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The NERIS roadmap: research challenges in emergency preparedness, response and recovery

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Abstract – NERIS as a European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery (EPR&R) has developed a roadmap setting out the key research challenges for radiation emergency preparedness, response and recovery. Research projects in this field have been summarised to demonstrate how important areas of development have been identified and addressed. Radiation EPR&R has a continuous need to evolve to meet societal demands, but also to keep pace with scientific and technological developments and opportunities and so the NERIS research priorities as published in the Strategic Research Agenda (SRA) are kept under review. Three challenge areas have been identified covering the topics of radiological impact assessment, protective action strategies and establishing a transdisciplinary and inclusive framework for emergency preparedness, response and recovery. The importance of these challenge areas and the underlying key topics for NERIS have been mapped across to the Joint Radiation Protection Roadmap developed by the consortium of European radiation research platforms known as MEENAS. The war in Ukraine triggered a new round of revision of the SRA that resulted in the identification of four topics as new or revised challenges for the NERIS community. These updated challenges are: (1) optimisation of management strategies for the transition and recovery phase, (2) uncertainty quantification, data assimilation and monitoring strategies, (3) inverse modelling, and (4) lessons identified from Ukraine and implications for emergency preparedness. These four areas will form the priority research areas for the NERIS community to help advance radiation emergency preparedness to meet current challenges and needs that have been identified.

Keywords: emergency planning / accident, management / accident, nuclear / radiation protection / recovery

1 Introduction

Emergency preparedness, response and recovery (EPR&R) related to nuclear or radiological accidents and incidents is a continuously evolving research and innovation field (Bertho *et al.*, 2022; Bourguignon, 2022). To address the complexity of emergency and recovery situations, there is a need to:

– establish robust, transparent and inclusive decision-making processes addressing the different phases of an accident, from early response to the long-term recovery phase and the needs of the different stakeholders;
– assess the consequences of the accident and the efficiency of potential protective actions;
– elaborate strategies to protect people and the environment;
– assess and address the related ethical, economic, social and environmental challenges.

To coordinate research in these areas, and facilitate multi-stakeholder exchanges regarding trends, arrangements and capabilities, the European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery (NERIS) was established in 2010. NERIS brings together a wide community of research, policy and practice in the field of EPR&R, including authorities, emergency centres, research

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organisations and academia, among others. Currently, it comprises 64 organisations from 25 countries (in April 2023). The main objectives of NERIS are to improve the effectiveness of current approaches for preparedness concerning nuclear or radiological emergency response and recovery, to promote more coherent approaches in Europe through the establishment of networking activities, to maintain and improve know-how and technical expertise among interested stakeholders, and to identify and address new and emerging challenges (Schneider *et al.*, 2016).

An integral part of NERIS activities is identifying gaps and needs for further research and development in EPR&R. These research' needs have been summarised in its Strategic Research Agenda (SRA), and further elaborated in a roadmap describing objectives and key research needed in the medium and long term (Croüail *et al.*, 2020). The roadmap is structured along three challenges, detailed in nine "Key Topics" (KTs) and thirty-three sub-topics, covering the next two decades.

This paper describes the process and the outcome of the visioning and prioritisation exercise leading to the NERIS roadmap. The next section summarises the state of the art in EPR&R and the progress achieved in recent European projects. The methodology behind the NERIS SRA and roadmap is then presented, followed by a description of the challenge areas and KTs. The paper concludes with a list of priorities for the near future.

2 Past research and state of the art

The EURANOS project ran from April 2004 to July 2009, and was the first large EU project in radiation emergency preparedness. It was funded by the European Commission, 23 European Member States, and involved 17 national emergency management organisations with 33 research institutes. The key objectives of EURANOS were to collate information on the likely effectiveness and applicability of a wide range of countermeasures, to provide guidance to emergency management organisations and decision makers on the establishment of an appropriate response strategy and to further enhance advanced decision support systems (DSS), in particular, RODOS (Raskob and Ehrhardt, 2000; Raskob *et al.*, 2016b) and ARGOS (Hoe *et al.*, 2009), through feedback from their operational use. Furthermore, the project developed a set of European handbooks for management of inhabited areas and food production systems (Raskob *et al.*, 2010), and contributed to emergency exercises, training and education.

The NERIS platform was established as part of the follow-on project NERIS-TP (2011–2014). This project included research activities to further develop mathematical simulation models considering the latest recommendations of the ICRP (International Commission for Radiological Protection) and to set up the coupling of DSS with emergency information systems such as the European wide information system ECURIE (Liland and Raskob, 2016).

The PREPARE project (2013–2016) aimed to close gaps identified during the response to the Fukushima accident (Raskob *et al.*, 2016a). To address communication gaps, a platform was developed allowing the exchange of information with governmental and non-governmental organisations, *e.g.* source term evaluations and other important messages. Other parts of the project dealt with the development of inverse models for source term reconstruction, atmospheric dispersion and transport models for long lasting releases and improvement of the aquatic models. An important aspect of the project was studies on public communication. A further task was the preparation of guidelines with relevant stakeholders for the management of contaminated goods.

Within the framework of the OPERRA project (2013–2017), three projects were related to NERIS interests:

- CATHyMara (Child and Adult THYroid Monitoring After Reactor Accident) (Broggio *et al.*, 2019) aimed at setting-up guidance for monitoring the internal contamination in the case of a large-scale nuclear accident, with a focus on the measurement of I-131 content in the thyroid, especially for children;
- HARMONE (HArmonising MOdelling strategies of European DSS for Nuclear Emergencies) (Schneider *et al.*, 2018; Moehrle and Raskob, 2019) developed a knowledge database and guidance that resulted in, according to the first event description, a management strategy to reduce doses, highlighting potential issues for dose assessment;
- SHAMISEN (Nuclear Energy Situations – Improvement of Medical and Health Surveillance) (Schneider *et al.*, 2020; Liutsko *et al.*, 2021b; Ohba *et al.*, 2021) provided a series of recommendations for health surveillance and medical follow-up of affected populations, including societal and ethical aspects.

The CONCERT project (2015–2020) established two open calls of which four funded projects were of direct interest for NERIS:

- CONFIDENCE (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs) (Raskob *et al.*, 2020) aimed to better understand uncertainties relevant for decision-making in the early and transition phases of an emergency, but also considered longer-term decisions made during these phases. To tackle this, ensemble approaches were proposed, and a combination of monitoring and modelling was explored to establish a better operational picture (Korsakissok *et al.*, 2020; Hamburger *et al.*, 2020). Uncertainties in the food chain modelling were identified and process-based simulation models proposed to close them (Beresford *et al.*, 2020). Modelling was used to give a better overview of health effects early in an emergency, supporting decisions on *e.g.* medical screening (Walsh *et al.*, 2019). Scenario-based workshops with stakeholders were used to explore and improve countermeasure strategies and decision-making processes (Duranova *et al.*, 2020). Considerations relating to social, ethical and communication aspects related to uncertainties were highlighted and guidelines developed (Turcanu *et al.*, 2020a; Charnock *et al.*, 2020; Montero *et al.*, 2020);
- TERRITORIES (To Enhance unceRtainties Reduction and stakeholders Involvement TOwards integrated and graded Risk management of humans and wildlife In long-lasting radiological Exposure Situations) (TERRITORIES Partners, 2020a, 2020b; Urso *et al.*, 2020) developed an umbrella framework that included guideline documents for dose assessment, risk management, and remediation of

NORM and radioactively contaminated sites as the consequence of an accident, with due consideration of uncertainties and stakeholder involvement in the decision-making process;
- ENGAGE (ENhancinG stAkeholder participation in the GovernancE of radiological risks for improved radiation protection and informed decision-making) (Turcanu *et al.*, 2019; Turcanu *et al.*, 2020b) identified and addressed key difficulties and opportunities for stakeholder engagement in fields of exposure to ionising radiation, in particular in the medical use of ionising radiation, post-accident exposures, and exposure to indoor radon. It formulated recommendations for strengthening stakeholder engagement in EPR&R (Geysmans *et al.*, 2020);
- SHAMISEN SINGS (Stakeholder INvolvement in Generating Science after nuclear emergencies) (Ohba *et al.*, 2020; Liutsko *et al.*, 2021a) aimed to further strengthen Citizen Participation in preparedness and recovery, with the provision of guidelines for developing mobile applications applicable for citizen-based dose measurements and for health monitoring.

Outside the EURATOM Programme, the BOOSTER (BiOdOSimetric Tools for triagE to Responders) project (2009–2013) provided a toolbox to address the effective management of an event involving the exposure of numerous people to radioactive material including triage of exposed individuals.

3 Methodology for building the NERIS Strategic Research Agenda and Roadmap

A key mission of NERIS is to identify gaps and needs for further research and development by addressing new and emerging challenges in the field of EPR&R. The SRA, coordinated by the NERIS R&D Committee, provides the basis for priorities regarding R&D (research & development), in particular the Key Topics to be dealt with in order to achieve a "vision". It has a clear focus on off-site emergency preparedness, response and recovery, and on radiation related aspects, but also includes non-radiological aspects such as socio-economic and ethical factors.

Formal development of the NERIS SRA was started in September 2011 by organising a brainstorm workshop in Brussels. It took as its basis a list of 24 relevant research topics identified by members of the Platform, and derived from the EURANOS project, including concerns on the security related aspects of malevolent acts with nuclear and radioactive materials, and the issues emerging from the accident at Fukushima. NERIS members and other stakeholders were consulted and a workshop was held in Bratislava in February 2012 focusing on implementation of the new ICRP recommendations in practical emergency response and recovery (ICRP, 2009a, 2009b; Duranova *et al.*, 2013).

In 2012 and 2013, the NERIS R&D Committee revised this first SRA version, taking account of the results of the European research project NERIS TP as well as the first lessons learned from the Fukushima accident and ongoing research in the PREPARE project.

The participation of the NERIS Platform in the OPERRA project together with the other European Radiation Protection research platforms (MELODI, ALLIANCE and EURADOS) was a key step to share common views and develop common approaches for the development of research in this field. This led to the publication of the second version of the NERIS SRA in April 2014.

In 2017, in the context of the "CONCERT-European Joint Programme for the Integration of Radiation Protection Research", the third update of the NERIS SRA was published, after consultation with NERIS members and stakeholders. This version introduced a new structure, which remains in place today. It starts from the definition of 3 areas, which are identified as equally important for attaining the overarching NERIS goals:
- challenges in radiological impact assessment during all phases of nuclear and radiological events;
- challenges in countermeasures and countermeasure strategies in emergency & recovery, decision support and disaster informatics;
- challenges in setting-up a trans-disciplinary and inclusive framework for preparedness for emergency response and recovery.

In total, nine key topics for R&D were defined in these three research areas. The SRA was supported by a NERIS roadmap that prioritised research needs in the short (up to five years), medium (six to ten years) and long term (beyond ten years). This roadmap was prepared in synergy with the other European research platforms with the aim of establishing a joint roadmap for the future of radiological protection research. For this purpose, the initial work was the development of two scenarios with societal concern related to NERIS issues:
- facing the consequences of a nuclear or radiological major accident or incident: how to optimise society's preparedness, and short term/long term response?
- facing the threat of a radiological terrorist act: how to minimise consequences?

The fourth update and current version of the SRA was released in November 2019. This version includes considerations resulting from a gap analysis and the results and insights gained by the recent European projects, as well as feedback from various stakeholder panels carried out within the CONCERT project. Following the publication of the updated NERIS SRA, the process of updating the NERIS long-term roadmap was initiated in parallel to the preparation of the Joint Roadmap on Radiation Protection Research established in 2020 within the EU Horizon 2020 CONCERT EJP. The process for updating the NERIS Roadmap included the organisation of a series of videoconference meetings between mid-March and end of May 2020, involving mainly members of the NERIS management board and R&D committee. Following a subsequent consultation with the NERIS community, the updated NERIS roadmap was published in May 2020 (Croüail *et al.*, 2020).

4 Challenge areas

4.1 Challenge area 1: Radiological impact assessment during all phases of nuclear and radiological events

Research within this area aims to improve radiological impact assessment for human dose and environmental impact. This includes research related to impact assessments for planning, real-time impact assessments during the response phase, dose reconstruction in a later phase, uncertainty quantification of the impact assessment and visualisation. For this purpose, three key topics have been identified: (1) improved modelling, (2) improved monitoring and (3) data assimilation/data science/artificial intelligence.

4.1.1 Improved modelling

The objective is to improve the reliability and accuracy of the forecasts on dispersion of radioactive materials in different media, human radiation doses and effects on the environment, taking into account uncertainties. This will be achieved through increasing the capabilities and extending the applicability of modelling suites that are applied for atmospheric transport and dispersion modelling (ATM/ADM), hydrological modelling, terrestrial modelling and dose modelling.

For ATM/ADM the following challenges are identified: (a) operational applicability of modelling approaches suitable for complex settings such as urban or confined spaces; (b) modelling of non-conventional sources of emissions, such as explosions, fires and releases (and subsequent dispersion) of radionuclides in particulate form; (c) treatment of atmospheric phenomena, such as low wind speed, very stable atmospheric conditions, high precipitation and different forms of precipitation; (d) quantification of uncertainties: meteorological data, source term, physical properties of dispersed material, dispersion modelling assumptions or parameterisations, natural variability of the atmosphere; (e) inverse source term/ source location estimation.

For hydrological modelling the research challenges identified are: (a) urban hydrology, including contamination of fresh water supply, waste water from decontamination and modelling of wash-off processes linked to actual or prognostic information on precipitation events; (b) improvements and operational applicability of 2-D and 3-D hydrodynamic models for inland waters and coastal circulation for real time predictions of transport of radioactivity; coupling with global hydrological models, weather forecast models, watershed runoff models (c) improvements in marine food-chain modelling; (d) uncertainty quantification for hydrological transport and dispersion models and for the integrated food chain modelling; (e) integration of the aquatic modelling components in a comprehensive modelling suite.

Improving terrestrial modelling requires the compilation of an improved database for radio-ecological models and their adaptation or customisation for specific environments (Mediterranean climate, arctic and sub-arctic, complex systems as agro-pastoral, forestry, etc.) and to areas that might need further consideration due to new reactors. The uncertainties estimation in the models and their propagation in environmental model chains need to be further investigated. Additional areas of research identified in previous projects are: (a) further development of process-based food chain models; (b) development of local radio-ecological models interlinked with monitoring information and global and food chain dose models; (c) incorporating the behaviour of hot particles in radio ecological models; (d) handling of multiple stressors by models; (e) compilation of an improved radio-ecological modelling suite and its integration in decision-support systems.

For dose models, the identified research challenges relate to: (a) dose assessment combining input from environmental monitoring and individual monitoring (*e.g.*, personal dosimeters, thyroid monitoring, whole body counting, bio-dosimetry); (b) individual dose assessment considering the real behaviour of the population and the efficacy of protective actions; (c) improved assessment of thyroid doses, their uncertainties, in particular among those exposed in utero, when newly born and in infancy, based on an analysis of thyroid measurement data and internal dose reconstruction; (d) implementation of shielding factors for new house type characteristics; (e) developing practical guidance for people and populations who want to assess their individual doses, recommending reliable methods and data sources; (f) development of information tools for individual dose assessment combining all available information.

4.1.2 Improved monitoring

The overall objective is to improve monitoring capabilities and efficiency in all phases. Three main directions of research have been identified: improvement of monitoring techniques and strategies; data collection and sharing for model validation and wider use; and optimisation of monitoring strategies by combining measurements and modelling results.

The improvement of monitoring techniques and strategies consists of developing novel devices and techniques as well as updating the guidelines for monitoring with due consideration of harmonisation for cross-border application and of different sources (*e.g.*, by professionals, NGOs and lay people). It also consists of developing harmonised monitoring strategies for all phases and for all types of radiological and nuclear events. Particular research directions include: (a) investigation of drones (and other autonomous moving monitoring devices) as part of a strategy and development of low-cost, nuclide-specific monitors for wider use; (b) optimised use of monitoring resources and integration of monitoring data of all origins into strategies and DSS; (c) improvement of existing monitoring techniques such as whole body, thyroid, lung counting; (d) improvement of techniques for measurement and/or characterisation of radionuclides both in laboratories and in the field, mainly focussing on non-gamma emitting radionuclides; (e) further improvement of the assessment of measurement uncertainties during emergency monitoring; (f) development of novel methods for local determination of environmental parameters governing radionuclide migration.

Research activities on data collection and sharing are aimed at compiling a comprehensive database of historical and new radiological data to be used for model validation. The data should be accompanied by information on background radiation and its variability. In addition, formulation of guidance on data to be collected for recovery operations has to be developed. Research should also be directed towards identification and integration of (new) data of interest for radiological impact assessments. Establishing a robust system for collecting and sharing data from measurement campaigns is also essential.

For the optimisation of monitoring strategies, research should address the development of advanced techniques that can be applied in air and water. This concerns both fixed, early-warning networks and mobile stations, during all phases. The linkage between dispersion modelling capabilities and available measurement resources should be studied considering different scenarios. The long-term goal is to develop operational tools that optimise the deployment of all measurement resources available or suitable in each particular situation, combining results of measurements and dispersion simulations.

4.1.3 Data assimilation/data science/artificial intelligence

This topic concerns the application of more "traditional" and novel data-related methodologies for combining modelling and monitoring and for providing operational solutions in improving the radiological impact assessment.

In relation to ATM/ADM, research is needed towards systematic testing and improvement of both simple and advanced methods for estimation of unknown source locations and/or source terms using data assimilation and inverse methods. Advanced source term estimation methods applied in case of an accident have to be combined with methods for assessing the plant status and its future development. For this purpose, development of links with plant status experts from the NUGENIA platform (Herranz *et al.*, 2020) is important. In addition, research is needed on the use of novel methods, such as ensemble dispersion modelling and big data and artificial intelligence technologies for inverse source term estimation. The long-term goal is the operational implementation of the above methodologies in DSS. Development of operational source term estimation methods for application in complex urban or industrial areas requiring computational fluid dynamics modelling is also an important research direction.

Combination of modelling and monitoring results can greatly improve the capabilities to assess the radiological situation in all phases and to quantify or reduce the related uncertainties. Future research should: (a) explore new developments in dosimetry to improve the estimation of the radiological picture in all phases; (b) refine the assimilation approach to better estimate the dose of individual people for dose reconstruction and medical follow-up; (c) explore the applicability of smartphone applications for operational use in emergency management; (d) combine bio-dosimetric approaches with others in an emergency situation for assessing impact on large groups of people; (e) integrate all tools into DSS including a medical follow-up and test the new approach with data from Chernobyl and Fukushima.

Finally, novel big data and artificial intelligence technologies should be exploited in developing advanced tools for improved decision-making. To this end, research should aim at developing computational structures (*e.g.*, platforms, aggregators) allowing storage, processing and exploitation in real-time of large volumes of heterogeneous data from different origins and of different quality (*e.g.*, modelling, measurements, social networks, mass media). Procedures employing these new technologies in different aspects of computational models (dispersion, inverse source term estimation, estimation of uncertainties, impact assessment, etc.) should be developed and tested. Research should be carried out to establish operational applicability and integration of the above technologies and tools in DSS.

4.2 Challenge area 2: Countermeasures and countermeasure strategies in emergency and recovery, decision support and disaster informatics

To define the management strategies together with stakeholders, development and improvement of simulation models, mathematical tools, monitoring devices and other integrated DSS are needed. Large uncertainties still exist in the application and efficacy of management strategies requiring further research, similarly for the consideration of uncertainties in the decision-making and in the communication to all relevant stakeholders and the public. For this purpose, Challenge area 2 focuses on research and technological development in: (i) countermeasures and countermeasure strategies, (ii) formal decision support, and (iii) disaster informatics.

4.2.1 Countermeasures and countermeasure strategies

The first research topic concerns improving the understanding of countermeasures (or protective actions) and their alternatives to favour the formulation and implementation of strategies throughout the cycle of an emergency (preparedness, response and recovery). The long-term needs include the review and update of countermeasures based on new technical advancements, methods for new types of environments, findings from the recovery work following the Fukushima accident and addressing scenarios other than NPP accidents. The aim is to better estimate the factors characterising countermeasures and countermeasure strategies (*e.g.*, effectiveness, costs, non-radiological effects, waste management) as function of environment, region and affected population and the consequent update of the parameter sets required by DSS. Additionally, the integration of the current countermeasure strategy development into an all-hazards approach has been identified. Development of practical information sheets for those implementing countermeasures is required to maximise their effectiveness.

The second topic addresses the implementation of countermeasures, which often depends on the timeline of the emergency and/or the application of reference levels. Research needs include the development of a methodological framework for the implementation and lifting of countermeasures based on monitoring. Of particular importance is the development of appropriate methods to define a process-based approach for lifting countermeasures, incorporating the needs and expectations of stakeholders. Feedback from the Fukushima accident emphasises the need for methodological support to address the lifting of the evacuation order. An important topic is to investigate the application of the OILs (operational intervention levels) as defined by the IAEA (International Atomic Energy Agency) to improve the decision-making process for all phases. In addition, criteria and indicators must be developed to optimise the countermeasure strategies and to measure the success/effectiveness of the strategy. Such developments are expected to result in new and better methods and guidance for the preparation of strategies in the transition phase.

4.2.2 Formal decision support

In the area of formal decision support, several gaps and further research needs were identified with the help of the CONFIDENCE and TERRITORIES projects. These include: (a) guidance for "good decision-making practice"; (b) development of structured methodologies to define generic scenarios for preparedness and planning considering different driving forces such as technical, societal, economic, environmental, and others, and finally; (c) further development of multi-criteria decision aiding tools (MCDA). This should be complemented by the identification and refinement of those methods for operational application, as well as the development of a comprehensive training program.

In the early phase of an emergency, information is highly uncertain and decision-making often relies on predicted or estimated data. To address this issue, new approaches and criteria have to be developed to identify robust indicators with respect to uncertainties of the prevailing situation. Furthermore, the current approaches for dealing with the affected population under high uncertainty together with the very limited handling of uncertainties in operational guidelines requires further research. A particular question is to what extent artificial intelligence (AI), big data and a combination of an agent-based simulation system with MCDA can improve decision-making under high uncertainty. The development of AI/machine learning techniques for decision-making and to combine all types of uncertainties is needed to address uncertainties in the decision-making process.

4.2.3 Disaster informatics

"Disaster informatics" addresses various aspects of decision-making such as mathematical tools, databases, operational DSS and advanced training facilities for first responders, decision makers and other stakeholders. Within the PREPARE project, a so-called Analytical Platform was developed, this requires further research to explore and possibly expand its functionality to establish the Platform as an exchange tool for secure and transparent communication in combination with big data approaches.

A knowledge database on accident scenarios and decisions taken was also established in the PREPARE project. Additional scenarios should be elaborated to expand the database and to allow the development of big data and machine learning approaches to improve the identification of the best solution for a new case/emergency. In addition, social media information could be integrated to further expand the knowledge base by including "soft" information important for decision-making. Finally, such a tool should be tested against the performance of the existing DSSs, to provide the operational community with balanced tools.

The existing DSSs with many users, ARGOS and JRODOS, were designed decades ago. This necessitates a thorough examination of the current user interfaces to improve and expand them with respect to new decision-making needs. In addition, research should be devoted to consider re-engineering the DSS and investigating to which extent AI and big data can be integrated. In particular, re-engineering should be considered for designing complex management strategies in the recovery phase. In this respect, the development of a new generation of DSSs based on advanced informatics and with new countermeasure modules should be considered allowing the end users to define their objectives/goals first with the system identifying the best possible strategies to achieve the specified objectives/goals with advantages and disadvantages automatically.

To address training needs, research proposals should aim to develop a suite of new training facilities using virtual and augmented reality for preparedness and testing of first responders, decision makers and other stakeholders. Of particular importance is the review and testing of modern approaches such as serious gaming and augmented reality. Such tools might be used for training of decision making in all phases, not only related to the urgent phase, but also to the transition and recovery phases. Finally, developments are needed to integrate these modern tools with DSSs, to provide state of the art training for first responders, decision makers and other relevant stakeholders.

4.3 Challenge area 3: Setting-up a transdisciplinary and inclusive framework for preparedness for emergency response and recovery

The complexity of dealing with the preparedness for, and aftermath of, potential accidents highlight the need for transdisciplinary research approaches involving different disciplines (*e.g.*, natural sciences, social sciences, humanities) and a wide range of societal actors (*e.g.*, radiation protection experts, authorities, citizens), with a view towards the entire process of preparedness and response.

While most effort has been dedicated to the early phase of an accident, there are significant research gaps remaining concerning the later phases of an accident. Challenge area 3 focuses on developing guidance frameworks for three interconnected areas: (i) establishment of radiological decision criteria and their practical implementation, (ii) communication and participation of various stakeholders, including the wider public, and (iii) integrated emergency management that considers the technical, social, ethical, economic dimensions in a holistic manner.

4.3.1 Establishment of radiological decision criteria and their practical implementation

To rehabilitate the living and working conditions of affected populations, appropriate reference levels (in terms of effective dose) should be established to reduce their exposures to as low as reasonably achievable, considering economic and societal factors. Currently, there is a need to develop transdisciplinary guidance frameworks and tools supporting European Member States with the application of the Basic Safety Standards and key decision criteria, sustainable preparedness and long-term management of contaminated areas taking due account of social factors. In addition, further developments are needed for the management of goods produced in affected areas, and the integration within an all-hazards approach. There is also a need for methodological and technical development of exercises and training for post-accident recovery.

Feedback experience has emphasised the importance of addressing the roles and duties of each actor with the stakeholders concerned in the preparedness phase. This includes many organisations and individuals who are not usually involved in the management of planned exposure situations. Processes are needed that foster the collective anticipation of the long-term consequences of protective actions during post-accident emergency and transition phases. Anticipation of local and regional vulnerabilities of potentially affected communities and their adaptive capacities should be further developed. In particular, the management of contaminated goods as a determining factor in the restoration of dignified living conditions for the affected populations needs to be addressed (Schneider *et al.*, 2021). The framework and modalities of health and environmental monitoring, the choice of radiological characterisation and contamination control techniques by measurement and addressing uncertainties in decision-making are fundamental subjects for further research. Developing dedicated training for key decision-makers for post-accident management through *ad hoc* exercises and drills is also an important research topic.

4.3.2 Communication and stakeholder participation

On the theme of communication and stakeholder engagement, further research is needed to establish guidance on effective engagement, where all stakeholders, including the general public, have the opportunity to take part in the preparation and identification of processes to allow their greater involvement in the rehabilitation following any accident. This guidance should also allow stakeholders to contribute to the adaptation of messages, modalities, tools and vectors of communication in a post-accident situation (Raisio *et al.*, 2023). Past events have also clearly shown the need for further research on the role of mutual learning and the training of many stakeholders in the measurement of radioactivity as a key factor of resilience of the affected populations. Fostering citizen science – in particular the measurement of radioactivity in the environment and in living areas – requires specific research on the integration of expert and citizen data. Citizen science research should contribute to the learning process for potentially exposed populations and guarantee a more informed assessment of the radiological situation in a territory, both before and after an accident.

4.3.3 Integrated emergency management

An integrated and holistic approach to post-accident management needs to address both radiological and non-radiological aspects (*e.g.*, mental health and well-being, economic aspects, social consequences, ethical principles) associated with the rehabilitation of living conditions. In this perspective, further research is needed in several areas such as the adaptation of health surveillance, the ethics of decision-making in post-accident situations, the consideration of societal and economic consequences after an accident, the anticipation of constraints and challenges in the management of waste arising from the decontamination of agricultural and urban and industrial areas or dismantling of damaged or contaminated infrastructures. Further developments in integrated monitoring of the radiological situation at all stages of post-accident management are needed. Research should improve the process of characterising the situation by measuring radioactivity (in food, consumer goods, natural areas, dwellings and living and working places) and disseminating and sharing measurement results through networking. Feedback experience highlights the importance of developing a practical culture of radiation protection in decision-makers at all levels, including local professionals involved in remediation and the affected residents themselves. Research on the conditions for the improvement and deployment of this radiation protection culture must be pursued in the framework of inclusive research projects.

5 Links between the Joint Roadmap game changers and the NERIS topical priorities

The Joint Roadmap (Impens *et al.*, 2019) has developed a common and shared vision for upcoming European radiation protection research by identifying eight joint challenges (A to H) across the radiation protection research platforms (MELODI, EURADOS, EURAMED, ALLIANCE, SHARE and NERIS) in the context of existing and potential exposure scenarios which are relevant from both a societal and radiation protection perspective.

In addition, the Joint Roadmap has identified a set of twenty priority issues related to these challenges, subdivided into sub-themes and referred to as "game changers". A game changer is defined as research question that, if successfully addressed, has the potential to significantly impact and strengthen the system and/or practice of radiation protection for humans and/or the environment through: (1) significant improvement of the evidence base, (2) development of principles and recommendations, (3) development of standards based on the recommendations, and (4) improvement of practices (Impens *et al.*, 2019).

The NERIS Roadmap aims to contribute to this paradigm shift by emphasising long-term objectives for the development of research addressing key challenges to improve preparedness for nuclear and radiological emergency response and recovery (EPR&R) in Europe and to contribute to international developments in this field.

A crosscutting analysis of both roadmaps allows us to identify the NERIS topical research priorities in relation to the common challenges and innovative changes identified in the Joint Radiation Protection Roadmap (JRPR). Table 1 illustrates the links between the two roadmaps.

By nature, the joint challenge to optimise emergency and recovery preparedness and response (**Challenge G** in JRPR) is closely linked to the key and core challenges of the NERIS SRA and Roadmap. Two innovative targets have been set for the coming years, which can be considered as the highest priorities for NERIS, namely:

- change of radiological impact assessments, decision support and response and recovery strategy through Artificial Intelligence and Big Data (**G1**);
- further development of risk assessment and risk management approaches and technological capabilities to cope with novel threats and accident scenarios arising from new and future nuclear and radiological technologies (**G2**).

Table 1. Links between the Joint Radiation Protection Roadmap and the NERIS Roadmap.

JRPR – Joint Radiation Protection Roadmap Challenges			**C**		**F**			**G**						**H**
			Effects on ecosystems		Environmental exposure and risk assessment			Emergency and recovery						RP in Society
JRPR Game Changers *			**C1**	**C2**	**F1**	**F2**	**F3**	**G1**			**G2**			**H1**
			Controversy in Chernobyl & Fukushima	Effects on ecosystem functioning	Human food chain contamination	Processes influencing radionuclide behaviour	Integrating risk assessment/ management	Artificial Intelligence and Big Data			Novel threats			Society, values, needs & expectations
								Methods and strategies for decision support	Participatory processes	Holistic management of the radiological situation	Accident scenarios	Combining modelling and simulation	Improved modelling	
NERIS Roadmap Challenge Areas (CAs) and Key Topics (KTs)														
CA 1 Radiological **impact assessment** during all phases of nuclear and radiological events	**KT1**	Improving **Modelling**		√	√	√						√	√	
	KT2	Improved **Monitoring**									√	√		
	KT3	**Data** assimilation – Data Science – Artificial Intelligence	√	√	√	√						√		
CA 2 Decisions on and implementation of **protective actions** during the emergency cycle, including justification and optimisation	**KT4**	**Countermeasures** and countermeasures strategies	√	√	√	√	√	√		√	√			√
	KT5	Formal **Decision** Support					√	√	√	√				√
	KT6	Information technology & disaster **Informatics**					√	√		√	√	√	√	√
CA 3 Setting-up a transdisciplinary and inclusive framework for **preparedness** for emergency response and recovery	**KT7**	Emergency response and recovery **Framework**				√	√		√	√				√
	KT8	**Stakeholder** engagement, involvement of the public & **Communication**	√						√		√			√
	KT9	**Integrated** emergency management					√	√	√	√	√		√	√

* No strong links have been identified so far between the NERIS roadmap and JRPR game changers A (understanding and quantifying health effects), B (improving concepts of dose quantities), D (optimising medical use of radiation) and E (improving occupational radiation protection).

Furthermore, due to the multidisciplinary nature of NERIS, some of its research priorities can also be interlinked and contribute to the development of innovative processes identified by other game changers in the JRPR. Among these, three common challenges can be highlighted:

- **Challenge F** of JRPR concerns the search for an integrated approach to environmental exposure and risk assessment of ionising radiation. Research on key topics of the NERIS Roadmap, such as the improvement of modelling (**KT1**) or the application of data assimilation technologies, data science or artificial intelligence (**KT3**), related to the challenges in radiological impact assessment during all phases of a nuclear or radiological event (**CA1**), can contribute to solving specific common issues such as **F1** (robust prediction of food chain contamination) and **F2** (key processes influencing radionuclide behaviour). In addition, there are several research needs identified in the NERIS Roadmap for improving the understanding of countermeasures and countermeasure strategies (**KT4**) to enable better decisions on and implementation of protective measures (**CA2**) and for developing decision criteria and guidance for response and recovery management strategies (**KT7**) into a transdisciplinary and inclusive framework (**CA3**), which may substantially contribute to or help progress the game changers F1 and F2. The specific game changer **F3** (integration of risk assessment and risk management) can be addressed in a more integrated way taking into account the research priorities identified in **CA2**, under the key topics **KT4**, **KT5** (formal decision support) and **KT6** (information technology and disaster informatics). Further research priorities needed to advance the development of guidelines and implementation of the framework for emergency response and recovery (**KT7**) as well as specific research on the socio-economic aspects of integrated emergency management (**KT9**), included in **CA3**, complement the abovementioned topics;
- **Challenge H** of JRPR is the integration of radiation protection into society. The NERIS Roadmap is strongly committed to developing mechanisms and systematic approaches to include the social dimension in all aspects of emergency response preparedness and management and post-accident recovery, fully in line with the innovative objectives of game changer **H1** (society's values, needs and expectations). Thus, aspects related to stakeholder engagement, involvement of the affected population and public, communication, psychological and socio-economic impacts, and so on, are addressed, in a transversal way, in the key topics **KT4**, **KT5** and **KT6** of **CA2**, and, more specifically, in key topics **KT7**, **KT8** (stakeholder engagement, public involvement and communication) and **KT9** in **CA3**;
- **Challenge C** of JRPR is related to understanding radiation-related effects on non-human biota and ecosystems. Some of the research priorities identified in the NERIS Roadmap may partially contribute to issues as **C1** (resolution of Chernobyl and Fukushima controversies) and **C2** (effects on ecosystem functioning), advocated under the joint challenge. This is the case for key topics **KT1** and **KT3** in **CA1**, and key topic **KT8** in **CA3**.

Based on this crosscutting analysis, four action lines have been established that bring together the main research priorities, revisiting and updating the challenges of NERIS for the next few years. These four new challenges are described in detail below. They are expected to make a decisive contribution to advance the holistic conception and development of EPR&R significantly in the coming years, according to the joint game changers for radiation protection.

6 Current challenges and further research proposals

Updating the NERIS SRA and roadmap is an ongoing activity due to the need to be reflexive to identified needs. In 2022, the war in Ukraine triggered a new round of revision that resulted in identifying the following four topics as new or revised challenges for the NERIS community. These four topics have been identified by the NERIS R&D Committee and the Management Board and approved by the General Assembly.

6.1 Optimisation of management strategies for the transition and recovery phase

Optimisation of management strategies is a key requirement in the decision-making process for all phases of an accident. This is most challenging in the transition and recovery phase as alongside radiological aspects, technical, environmental and socio-economic factors as well as reference levels, waste management and context-specific constraints and possibilities need to be considered. War conditions, novel threats and accident scenarios arising from the use of new and emerging nuclear and radiological technologies are so far not sufficiently investigated. The structure of existing Decision Support Systems (DSS) may require adaptation to allow a more focused optimisation process and guidance for the end user. Research areas that require consideration are, among others: (1) the improvement and the extension of the European Handbooks, including the experience gained over the last decade, (2) consideration of new threats in decision support material, (3) monitoring strategies and data assimilation to optimise the practical implementation of a protective action strategy, (4) big data technologies and AI based methods to analyse requirements and optimise general preparedness for a wide-range of scenarios, (5) adaptation of existing DSS to allow the application of AI based optimisation methodologies, (6) application of a more comprehensive view on the concepts of tolerability and reasonableness, and (7) processes for direct stakeholder involvement and co-expertise (Thu Zar *et al.*, 2023).

6.2 Uncertainty quantification, data assimilation and monitoring strategies

It is widely recognised that uncertainties in the consequence assessment of nuclear and radiological accidents and incidents need to be quantified and considered in all steps of the decision-making process. For quantification of uncertainties, research should aim towards improving the *a priori* knowledge of different sources of uncertainties, reducing uncertainties using observational data sets – for example using data assimilation and data fusion techniques to combine all information in a consistent way, developing novel approaches to improve calculation efficiency – such as AI/machine learning or other advanced computational and/or statistical methods, and the integration of the latest developments in risk science. To optimise the use of monitoring data for reducing uncertainties during the different phases of a radiological crisis, measurement strategies using novel technologies – such as deployment of Unmanned Aerial Vehicles (UAVs) – but also strategies for monitoring radionuclides that emit no or very limited gamma rays need to be developed. Furthermore, the research should address different understandings of uncertainties by various stakeholder groups, additional uncertainties linked to communication and decision-making processes and the implications of uncertainties on ethical and societal issues. Finally, research is needed for uncertainty quantification in consequence assessment related to novel threats and scenarios, such as nuclear or radiological incidents inside urban areas, in cases of war or armed conflicts and of natural disasters.

6.3 Inverse modelling

Inverse modelling is a key instrument for localising and quantifying unknown sources of radioactive substances that have been detected in the atmosphere, but without or with limited prior information. It is relevant nowadays to develop the ability to assess potential radioactive releases to the environment when prior information on the state of nuclear facilities may not be available in new threat situations linked for example to an armed conflict involving highly nuclearized countries. In this context, the acquisition and exploitation of different types of monitoring data (air concentrations, ambient gamma dose rate, surface deposition, physicochemical forms, soil and other material characteristics) as well as the assessment and reduction of errors (from measurements, meteorological fields and dispersion models) remains a major issue to tackle in order to significantly improve the source term assessment both in real time and for dose reconstruction. Furthermore, the ability to reconstruct simultaneous radionuclide releases from several sources (*e.g.*, wildfires, Sahara dust, and potential nuclear accident) by inverse modelling remains a challenge to take up. Finally, to obtain open, transparent and trustworthy assessments for European citizens, sharing, centralisation and treatment of measurements including handling incomplete/faulty/fake data and data from different origins and of different quality, is essential. The employment of novel approaches such as AI and big-data technologies may offer solutions to the above issues and will be explored.

6.4 Lessons identified from Ukraine and implications for emergency preparedness

The war in Ukraine that started in February 2022 has received regular media and international focus on the status of the nuclear facilities in Ukraine as well as discussion on the potential use of nuclear weapons within the country. This conflict situation has identified several areas where there is a requirement to develop the emergency preparedness and response approaches typically used to protect the public during radiation emergencies. The risk assessment and risk management approaches as well as the technological capabilities typically used for such emergencies were not necessarily designed to cope with scenarios involving war or armed combat. A review of these capabilities should be performed including consideration of the social, ethical and legal aspects. Key areas that present challenges in such conflict situations cover various aspects, linked for instance to the fundamental assumptions made in existing systems for radiation emergency preparedness and response and whether these are resilient in armed conflict situations and by analogy potentially for some natural disaster situations; the potential for nuclear facilities to be deliberately attacked and the resulting source terms; the role of inverse modelling in such situations; for the consideration of monitoring in conflict situations, how information will be communicated to citizens and how behaviours might be changed by the situation and therefore impact on the effectiveness of any protective action strategy.

Conflict of interest

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References

Beresford NA, Barnett CL, Chaplow J, Lofts S, Wells C, Brown JE, Hosseini A, Thørring H, Almahayni T, Sweeck L, Guillén J, Lind O-C, Oughton DH, Salbu B, Teien H-C, Perez-Sánchez D, Real A. 2020. CONFIDENCE overview of improvements in radioecological human food chain models and future needs. *Radioprotection* 55(HS1). https://doi.org/10.1051/radiopro/2020019.

Bertho JM, Gabillaud-Poillion F, Reuter C, Rivière O. 2022. Comparative study of nuclear post-accident management doctrines in Europe and North America. *Radioprotection* 57(1): 9–16.

Bourguignon M. 2022. The necessary development of post-nuclear accident management preparedness. *Radioprotection* 57(1): 7–9.

Broggio D, Baudé S, Belchior A, Berkovskyy V, Bonchuck Y, Dewoghélaëre J, Etherington G, FojtÍk P, Franck D, Gomez-Ros JM, Gregoratto D. 2019. Child and adult thyroid monitoring after a reactor accident (CAThyMARA): Technical recommendations and remaining gaps. *Radiat. Meas.* 128: 106069.

Charnock T, Andersson K, Trueba C, Montero M. 2020. Uncertainties confronting stakeholders and decision-makers in planning intervention in urban and agricultural scenarios in the transition phase of a radiological emergency. *Radioprotection* 55(1): S119–S125.

Croüail P, *et al.* 2020. NERIS Roadmap on medium and long-term research on preparedness for nuclear and radiological emergency response and recovery. Version 2, May 29, 2020. EJP-CONCERT European Joint Programme for the Integration of Radiation Protection Research H2020, Grant 662287.

Duranova T, Raskob W, Mustonen R, Schneider T. 2013. First NERIS Platform Workshop – Preparedness for nuclear and radiological emergency response and recovery: Implementation of ICRP recommendations. *Radioprotection* 48(5): Supplement 2013.

Duranova T, Bedwell P, Beresford NA, Bleher M, Gering F, Geertsema G, Hamburger T, Kaiser JC, Korsakissok I, Leadbetter SJ, Montero M. 2020. CONFIDENCE dissemination meeting: Summary on the scenario-based workshop. *Radioprotection* 55 (HS1): S17–S37.

Geysmans R, Zeleznik N, Abelshausen B, Duranova T, Schieber C, Schneider T, Croüail P, Turcanu C, Liutsko L, Cantone MC. 2020. Broadening and strengthening stakeholder engagement in emergency preparedness, response and recovery. *Radioprotection* 55(HS22): S219–S225.

Hamburger T, Gering F, Yevdin Y, Schantz S, Geertsema G, de Vries H. 2020. Uncertainty propagation from ensemble dispersion simulations through a terrestrial food chain and dose model. *Radioprotection* 55(HS1): S69–S74.

Herranz LE, Bentaib A, Gabrielli F. 2020. NUGENIA/TA2 achievements in severe accidents research (2015–2020). *J. Nucl. Esp.* 2020: 1–6.

Hoe S, McGinnity P, Charnock T, Gering F, Jacobsen LS, Sørensen JH, Andersson KG, Astrup P. 2009. ARGOS decision support system for emergency management. In: *Proceedings of the 12th International Congress of the International Radiation Protection Association, Buenos Aires, Argentina, IRPA*. https://core.ac.uk/download/pdf/13723365.pdf.

ICRP Publication 109. 2009a. Application of the Commission's recommendations for the protection of people in emergency exposure situations. *Ann. ICRP* 39(1).

ICRP Publication 111. 2009b. Application of the Commission's recommendations to the protection of people living in long-term contaminated areas after a nuclear accident or a radiation emergency. *Ann. ICRP* 39(3).

Korsakissok I, *et al.* 2020. Uncertainty propagation in atmospheric dispersion models for radiological emergencies in the pre-and early release phase: Summary of case studies. *Radioprotection* 55 (HS1): S57–S68.

Impens N, *et al.* 2019. D3.7 – Second joint roadmap for radiation protection research. EJP-CONCERT European Joint Programme for the Integration of Radiation Protection Research H2020 – 662287.

Liland A, Raskob W. 2016. Towards a self-sustaining European platform on nuclear and radiological emergency preparedness, response and recovery. Key results of the NERIS-TP European project. *Radioprotection* 51: 1–3.

Liutsko L, Cardis E, Oughton D. 2021a. Citizen participation in post-accidental recovery: Radiation doses and welfare measurements. In: *Research ethics for environmental health* (F. Zölzer, G. Meskens, Eds.), pp. 145–157. Routledge.

Liutsko L, Oughton D, Sarukhan A, Cardis E, SHAMISEN Consortium. 2021b. The SHAMISEN recommendations on preparedness and health surveillance of populations affected by a radiation accident. *Environ. Int.* 146: 106278.

Moehrle S, Raskob W. 2019. Reusing strategies for decision support in disaster management – A case-based high-level petri net approach. *Adv. Artif. Intell.: Rev.* 1.

Montero M, Sala R, Trueba C, García-Puerta B, Abelshausen B, Bohunova J, Croüail P, Durand V, Duranova T, Hilliard C, Maître M. 2020. Stakeholder involvement through national panels and surveys to address the issues and uncertainties arising in the preparedness and management of the transition phase. *Radioprotection* 55(HS1): S127–S134.

Ohba T, Goto A, Nakano H, Nollet KE, Murakami M, Yoshida K, Yumiya Y, Honda K, Kuroda Y, Kumagai A, Ohira T. 2020. Implementing eHealth with radiation records: A new support package for evacuees returning to areas around the Fukushima Daiichi nuclear power station. *Radioprotection* 55(4): 291–295.

Ohba T, Liutsko L, Schneider T, Barquinero JF, Croüail P, Fattibene P, Kesminiene A, Laurier D, Sarukhan A, Skuterud L, Tanigawa K. 2021. The SHAMISEN Project: Challenging historical recommendations for preparedness, response and surveillance of health and well-being in case of nuclear accidents: Lessons learnt from Chernobyl and Fukushima. *Environ. Int.* 146: 106200.

Raisio H, Puustinen A, Lindell J, Wiikinkoski T, Valtonen V. 2023. Could virtual volunteerism enhance information resilience in a nuclear emergency? The potential role of disaster knowledge workers and virtual emergent groups. *Radioprotection* 58(1): 11–18.

Raskob W, Ehrhardt J. 2000. *The RODOS system: decision support for nuclear off-site emergency management in Europe*. Forschungszentrum Karlsruhe.

Raskob W, Hugon M, Nisbet AF, Brown J, Howard BJ, Beresford NA, Ollagnon H, Turcanu C, Camps J, Andersson K, Rantavaara A. 2010. Decision aiding handbooks for managing contaminated food production systems, drinking water and inhabited areas in Europe. *Radioprotection* 45(5): S23–S37.

Raskob W, Schneider T, Gering F, Charron S, Zheleznyak M, Andronopoulos S, Heriard-Dubreuil G, Camps J. 2016a. Innovative integrative tools and platforms: Key results of the PREPARE European Project. *Radioprotection* 51(HS2): S59–S61.

Raskob W, Landman C, Trybushnyi D. 2016b. Functions of decision support systems (JRodos as an example): Overview and new features and products. *Radioprotection* 51: S9–S11.

Raskob W, Beresford NA, Duranova T, Korsakissok I, Mathieu A, Montero M, Müller T, Turcanu C, Woda C. 2020. CONFIDENCE: Project description and main results. *Radioprotection* 55(HS1): S7–S15.

Schneider T, Lafage S, Bardelay J, Duranova T, Gallego E, Gering F, Hardeman F, Hériard-Dubreuil G, Murith C, Oughton D, Raskob W. 2016. NERIS: European platform on preparedness for nuclear and radiological emergency response and recovery – Activities and perspectives. *Radioprotection* 51(HS1): S5–S8.

Schneider T, Andronopoulos S, Camps J, Duranova T, Gallego E, Gering F, Isnard O, Maître M, Murith C, Oughton D, Raskob W. 2018. The work programme of NERIS in post-accident recovery. *Ann. ICRP* 47(3-4): 221–228.

Schneider T, Oughton D, Cardis E. 2020. Guest editorial: The SHAMISEN project – Applicability or lessons learnt and recommendations for disaster situations. *Environ. Int.* 144: 106000.

Schneider T, Lochard J, Maître M, Ban N, Croüail P, Gallego H, Homma T, Lecomte JF, Takamura N. 2021. Radiological protection challenges facing business activities affected by a nuclear accident: Some lessons from the management of the accident at the Fukushima-Daiichi nuclear power plant. *Radioprotection* 56(3): 181–192.

TERRITORIES Partners. 2020a. D9.71 – Guidance for management/post-accident recommendations based on output of the TERRITORIES project. EJP-CONCERT European Joint Programme for the Integration of Radiation Protection Research H2020 – 662287. https://territories.eu/assets/files/publications/D9.71_Guidance-for-management-Post-Accident_approved21022020.pdf.

TERRITORIES Partners. 2020b. D9.72 – Guidance for management/NORM recommendations based on output of the TERRITORIES project. EJP-CONCERT European Joint Programme for the Integration of Radiation Protection Research H2020 – 662287. https://territories.eu/assets/files/publications/D9.72_Guidance-for-management-and-NORM_approved21022020.pdf.

Thu Zar W, Lochard J, Taira Y, Takamura N, Orita M, Matsunaga H. 2023. Risk communication in the recovery phase after a nuclear accident: the contribution of the "co-expertise process". *Radioprotection* 57(4): 281–288.

Turcanu C, Abelshausen B, Geysmans R, Van Oudheusden M, Meskens G, Schieber C, Schneider T, Zeleznik N, Pölzl-Viol C. 2019. D9.94 – Final report of the ENGAGE project. EJP-CONCERT European Joint Programme for the Integration of Radiation Protection Research H2020 – 662287. https://concert-h2020.eu/sites/concert_h2020/files/uploads/Deliverables/D9/ENGAGE/_Lists_Deliverables_Attachments_199_D9.94_Final-report-of-the-ENGAGE-project_approved13012020.pdf.

Turcanu C, *et al.* 2020a. Social, ethical and communication aspects of uncertainty management. *Radioprotection* 55(HS1): S145–S149.

Turcanu C, Van Oudheusden M, Abelshausen B, Schieber C, Schneider T, Zeleznik N, Geysmans R, Duranova T, Perko T, Pölzl-Viol C. 2020b. Stakeholder engagement in radiological protection: Developing theory, practice and guidelines. *Radioprotection* 55(HS2): S211–S218.

Urso L, *et al.* 2020. D9.62 – Methodology to quantify improvement – Guidance on uncertainty analysis for radioecological models. EJP-CONCERT European Joint Programme for the Integration of Radiation Protection Research H2020 – 662287. https://territories.eu/assets/files/publications/D9.62_guidance-on-uncertainty-analysis-for-radioecological-models.pdf.

Walsh L, Ulanowski A, Kaiser JC, Woda C, Raskob W. 2019 Risk bases can complement dose bases for implementing and optimising a radiological protection strategy in urgent and transition emergency phases. *Radiat. Environ. Biophys.* 58: 539–552.

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