (2019) 920,
https://doi.org/10.1088/1361-6498/ab18ca

[50] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Reference Radiation Fields for Radiation Protection – Definitions and Fundamental Concepts, ISO 29661:2012, ISO, Geneva (2012).

[51] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Radiological Protection – X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining Their Response as a Function of Photon Energy – Part 1: Radiation Characteristics and Production Methods, ISO 4037-1:2019, ISO, Geneva (2019).

[52] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Radiological Protection – X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining Their Response as a Function of Photon Energy – Part 2: Dosimetry for Radiation Protection Over the Energy Ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV, ISO 4037-2:2019, ISO, Geneva (2019).

[53] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Radiological Protection – X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining Their Response as a Function of Photon Energy – Part 3: Calibration of Area and Personal Dosemeters and the Measurement of Their Response as a Function of Energy and Angle of Incidence, ISO 4037-3:2019, ISO, Geneva (2019).

[54] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Radiological Protection – X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining Their Response as a Function of Photon Energy – Part 4: Calibration of Area and Personal Dosemeters in Low Energy X Reference Radiation Fields, ISO 4037-4:2019, ISO, Geneva (2019).

[55] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Nuclear Energy – Reference Beta-Particle Radiation – Part 1: Methods of Production, ISO 6980-1:2023, ISO, Geneva (2023).

[56] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Nuclear Energy – Reference Beta-Particle Radiation – Part 2: Calibration Fundamentals Related to Basic Quantities Characterizing the Radiation Field, ISO 6980-2:2023, ISO, Geneva (2023).

[57] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Nuclear Energy – Reference Beta-Particle Radiation – Part 3: Calibration of Area and Personal Dosemeters and the Determination of Their Response as a Function of Beta Radiation Energy and Angle of Incidence, ISO 6980-3:2023, ISO, Geneva (2023).

[58] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Neutron Reference Radiations Fields – Part 1: Characteristics and Methods of Production, ISO 8529-1:2021, ISO, Geneva (2021).

[59] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Neutron Reference Radiations Fields – Part 2: Calibration Fundamentals of Radiation Protection Devices Related to the Basic Quantities Characterizing the Radiation Field, ISO 8529-2:2000, ISO, Geneva (2000).

[60] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Neutron Reference Radiations Fields – Part 3: Calibration of Area and Personal Dosemeters and Determination of Their Response as a Function of Neutron Energy and Angle of Incidence, ISO 8529-3:2023, ISO, Geneva (2023).

[61] EUROPEAN ASSOCIATION OF NATIONAL METROLOGY INSTITUTES, Harmonization, Update and Implementation of Standards Related to Radiation Protection Dosimeters for Photon Radiation, https://www.euramet.org/research-innovation/search-research-projects/details/project/harmonisation-update-and-implementation-of-standards-related-to-radiation-protection-dosimeters-for-photon-radiation

[62] AL QAAOD, A.A., REGINATTO, M., ZBOŘIL, M., ZIMBAL, A., The impact of new ICRU95 quantities and spectrum data on the dosimetric quantities of the neutron reference fields at PTB, Radiat. Prot. Dosim. **199** (2023) 572, https://doi.org/10.1093/rpd/ncad046

[63] MERZA, V., HRANITZKY, C., STEURER, A., MARINGER, F.J., Examination of applicability of the ISO slab phantom as calibration phantom for the new ICRU 95 operational quantity personal dose, J. Radiol. Prot. **42** (2022) 021512, https://doi.org/10.1088/1361-6498/ac4ac7

[64] MERZA, V., HRANITZKY, C., STEURER, A., MARINGER, F.J., Should the ISO slab phantom be used for calibrations in terms of the new ICRU 95 operational quantity personal dose?, Radiat. Prot. Dosim. **199** (2023) 754, https://doi.org/10.1093/rpd/ncad076

[65] PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, Standards Collection for Radiation Protection: Dosimetry of External Radiation (AKD), https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_6/6.3/information/norm_lst.pdf

[66] EUROPEAN UNION, Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionising Radiation, and Repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom, Off. J. Eur. Union L 13, EU Publications Office, Luxembourg (2014).

[67] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Basic Anatomical and Physiological Data for Use in Radiological Protection, Publication 89, Ann. ICRP 32, Elsevier, Amsterdam (2002).

[68] BEHRENS, R., DIETZE, G., Dose conversion coefficients for photon exposure of the human eye lens, Phys. Med. Biol. **56** (2011) 415, https;//doi.org/10.1088/0031-9155/56/2/009

ABBREVIATIONS

CPE	charged particle equilibrium
EURATOM	European Atomic Energy Community
Gy	gray
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
keV	kilo-electron volt
kV	kilovolt
MeV	megaelectronvolt
mm	millimetre
SI	International System of Units
Sv	sievert
TECDOC	Technical Document

CONTRIBUTORS TO DRAFTING AND REVIEW

Bokulić, T.	University of Zagreb, Croatia
Callis Fernández, E.	Nuclear Regulatory Authority, Argentina
Cruz Suárez, R.	International Atomic Energy Agency
De Souza Santos, D.	Institute of Radiation Protection and Dosimetry, Brazil
Hajek, M.	International Atomic Energy Agency
Hupe, O.	Federal Institute of Physics and Technology, Germany
Koguchi, Y.	Chiyoda Technol Corporation, Japan
Merza, V.	University of Lisbon, Portugal
Milcewicz-Mika, I.	Institute of Nuclear Physics, Poland
Monteiro de Barros, V.S.	Federal University of Pernambuco, Brazil
Vanhavere, F.	Belgian Nuclear Research Centre (SCK CEN), Belgium
Waller, E.	Ontario Tech University, Canada
Yukihara, E. G.	Paul Scherrer Institute, Switzerland

Consultancy Meetings

Vienna, Austria (hybrid): 5–7 September 2023, 5–8 March 2024, 21–25 October 2024, 24–28 March 2025

Technical Meeting

Vienna, Austria (hybrid): 21–23 October 2024

IAEA SAFETY RELATED PUBLICATIONS

SAFETY STANDARDS

Under Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

The publications through which the IAEA establishes standards are the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety, waste safety and emergency preparedness and response. The Safety Standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. The IAEA Safety Standards Series has the following hierarchy:

Safety Fundamentals present the fundamental safety objective and principles of protection and safety, and provide the basis for the Safety Requirements. The principles are expressed as 'must' statements.

Safety Requirements establish the requirements to be met to ensure the protection of people and the environment, both now and in the future. The format and style of the requirements facilitate their use in a national regulatory framework. Requirements are presented as numbered 'overarching' requirements in bold, followed by a number of associated requirements; all are equally important and are expressed as 'shall' statements.

Safety Guides provide recommendations on how to comply with the Safety Requirements. Safety Guides present international good practices and, increasingly, best practices. The recommendations provided in Safety Guides are expressed as 'should' statements.

INFORMATIONAL PUBLICATIONS

Under Articles III and VIII of its Statute, the IAEA makes available and fosters the exchange of information on the peaceful uses of atomic energy and serves as an intermediary among its Member States for this purpose. Safety related information is shared through various types of publication.

Safety Reports provide practical examples and detailed methods that can be used in support of the Safety Standards. Other safety related IAEA publications include **Emergency Preparedness and Response** publications, **IAEA Services Series** publications, **Proceedings Series** publications, **TECDOCs**, **Technical Reports**, **Training Course Series** publications and a range of non-serial publications.

The IAEA's safety related informational publications are not based on international consensus and therefore do not establish any requirements or provide any recommendations.

IAEA
International Atomic Energy Agency

No. 28

Feedback on IAEA publications may be given via the on-line form available at:
www.iaea.org/publications/feedback
The form may also be used to report safety issues or submit environmental queries concerning IAEA publications.

Alternatively, contact IAEA Publishing directly:

Publishing Section, Dissemination Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530
Email: sales.publications@iaea.org
www.iaea.org/publications

ORDERING LOCALLY

To purchase priced IAEA publications, please contact either your preferred local supplier or the IAEA's lead distributor:

Mare Nostrum Group

39 East Parade
Harrogate
North Yorkshire
HG1 5LQ
United Kingdom
Email: enquiries@mare-nostrum.co.uk
www.mngbookshop.co.uk

Trade Orders and Enquiries:

Telephone: +44 1243 843 291
Email: trade@wiley.com

Individual Orders and Enquiries:

Email: mng.csd@wiley.com

Priced and unpriced IAEA publications may also be ordered directly from the IAEA by contacting IAEA Publishing. The recipient is responsible for shipping costs and any customs and duties.

26-11484E