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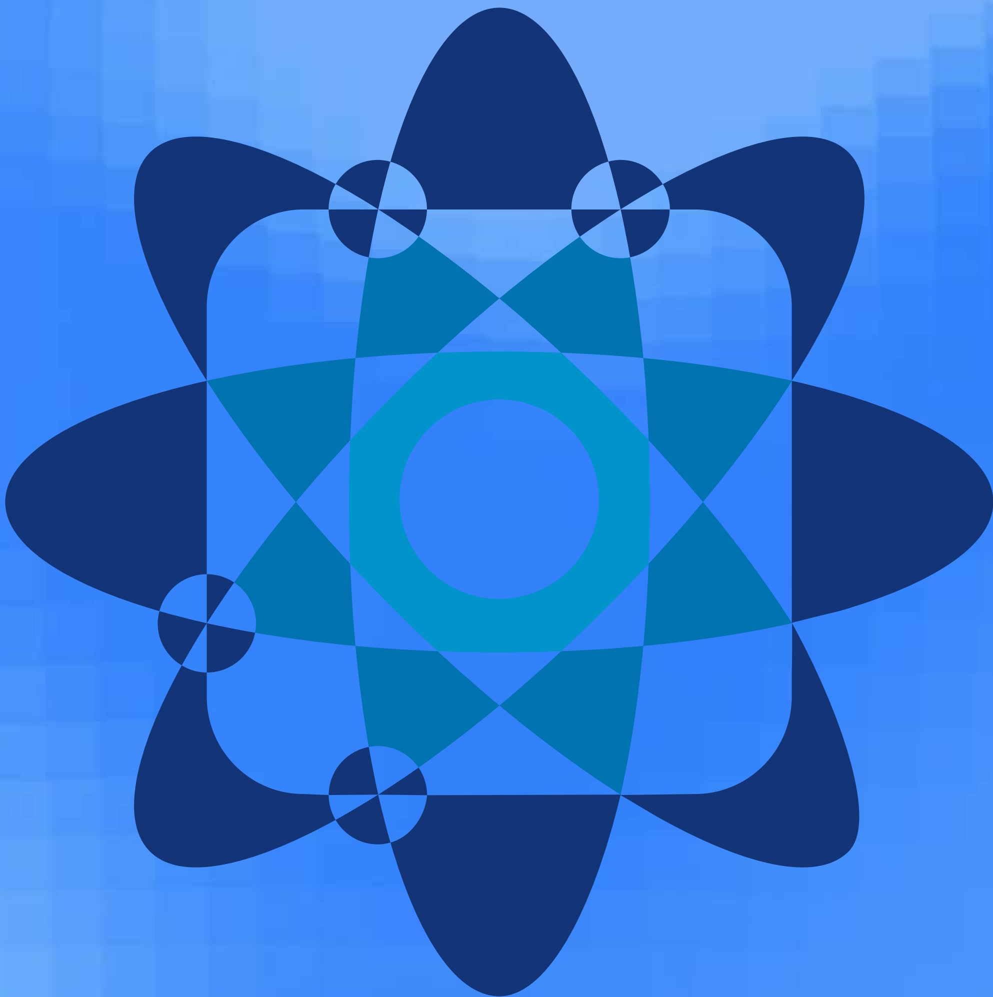
5th International Conference on Radioecology and Environmental Radioactivity

ICRER pre-conference online event

Report of an International Conference, 29 June–1 July 2021



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5th International Conference on Radioecology & Environmental Radioactivity: Report on the Pre-Conference Online Event 29 June – 1 July 2021
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Abstract
This report includes a summary of the presentations, discussions and conclusions of an online event held in June 2021 to provide input to the 5th International Conference on Radioecology & Environmental Radioactivity. This report reflects the presentations and discussions at that event. The views presented do not necessarily represent those of DSA.

Referanse
Den 5. internasjonale konferansen om radioøkologi og miljøradioaktivitet: nettbasert arrangement 29. juni–1. juli 2021

DSA-rapport 05:2022

Språk: Engelsk

Stikkord:
Internasjonalt, konferanse, radioøkologi, miljø

Abstrakt
Denne rapporten inneholder et sammendrag av presentasjonene, diskusjonene og konklusjonene fra et nettbasert arrangement som ble holdt i juni 2021 for å gi innspill til den 5. internasjonale konferansen om radioøkologi og miljøradioaktivitet. Sammendraget ble utarbeidet av medlemmer av konferansens organisasjonskomité, med støtte fra RadEcol Consulting. Denne rapporten gjenspeiler presentasjonene og diskusjonene på det arrangementet. Synspunktene som presenteres representerer ikke nødvendigvis synspunktene til DSA.

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5th International Conference on Radioecology and Environmental Radioactivity

ICRER pre-conference online event

Report of an International Conference, 29 June–1 July 2021

Executive Summary

The International Conference on Radioecology and Environmental Radioactivity (ICRER) pre-conference online event was organized with the aim of providing a preview of some of the key scientific topical issues that will be explored in more detail at the physical conference in September 2022, which was necessarily delayed from April 2020 as a result of the Covid-19 pandemic. The online event took place during three days, from 29 June to 1 July 2021, and the main topics in the program were:

- → environmental levels and assessments related to the Fukushima Daiichi accident in 2011;
- → key developments related to application of radioecology for radiation protection, notably related to decommissioning and the management of nuclear and other legacies;
- → public engagement and risk communication; and
- → key projects undertaken by cooperating regional and international organizations.

Around 450 participants across all 6 continents registered to attend the online event, which included a wide range of presentations from experts from international organizations and research groups and other organizations from around the world. The presentations, followed by discussions, were organized into five topical areas:

- → updates on projects/work programs from international/regional and cooperating organizations;
- → public engagement and risk communication, based on case studies;
- → the Ecosystem approach;
- → application of radioecology to radiation protection; and,
- → radioecology and management of nuclear and other legacies.

Conclusions from the presentations and associated discussions

International cooperation and joint research is crucial for gaining proper perspective around radiation protection issues and the exposure of the public, workers and non-human biota. Integration activities both within radioecology and also with other disciplines have benefitted the global radiation protection community, resulting in new research projects, changes to recommendations and guidance as well as legislative changes.

In addition to the evaluation of exposure and effects, ethical, social and economic aspects need to be addressed. There has been a notable shift away from a rigorous technical and scientific approach to radiation protection to programs more focused around affected areas and affected people, with the aim of taking account of the complex interactions between society, economy and the environment. In the case of legacy and complex sites, a wide range of radiological, chemical and physical hazards need to be addressed, often alongside complex social contexts. A harmonized and proportionate risk management approach to decommissioning, legacy and waste management is therefore needed that includes effective dialogue with relevant stakeholders in order to appropriately address all hazards and optimize between benefits and disadvantages.

The shift from anthropocentrism towards ecocentrism, where all complex and interrelated conditions are considered in an integrated manner has been evolving, but further development is required. For example, understanding of what constitutes a significant effect at population and ecosystem levels needs to be developed. The science of how multiple stressors interact in the environment also needs to evolve along with the continued development of approaches to support evaluation of multiple stressor effects.

Radioecology has been, and will continue to be, essential in supporting the development and application of radiation protection regulations, including regulatory compliance demonstration. It is clear from the presentations and discussions during the event that scientific developments have continued through the Covid-19 pandemic, and further progress is needed, including interaction between the different disciplines and between the science community, operators and regulators to ensure key challenges are identified and solutions to those challenges developed. One area that has progressed during the pandemic has been the further substantial development of the ERICA assessment tool that has been applied to evaluate dose rates to non-human biota under planned, existing and emergency exposure situations for the NORM industry, nuclear facilities, decommissioning and radioactive waste management. Developments include new dosimetry, updated parameter databases and the addition of new functionality such as the ability to evaluate dose rates for noble gases, including radon.

The number of scientific publications in the field of radioecology has been steadily increasing but there is also a growing awareness of issues such as bias in preparing publications and in the review process, as well as fake news relating to radiation science. To move forward and address issues, proper hypothesis setting and testing is needed, along with a focus on repeatability of experiments and results. It is also important to encourage the reporting of negative results as well as greater international scientific exchange and debate around results and emerging theories through consensus conferences and dedicated discussion sessions.

Many of the key scientific topical issues and motivations identified during the event will be explored in more detail at the physical conference that will take place in Oslo from 4-9 September 2022. The conference will provide an opportunity to meet in person and further discuss radioecology and environmental radioactivity science needs and developments. Further information on the conference is available from www.icrer.org.

Abbreviations

AEP	Aggregate Exposure Pathway
AMAP	Arctic Monitoring and Assessment Programme
AOP	Adverse Outcome Pathway
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
BSS	Basic Safety Standards
CDLM	Committee on Decommissioning of Nuclear Installations and Legacy Management (NEA)
CERAD	Centre for Environmental Radioactivity (Norway)
CEZ	Chornobyl Exclusion Zone
COMEST	Commission for Ethics of Scientific Knowledge and Technology
CR	Concentration Ratio
CRA	Cumulative Risk Assessment
DCC	Dose Conversion Coefficient
DCRL	Derived Consideration Reference Level
DSA	Norwegian Radiation and Nuclear Safety Authority
DWG	Drinking Water Guidelines
EGCDL	Expert Group on Costing for Decommissioning of nuclear installations and Legacy management (NEA)
EGCUL	Expert Group on the Characterization of Unconventional and Legacy waste (NEA)
EMCL	Environmental Media Concentration Limits
ERICA	Environmental Risk from Ionizing Contaminants: Assessment and Management
ERA	European Radioecology Alliance
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FSC	Forum on Stakeholder Confidence (NEA)
HDCS	Expert group on Holistic process for Decision making on decommissioning and management of Complex Sites
IAEA	International Atomic Energy Agency
ICRER	International Conference on Radioecology and Environmental Radioactivity
ICRP	International Commission on Radiological Protection
IGSC	Integration Group for the Safety Case (NEA)
IRSN	Institute for Radiation Protection and Nuclear Safety (France)
IUR	International Union of Radioecology
JER	Journal of Environmental Radioactivity
MEREIA	Methods for Radiological and Environmental Impact Assessment
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NGO	Non-Government Organization
NORM	Naturally Occurring Radioactive Material
NPP	Nuclear Power Plant
PHE	Public Health England
QSAR	Quantitative Structure Activity Relationships
RAPs	Reference Animal and Plants
RBE	Relative Biological Effectiveness
RF	Regulators Forum (NEA)
ROV	Remotely Operated Vehicle
RWMC	Radioactive Waste Management Committee (NEA)
SRA	Strategic research Agenda
STOP	Source To Outcome Predictor
TREE	Transfer-Exposure-Effects
UKCEH	UK Centre for Ecology & Hydrology
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization
WPMO	Working Party on Management and Organization (NEA)
WPTES	Working Party on Technical, Environmental and Safety (NEA)
WTD	Wildlife Transfer Database

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1 Introduction

The series of International Conferences on Radioecology and Environmental Radioactivity (ICRER) began in 2008 in Bergen, Norway as a result of the joining of two separate series of conferences; one on Radioecology, organized by the Norwegian Radiation and Nuclear Safety Authority (DSA) together with the International Union of Radioecology (IUR), and one on Environmental Radioactivity, organized by the Institute of Radiological Protection and Nuclear Safety (IRSN). Subsequent ICRER events took place in Hamilton, Canada, in 2011; Barcelona in 2014 and Berlin in 2017. A 5th ICRER had been planned to take place in April 2020 in Amsterdam, but was postponed due to the Covid-19 pandemic. That conference will now take place from 4-9 September 2022 in Oslo, Norway, and will provide an opportunity to bring together regulators and scientists to exchange views on important topics. Since the duration between conferences has been considerably extended as a result of the pandemic, the decision was made to organize an online event that will feed into the 5th ICRER.

The online event, which took place from 29 June to 1 July 2021, was organized by DSA, IRSN and IUR in cooperation with the European Commission, International Atomic Energy Agency (IAEA), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Commission on Radiological Protection (ICRP), Nuclear Energy Agency (NEA), Food and Agriculture Organization of the United Nations (FAO), European Radioecology Alliance (ERA), Arctic Monitoring and Assessment Programme (AMAP), Centre for Environmental Radioactivity (CERAD), Roshydromet, and Journal of Environmental Radioactivity (JER). The aim of the event was to provide a preview of some of the key scientific topical issues that will be explored in more detail at the physical conference in September 2022. These issues include:

→ environmental levels and assessments related to the Fukushima Daiichi accident in 2011;

→ key developments related to application of radioecology for radiation protection, notably related to decommissioning and the management of nuclear and other legacies;

→ public engagement and risk communication; and

→ key projects undertaken by cooperating organizations.

The event was opened with a welcome by Per Strand, head of DSA and president of the IUR, and chaired by Astrid Liland (DSA).

1.1 Participation and program

Around 450 participants across all 6 continents registered to attend the online event, which was organized into the following topical areas:

→ updates on projects/work programs from international/regional and cooperating organizations;

→ public engagement and risk communication, based on case studies;

→ the Ecosystem approach;

→ application of radioecology to radiation protection; and,

→ radioecology and management of nuclear and other legacies.

The full event program is provided in Appendix A.

1.2 Preparation and structure of this report

The report is structured in line with the event program, as follows:

- → Chapter 2 presents summaries of presentations from International/regional and cooperating organizations;
- → Chapter 3 summarizes presentations on Public engagement and risk communication;
- → Chapter 4 outlines presentations on the topic of the Ecosystem approach;
- → Chapter 5 summarizes presentations on the Application of radioecology to radiation protection; and,
- → Presentations in the session on Radioecology and the management of nuclear and other legacies are summarized in Chapter 6.

Overall conclusions are then presented in Chapter 7.

2 International/Regional and Cooperating Organizations

2.1 The UNSCEAR 2020 Report on Fukushima: Implications of information published since the UNSCEAR 2013 report

Gillian Hirth (Chair of UNSCEAR) presented.

UNSCEAR published its first report, the UNSCEAR 2013 Report on the levels and effects of radiation exposure due to the 2011 Fukushima nuclear accident in 2014 following a 2-year assessment of the levels and effects of radiation resulting from the accident. An Expert Group was subsequently established to review new scientific information as it became available and to consider the implications for findings of the UNSCEAR 2013 report. In the period up until 2017, no challenges to the conclusions of the 2013 report were found in new scientific publications, but new interesting and relevant information and scientific developments were noted that could be taken into account in order to refine and improve understanding of the levels and effects of the radiation exposures resulting from the accident. Therefore, in 2018, a new project was initiated by the Committee to report on all available information up to the end of 2019 and to consider the implications of that new information on the UNSCEAR 2013 report. The new UNSCEAR 2020 report, available from https://www.unscear.org/unscear/en/fukushima.html, was published in March 2021, just prior to the 10-year anniversary of the accident. The report was developed with input from over 30 experts from 12 countries, with over 1600 peer reviewed articles being reviewed.

The report summarizes current understanding around 7 topical themes:

- → Releases to atmosphere, dispersion, and deposition
- → Releases to and dispersion in the marine environment
- → Transport through the terrestrial and freshwater environments
- → Doses to the public
- → Doses to workers
- → Health implications
- → Doses and effects in non-human biota

The experts also validated or revised the estimates of doses to the public and their health implications.

Overall, no changes were made to the total amounts of radionuclides released to the environment, but there were significant changes in the temporal patterns of release. Discharges of radiocaesium to the marine environment continue to occur from site groundwater and draining of catchment areas, but the activities now being discharged are orders of magnitude lower than the releases that occurred in 2011. Furthermore, in terms of transport through terrestrial and freshwater systems, concentrations of radiocaesium in monitored foodstuffs since 2015 remained below Japanese limits and guideline levels for international trade. An extensive 5-year decontamination program was implemented in affected areas that reduced annual doses to below 1 mSv and allowed people to return to many of the evacuated municipalities.

In terms of the estimated exposure of the Japanese public, annual effective doses to infants in the first year following the accident have been reduced, on average, by around a factor of 10 as compared with the 2013 estimates for municipalities with lower doses and up to around 40% lower for municipalities with higher doses. Thyroid doses for infants were also reduced. These reductions are counterbalanced, to an extent, by modest increases in external exposure estimates resulting from the use of an improved and validated model based on results from Japanese scientists.

In the 10 years since the accident, effective doses increased above the first-year dose by between 2 and 3 times and by about 4 times for lifetime doses. Doses for 2021 are estimated to be below 0.5 mSv in all non-evacuated areas of the Fukushima prefecture and below 0.1 mSv in the rest of the population. In communities where evacuation orders have been lifted, doses in 2021 are estimated to be below 1 mSv, taking into account completed remediation work.

Improvements in the estimate of public exposure in the UNSCEAR 2020 report arise from more information and monitoring data being available from extensive measurements having been made of radionuclide concentrations in environmental media and in people and from personal dosimetry campaigns in affected municipalities. There have also been numerous publications on doses resulting from different exposure pathways. Differences also relate to improved, more robust and realistic models that were based on an improved source term with better information on dispersion and deposition in the environment. A new model was also developed to estimate external doses from radionuclides deposited on the ground and taking into account soil types and climate conditions. Further model developments to account for the Japanese situation resulted in improved estimates for a range of exposure pathways with Japanese habits and behavior being taken into account, such as the use of air filters in homes and improved information on foods consumed. Overall, the revised estimates of exposures and associated uncertainties provide a more realistic estimate of exposure as compared with the UNSCEAR 2013 report.

Distributions of individual doses within municipalities have also been developed using a Monte-Carlo approach, taking into account factors that can influence exposures, such as diet and lifestyle and where people live and work. The distribution for effective dose in the Fukushima prefecture in the first-year post-accident were within a range of 10 times lower to 3 times higher than the prefecture average dose of 2 mSv.

Further research around the effect of remediation work on reducing doses as measured on people would be useful. Data on radionuclide concentrations in air would also be useful in improving thyroid dose estimates. However, human measurements provide the best basis for estimating doses and, if such measurements were not made at the time, it will not be possible to obtain such data. As a consequence, large uncertainties around dose estimates will remain and further research is unlikely to reduce those uncertainties significantly.

An improvement in the UNSCEAR 2020 report as compared to the UNSCEAR 2013 report is the use of more realistic evacuation scenarios in estimating the exposures of evacuees. In the UNSCEAR 2013 report, 18 evacuation scenarios developed by the Japanese National Institute for Radiation Sciences (NIRS) were used, based on results of a survey across the whole of the Fukushima prefecture. For the UNSCEAR 2020 report, there were 37 scenarios derived from random sampling of behavioral questionnaires of children from each of 7 municipalities in the evacuation area, as well as three scenarios from the UNSCEAR 2013 report that were not covered by the new scenarios. Estimated effective dose in the first year to infants for different evacuation groups ranged from 0.2 mSv to about 8 mSv whereas for adults the upper range was less than 6 mSv. The fact that high doses didn't occur was due to the evacuation, but also as a result of non-human factors, including the wind blowing to the ocean in the first days after the accident. On average, estimated doses in the UNSCEAR 2020 report are around a factor of 2 lower than in the UNSCEAR 2013 report.

The evacuation of people following the accident also reduced absorbed doses to the thyroid with the reduction in dose to infants being estimated at up to 500 mGy. The estimates of thyroid doses in the UNSCEAR 2020 report are also reduced as compared with the UNSCEAR 2013 report. The reduction in estimated doses for evacuees is again a result of improved models and data in the years since the accident. In terms of the distribution of doses among evacuees, it is estimated that effective doses range from between 0.1 and 5 mSv with the majority being below the average.

For worker doses, there were just under 25,000 on site workers in the period from March 2011 to October 2012. Delays in thyroid monitoring in some workers has led to increased uncertainty in the reported thyroid doses to workers. Since the 2013 report, there have been two re-evaluations of reported doses, but the general findings of the UNSCEAR 2013 report remain valid. The UNSCEAR 2020 report also includes dose estimates for off-site environmental remediation workers, of which there were around 77,000 in the period from 2012 to 2016. The average cumulative dose received was around 1 mSv, demonstrating that doses to remediation workers were small.

With regard to health effects in the general population in the Fukushima prefecture, the findings of the UNSCEAR 2020 report are generally consistent with the UNSCEAR 2013 report, but there is more information underpinning those findings. Future discernible cancer excesses, including of thyroid cancer, are unlikely given the generally low doses. The fact that a large number of thyroid cancers have been diagnosed were judged to be due to the ultra-sensitive thyroid screening, and not as a result of the radiation exposure. Studies showed no discernible excess of adverse reproductive outcomes (birth defects, stillbirths, pre-term births or low birth weights) although an increase in cardiovascular and metabolic conditions has been reported among evacuees, but not non-evacuees, but this is most likely a result of lifestyle changes and psychosocial stresses rather than radiation exposure. Such health, wellbeing and social impacts are an important issue for the population but were outside of the remit of UNSCEAR and are not, therefore, addressed in either the UNSCEAR 2013 or 2020 reports.

In terms of effects on wildlife, there is broad consensus around the levels of exposure and regional impacts on populations are considered unlikely. Individual impacts have, however, been observed.

Key lessons from Fukushima include the importance of collecting measurement data in both people and the environment both during and immediately after an accident in order to allow realistic dose estimates to be made, recognizing that modelling tends to produce more conservative dose estimates. It is also important to understand the baseline rates of cancers in a population and the sensitivity of screening techniques that may be applied to detect cancers following an accident.

The UNSCEAR 2020 report is an authoritative, independent, and up to date assessment of the levels and effects of radiation exposure due to the Fukushima accident. The main findings are robust and are unlikely to change significantly in the foreseeable future as further new information becomes available.

Discussion

Changes in temporal distribution patterns contributed to more realistic dose assessments but other improvements in monitoring can improve future dose assessment work and reduce uncertainties. For ongoing exposures, continual monitoring will be important but also gaining a greater understanding of the remediation activities and the impact they may have on affected areas and the exposure of the population will also be important. There have been multiple workings around the source term, and it is unlikely that this will change. It is also unlikely that estimates around temporal distribution patterns will change considering we are now 10 years post-accident. There may still be some data sets within Japan that have not yet been taken into account, such as data from personal dosimetry campaigns and such data could become available in the future and provide more information on the exposure of people.

It is unlikely that UNSCEAR will undertake to make a significant comparison between the Chornobyl and Fukushima accidents beyond the comparison of exposures and population and worker impacts included in the UNSCEAR 2020 report. The radionuclides released and the manner in which the accidents progressed were considerably different, which limits the ability to make useful comparisons. The Chornobyl accident occurred 35 years ago and the most recent report on this by UNSCEAR was a white paper published in 2017 that evaluated the data on thyroid cancer in the regions affected by the Chornobyl accident. For Fukushima going forward, there will be ongoing work and UNSCEAR has a future program of work, including a public exposure project that will be able to consider new information on public exposures and remediation efforts, subject to published information being available to the Committee.

2.2 Trends in radiocaesium and remaining issues in Fukushima after the 2011 accident

Hirofumi Tsukada (Institute of Environmental Radioactivity, Fukushima University) presented[1].

Ambient dose rates have been continually decreasing over the 10 years since the Fukushima accident in 2011. Activity concentrations of Cs-137 in the atmosphere dramatically decreased in the first months after the accident from over 10 mBq/m^3 in April 2011 to 0.1 mBq/m^3 by December 2011. More stable values have been recorded since this time.

Most Cs-137 deposited on forest soils remained in the surface soil in the 5 years following the accident but a different trend is observed for paddy fields where contamination is evenly distributed throughout the cultivation layer of the soil. Prior to the accident, Cs-137 was present in paddy field soils as a result of global fall out but was gradually decreasing over time to around 8 Bq/kg in 2000. However, following the accident, mean activity concentrations in paddy soils collected from throughout Japan increased to around 43 Bq/kg whereas activity concentrations in soils collected from paddy fields in the Fukushima prefecture in 2011 and 2012, prior to any decontamination efforts, ranged from several hundred to several thousand Bq/kg.

Rice is a staple food in Japan and huge amounts of irrigation water are required in rice cultivation. Irrigation reservoirs are therefore common with around 3700 such reservoirs being present in Fukushima prefecture. Radiocaesium in water exists both in dissolved and suspended forms and use of irrigation water is therefore an important pathway in the transfer of radiocaesium to rice. it has previously been reported that around 95% of radiocaesium is in the suspended fraction which is strongly bound and unavailable for uptake by rice. Activity concentrations in the dissolved fraction, which is available to plants, have been gradually decreasing over time. Over 50 samples of irrigation water have been collected from within the 80 km zone around the Fukushima accident site and analyzed. Over 80% of Cs-137 in the dissolved fraction existed in cation form, which is mobile and phytoavailable.

In order to reduce soil to plant transfer, decontamination measures have been undertaken through the stripping of surface soils and the application of potassium fertilizer. Around 10 million 30 kg bags of rice have been inspected annually from the Fukushima prefecture and, since 2015, no rice has been measured to have activity concentrations above the standard limit of 100 Bq/kg. Rice harvested from designated paddy fields throughout Japan has been subject to monitoring for Cs-137 and Sr-90 activity concentrations since 1965. Results show that activity concentrations of Cs-137 gradually declined over time to around 0.1 Bq/kg on average in 2010 with activity concentrations in rice from Fukushima prefecture falling within the overall range across Japan. In 2011, activity concentrations in rice from Fukushima prefecture reached around 10 Bq/kg but reduced to less than 1 Bq/kg from 2013, which was similar to the values reported for the 1960s to 1970s. Activity concentrations of Sr-90 were similar to levels across Japan suggesting that the source was global fallout rather than resulting from the accident.

[1] Further detail is available in Radiocaesium in the environment of Fukushima (sagepub.com).

Within the evacuation zone, populations of wild animals have been increasing and monitoring has shown that activity concentrations of radiocaesium have been increasing. It is therefore forbidden to hunt wild animals for food. Activity concentrations of Cs-134 and Cs-137 are highest in wild boar, which also show the greatest range in activity concentrations, but are decreasing (from around 1160 Bq/kg in 2011 to 113 Bq/kg in 2020). Seasonal variation in concentrations is observed with lower concentrations occurring through the summer season as compared with the winter season (September to March).

The long-term trend in Cs-137 in surface seawater prior to the accident show a continued decline. Following the accident there was an immediate increase in Cs-137 concentrations in seawater off the coast and in the neighboring prefecture. Activity concentrations have decreased since and are currently close to pre-accident levels. Activity concentrations in marine biota following the accident increased with the extent of increase varying with distance from initial deposition areas and were affected by transport by ocean currents. Activity concentrations from biota sampled from the East Pacific were relatively high, ranging from 0.2 to 110 Bq/kg just after the accident, decreasing to around 3 Bq/kg in 2016.

The internal radiation dose from inhalation in 2012 was very small and lower than that arising from the intake of agricultural food. Overall, internal dose was lower than external dose, which contributed around 95% to total radiation doses. Dose arising from the ingestion of food contributed less than 5% to the total dose. Internal doses are also decreasing as a result of several factors, including market dilution and culinary processing. Internal doses to adult men and women, determined by a market basket approach, reduced by around a factor of 10 in the period from 2012 to 2017.

It was concluded that, over time, activity concentrations of radiocaesium in the environment are decreasing. Transfer of radiocaesium to plants, animals and people have also been reduced as a result of countermeasures, decontamination activities and the use of potassium fertilizer and a change in Cs-137 from mobile to immobile fractions. As a result, internal doses are negligibly small and overall radiation doses are less than 1 mSv with external exposure being the greatest contributor to dose.

A number of issues arising as a result of the accident remain to be solved. Decommissioning, treatment of water and decontamination of waste will lead to a long-term solution, but other factors also need to be considered, including the increase in wildlife populations as a result of resident evacuations and abnormalities reported in pine trees etc. that need to be investigated.

Discussion

Consumption of rice from paddy fields is an important pathway for the Japanese and is a pathway that was not considered after the Chornobyl accident. It is, therefore, a new and interesting pathway from a scientific perspective. The food screening program for the affected districts has helped in gaining public trust.

The seasonal differences observed in Cs-137 activity concentrations in wild boar relate to differences in food consumption by the boar population through the year. The agricultural food monitoring program has been funded primarily by the government, including local government, but private companies have also been involved, such as in the provision of some monitoring equipment for supermarkets. The use of decontamination and fertilizer application measures has resulted in a considerable decrease in Cs-137 activity concentrations in agricultural crops.

To date, no clear evidence of radiation effects in wildlife as a result of the accident has been published.

2.3 Trends in radioecology: last decade through the lens of the Journal of Environmental Radioactivity (JER)

Che Doering (JER) presented.

The JER is a hybrid open access journal for original research and review papers on any aspect of radioactivity in natural systems that was founded in 1984. Since then, over 5,000 papers have been published, including in 47 special issues. The journal has a good CiteScore and impact factor for what is a niche discipline. It is supported by an editorial board from around the world.

The JER was used as an index of radioecology to look at trends from 2010 to 1019 and to compare to prior decades, back to the 1980s. Citations were downloaded and compiled in a MS Excel spreadsheet. In undertaking topic searches on titles, abstracts, keywords etc. it was assumed that if the topic was mentioned then the paper would be highly applicable to that topic. The number of papers for each search were counted and information on the country the lead author was from was identified.

In terms of the number of papers published in the last 4 decades, it is evident that more and more papers are being published each decade with an interest in radioecology with an increase of over 800 publications each decade. Furthermore, each decade, the number of countries represented by authors has increased such that today, radioecology is a truly international discipline with countries from all continents being represented although north America, Asia and Europe are the most represented with Australia being the only southern hemisphere country in the top 10 and is an example of a country where the number of papers has increased rapidly over the last 4 decades. The top 10 countries involved in the field of radioecology, based on publications, were Japan, USA, France, China, UK, Spain, Germany, Russia, Canada and Australia. The proportion of papers with authors from Australia has also increased over the last four decades, from 0 to 5%. A similar trend is observed for China and Japan whereas the number of authors from the UK has plateaued, resulting in a decrease in the proportion of papers with UK authors from 20% to less than 10%. The proportion of authors from Germany has remained more stable over time.

In terms of radionuclides of interest between 2010 and 2019, caesium has been the most studied element (and especially
Cs-137) with naturals being the next most studied (uranium, radon, radium, lead, potassium and thorium) with iodine, plutonium and strontium then completing the top 10. The number of studies relating to caesium has remained relatively constant at around 40% of the papers published. For naturals, the proportion of papers has increased, suggesting an increased interest in natural radionuclides. For plutonium etc., the proportion of papers has decreased although the number of papers has plateaued. Xenon does not appear in the top 10, but there has been a rapid increase over the last decade from 0% to 2% of papers.

For significant events releasing radioactivity to the environment, Fukushima has naturally featured highly over the last decade with over 400 papers being published around this event. Chornobyl was the next most published event, followed by past nuclear weapons testing. The next most significant events cited in papers were Sellafield, Goiania and Three-mile island. Papers on Chornobyl have plateaued, and the proportion has been decreasing over the last decades. For nuclear weapons, the number of papers has increased steadily, but the proportion has decreased.

The most cited environment types over the last decade have been (in order) the atmosphere, oceans, rivers, forests and lakes. Polar regions were less studied. Environmental uses were mainly transfer, transport, deposition and sedimentation. The main industry types cited were nuclear power and waste, but there were also a lot of papers on NORM industries, including mining.

The JER is therefore a growing index of radioecology that can be used to analyze trends in different disciplines. Authorship continues to increase, especially from Asia and Australia with natural decay series and xenon and krypton gaining in popularity. Fukushima is the most significant event of the last decade and atmosphere and oceans are the main environment types studied with wetlands, deserts and polar regions being less studied.

Discussion

The increase in papers relating to xenon is believed to result from the roll out of an international monitoring system that includes xenon monitoring stations worldwide. Polonium was also an important element but fell just outside the top 10 elements focused upon in the published papers. It is trickier to measure than other natural radionuclides and this may be why it doesn't rank higher. The gender and age of authors are not reported in papers so unfortunately cannot be analyzed. There has been a strong increase in the number of papers relating to non-human biota. Trends in the number of papers relating to human dose assessments were not analyzed.

2.4 Joint IAEA/FAO/WHO Project on Radionuclides in Food and Drinking Water in non-emergency situations

Tony Colgan (IAEA) presented.

Historically, the IAEA Safety Standards only referred directly to radionuclides in food and drinking water in relation to responses to large scale nuclear emergencies. This, however, changed in 2014 with the publication of General Safety Requirements (GSR) part 3 on 'Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards'. GSR Part 3 covers all three ICRP exposure situations (planned, emergency and existing), all categories of exposure (workers, patients, public and environment) and addresses both natural and anthropogenic radioactivity.

There is a specific requirement in section 5 of the GSR Part 3 (which addresses existing exposure situations) to establish specific reference levels for food, feed and drinking water, based on the annual effective dose to the representative person, that does not exceed a value of about 1 mSv in a year. Control on the transfer of radioactivity to food in planned exposure situations can be achieved through controls on discharges. However, in the case of existing exposure situations there can be many different sources contributing to the radioactivity observed in food and many of these may not be either identifiable or controllable. Therefore, both justification and optimization play an important role in managing doses from radioactivity in food and drinking water in existing exposure situations.

In developing guidance for Member States, advice from the World Health Organization's Guidelines on Drinking-water Quality (WHO-GDWQ) and the Codex 193-1995 standard were summarized (Table 1) and some inconsistencies and gaps are evident when compared with GSR Part 3. For example, dose criteria and age groups differ. Whether or not natural radionuclides are included also varies, along with terminology and work is needed to clarify the situation. In GSR Part 3 the Reference Level applies to both natural and anthropogenic radionuclides. However, there has been the view that natural radioactivity is not controllable and, as such, should be excluded from the scope of the Requirements. This is despite the fact that natural radioactivity is normally by far the dominant source of exposure from the diet.

There are choices that can affect food contamination. For example, the choice could be made not to grow food in contaminated soils and discharges from mining activities could be controlled to limit uptake in downstream fish farms. As an extreme measure, for example in the immediate aftermath of a nuclear accident, consumption of contaminated foods can be controlled. There are fewer options, however, to control the uptake into food of natural radionuclides present throughout the environment.

Table 1 Comparison of guidance for radioactivity in food and drinking water.

	IAEA GSR Part 3	WHO-GDWQ	Codex 193-1995
Scope	Non-emergency	Non-emergency	Relevant after an emergency
Dose criteria	1 mSv/y	0.1 mSv/y (Individual dose criterion)	1 mSv/y (assuming 10% of the diet is affected)
Activity concentrations	No	Yes	Yes
Age groups	Representative person	Adults	Infants/non-infants
Radionuclides	Both natural and anthropogenic	Mainly natural, but also covers anthropogenic	Some anthropogenic
Terminology	Reference level	Guidance level	Guideline level

Some information on natural radionuclides in food is available from UNSCEAR (2000) that identifies four key radionuclides in terms of radiation dose (Ra-228, Ra-226, Pb-210 and Po-210) and gives reference values for natural radionuclides in 6 food groups and drinking water. Concentrations of natural radionuclides in foods tend to be considerably higher than in drinking water, and relatively high concentrations of Po-210 are often observed in fish and shellfish.

An international steering group was set up in 2017, which was chaired by Per Strand (DSA), and had a joint secretariat from WHO, FAO and IAEA to advise on work in this area. It was recognized that more information on the levels of natural radionuclides in food was needed, so the work program started with a review of recent literature (1998 – 2017) and Member States were requested to provide monitoring results where available. The steering group also reached out to the Codex Committee on Contaminants in Food to raise awareness of radioactivity in food among those responsible for overall food quality.

The ultimate objective of the project is to develop an approach to deal with both natural and anthropogenic radionuclides in food and drinking water, but avoiding setting criteria for natural radionuclides in foods that may be interpreted as limits.

The various approaches to diet sampling were reviewed and 158 studies from 45 countries were identified and evaluated. The review focused on sampling and analysis of the total diet, rather than individual foods. The importance of the aquaculture industry was considered. Currently, around half of the fish and shellfish consumed is farmed and this is likely to increase in the future. There was therefore interest in whether farmed fish had higher or lower concentrations than wild fish. Activity concentrations in mineral waters were also reviewed to determine how they compared with those drinking tap water. A detailed review of radioactivity in wild foods was also undertaken.

The diet studies indicate that there are seven radionuclides (or 8 if Cs-134 and Cs-137 are considered separately) that are the main source of radiation doses from food: Ra-228, Ra-226, Pb-210, Po-210, Cs-134+137, Sr-90 and C-14. Doses from K-40 were not considered since doses from this radionuclide are fixed, irrespective of diet. 95% of the dose is attributed to the four natural radionuclides. The contribution from C-14 was a surprise, with this radionuclide contributing to around 3% of dose. No difference was observed in the dose received by infants, children and adults, but there were limited data available. And also large variability between the various studies. Po-210 was the dominant radionuclide in most diets with concentrations being particularly high in seafood, especially molluscs. There was also some evidence that concentrations of Po-210 were lower in farmed fish that were fed than in wild fish, but this does not affect shellfish since these are seldom artificially fed.

The groups receiving higher doses were also considered. Certain wild animals and mushrooms accumulate Po-210, Cs-137 accumulates to varying degrees in forest products and both Cs-137 and Sr-90 are known to accumulate in freshwater fish. In some Scandinavian countries and in the UK, there are some areas where there can be high uptake of Cs-137 from marginal lands to agricultural products such as meat and milk.

The data available indicated that doses from natural mineral waters were generally low; similar to those in drinking water and much lower than those observed in food. However, a small number of mineral waters had very high concentrations with Pb-210 being the most important radionuclide.

Average values for doses from the diet indicate that, of a total annual dose of around 0.26 mSv, 0.14 mSv is attributed to Po-210 (Table 2). When one excludes K-40 from the dose estimate published by UNSCEAR, the annual dose determined in this project is around twice that from UNSCEAR but still extremely low. The approaches taken were completely – the UNSCEAR approach uses activity concentrations in individual foods rather than in the total diet – and so a difference of a factor of two should not be surprising.

Table 2 Average doses from the diet

Radionuclide	Annual dose (mSv)
Po-210	0.14
Pb-210	0.05
Ra-228	0.03
Ra-226	0.02
C-14	0.009
Cs-137+134	0.004
Sr-90	0.003

In terms of the range of activity concentrations from various radionuclides in diets, there is evidence that some individuals could receive perhaps 2 mSv from Po-210, Ra-228 and Ra-226. More information is, however, needed on Ra-228 as there was significantly less data on this radionuclide than the other natural radionuclides.

The 95th percentile of the worldwide distribution of the activity concentrations of natural radionuclides per food group were determined. For Po-210, the highest values are associated with aquatic foods and lowest with agricultural foods. It is proposed that the percentile values could be used by member states to identify whether their data falls within the normal worldwide ranges. If data fall outside these ranges, a first step would be to consider whether the data are correct (i.e., whether the measurements are accurate) and then whether further analysis is necessary. This is broadly similar to the approach advocated by WHO in dealing with radioactivity in drinking water.

The report has been finalized and will be published in the near future. The IAEA will continue consultation with its Member States and with the relevant international organizations on how to implement the GSR Part 3 requirements for radioactivity in food and drinking water.

Discussion

It is clear from discussions with member states and among the steering group that there is no expectation to establish limits for natural radionuclides in foods. The focus is usually on anthropogenic radionuclides, even though doses from natural radionuclides tend to be considerably higher. Reference levels for natural radionuclides would need to take account of the degree of controllability and optimization is a key issue. The question should always be whether there is anything reasonable that can be done to reduce doses, which may be in the form of providing advice rather that imposing restrictions on the consumption of certain foods.

Mushrooms are known to accumulate Po-210 and certain wild animals that are widely consumed by sub-groups of the population also accumulate this radionuclide. In the case of reindeer and caribou, increased accumulation arises from their diet (lichens accumulate Po-210). Since Po-210 is a key contributor to the dose received from diets, there may be merit in encouraging more research to be undertaken on this radionuclide (Po-210 did not make the top 10 list of most researched radionuclides, as presented by Che Doering – see section 2.3). More work around C-14 in foods may also be warranted.

The level of Po-210 in foods could result in some doses from diet in excess of 1 mSv in a year, particularly where seafood consumption rates are high. However, whether dose from natural radionuclides should be subject to additional controls needs to be carefully balanced since there can be economic implications. Providing information will enable people to make informed decisions.

2.5 Status of Plans for a program to follow MODARIA II

Joanne Brown (IAEA) presented.

The MODARIA II program ended in the autumn of 2019. It was the latest in a series of programs organized by IAEA with the aims to improve capabilities in the field of environmental transfers of radionuclides and public and biota dose assessments through improved data and consensus on model approaches and parameters, and to build an international forum for the exchange of information and support in the development of assessment tools etc. Various topics have been considered, including transport in the marine environment, exposure and effects to biota, transfer parameter data, urban environments, biosphere modelling and norm and legacy sites. A lot of work has been undertaken to compile new Kd data, and an IAEA TECDOC on transfer parameters for caesium based on data following the Fukushima accident, as well as new data compilations for arid and tropical environments.

A key focus of previous programs has been on producing IAEA publications on the work of the different Working Groups, usually as IAEA TECDOCS. The IAEA has been considering whether this is the best approach to make the work available moving forward, as they can be time consuming to produce. A lot of journal publications have also been produced and a special issue of the Journal of Radiological Protection is planned for 2022 that will cover the output from the MODARIA I and II programs.

Feedback on the programs to date suggest that there is support for them to continue and work has therefore been undertaken over the last 6 months or so to consider the scope, objectives and delivery of the next program - Methods for Radiological and Environmental Impact Assessment (MEREIA). Overall, the aim of the new program is to ensure capabilities in countries to address actual problems in the field, including how to select the right assessment approach for a given situation and to understand when there is a need for more complex models or where simpler modelling approaches are appropriate. The new program will therefore aim to identify where there are gaps in guidance that would help support countries and to encourage countries to make the most of what has been developed so far (e.g., pulling together information from different TECDOCs to make it more accessible). There will also be a greater focus on future generations and encouraging and supporting/training young professionals through a mentoring type of framework. Consideration will also be given as to how new member states can be attracted and efforts will be made to avoid duplication of effort with other forums and research programs.

The way in which information is disseminated has been reviewed and the suggestion made to have a final symposium at the end of the program and to include more workshops, guidance publications and the use of digital platforms. Efforts will be made to place radioactivity in the context of wider environmental assessments and to start discussions in terms of practical guidance by bringing both experienced and less experienced people together. There will be fewer thematic areas than in previous programs with a more matric approach being applied to integrate topics within thematic areas. A focus on whole radiological scenarios is intended rather than only dose assessments, taking account of wider social and environmental aspects, to consider how best to use models and research to support application and assessment of radiological impacts in order to bridge the gap between academia and assessments/solutions. A key focus will therefore be on the use of fit-for-purpose models and the development of assessment approaches and guidance to inform on what is needed for different situations.

The program will aim to support the professional development of those new to the field and it is hoped that a forum or network of mentors can be developed to support those new to the field in the writing of papers and in exploring ideas. Consistent with previous programs, it is intended that a single plenary session will be held annually, but advantage will be taken of virtual platforms throughout the year to encourage greater networking. There will also be the opportunity for increased training on the use of models etc., and for young professionals to present their work.

An outline scope and objectives for MEREIA was developed in June and consideration is now being given as to how best to take this forward. A virtual meeting was held 4-8 October 2021 to launch the program and to develop and agree on thematic areas and activities.

Discussion

The idea of a final symposium at the end of the program to disseminate output was welcomed, as was the idea around collaborating with other programs. There are several ongoing coordinated research programs, including one of transfers in arid environments and a near-surface disposal forum that is looking at tools and approaches to support assessments for near-surface radioactive waste disposal. The aim will therefore be to make the best use of the data and knowledge obtained from such programs, such as the application of approaches from near-surface disposal assessments to support assessments around site remediation. It is recognized that time and resources are limited so active working between groups will be encouraged by inviting participation between the different forums.

The research element is extremely important and underpins assessments and the development of safety standards and tools . The importance of bridging between academia and the assessment / regulatory community is recognized.

With the increased use of virtual meetings, it is hoped that more people can be reached, with events being organized throughout the year in addition to an annual face-to-face meeting.

2.6 Radiation weighting factors for Reference Animals and Plants

Kathryn Higley (ICRP) presented.

A new ICRP report has been developed on radiation weighting factors for animals and plants (ICRP Publication 148).

It has been recognized for a long time that biological impact can vary depending on the type of radiation involved and, as a consequence, there have been both in vivo and in vitro studies that have shown that the magnitude of the effect depends not just on the dose and type of radiation delivering the dose but also on the rate at which the dose is delivered and the endpoint. These relative biological effects (RBE) data have been looked at in order to derive radiation weighting factors for humans in order to derive equivalent dose in sieverts as a means of limiting stochastic effects in people. For protection of biota, the focus tends to be on the protection of populations. ICRP Publication 148 therefore reviewed RBE data relevant to biota for one low beta emitter (tritium) and alpha emitting radionuclides.

The ICRP Reference Animals and Plants (RAPs) was first introduced in ICRP Publication 108. The ICRPs environmental protection aim is to reduce the frequency of effects on biota to a level where they would have a negligible effect on the maintenance of biological diversity, the conservation of species and the health of natural habitats, communities and ecosystems. A set of derived consideration reference levels (DCRLs) were established, following review of available effects data, for a range of different RAPs. The DCRLs are order of magnitude bands of dose rates within which there is some chance of deleterious effect to individuals of that type of RAP and are intended as points of reference to be used alongside other relevant information. The DCRLs do not, however, include any radiation weighting.

For humans, doses to organs and tissues for different radiation types are multiplied by the appropriate radiation weighting factor to derive equivalent dose. The weighting factors are largely based on experimental data relating to stochastic effects. Therefore, Publication 148 includes a review of RBE data for exposure to tritium beta particles and alpha emitters and, based on this review, weighting factors are proposed for RAPs. It is intended that these can be used to derive weighted dose rates for RAPs that, combined with the DCRLs, can be used in assessments.

The biological endpoints of relevance for biota are those that could lead to changes in populations, i.e., deterministic effects including survival, fecundity and reproductive and developmental impairments. However, data are limited and, for the protection of non-human biota, mutations, chromosomal aberrations etc. tend not be assessed in terms of population viability and are taken to occur without thresholds. Therefore, for the review, RBE as a function of dose rate was reported in four categories:

- Early mortality;
- Reproductive failure;
- Morbidity (including data on cancer induction); and
- Chromosomal damage and mutation.

RBE values for early mortality for tritium beta particles were determined to be in the range from 1 to 1.7. For reproductive dysfunction, the range was from 1 to 3.9 and RBE values relating to morbidity were in the range of 1 to 2.5. For the induction of chromosome damage and mutation, RBE values ranged from 1 to 3.8. All available data related to tritiated water and the majority were for small mammals. All the values were obtained at dose rates that were above or within the relevant DCRL bands and RBE was shown to increase with decreasing dose rate. Consistency in the spread of data (from 1 to around 4) was observed across species. Overall, and consistent with the findings of UNSCEAR, values centered around 1.5 to 2 as compared with x-rays and 2 to 2.5 compared with gamma rays.

The review of RBE for alpha particles identified around 90 relevant publications, but only 58 of these were reviewed in detail due to limitations in the remaining publications. The majority of the reviewed articles either directly reported RBE values or provided sufficient data to allow RBE to be calculated. The maximum RBE for very low dose rates were also calculated for stochastic endpoints where possible. The review found that, for reproductive dysfunction, there was a wide range of reported RBE values, but most were in the range of 1 to 5. Only 6 articles reported data in relation to morbidity for alpha particles, and the majority of values were again less than 5. For chromosome damage and mutation (which are difficult to relate to population impacts), most values were in the range of 1 to 10 with a few papers showing values around 20. As with the data for beta particles, the majority of data available related to vertebrates, especially small mammals, and related to reproductive dysfunction and morbidity. Overall, the data were very limited adding to the challenge around alpha dosimetry (e.g., heterogeneous distribution and the short range of energy deposition). All RBE data for alpha emitters were obtained at dose rates that were in or above the relevant DCRL bands and data were extremely limited for the species included. Nonetheless, the values obtained, whilst widely ranging, center around values of the order of 10.

The publication therefore provides a review of RBE data for low-energy beta particle emissions from tritium and alpha-particle emitting radionuclides to consider whether RBE values should be used to modify absorbed dose rate calculations for non-human biota for comparison against the relevant DCRLs. The RBE values varied according to factors such as the endpoint and dose rate, but in general there was some consistency in values across species. The lack of observed differences between species suggests that the derived RBE values can be applied across species. For tritium, reported values centered around 1.5 to 2 compared with x-rays and 2 to 2.5 compared with gamma rays whereas values for alpha particles were generally higher at around 10. The review did, however, conclude that further RBE data for a range of different species are needed.

The ICRP approach to protection of the environment is intended as a reasonable and prudent approach to determining whether there is a reasonable chance of impacts occurring to populations of non-human species. As such, it was concluded that it may be appropriate to take RBE into account but does not advocate the use of a separate weighting factor terminology and research is needed to clarify the mechanisms at play in radiation inducing the effects of interest. Where RBE is used, there should be clear documentation on the original values and the values of weighting applied to ensure transparency and reproducibility of results.

Discussion

Studies show that RBE is higher for various endpoints for lower dose rates. Therefore, ideally the stable maximum value of RBE at lower dose rates should be used, but this requires extrapolation from survival curves which can be challenging and there may not be sufficient data to support such analysis. Overall, greater data across RAPs would be useful to improve the assessments. Whilst available RBE values do indicate some consistency across species, but most data are for small mammals/rodents so it would be useful to have additional data for a wider range of species, including plants. It is, however, recognized that such studies can be challenging. The studies available came from a range of institutions and over several decades. Nonetheless, the overall number of data were limited, and additional data would support a more robust analysis in the future.

2.7 Feasibility study and preparation for the implementation of an Action Plan concerning the safe and secure management/disposal of sunken radioactive objects in the Arctic Sea

Alain Van Den Brande (EC) presented.

A feasibility study was funded by the EU within its framework for international cooperation on nuclear safety. The study lasted 5 years, ending in 2020. The overall objective was to improve living and working conditions in the Arctic area as a first step toward environmental sustainability. The study deliverables included an inventory of the sunken radioactive objects and their location and condition; identification of the risks and the top 5 or 6 most critical objects along with an assessment of the potential impact of those objects on people and the environment in the long-term and associated with any retrieval operations; analysis of options for the safe and secure management of the options; and the development of an Action Plan.

Around 17,000 objects were dumped between 1959 and 1992 as a result of 80 dumping operations or accidents. Together, the objects represent around 40,000 m^3 of radioactive waste. Most of the operations took place in the 1960’s and 1980’s and with an accident that occurred in 2003 with nuclear submarine K-159. The most active objects are nuclear submarines and reactor components and compartments containing nuclear fuel. Over 3 decades, dumping of solid radioactive waste was only authorized at 7 specially designated sea sites that were primarily off the coast of an island along with a single deep-water site, further offshore. The majority of radioactivity is located at depths of less than 60 m below sea level. It has been possible to locate accurately some objects due to convergence data from a range of sources, but the accurate location of other objects will require further investigation prior to retrieval due to divergent information.

In order to identify the most critical objects, a risk assessment was undertaken, taking into account the inventory of sunken objects (isotopes and activity levels), criticality risk during retrieval, containment condition (dumping time and number of barriers) and environmental parameters such as depth, fishing and commercial activities and vicinity to populated or protected areas. Each of these four categories was given a specific weighting that was used to calculate overall risk scores for each object. In recognition that the weighting between categories can be somewhat subjective, an exercise was undertaken to look at the weighting of the categories and examine their effect on the overall scores and the output was also compared against a different method of scoring to test the robustness of the output.

As would be expected, the highest risk objects are those still containing some nuclear fuel. Irrespective of the method considered, the same 6 objects ranked highest. These are nuclear submarines K-27, K-159 and K-11, reactor compartments of submarines K-19 and K-140, and shielding from the icebreaker OK-150 Lenin. For each, 6 options were considered ranging from long term monitoring to full retrieval or retrieval of reactor components only.

For the nuclear submarines K-27 and K-159, the best option was deemed to be full retrieval using pontoons. The use of hydraulic jacks or a crane could be used for retrieval, but these were considered less optimal on the basis of either safety or financial viewpoints. For the other objects, long term monitoring on the seabed was the preferable option. The cost of retrieval of K-27 and K-159 are estimated to be around 120 million Euros plus an annual cost of 1 million Euros for monitoring of the other objects. These estimates apply to retrieval or monitoring operations, apart from any additional cost for dismantling, storing or depositing the objects. All estimate costs will be updated as the actual operations are considered.

The Action Plan has four steps:

- → Legal/administrative
- → Survey
- → Final design
- → Operation

At the time of the study there was no legal framework delegating the objects to any Russian institution, with the exception of K-159 which can be considered the property of the Ministry of Defense of the Russian Federation as it was not transferred to any plant for decommissioning. The legal administrative step could last around 1 year. A survey then needs to be conducted for each object to confirm its location and condition and the appropriateness for the option initially selected. The survey step could last around 18 months. The design step could then last around a year with operations then lasting between 1 and 3 years for each of the nuclear submarines. Therefore, in total, the Action Plan could take around 6 years to complete and excludes any further required activities such as dismantling, conditioning or waste disposal.

Discussion

The largest uncertainty relates to the actual condition of the objects. In most cases, the study could be performed based on archived information in order to define their current condition, but for K-140 the exact condition of the reactor compartment remains unknown. As such, retrieval or monitoring operations for any of the objects will require further investigations to be performed to determine or confirm their actual condition. The Action Plan will define who is responsible for which object as a first step, including who is the final owner of the objects. It is known that they all belong to the Russian Federation but no delegation is given to particular institutions or ministries that would allow them to take responsibility for any retrieval or post-retrieval operations. It is clear, however, that the Russian Federation has the full technical capacity to proceed with any post-retrieval operations.

2.8 The future of European Radiation Protection Research and the role of the ALLIANCE

Hildegarde Vandenove (ALLIANCE, SCK·CEN) presented.

ALLIANCE is a European platform on radioecology that was formed in 2009 in order to develop a vision on long-term research needs in radioecology and to foster cooperation between organizations and ensure sustainability in the field of radioecology. The objectives were to coordinate and promote research in radioecology, act as a research platform and to promote radioecology. Initially there were 8 founding members, but as of June 2021, membership had increased to 32 members from 17 countries.

A Strategic Research Agenda (SRA) was developed that was largely focused on environmental exposures and the assessment of human and ecological risk and its management. The ultimate goal is to enhance our mechanistic understanding of all the domains of radioecology in order to provide fit-for-purpose human and environmental impact assessments that will allow human and wildlife protection. Three main challenges were identified:

1. To predict human and wildlife exposures in a robust way by quantifying key processes, which is supported by source term analysis and modelling dispersion and transfers in the environment and exposure of people and wildlife.
2. To determine ecological consequences under realistic exposure conditions where the consequences of exposure are evaluated from an individual up to a population level or even ecosystem level.
3. To improve human and environmental protection by integrating radioecology by combining exposure and effects which leads to risk characterization and deal with the management of sites, including those with radioactive and non-radioactive contaminants.

A number of working groups have also been established on the topics of atmospheric radionuclides in transfer processes, marine radioecology, human food chain, naturally occurring radioactive materials (NORM) and transgenerational effects and species radiosensitivity. An implementation plan has been developed for all these working groups. As a result of the NORM working group, a RadoNorm project has been developed. There are also generic working groups that deals with the SRA, training, infrastructure and stakeholders.

One important project has been CONCERT that helped with the integration of radiation protection research that aimed to promote and accelerate radiation protection. CONCERT ran from June 2015 to May 2020. There were a number of work packages that were dealing with the development of a SRA, and the development of a joint roadmap for radiation protection at a European level. There were also a number of research projects.

The joint roadmap was established on the basis of the SRAs from the different platforms. The roadmap defines the priority areas and strategic objectives and provides a vision for a European radiation protection research program to 2030. It also presents priority research challenges for all the different exposure scenarios that are dealt with in radiation protection and, within these challenges, game changers were identified that were research issues with the potential to substantially impact and strengthen the system of radiation protection. The roadmap is also intended to serve as a guide for future research calls.

The platforms included, in addition to ALLIANCE: MELODI on low dose research; NERIS on emergency management; EURADOS on dosimetry; EURAMED for medical applications; and SHARE for social sciences and humanities. The platforms therefore represent all aspects of radiation protection.

Two of the challenges identified had strong links to radioecology. These were 'understanding radiation-related effects on non-human biota and ecosystems' and 'integrated approach to environmental exposure and risk assessment from ionizing radiation'. Example 'game changers' for the first of these challenges included lifting the controversy with regard to effects on wildlife reported in the Chornobyl and Fukushima exclusion zones and how to determine the effects of radiation on ecosystem functioning. For each game changer, what needs to be done to address the challenges was identified as a function of time. The game changers were also prioritized.

Within CONCERT and other projects, ALLIANCE contributed with research, such as the TERRITORIES (To Enhance unceRtainties Reduction and stakeholders Involvement Towards integrated and graded Risk management of humans and wildlife in long-lasting radiological Exposure Situations) and Confidence (Coping with uncertainties for improved modelling and decision making in nuclear emergencies) projects. One of the benefits for ALLIANCE resulting from the Confidence project was improved decision making during early and transitional phases of emergencies by reducing uncertainties in radiological data and model predictions.

A new project SINFONIA began in 2020 and will run until August 2024 on the management of patients with lymphoma or brain tumors where radiation is used in treatment and/or imaging. Benefits for ALLIANCE from this project will be the gathering of modelling parameters and data for medically-relevant radionuclides and a first-stop practical method for assessing the impact of releases from medical facilities to people and the environment in routine and accidental situations.

It is not just the SRA and roadmap that are important for ALLIANCE, there is also a lot of science involved.

Within the CONCERT project, a memorandum of understanding was developed between the six platforms in order to have one strong voice on the topic of radiation protection in Europe (MEENAS). MEENAS began in March 2020 and has developed a draft proposal for a European partnership for radiation protection research under Horizon Europe, with input from representatives from major European research institutes, and has a strong emphasis and link with medicine / health. Four specific objectives have been identified, two of which are linked to radioecology:

- To consolidate regulations and improve practices in the domain of low dose exposures of humans and the environment by further understanding and reducing uncertainties associated with risk estimates.
- To be better prepared for response and recovery from a potential radiological event or nuclear accident and to improve the know-how to manage legacy sites.

This has resulted in a new EURATOM call for 2022-2025 on a European partnership for research in radiation protection and detection of ionizing radiation. Within the project structure there is again a strong influence from the different platforms involved.

The integration of the European platforms has led to integrated radiation protection strategies and provide the pillars for sustainability and for representing the voice of the whole radiation protection community.

Discussion

There continues to be a lot of students applying for PhD positions in the field of radioecology, which suggests that this subject remains interesting for the younger generation and it is hoped that the platforms will lead to more integration and better cooperation across different fields. The collaboration between platforms has led to a positive evolution and greater voice for radioecology and provides a better inroad to European funding through Euratom calls, ensuring that research continues and that the different parts of radiation science are addressed at the correct level.

3 Public Engagement and Risk Communication (Case Studies)

3.1 Monitoring and communication of environmental survey results: Case study in Yamakiya District

Tetsuo Yasutaka (National Institute of Advanced Industrial Science and Technology) presented.

Yamakiya district is a small district located in the northwest area of Fukushima Daiichi nuclear power plant (NPP) evacuation zone. An environmental survey has been undertaken over a period of 10 years and communicated with local stakeholders, which has led to a number of scientific publications, including:

- Yasutaka et al (2020). Dialogue, radiation measurements and other collaborative practices by experts and residents in the former evacuation areas of Fukushima: a case study in Yamakiya District, Kawamata Town star. Radioprotection 55: 215-224.
- Schneidert et al (2019). The role of radiological protection experts in stakeholder involvement in the recovery phase of post-nuclear accident solutions: some lessons from the Fukushima-Daiichi NPP accident. Radioprotection 54: 259-270.

The monitoring program has required the development of a method for analyzing caesium in freshwater, seawater and paddy fields to study environmental dynamics and has also involved developing and applying a risk analysis and management method for radiocaesium in soils. There is around 13 million tons of contaminated soil within the prefecture that needs to be moved out of the prefecture for disposal. Social acceptance is needed for the final disposal of these contaminated soils. Communication is very important and research results need to be shared with local stakeholders including local authorities and residents. A number of mistakes were made initially during the monitoring and communication program in the communication with local people that led to improvements in the approach.

The Yamakiya district is located around 40 km from the NPP, on the edge of the most contaminated area and was, therefore, subject to an evacuation order in April 2011, requiring all residents to leave. This order was only lifted in March 2017, 6 years after it was initially implemented.

Between 2011 and 2016, a monitoring program was implemented with environmental survey results being communicated back to the local people. In June 2011, a meeting with the leader of the local agricultural promotion team, who was undertaking phytoremediation experiments in the district, allowed for exchange of information on the monitoring program and local people and habits as well as discussion on research topics. Investigations started in 2011 and dialogues were held 1 to 3 times per year with local farmers to discuss results of the environmental survey, anxieties and interests and monitoring targets. The monitoring targets included river water, groundwater, forest litter layer, leaves, wild plants, vegetables and mushrooms.

Local residents wanted more detailed information on caesium concentrations in rivers, streams and groundwater as needed data from the government were mostly reported as not detected (the detection limit being 1 Bq/l and background concentrations are generally below this). A second topic of concern was the risk of recontamination of paddy fields following their decontamination through the use of irrigation water containing caesium. There was also concern that caesium in the surrounding mountain forests that were not decontaminated could be released.

Groundwater monitoring results showed that concentrations of radiocaesium were in the range of 0.3 to 0.5 mBq/l. To detect such activity concentrations, it was necessary to concentrate 2,000 liters of groundwater. The national standard for drinking water was 10 Bq/l so groundwater activity concentrations were very low.

Radiocaesium concentrations in irrigation water were also measured to evaluate the risk of recontamination of paddy fields. Rivers are the main source of irrigation water in the district and were therefore monitored. Concentrations of radiocaesium were below 0.05 Bq/l, indicating that paddy fields are unlikely to be recontaminated through the use of irrigation water.

The survey of agricultural products showed that almost all concentrations were below the detection limit of 1 Bq/kg with the exceptions of soy and watercress. The activity concentrations were all below the national standard of 100 Bq/kg. Concentrations in some wild plants were, however, found to be high with one species having radiocaesium concentrations over 1000 Bq/kg.

External doses to people were also measured to evaluate the dose to people returning to the area following the lifting of the evacuation order. The annual external exposure was around 0.9 mSv in 2018. This was an important result for the local residents.

The survey results were reported to the local residents regularly between 2012 and 2018. However, in the beginning, communication was one sided and local residents did not engage and no questions were asked. The communication approach was inadequate, and residents fed back that it was too difficult to understand. Improvement was therefore needed. The communication approach was therefore improved. Based on experience, the following five suggestions are made with regard to communication of survey results with local people:

- → Results should be fed back to the local residents. Sometimes papers are published, but it is forgotten to communicate directly with the local people that supported the research. It is also important that researchers recognize that residents of affected areas are victims, and it is important to be considerate in sharing and explaining results directly to those residents.
- → An atmosphere should be created that encourages residents to talk by holding round table discussions with a small group of people rather than a school-style briefing. Prior to meetings, working together is encouraged (e.g., farm work and/or preparing lunch) to build trust between the groups. It can also be beneficial to encourage the local residents to become the teachers through informing on local foods, the area and life for them. Sharing a meal after the meeting also provides an opportunity for further discussion around the survey and results.
- → Communicate in a way that is easy to understand. Complex figures and technical terms should be avoided, and font size should be large to account for older residents. Presentation times should be short with regular breaks being provided and a short and simple summary using a large font can be useful.
- → Understand the interests of local people. There tends to be a gap between researcher interests and what residents want to know. For example, researchers may be focused on transfers or leaching in soils whereas residents are more likely to be interested to know the concentrations of contaminants in the food they eat. It is also important to recognize that research ideas can arise through discussion with affected stakeholders.
- → Investigate together if possible. By working together, there can be many insights both for the researcher and the local people and, for the local residents, involvement in the sampling of plants etc., can encourage a feeling of owning the results of the research and that their interests are being addressed.

Based on the experience gained from communication with society following an environmental disaster, it is important for researchers to recognize disaster-related research should not only focus on accumulating/advancing scientific knowledge, but should also aim to benefit the people within the affected area. A good and relaxed atmosphere should be created between researchers and the local residents to encourage two-way communication that helps develop understanding around resident's interests, including social and economic aspects.

In 2017, following the environmental recovery process, a small program started with the local residents that moved from the environment/radiation problem to look more at the social and economic problems. Following lifting of the evacuation order, rice planting and other cultivation resumed, and the local food market reopened. However, there were a number of problems. For example, prior to the accident the local population was around 1200 residents. As of June 2021, there were 330 residents so only around 30% of the local population returned. The concern for local residents has therefore changed from concern around the environment and radiation to social and economic concerns. For example, the low population has resulted in a labor shortage and difficulty in maintaining agricultural land and facilities. There has also been a loss of exchange activities with people outside of the district. Together, these factors have led to a reduced quality of life.

A new interactive program was therefore started, called Yamakiya School, to restart exchange activities with people outside the district, to support local agriculture and to share knowledge. As a result of the program, more than 500 people have visited the area more than 29 times in 4 years from inside and outside of Japan for agricultural experiences, learning about radiation, and to attend workshops, music concerts and international conferences etc. A community-based local support system was also developed.

The recovery process following a nuclear accident therefore has three phases. Phase 1 is the emergency period focused on radiation protection. Phase 2 continues to focus on radiation protection, but also moves to environmental recovery with radioecology and waste management being important components. Phase 3 is then the social and economic recovery process for which a transdisciplinary approach is needed. It is important to recognize that, at each stage, local authorities and residents need different support.

Discussion

It is not always obvious that monitoring / survey programs can involve members of the public (i.e., citizen science) so it is important to discuss their needs and concerns, and for those concerns to then be addressed. There can also be issues around sectionalism during recovery phases whereby different aspects are focused on in isolation rather than a collaborative approach being taken.

It is unlikely that the population in the district will further increase from natural population growth since the average age of the population is 60. There is, however, hope that the area could be revitalized through industrial and agricultural development such as young farmers being attracted to the area to try new types of agriculture.

3.2 Legacy, remediation, waste and stakeholders – what lessons have we learned?

Marcus Grzechnik (ARPANSA) presented.

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) was formed in 1999, but prior to this, Australia received some radium from France (approximately 1 g according to a Marie Curie letter) and formed the Commonwealth Radium Laboratory in 1929 in Melbourne. The remit of the laboratory was widened in 1935, leading to the formation of the Commonwealth X-ray and radium laboratory and eventually, in 1972 this became the Commonwealth Radiation Laboratory and then the Australian Radiation Laboratory in 1973. In 1978, the Australian Radiation Laboratory moved to the suburbs of Melbourne where it remains today as a fit-for-purpose building containing laboratories and around 100 people on site. In

1999, an Act of Parliament brought the laboratory together with the Nuclear Safety Bureau, which was based in Sydney, forming ARPANSA. The Sydney office is the main regulatory branch.

The former building was cleaned up and handed back to the owners in 1981. Drums of waste are stored in the facility and parts of the laboratory had flooring removed etc. to address hotspots of contamination. The radiation protection officer responsible for the cleanup produced a report on the appropriateness of the clean-up concluding that this was cleaned to levels considered clean by international standards – the owners were happy with the clean-up. However, today, the owners want to use the site for a different purpose with the plan being to have green space and to later decide on what to do with it.

The stakeholders include:

→ ARPANSA. Whilst ARPANSA had handed back the site having deemed the building safe, there remained some responsibility for the legacy contamination and therefore had a role, but not as a regulator.

→ The owners of the site responsible for the remediation of the site as the regulated entity.

→ The independent contractor undertaking the remediation which was radiation-focused.

→ The regulator for the remediation which was under State jurisdiction rather than the Commonwealth, which would have resulted in ARPANSA having regulatory responsibility.

The remediation plans were initially for demolition, soil removal and then bringing in clean fill. It was due to be a four-month project with a proportion of waste being stored or disposed of by ARPANSA as the legacy owner. Complications slowed progress, however. There were conservative radiological surface contamination criteria and some of the field methodology was also conservative. There was a lot more contamination outside the spaces that people would normally occupy within the building such as within the roof cavity and under floors, which may have resulted from a fire. Records were not available to confirm this. Other contaminants were also discovered onsite. As a result, the project took around 2 years as it had to be undertaken piece by piece rather than quickly demolishing. A further complication was that the demolition contractor was not based in Melbourne, so were not full time working on the site. Soil clearance then took over a year due to discovery of heavy metals, including mercury, that were probably present in the soils prior to the building having been constructed. In June 2019 there was a method adjustment which reduced the activity concentration of soil being classed as waste. Following in-situ and laboratory measurements being made on the soils delivered as waste, a meeting was held with stakeholders and it was agreed that the field methodology needed to be adjusted to avoid the generation of many drums of waste that were below the exemption level, and could be considered to be just soil. The clean fill stage of the remediation works went according to the plan.

Overall, there was a significant overrun in the remediation project from 4 months to 36 months. There was also an increase in the volume of waste and disposal costs due to the presence of heavy metals that had to be disposed of to a contaminated landfill. The increased duration of the project also increased the costs associated with the project.

Approximately 210 drums of waste were generated during the remediation works, but there was not a lot of activity associated with the waste (less than 120 MBq Ra-226). The drums are stored in a ventilated and monitored store that was constructed in 2018 on site. Some waste consolidation is possible, and it is planned to ultimately dispose of the waste to a national facility if available in the future.

ARPANSA national guidance on radiation protection in existing exposure situations was released in 2017 but was not agreed and adopted in time for the remediation project. The guidance is based on IAEA GSR Part 3 with protection being based on assessment and the use of reference levels with a national reference level being set at 10 mSv/y for existing exposure situations.

In terms of lessons learned, it is important to consider all hazards and contaminants when undertaking remediation. The history of the building or site may not be known so it is important to not focus on just one contaminant but rather look at all possible contaminants. The meaning of 'radioactive material' should also be defined and agreed amongst all stakeholders to avoid wastes being generated that are not really wastes, which adds to both the amount of time taken to remediate the site and the costs involved. It is also important to agree the methodology in advance and to base radiological decisions on a dose assessment and justified and optimized reference level, noting that justification and optimization should be part of any intervention into an existing exposure situation.

Discussion

As the legacy owner, ARPANSA was not responsible for worker protection or for the decision-making process but did give advice when asked. Those undertaking the remediation works were experienced and took the necessary precautions, so worker doses are expected to have been low.

Regarding the context of multiple hazards exposure decision making, the existing exposure guidance that has now been published considers all hazards but doesn't lay out a methodology for dealing with all hazards. Rather, it focusses on radioactivity but does advise that other hazards be considered.

3.3 Rehabilitation of the Chornobyl affected areas: exploring attitudes of local residents

Yevgeniya Tomkiv (Norwegian University of Life Sciences, CERAD - Centre for Environmental Radioactivity) presented.

A study has been undertaken to explore the attitudes of local residents within the Chornobyl Exclusion Zone (CEZ) towards plans for rehabilitation of the area. The study forms part of the iCLEAR[2] project which aims to support in planning the future management of the CEZ and the zone of obligatory resettlement. An important feature of the project is that the aims are driven by the needs of stakeholders and end users such that they are heavily involved through all stages of the project.

Of the areas impacted as a result of the Chornobyl accident, the CEZ is the most highly contaminated. Future development of this area includes the possibility of opening areas around the reactor for tourism and the creation of nature reserves. One such reserve was created in 2016 – the Chornobyl Biosphere Reserve[3] with an area of 2,270 km^2. The CEZ also serves as a unique field laboratory for radioecology research. Another area affected by the accident was the zone of unconditional (obligatory) resettlement, which was also quite highly contaminated. Future development opportunities for this area include resettlement and agricultural production.

iCLEAR has a number of different tasks related to the development of the CEZ and participate in assessments that that support development of a new management strategy for how to deal with the diverse water resources, wildlife conservation and potential for ecological tourism. iCLEAR also supports the collection of information that supports that strategy and decision making, including mapping of contamination and discussing how we value natural resources within reserves.

Within the zone of obligatory resettlement, iCLEAR has been developing a protocol to clear lands for agricultural reuse and a lot of attention has been paid to studying stakeholder concerns around the reuse of the territory.

[2] https://tree.ceh.ac.uk/content/iclear-0
[3] https://zapovidnyk.org.ua/

The zone of obligatory resettlement was defined following the Chornobyl accident and mapping of the areas of contamination. The areas that were deemed too contaminated for permanent resettlement of people were delineated as obligatory resettlement zones and people residing in those areas were to be offered alternative accommodation elsewhere in Ukraine. However, for various reasons, many people stayed. Some people never received an offer of alternative accommodation whereas some received the offer but chose to come back and others moved to this zone from more contaminated evacuation areas. One of the resettlement zones currently has around 2,800 residents and if villages around are taken into account there are around 11,000 residents in the region. Nonetheless, the area is currently still classified as a zone of obligatory resettlement and there are a number of restrictions in place. For example, industrial and agricultural activities are not permitted and the owning of private property or development of infrastructure are not allowed. However, a lot of time has passed since the accident and contamination levels are decreasing. Furthermore, initial regional mapping of contamination may not have been detailed. As such, there may opportunities to change the zones to put them into less restrictive categories and to release areas for agricultural reuse.

The attitudes of the local population to possible rezoning and lifting of restrictions in the affected areas has been studied with local residents of Narodychi and two neighboring villages being consulted. Around 40 resident interviews took place in October 2018. In order to get a wide range of views, the age range of those interviewed was wide (22 – 80 years of age). Since they were easier to get in touch with, around 75% of those interviewed were women.

The interview process began by going door to door and most interviews were therefore with retired or unemployed people. As such, a second round of interviews took place with workplaces being visited to ensure the opinions of employed people were also captured. A wide range of opinions were expressed.

People were asked what they generally have concerns about and health was one of the biggest concerns but beyond that the greatest concerns related to the economic situation in the area. They were also asked how the Chornobyl accident had impacted them and unsurprisingly any health troubles were considered linked to the accident. Economic consequences were also recognized through agriculture and industry shutting down as a consequence of the accident, which in turn led to a population decline and the loss of friends and neighbors due to relocation. Some positive impacts were, however, expressed such as rehabilitation programs for children that provided some opportunities that they otherwise would not have had, and the conservation effect the accident had on the local forest.

In terms of attitudes toward changing land use to make land available once more for agricultural production, many recognized the potential for economic development and creating work. In Ukraine there is a strong connection to the land so many people consider soils to be a valuable resource, but the positive attitude to reuse of the land was very much conditional on the land being actually clean or being cleaned to a satisfactory extent and that independent experts would be involved in assessments and the decision-making process. On the against side, the most common opinion against related to disbelief that common residents would benefit from any changes. There was also concern that the locals, who are very dependent on using the environment such as for pasture for domestic animals and gathering mushrooms etc. would be restricted as a result of any changes. There were also concerns that the land would be unsuitable for reuse as a result of contamination.

Attitudes to rezoning were largely favorable with many being positive about the lifting of restrictions meaning the possibility of owning the houses they live in and that, by rezoning, there would be less stigma and people wouldn't be afraid to resettle in the area which would lead to more development, investment and opportunities. There was also a lot of uncertainty amongst the population as to just how contaminated the land is with the opinion that if it isn't that contaminated then rezoning should be allowed but that international scientists should be involved in the process. The main arguments expressed against rezoning were that there would be a risk that state benefits would be lost if restrictions were lifted.

There is a huge information gap with very little information being available on the levels of radiation in the region and they were unaware that discussions around rezoning and land reuse were happening. There is also a lack of information on how any developments would happen and what that would mean for the local people. Furthermore, the local people have little trust in the authorities. The intention had been to address the gaps by holding public information/consultation meetings in the spring of 2020 to which experts would be invited, along with those that could answer questions around benefits etc., but it was necessary to cancel these due to the pandemic and it is not clear when it will be possible to reorganize such meetings.

The protocol for reclassifying land has been developed but still needs to be accepted by stakeholders and certain legal and financial issues require clarification, such as who would pay for the measurements required to support land reclassification and also who owns the lands in the area since Ukraine was part of the Soviet Union at the time of the accident.

Discussion

The issue of loss of compensation has also been seen in Japan where compensation ceases if people return following evacuation. In Ukraine, there are lots of different benefits so the situation is complex. Some benefits relate to living on a contaminated territory so there is compensation to provide clean food. Others relate to being a person affected by the accident, but there are different categories relating to medical services, electricity and other subsidies etc. and there is concern that some or all of these could end if the current zone classification is lifted. There has been no communication around the benefits situation, so people fear the worst. Overall, an increase in the information provided to people, including how developments will benefit local people, will help alleviate concerns and may also lead to increased support for the lifting of restrictions in the area.

The situation around home ownership is also unclear. People were meant to be offered alternative accommodation but either didn't receive offers or decided to remain (or return). The houses are therefore rented from the local authority and cannot be sold or bought, but there is a black market that enables houses to be taken over. For land ownership, the situation is also unclear. Where people had owned a patch of land, they may have moved away or died, and their children may not know they have inherited the land. There is therefore huge uncertainty around land and property ownership.

There is already some ecotourism in the region, but most tourism currently relates to Chornobyl itself and the abandoned villages. There will be a need to balance goals in further developing ecotourism to ensure an influx of tourists does not adversely affect the thriving natural reserve that has formed as a result of the evacuation of people from the area.

3.4 Trust, reproducibility and sustainability: What can radioecology learn from Covid-19?

Deborah Oughton (CERAD and COMEST) presented.

Similarities in the challenges raised by Covid-19 and nuclear emergencies were noted soon after the impacts of the pandemic became evident. Actors working with radiological protection, nuclear emergency preparedness, risk communication and radioecology highlighted a number of commonalities. These include the importance of indirect health effects, such as mental health and stress, the huge economic and societal consequences, risks of stigma and discrimination, and questions of public trust in authorities.[4] For

[4] See, for example, the series of Webinars sponsored by SHARE and NERIS (Mexitell at al. 2022), ISGlobal "COVID-19: What Can Past Nuclear Accidents Teach Us?".

radiological accidents, experts have long recognized that emergency management needs to address more than dose and cost; likewise, for Covid-19, the issues go beyond those related to health and wealth.

Like many other international organizations, the UNESCO World Commission for Ethics of Scientific Knowledge and Technology (COMEST) and the UNESCO International Commission on Bioethics were quick to release a statement on Covid-19. Their joint statement "Ethical Considerations from a Global Perspective" from April 2020 listed 10 ethical considerations that need to be addressed in meeting the COVID-19 pandemic. These included recognizing that Covid raised ethical challenges as much as scientific challenges, the potential threats to human rights, privacy and research ethical standards, and a particular concern for the impacts on the most vulnerable members of society. Follow-up statements have covered challenges related to information technology, including COVID-19 certificates, vaccine passports and tracing apps, as well as impacts on sustainable development.[5]

In all cases, there is a need to reflect on the wider ranging consequences of actions, and in this respect the World Health Organization statement from 1948 that: "*health is not just the absence of disease or infirmity but is a state of complete physical, mental and social well-being*" is particularly appropriate. Emerging issues in all areas of science and technology assessment include the ethical challenges raised by information technology, concerns about research integrity and reproducibility, and an increased focus on sustainability. Building on the work of COMEST and the radiation protection community, the present paper will explore how radioecology can learn from Covid-19 (and vice versa) in these three areas.

Information Technology (IT): Emerging technologies such as machine learning, artificial intelligence (AI) and the "internet of things" (IOT – linked to the sharing and transfer of information between different technologies) have wide-reaching implications for society. These emerging technologies were widely used in dealing with the pandemic, but also raised ethical questions about privacy, data sharing and surveillance issues, particularly linked to test and trace apps and vaccination "passports". Other concerns were linked to discrimination that could arise from differences in access to technology, for example if eating in restaurants, going to the theatre or ordering drinks in bars would be impossible without such technology. Such technological developments are also being seen in radiation protection and nuclear safety, from advanced AI applications to apps that can turn mobile phone cameras into rudimentary monitors of radiation exposure. The latter can be helpful in getting people involved in radiation monitoring, but there are also challenges in the ways that data are shared and privacy issues of people participating. Like for Covid-19 apps, there is a particular concern about the relationship between commercial developers and national and international authorities, and hence important to have discussions of ethical issues upstream of their development.[6]

Trust, reproducibility and integrity. From the very start of the pandemic, there was a focus on what this meant for public trust in science. It could strengthen trust through, for example, the development of vaccines and the awareness of the importance of science to inform us and underpin decisions that would help address the pandemic. But there were also concerns about that scientific integrity could be damaged by fake news and controversy over the robustness of data being rapidly published without peer review. This links to the ongoing discussion on reproducibility, which goes back to the classic paper by Ioannidis, published in 2005 "*Why Most Published Research Findings Are False*". Covid-19 saw many preprint scandals (including one co-authored by Ioannidis, and in high impact journals like the Lancet) where pre-prints of articles were published online, and then found to be seriously flawed (e.g., hydroxychloroquine as a treatment for Covid-19), requiring retractions to be made. The use of preprints can be beneficial as it leads to a broader review process, but there is risk that results can be reported in the media, as happened in the case of Covid-19, with wide ranging consequences for public trust in science. The issue goes beyond scientific integrity and communication, going beyond scientific disagreements that we know exist, to fake

[5] All statements available at: World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) (unesco.org)
[6] See the EU Shamisen and Shamisen-Sings projects for more details, and Oughton et al., 2022.

news and conspiracy theories. Reproducibility has also been linked to publication bias, and the need to recognize different types of bias. These include publishing only positive results, outcome reporting bias (where hypotheses are changed to match the findings), spin in terms of the way things are presented and citation bias. Covid-19 has highlighted the need to be sensitive to these challenges and there are calls for pre-registration of trials and experiments as a way of avoiding some of the sources of bias. Of course radioecology has been long challenged by disagreements about impacts of radiation. A recent example being the controversy around 'Manual for Survival' published by Kate Brown, which presents research connected to Chornobyl almost as a conspiracy, but underlines the complexity of communication on radiation issues.

Sustainability: Radioecologists have been championing an ecosystem approach for many years (see following presentations). COMEST work on environmental ethics, sustainability and UN sustainable development goals has also focused on the interdependency of humankind and the environment, and the need to move from a purely anthropocentric view to a more ecocentric perspective. Sustainability needs to address more than just physical and economic considerations, but also societal and cultural impacts and acknowledge the dilemmas that can arise from interactions between sustainable development goals.[7] Pandemic warnings have been around for at least a decade and experts have been warning that deforestation, climate change and habitat loss, has the potential for increasing zoonoses (i.e., the transfer of pathogens from animals to humans). Other emerging issues that are also important to radioecology, include climate change impacts on land use, biodiversity and ecosystem services.[8] The next decade (2021-2030) represents the United Nations decade on ecosystem restoration and will look closely at the challenges of restoration of ecosystems.

The environmental consequences of Covid-19 are complex. In the short-term there has been a reduction in global carbon emissions from the lack of travel and data on reduced air pollution in cities leading to reduced deaths and asthma outbreaks (International Energy Agency, 2021). A drop in global carbon emissions of 7% was observed in 2020, and attributed to the pandemic, but IEA predictions suggest that increased travel once restrictions are lifted will offset these reductions. The European Environment Agency has also done a study on the consequences of Covid-19, focusing on the environmental costs and benefits (EEA, 2021). Environmental costs of Covid-19 include delays in climate action and not meeting carbon emission goals. Furthermore, because of the loss of tourism, there has been an increase in illegal hunting and resource exploitation, particularly in developing countries. These countries are also likely to be more severely impacted in the long-term through the lack of vaccines and ongoing tourism restrictions. EEA also reported a measurable increase in plastic waste because of increased use of personal protective equipment such as facemasks.

The take home message is that this is an extremely complex topic. The radioecology field can learn from Covid-19 experiences, but Covid-19 could also learn from the nuclear sector. Experience from nuclear accidents has taught us that economic consequences include not only direct loses from loss of sale of food products but also from decreases in market value due to consumer perspectives. In terms of environmental consequences there can be ecological benefits from reduced human impacts, but remediation (such as removal of topsoil) can also have impacts on organisms. Societal and demographic consequences of accidents, such as from loss of livelihood, can be enormous, and other societal impacts can result from loss of access to cultural sites, graves and heritage areas. These are all areas where there are overlaps between Covid-19 and radioecology. Ethics can often help in this regard, giving awareness on different perspectives.

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[7] COMEST Land Ethics (2021) and Water Ethics (2017) reports (accessible UNESCO/COMEST)

[8] IPCC (2019). Special report on climate change and land; IPBES (2019). Global assessment report on biodiversity and ecosystem services.

Discussion

It can be difficult to address instances of fake news. We often want to speak out about it, but consideration needs to be given to how best to do this, since one might want to avoid giving further media coverage to the issues. But participating in debates is necessary and it's important to recognize that there will be debates with different perspectives raised. Focus should therefore be on the science and what it tells us, but also recognizing that there can be different interpretations. We can for example agree on what the radiation doses are, but still disagree on whether they are acceptable. There will always be differences in opinions.

4 Ecosystem Approach

4.1 IUR: Ecosystem approach and consensus conferences, an overview

François Brechignac (IUR) presented.

The International Union of Radioecology (IUR) has long been a strong voice in support of having a good system for protection of the environment from ionizing radiation and has argued for more ecology in radioecology. At its origin, radioecology was clearly grounded in ecology with many early radioecology scientists starting as ecologists. Since then, however, radioecology has become dominated by anthropocentrism with radioecology largely serving radiation protection that was exclusive to the protection of people. Radioecology therefore largely focused on transfers to people through the environment and was shaped to support the requirements for radiation protection which were, at that time, very much focused on protecting human beings. This was clearly reflected by the ICRP position at that time that if man was protected then the environment would also automatically be protected as people are mammals and mammals are among the radiosensitive species. This position has been greatly criticized for not considering protection of the environment in its own right.

A first conference on environmental protection from ionizing radiation was held in Stockholm in 1996. The conference was headed by the president of the ICRP at that time who was convinced that a move from their position on radiation protection was needed. Following the conference, several new projects were developed focused on radiation protection of the environment and the IUR took a position to clearly state its opinion on the direction to take. The IUR therefore wanted to promote a move towards ecocentrism, with a widening of the scope of radiation protection to encompass environmental radiation protection in its own right and for human and environmental protection to be integrated within a coherent framework in an 'ecosystem approach'. The first time the IUR expressed the need for an ecosystem approach was in 2003 in a statement on protection of the environment in the 21st century that was for the protection of ecosystems, including humankind.

The first main document on the ecosystem approach was published in 2012 titled 'Towards an ecosystem approach for environment protection with emphasis on radiological hazards' (IUR Report No.7). This was produced by a team of 12 radioecologists and captured what was going on with regards to environmental protection from the chemicals field and why an ecosystem approach should be developed for radiation protection as well as what is meant by an ecosystem approach.

A workshop was then organized in the following year in Stockholm on 'Ecological risk assessments for radiation – putting the ecosystem approach into practice'. This was aimed at brainstorming around the development of a practical approach and the work is captured in a 2014 Journal of Environmental Radioactivity (JER) paper titled 'Using an ecosystem approach to complement protection schemes based on organism-level endpoints' (JER 136: 98-104). The workshop was largely focused on the scientific limits of the current ICRP approach, which is based on individual organisms (the ICRP Reference Animals and Plants) and pointed out problems around nonlinearity of ecosystems and the need to take account of inter species linkages that can lead to indirect effects. Recommendations were also made on how to develop higher level endpoints that relate to populations, communities, and ecosystem functions.

In the meantime, the Fukushima accident had happened, and people started to collect data and express views on effects of radiation observed or not observed on biota in the Fukushima area. This turned out to be controversial and led to further discussions around Chornobyl data. There were several controversies that developed at this time, that were more than just discrepancies. In response, the IUR decided to assemble a consensus symposium to bring together people with different interpretations of the data and with contrasting views to see where there was agreement and where there were disagreements and contrasting interpretations in order to try to resolve them. The aim was to promote positive discussion to try and understand why disagreements had arisen. The disagreements were largely related to different manners and ways of developing the science and methods and whether the science was performed in the laboratory or in the field or focused on individuals or populations. The aim of the symposium was to issue consensus statements around the issues and 7 such statements were developed and published as a JER paper titled 'Addressing ecological effects of radiation on populations and ecosystems to improve protection of the environment against radiation: agreed statements from a consensus symposium' (JER 158-159: 21-29). One of the consensus statements recognized that successful environmental protection requires an ecosystem approach that recognizes natural populations, their dynamics and species interactions. The role of reference organism approaches was also recognized as an important first step, but that there are significant limitations and a greater understanding of the mechanisms and processes involved in inducing radiation effects and how they are manifested in natural ecosystems. The need for a multidisciplinary approach to tackle the issue was also recognized.

In order to try and open up discussions and bring together the different communities, a second consensus conference was organized in 2016 that brought together radioecologists and ecosystem scientists. Discussions were structured around three questions:

- → How can ecosystem science support ecological risk assessment?
- → What ecosystem level endpoints potentially could be used for radiological risk assessment?
- → What inference strategies and associated methodologies would be most appropriate to assess the effects of radionuclides on ecosystem structure and function?

Results of discussions were that it would be possible to evolve to ecosystem level endpoints and to apply these an ecosystem approach. Then, in 2017 there was a subsequent workshop held between radioecologists and radiobiologists with an emphasis on the RAPs approach and elaborating on the fact that radiobiologists were feeling that a systemic biological approach was necessary that paralleled the ecosystem approach being promoted. This was followed in 2018 by a further workshop, again with the radiobiology community, on the subject of low doses. A major conclusion from this workshop was that the extrapolation of effects from high doses to low doses was not possible. Another similar workshop took place a year later in Manchester but with a specific focus on the ecosystem approach. The discussions brought together people with different interests and were very interesting.

The Covid-19 pandemic has resulted in a slowing of progress, but the ecosystem approach is no longer restricted to theoretical grounds but has started to be tackled in the laboratory using micro- and mesocosms and also in the field and significant progress for application in radiation protection is awaited. Experimental approaches have been undertaken by CERAD and two publications on the subject include:

- → Haanes et al. (2019). Realism and usefulness of multispecies experiment designs with regard to application in radioecology. Science of the Total Environment 718: 134485.
- → Hevrøy et al. (2019). Radiation effects and ecological processes in a freshwater microcosm. JER 203: 71-83.

There have also been several studies and associated publications by E. Pryakhin's group from Russia that have been working on the Mayak ponds for quite some time, observing the ecosystem evolution of the ponds by studying the species and populations in parallel to the chemical and physical characteristics of the ponds. A similar program of work is also under development by a group in Cadarache, France, and outdoor mesocosms have been built at Savannah River Laboratory in the USA.

The ecosystem approach is now fully justified and well described and has been applied in some cases outside the field of radiation protection. What is missing, however, is the development of an operational method that uses ecosystem level endpoints that can be implemented in practice. IUR has therefore funded work to explore the feasibility of using ecological network analysis, which is a promising method to rate quantitatively ecosystem interactions as affected by pollutants (see Section 4.3).

4.2 Towards a holistic approach to protection of inhabitants of contaminated environments: the role of non-targeted effects

Carmel Mothersill (McMaster University) presented.

The bystander effect means that the outcomes of radiation interactions are not independent so organisms receiving a dose can signal to other organisms in the environment. Genomic instability means that an initial dose experienced by a population can result in transgenerational effects in the population. In both instances, the effect can be disassociated from the actual exposure to radiation, with the response being non-linear and saturable such that the effect can be turned on at a low dose, but the effects do not increase with dose. Neither bystander effects or genomic instability are included in radiation protection risk assessments.

The proposed mechanism for non-targeted effects is that a first exposure event leads to excitation decay related photon emission that alters mitochondrial metabolism and stimulates membrane channel signaling pathways. The signals are received by other cells (or organisms) that then initiate 'bystander' responses such as genomic instability, lethal mutations and adaptive responses. There is also a higher risk of mutations in progeny that could potentially feed into evolutionary processes such as natural selection. Such outcomes need to be understood if an ecosystem approach to radiation protection is to be developed.

Radiation-induced bystander effect cells are at an increased risk of delayed effects and bystander factors have been found in the plasma of atomic bomb survivors and Chornobyl liquidators twenty years after exposure. They have also been found in fish that have never been exposed to radiation, but that have received signals from other fish that have been exposed. Radiation-induced genomic instability has been demonstrated in children of irradiated parents from Chornobyl where an increased frequency of aberrant genomes has been measured. An elevated frequency of chromosome aberrations and increased embryonic mortality has also been reported in bank voles in the Chornobyl exclusion zone twenty years after the accident.

The evidence for non-targeted effects has led to a new concept in radiobiology to incorporate historic dose and effects within radiation protection. Overall, little is known of the effects of low-level radiation exposures on biota populations. Elevated mutation effects have been reported that are higher than would be expected based on current dose rates in Chornobyl bird populations and in butterflies and voles at other legacy sites. there was therefore interest in testing whether the higher mutation rates were due to an initial acute radiation exposure inducing non-targeted effects rather than being a result of ambient chronic low dose, low dose rate exposures. Discrepancies have been observed between field and laboratory studies with a 10-fold difference in sensitivity being observed, with field studies being the more sensitive to radiation. There are several reasons why this could be the case, including the varied ecosystem interactions such as predation stress, food availability etc. that all contribute to the measured outcome.

A historical effect is defined as an initial effect plus any other subsequent cumulative environmental effect up to the time the 'ambient' measurement was taken and includes delayed and non-targeted effects, which are assumed to be heritable. Initial analysis shows that genomic instability effects can contribute. Following initial exposure, acute and chronic effects are induced, but also a legacy effect due to genomic instability mutations in progeny. The decay of radiation dose over time affects the population, but there is also a component of non-targeted genomic instability leading to increases susceptibility that needs to be factored in and added to the conventional direct effect in order to evaluate the cumulative effect at any given time.

The concept has been tested using Fukushima butterfly data. Historic dose has been reconstructed to calculate the non-targeted component. A component of genomic instability appears to be present and is a saturable effect as expected so that it doesn't increase with dose. Effects have been observed in butterfly generations five and six that were not exposed and a number of papers have been published on these transgenerational effects. The calculation of historic dose is therefore possible and is necessary if ambient dose effects are to be understood.

Genomic instability is therefore a late non-targeted effect after low dose irradiation, but is not included in modeling or radiation protection risk assessments, but can be evaluated through historic dose reconstruction. Re-analysis of field data to include the historic genomic instability component has confirmed a non-targeted effect pattern of dose response plateau in progeny.

Discussion

The propagation of effects through generations has been studied in the Chornobyl exclusion zone with samples being collected from high, medium, and low contamination areas. A huge variation was observed between samples, but this was random (i.e., not correlated with the level of contamination where samples were collected). This therefore needs to be investigated further as the results suggest that other factors could be at play or the type of contamination may overwhelm non-targeted effects.

4.3 Applying an ecosystem approach in radioecology: from experimental to field data

Anna-Lea Golz (Alfred Wegener Institute) presented.

In a lot of ecotoxicology and radioecology studies, there is a tendency to focus on a single species under ideal conditions to evaluate the direct effects of the contaminant on that species. Such an approach fails to take into account the indirect effects that can occur in natural ecosystems where there is competition, predation and also habitat forming species that are all very important. In order to look further into the implications of indirect effects, ecological network analyses were applied as a tool to look at linkages and trophic interactions etc., where ecological networks are simplified representations of functional species interactions. The diagrams (see Figure 1) depict compartments (species, functional groups or individuals) as nodes and the interactions (e.g., trophic interactions) as links between the nodes.

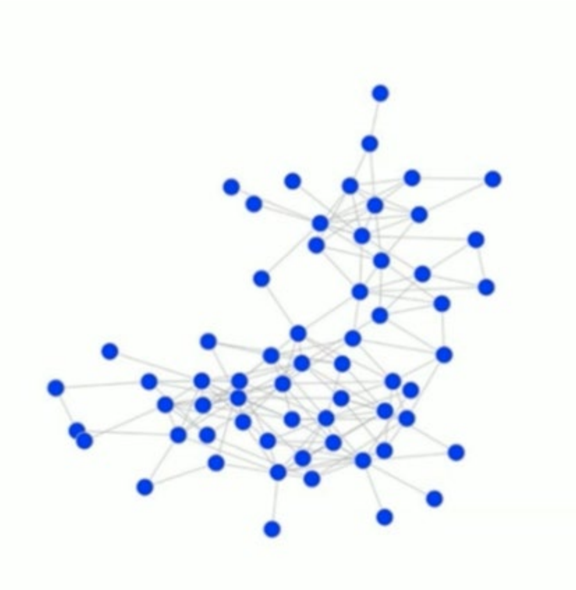

Figure 1 Illustration of an ecological network diagram.

There are two different types of network. One is more focused on the structure of the networks and how the removal of certain nodes affects the overall network. The other focusses on community level effects such as looking at how populations are structured and/or the importance of different populations within communities.

In ecological network analysis, quantitative data are needed, including the biomass of each system compartment (e.g., from detritus to plankton up to fish, birds and mammals), which needs to be area specific. The energy requirements of each compartment (e.g., production, respiration, and consumption) are also required along with the trophic interactions, i.e., who eats whom and at what rate.

A freshwater microcosm study was performed where aquaria were exposed to gamma radiation for a period of three weeks. The community within the aquaria consisted of either species that have been used previously in single species studies or that were representative of Nordic ecosystems. In putting together communities, interactions were kept in mind so macrophyte species selected would be competing with phytoplankton for nutrients and a grazer was selected that would feed on the macrophytes and Daphnia would feed on the phytoplankton. The experimental set up allowed for five different dose rates (including the control group that was in a shielded area of the laboratory). The dose rates ranged from 0.72 to 19 mGy/h, which are within the range of dose rates observed at contaminated sites. The aim was to investigate the effect of ionizing radiation on the model ecosystems and to investigate the pathways and interactions between the species and components of the ecosystems.

The largest effect observed was on primary producers and the rate of photosynthesis. As dose rate increased, a decrease was observed across photosynthetic parameters. No direct or indirect dose rate effects were observed on consumers.

The carbon concentration in each compartment (i.e., species) was measured, along with primary productivity and respiration. From this, ecological networks were constructed that included the primary producers, grazers as well as bacteria and sediments, inclusive of detritus. Analyses were performed and many different indices on how the system changed. As an example, total system throughput was calculated by summing all flows in the network as a measure of ecosystem size or activity and a clear decline was observed with increasing dose rate. Input analysis was also performed to look at the relative circulation of all imports to the system and it is seen that productivity moves from macrophyte primary production to carbon remobilization and bacterial production as dose rate increases. Consumption by snails also increased and this increase in energy uptake could be a reason why negative radiation effects were not observed.

More qualitative networks have been constructed based on field data from Mayak freshwater reservoirs that were used for the storage of liquid radioactive waste. The reservoirs therefore have high activity concentrations, equating to total alpha activity of around 8.3E+4 Bq/L in the most contaminated reservoir. A monitoring program has resulted in well quantified data being available on species abundance and composition and concentrations for radionuclides and other contaminants. The data on radionuclide concentrations and biomass were used to construct networks with nodes representing taxa or functional groups and links being made between prey and predators. These linkages were qualitative, being based on review and expert opinion rather than being measured.

Network analysis shows that in less contaminated reservoirs, all four trophic levels are represented. However, in the highest contaminated reservoir, the network is eroded to just two trophic levels with rotifers and insects persisting along with bacteria and phytoplankton species. In the medium contaminated reservoirs, some effects are shown with some species being lost and links start to disappear.

The network analyses allow quantitative indices to be calculated for each reservoir, but they tend to co-vary to a degree so principal component analysis was performed which places points together based on their similarity to help explain variation. In this case, 93% of variation is explained by two axis (PC1 and PC2) so that there are two clusters formed. The PC1 axis explained 77% of the variation and 15% was explained by PC2. The negative scores from the analysis are related to network complexity, i.e., how long is the food chain and how many links there are in the network whereas positive scores indicate an increase in top and basal species and an increase in the proportion of links between top and basal species. In the highest contaminated reservoirs, there are only two trophic levels with links between them and there is erosion of the trophic network. Regression analysis was performed for the PC1 score against radionuclide concentration and a clear positive relationship was observed. Increasing caesium and strontium concentrations in sediments and water were correlated with increasing negative effects on network complexity. Similar trends were also observed for other contaminants such as nitrates and salt content.

Species abundance and monitoring data can therefore be used to apply network analyses and investigate indirect effects, including quantification of the indirect effects. Network analysis can also detect subtle effects. Therefore, both experimental and field monitoring data can be used to apply an ecosystem approach in radioecology with network analyses being a useful tool to analyze whole ecosystem level effects. These indices could be used in management and risk assessment.

Discussion

Other researchers are also performing experiments using aquatic mesocosms, but many are focused on bacteria or other lower organisms and higher dose rates – it is unusual to see experiments being performed for low dose rates. Should the experiments discussed in the presentation be repeated, some adjustments would be made to include more natural communities where interactions are already established so that greater impacts on consumers may be observed.

The effects observed indicate that daphnids appear to be less sensitive to radiation exposure in mesocosm experiments than has been observed in single species experiments so there does appear to be some differences in how species respond within communities as compared to when studied individually.

Network analysis studies can help in identifying what is happening in terms of species effects and the effects on interactions between species and are already being applied in fisheries management.

4.4 Why many Chornobyl radiation effects studies are wrong

Mike Wood (University of Salford) presented.

The intention of the presentation was to encourage people to think critically about studies undertaken in the Chornobyl Exclusion Zone (CEZ) and how those studies are interpreted.

At the time of the Chornobyl accident, a significant impact occurred in the near field and particularly the Red Forest where pine trees were killed. People have been excluded from the area because of the accident, resulting in the establishment of the CEZ. This area has a gradient of contamination across various different habitat types and has become the focus for radioecological research. Many different research groups have used the CEZ as a natural laboratory, including a UK consortium with the TREE (Transfer – Exposure – Effects) project (2013-2018).

The Chornobyl natural laboratory provides a valuable resource where radiation effects can be studied on wild populations. Such studies have real world implications for regulation on the use of radioactive substances. One of the fundamental questions that is asked repeatedly and needs to be answered to feed into appropriate regulation is at what level of radiation exposure do population level impacts occur? This question continues to pose many challenges. If we look at mainstream media there are conflicting headlines indicating contrasting views both in science research and in the news. For example, one news headline suggests that forests around Chornobyl aren't decaying properly whereas another contradicts this by saying that radiation is not affecting leaf litter decomposition. These contrasting views reflected in mainstream media are due to contrasting findings in scientific research. The lack of scientific agreement on radiation effects is the biggest controversy being faced in radioecology and environmental protection and we need to find ways to move this area forward.

It is worth noting that if you look for media reports on leaf litter degradation, it is easy to find information to say that leaf litter is not decaying properly. However, it is much harder to find anything by way of a mainstream headline to say that, irrespective of the radiation contamination, leaf litter decomposition doesn't vary much. This reflects two key problems: (i) media reports tend to have a bias to the more sensational headlines, so a null finding is less likely to be reported; and (ii) academics are pushed to increase their media profile and this can lead to a chasing headlines approach. As researchers, we need to ensure that a balanced and evidence-based scientific view is maintained.

The importance of balanced scientific views and being transparent and open in findings has been raised previously. For example, the book 'Bad Science' by Ben Goldacre covers important topics such as the need for appropriate controls, the importance of being open and transparent by providing necessary details when publishing research and the importance of logic and sound reasoning. A paper by John Loannidis on 'Why most published research findings are false' has been very influential in getting people to think about the robustness of research design etc. It highlights issues such as shotgun approaches to hypotheses, where the hypothesis is developed to fit the research findings rather than a hypothesis being set and thoroughly tested.

Bias is very difficult to overcome. If there is unconscious observer bias, this can affect a study. There are also challenges around reproducing research due to costs and access issues. It is also important that data are made available to others. It can be difficult to share direct observations in the field, but what you can do is find ways of capturing data through recording devices that can then be made available to others to analyze independently.

In looking at issues around research, we shouldn't just focus on other people's research, but we should also look at our own. One study recently published has been on gut biomes of small mammals from the CEZ where the relationship between dose and gut microbiomes is shown to differ notably depending on whether total dose rate or ambient dose rate is considered. Given these findings, consideration needs to be given to the appropriateness of using only ambient dose rate in radiation effects studies. The ambient dose gives us an approximation of external dose rate and may correlate but it will be affected by the heterogeneity of contamination and animal behavior.

A study at a reference site in the CEZ looked at quantification of dose rates to animals based on direct measurements of activity concentrations and compared those with ambient dose rates. Internal dose rate can contribute up to 90% of the total dose rate so ambient dose rate measurements are at best a blunt instrument for quantifying dose. They are largely driven by gamma emissions so, whilst they give some means of approximating Cs-137 activity concentrations in the environment from which estimates of internal concentrations can be derived using concentration ratios, the study results show that Cs-137 contributes less than 50% of the internal dose. The major contributor was Sr-90, so studies ignoring Sr-90 in the CEZ will significantly underestimate the total dose rate.

To try and move this forward, a detector has been developed that allowed live measurements to be made on small mammals in the field and quantify both Sr-90 and Cs-137. This allowed activity concentrations in individual animals to be quantified and estimated total dose rates to be compared against ambient dose measurements at the collections sites. Results indicate that there was no good evidence that ambient dose rate would be a good predictor of actual total dose rate. Indeed, at some of the lower ambient dose rate sites, some of the highest total dose rates were observed. This highlights the need to get the dose quantification right in field studies.

It is also important to consider historical dose rate implications for sites. If there is a large single point in time event with subsequent radioactive decay over time, there can be a big difference between initial dose rates and those observed now. If we compare these against continual release situations, there may be a point at which the exact same dose rate may occur, but the contamination history of those sites is very different and needs to be considered when interpreting results of radiation effects studies. We also need to recognize that there is no perfect control in field science as there are always confounding factors that need to be considered. For example, for the CEZ, the forest fire history will influence what we see today. Human disturbance factors are also important. With abandonment of the most contaminated areas there has been a shift away from a managed system back to more natural landscapes, which occurs as a continual process. Observations made at different stages of that process need to recognize the stage of the succession process. There are also tourism hotspot areas where human disturbance will be a factor. Studies on radiation effects will therefore need to consider the significant legacy of contamination, the history of the ecosystem as well as human disturbance factors.

There are many challenges when interpreting Chornobyl radiation effects studies. Many studies give firm conclusions but do this without acknowledging the challenges and issues. To move forward, we need a clearer understanding of the level of impact that occurs on wildlife populations because of different levels of radiation. Further research is therefore needed but studies need to be designed robustly, acknowledging time and budget restraints and we need to be transparent on findings and share data. It is also important that we share negative findings. We are in a good place currently in terms of publishing negative findings in radioecology and journals need to continue to publish such findings into the future.

Discussion

There will always be challenges in ensuring publications are not misleading, but there are ways the process could be improved. For example, more open peer review processes can be applied rather than using a two review and editor decision approach. Research can also be put up for critical review within the community and open data exchange could also help address some issues.

5 Application of Radioecology to Radiation Protection

5.1 Background to the ERICA Assessment Tool

Carol Robinson (DSA) presented.

ERICA is the acronym for the Euratom funded project 'Environmental Risk from Ionizing Contaminants: Assessment and Management' that ran from 2004 until 2007. Outputs from the project were the ERICA Integrated Approach for performing environmental assessments for radioactivity that includes impact assessment, risk characterization and environmental management considerations and the ERICA assessment tool that guides users through the assessment process and performs the calculations that allow risks to selected plants and animals to be estimated. The project included a wide range of partners, including regulators and science organizations, many of whom have continued to be involved in the continued development of the ERICA tool.

ERICA dose assessments start from radionuclide activity concentrations in reference media (e.g., soil, water, sediments) and models the transfer of those radionuclides through the system, using simplifying assumptions such as equilibrium concentration ratios (CRs) and occupancy factors, along with dose conversion coefficients (DCC) to calculate the internal uptake of radionuclides into organisms and to calculate internal and external dose rates. The total dose rate is then compared against benchmarks, such as the ERICA screening level, effects data within the FREDERICA database or natural background in order to evaluate the significance of the dose rates received by organisms. The key components are illustrated in Figure 2. The assessment tool includes a range of default reference organisms that represent the main types of plant and animal within European ecosystems.

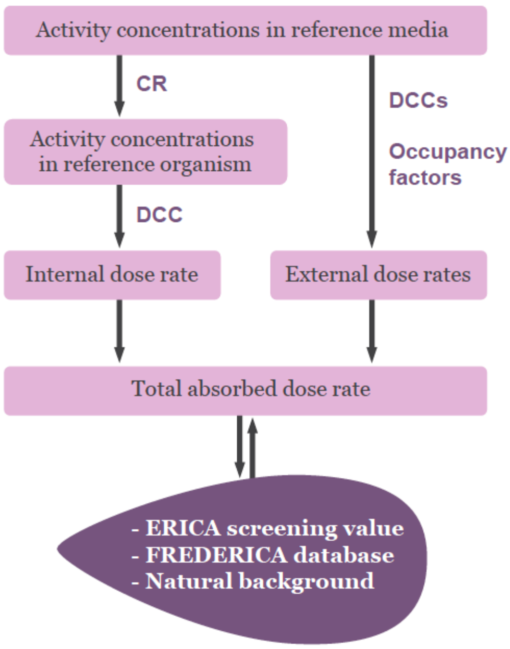

Figure 2. Key components of the ERICA biota dose assessment approach.

The ERICA tool provides a tiered approach to assessments. At tier 1, concentrations of radionuclides in the environment are compared against pre-calculated Environmental Media Concentration Limits (EMCLs) to estimate risk quotients. The EMCLs are conservative values and as users move through the tiers, assessments become less conservative. Tier 2 tends to be the most used assessment tier, at which dose rates to defined reference organisms are calculated, but users can edit parameters and add additional radionuclides beyond those included as default options. There is also the option for users to define additional representative species. Tiers 1 and 2 also include the IAEA SRS-19 dispersion models for discharges that allow activity concentrations in environmental media to be calculated for discharges to the environment. Tier 3 then allows probabilistic assessments to be performed and direct comparison with radiation effects data within the FREDERICA database.

Since the initial development of the ERICA assessment tool there has been continued maintenance and development of the tool. This has involved a number of partners led by DSA, including ARPANSA, Ciemat, Environment Agency, IRSN and SSM. The various partners provide advice and or financial support. A number of additional organizations, such as the UK Centre for Ecology & Hydrology (UKCEH) and University of Stirling provide scientific/technical input, including access to underpinning databases that the tool is dependent upon such as the wildlife transfer database and FREDERICA. New contribution agreements and memoranda of understanding are in the process of being established to ensure continuing support for the maintenance and development of the tool. From the outset, software development has been undertaken by Facilia (now part of AFRY).

Following the initial release of the ERICA tool, a number of updates have been made. These include a version 1.2 release in 2014 that included new default radionuclides, updates to assessment parameters (CRs) and recalculation of EMCLs to account for those updates. Reference organisms were also rationalized to be consistent with the ICRP Reference Animals and Plants and to address gaps in the types of organisms in order to ensure that the full range of protected species throughout Europe was represented. Version 1.3 was then released in 2019, which included more functional developments to make the tool more user friendly. This included adding a multiple series data function, including a MS Excel import function, to allow temporal and/or spatial data series to be assessed

5.2 Feedback on the ERICA user survey

David Copplestone (University of Stirling) presented.

A user survey was developed and distributed to ERICA tool users towards the end of 2020. The survey aimed to:

- → develop understanding of the ways in which the tool has been used and the level of take up for wildlife dose assessments in different countries and explore issues around the application of radiation protection in those countries;
- → explore whether and how people engage with stakeholders on environmental radiation protection issues;
- → evaluate what training has been received and whether it helped users; and
- → evaluate whether the ERICA tool meets end-user needs and is considered fit-for-purpose and gather ideas for future improvements to the tool.

The survey was conducted using an online survey form that include 38 primary questions. A link to the survey was emailed to all ERICA registered users and 57 users from 36 countries responded. The respondents were a relatively even mix of regulators, industry and academics. Of the countries represented by respondents, more than 50% recommend wildlife dose assessments, which illustrates how common wildlife dose assessments have become in order to meet regulatory requirements for environmental protection. When asked, 85% of respondents, representing half of the countries, said that ERICA was recommended for use in their country, but in some cases other tools were also recommended, and 97% of respondents said they used the ERICA tool themselves. The majority (63%) used the tool for assessments relating to planned exposure situations and 54% used for existing exposure situations.

Surprisingly, 16% said they had used that tool for emergency exposure situations, which was interesting as the tool uses equilibrium transfer factors that are not best applied to the highly dynamic conditions that would be present during an accident. Assessments were also performed for a wide range of sectors, the most common being nuclear licensed site permit applications, research purposes, activities associated with NORM and radioactive waste management.

Several different tools and resources have been used in assessments, including resources such as the wildlife transfer database and FREDERICA. In terms of assessment tools, 67% of respondents said that equilibrium-based models were adequate for their purposes and more than 50% recommended the use of TRS479 as a source of transfer parameters.

It is recognized that assessments are often needed for noble gases, particularly in relation to nuclear power where around 70% of the total radioactivity released to the environment can be noble gases, but not all tools include this capability. Around 45% of respondents identified the need to assess the exposure of wildlife to noble gases and around half of those used a noble gas calculator. The suggestion was therefore made that it would be useful to include the capability to assess doses to wildlife from noble gases within ERICA.

The majority of respondents had only conducted a few assessments (<10), but several responded to say they had done between 30 and 50 assessments routinely. However, some of those responding to say they had only done a few assessments had only recently undertaken training so may be more likely to use more frequently in the future.

A spatial and temporal assessment function was included in the version 1.3 release of ERICA and there was interest in understanding how people consider spatial aspects and address heterogeneous contamination in the environment. Around 50% of respondents said that they did consider spatial aspects with some drawing on guidance provided in the BIOPROTA report 'Scales for Post-closure Assessment Scenarios (Space)'. The inclusion of the temporal and spatial functionality in the ERICA tool was considered useful and improved the user-friendliness of the tool.

In terms of benchmarks used in assessments, over 80% of respondents said they used the ERICA screening value as a convenient benchmark for comparison in order to screen sites of negligible concern. The IAEA/UNSCEAR values were also used, but are considered more complicated to apply. Less than 40% applied the ICRP DCRLs, but there is interest in understanding how the DCRLs apply at the population level and work is ongoing within the ICRP to consider this further.

There has been an increasing role for stakeholder engagement in assessments and responses showed that a broad range of stakeholders have been engaged, including member of the public, non-government organizations, the media, industry and regulators. Fewer than 20% of respondents hadn't interacted with stakeholders. Around 60% of respondents felt there had been a moderate or significant increase in stakeholder perceptions in recent years, some of which may have been driven by recent newsworthy research findings and as a result of having greater access to information. Indeed, almost 45% of respondents said that a key challenge for stakeholder engagement was responding to comments that radiological impacts occur below benchmarks. Other stakeholder engagement and communication challenges related to explaining radiation risk and providing assurance that assessment tools are fit-for-purpose as there is a sense that CRs can be considered too simplistic to represent transfer through ecosystems. This is almost certainly true from a science perspective, but it is necessary to have pragmatic assessment approaches for regulatory purposes. This requires us to be open and transparent around the uncertainties and limitations of wildlife assessments and to ensure that tools are fit-for-purpose.

Over 40% of respondents had been on a wildlife dose assessment training course, which included those associated with tools such as ERICA or RESRAD-Biota, more general courses on radioecology that included aspects on radiation protection or conference events. Of those that had undertaken training, all said that the courses had increased their confidence in conducting assessments and most felt they had a better understanding of the underpinning science and increased their ability to communicate the assessment output to stakeholders.

A number of suggestions were put forward to improve the ERICA tool. These included adding the functionality to allow EMCLs to be calculated in tier 1 for new radionuclides; adding dynamic modelling options and improving tier 2 dispersion models (updated SRS-19 dispersion models are due to be released by the IAEA and will need to be updated within ERICA); allowing calculation of C-14 dose rates from soil activity concentrations; and adding functionality to allow the sharing of user-defined organisms between computers. Several other suggestions were also made that have already been addressed in a new version 2.0 ERICA release.

5.3 Launch of ERICA Tool Version 2

Carol Robinson (DSA) presented.

Since the last version 1.3 release of the ERICA tool in 2019 there have been significant developments made to the tool. In recognition of the significant step forward these developments represent, a version 2.0 release is planned. Some of the developments that have been made were identified as needed developments in user survey feedback (e.g., the inclusion of noble gas dosimetry), as discussed in the previous presentation and demonstrates that feedback is taken into account to ensure the tool continues to develop in a way that is useful to everyone. The main developments in version 2.0 include a new dosimetric approach, consistent with the ICRP approach; updating of CRs and freshwater Kds and recalculation of tier 1 EMCLs; inclusion of noble gases (including radon); and the inclusion of a function to allow multiple user-defined organisms to be added through a MS Excel import function.

The new dosimetry in ERICA has changed the way in which decay chains are dealt with. The original dose conversion coefficient (DCC) calculations in ERICA were well elaborated and adopted by the ICRP in Publication 108. In that approach, decay chains were truncated at the point where the half-life of a radionuclide equated to 10 days or less. The ERICA dosimetry has been updated to be consistent with the ICRP-136 methodology through a close collaboration with the ICRP Biota-DC developer, Alexander Ulanovsky. In implementing the new dosimetry, some simplifications were necessary. For example, in the ICRP approach the integration time can be selected to be pertinent to a specific assessment whereas in ERICA the integration time has been taken to be 1 year in all cases. Furthermore, with the change to the way decay chains are addressed, it is necessary to include all radionuclide DCCs explicitly, including for short-lived progeny. This also requires the inclusion of necessary assessment parameters (i.e., CRs and Kds) for those short-lived radionuclides and the inclusion of a correction factor to account for the decay of the ‘unsupported’ component of those radionuclides over the integration period.

Another problem identified previously was the application of CRs based on stable elements or long-lived radionuclides to radionuclides with short physical half-lives. An adjustment is needed in such instances to allow for radioactive decay. As such, a new equilibrium correction factor has been incorporated, based on a solution for freshwater organisms given in IAEA TRS-472 and expanded to all ecosystems.

Data from the wildlife transfer database (discussed in Section 54.) have been extracted and used to update the ERICA CR databases, in collaboration with UKCEH. New data gap filling methods have also been incorporated. Updates have also been made to the freshwater Kd database, using new data compiled by an IAEA MODARIA working group.

As a result of the changes to the dosimetry, CRs and Kds, dose rates for organisms will change and it has therefore been necessary to recalculate all tier 1 EMCL values. The EMCL is the most limiting activity concentration for a given environmental media (soil, sediment or water) that gives rise to a dose rate to the most exposed reference organism that is equal to the screening dose rate. Considerable quality assurance has been undertaken in relation to the EMCL updates to understand what has led to the various changes in the EMCL values (i.e., whether changes are driven by the new dosimetry and/or revisions to assessment parameters) and to ensure the changes are justifiable and not a result of errors.

As noted previously, noble gases were not included in previous versions of ERICA and this was a known deficiency. This deficiency has now been addressed and a suite of noble gases is now available within Tier 2 of the tool. It is assumed that noble gases will not interact with environmental media or biological material. Therefore, all CRs and Kds for noble gases are set to zero by default. Immersion DCCs have been calculated using the ICRP Biota-DC tool and it is assumed that terrestrial organisms spend 100% of their time in the contaminated air, irrespective of whether they would normally reside above or below ground. In the case of radon and thoron, the contribution of these radionuclides to dose rates arising from inhalation and deposition in the lung is also taken into account. This component of dose is treated as an internal contribution to exposure and is based on the methodology of Vives i Battle et al. (2017) and was further developed for the ERICA reference organisms in consultation with Jordi Vives i Battle.

Finally, a new ‘add organism’ wizard has been developed. This is a new function to allow multiple new user-defined representative organisms to be added to the tool at one time. An import/export function creates a structured MS Excel file that can be completed by the user and uploaded to the tool, enabling DCCs to be calculated for each organism. A wizard-specific help file has been developed to guide users through the process. The use of the add organism wizard also supports the sharing of user-defined organisms between assessors.

In addition to the developments that have already been made for the version 2.0 release, a number of further developments are planned. The ERICA end-user’s questionnaire responses will be further analyzed to identify additional end user needs and aspirations and will be used to update ideas for future developments. Two development ideas are already underway. These include updating the summary radiation effects tables that are available at tier 2 and implementation of dynamic model functionality.

Version 2.0 is freely available for download from http://erica-tool.com/ and training courses on the new version will be developed. It is intended that these will include full training courses to those new to ERICA as well as update/refresher courses focusing on the new features of the tool. Information on training courses is provided on the website.

5.4 Update of the wildlife transfer database

Nick Beresford (UKCEH) presented.

The Wildlife Transfer Database (WTD) has been developed over many years and, as noted in Section 5.3, has recently been used to update the CR databases within the ERICA assessment tool.

In order to estimate internal dose rates in radiological environmental assessment models, an estimate of the activity concentrations of radionuclides in the body of organisms is needed. If measured data are not available, a method for calculating transfers is required. Most approaches use a whole organism to environmental media CR. In aquatic ecosystems, this usually relates to activity concentrations in filtered water whereas for terrestrial ecosystems CRs relate to soil with the exceptions of tritium and C-14 for which CRs relate to concentrations in air. The application of a CR therefore enables the activity concentration in an organism (Bq/kg fresh matter) to be calculated from the activity concentration in soil (Bq/kg dry matter), air (Bq/m^3) or water (Bq/l).

A number of biota dose assessment models have developed over the last few decades and early model intercomparison exercises identified transfer to organisms through the application of CRs as the main uncertainty in assessments. As such, there has been considerable international effort to collate CRs and, within the IAEA EMRAS program, the online WTD was created (https://www.wildlifetransferdatabase.org/).

The initial ERICA database incorporated CR reviews undertaken within the FASSET and EPIC programs, as well as new data generated within the ERICA project. The WTD was then developed in around 2010. At that time, the ERICA database was the most comprehensive source of CR data and it was the foundation for populating the WTD. The data in the WTD were then used as the basis for ICRP Publication 114 and IAEA TRS-479. At that time, the WTD contained around 87,000 CR values for 71 elements. Subsequent addition of new data and quality control of the database led to there being around 104,000 CRs for 80 elements in a 2013 version of the WTD. This version was used to update the ERICA databases in the ERICA version 1.2 release (version 1.3 used the same CR database).

ERICA version 2.0 has been further updated to be consistent with the WTD 2020. This includes additional data from 'reference site' studies where a number of RAPs have been sampled from single sites. The sites include the CEZ, plus sites in Norway, Spain, and the UK. Wild rodent data from Fukushima have also been included. The 2020 version has over 74,000 entry lines and around 110,000 CR values for 79 elements (one element was removed from the previous version of the WTD as a consequence of quality control checking).

ERICA version 2.0 has 6 new elements to account for the new decay-chain dosimetry approach and CR data were therefore required for these elements. There has also been a change for sulphur and phosphorus in the terrestrial system. Previously, CRs for these elements related to air, but this has now changed to soil as CR data have become available. As a result of the updates, around 50% of the CRs within the ERICA version 2.0 database are now based on empirical data. Extrapolation approaches are therefore still required to address data gaps. The approach to addressing data gaps has tended to be to select the most conservative value where there is more than one extrapolation option available as this supports a conservative assessment at tier 1 of the ERICA Tool.

Figure 3 illustrates the ratio of CRs between ERICA versions 2.0 and 1.3 for terrestrial mammals. Where the ratio is greater than 1, this indicates that the CR has increased in version 2.0. Most CR values are within one order of magnitude. Where variations are greater than this, this tends to result from a move away from a conservative extrapolation approach to the use of new empirical data.

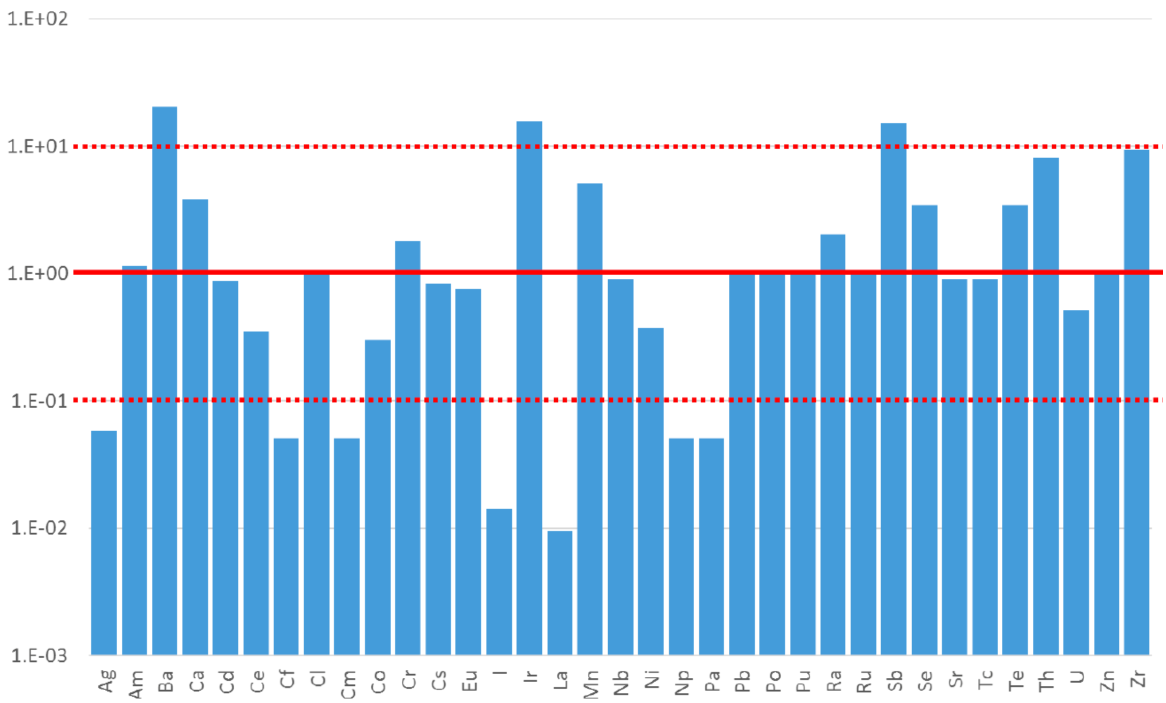

Figure 3. Ratio of CRs between ERICA version 2.0 and version 1.3 for terrestrial mammals.

In previous versions of ERICA, CRs were element specific. For example, in version 1.3, the same single CR value was applied across all isotopes of iodine. In version 2.0, a new equilibrium correction factor has been applied to account for the biological half-life and decay of shorter-lived radionuclides. As a result, different CRs are applied for each isotope. The difference is illustrated in Table 3 for isotopes of iodine.

Table 3. Implications of the use of an equilibrium correction factor on CRs for isotopes of iodine in version 2.0 compared with the version 1.3 approach.

Isotope	**CR**
I (version 1.3 approach)	*5.65E-3*
I-129	5.65E-3
I-125	3.75E-3
I-131	1.19E-3
I-132	1.80E-5
I-133	1.59E-4

Where extrapolation approaches have been necessary to address CR data gaps, the approach has always been to ensure transparency. However, this was not the case for empirical data – there was no information provided on the robustness of the data (e.g., whether a CR value was based on multiple data points or a single value). This has been corrected in version 2.0. Now, when a CR is selected within the ERICA Tool, information is presented on the number of data points and publications that underpin that CR. A link has also been provided through to the WTD references used to derive the CR for each element.

In addition to ERICA, the WTD is also being used by the IAEA to update the SRS-19 approach to include wildlife. It is also being used to investigate taxonomic models. Concentration ratios are recognized as a simple concept, but they are highly variable for a given radionuclide and organism. Taxonomic models are therefore being used to rank taxa and generate adjusted mean values by essentially removing the influence of a site. Further information on the approach is provided in Beresford & Willey (2019)[9].

An assumption within the WTD is that stable element data can be applied such that the CR for caesium is likely to be based on both Cs-137 and stable Cs data. This is an accepted approach, but recent

[9] Journal of Environmental Radioactivity 208-209: 106020.

publications have questioned the approach since measurements of both stable Cs and Cs-137 have indicated that CRs for Cs-137 tend to be higher, which is also the case for Sr-90 as compared with stable Sr[10]. It may, therefore, be necessary to re-evaluate the assumption for some radionuclides although where alternative data are limited it may continue to be necessary to use the stable element data.

The WTD 2020 CR summaries have not yet been added to the website. Further updates to the WTD will be ad hoc as funding allows.

Discussion

The quality assurance process for the WTD can be quite challenging as it is necessary to rely on the data that is sent in by people. Where those data are published it is possible to make some judgements on the quality. In the original version of the WTD a lot of data from Australia were included and those data have now been quality assured by those that were involved in generating the data. Best efforts are therefore made, and data have been regularly reviewed to date.

5.5 Cumulative hazard and risk assessment for radioactive and chemical contaminants

Knut Erik Tollefsen (NIVA and NMBU) presented.

The Centre for Environmental Radioactivity (CERAD), the Norwegian Institute for Water Research (NIVA) and the Norwegian University of Life Sciences (NMBU) have been working on investigation of multi-stressor effects and cumulative hazard and risk assessments.

Risk assessments involve hazard and exposure assessments following problem formulation to characterize risk. These, together with uncertainty assessment around the data used in assessments, allow conclusions to be drawn on impacts and risks and whether exposures are safe. In terms of cumulative risk, the group are engaging from a multi-source, multi-stressor and multi-organism perspective where the stressors are fundamentally different. The goal is to expand and investigate how to integrate the chemical-centric approach into the radioactive field in order to have a common approach and to develop understanding around the complexities. As such, the approach is to work from the source to evaluate exposures through aggregate exposure pathway analysis (AEP) and similar challenges are seen between chemicals and radionuclides such that similar governing principles are valid. The starting point is to look at stressors individually and consider both internal and external exposures. The second stage is then adverse outcome pathway (AOP) analysis that looks to link exposures to multiple levels of impacts. If successful in linking together AEP and AOP, the result is a continuum from stressor to impact, which is referred to as source to outcome pathway.

A cumulative risk assessment (CRA) tool is under development to combine both chemicals and radioactivity that is both AEP and AOP informed. A supporting database has also been developed to organize effects data for the CRA, but this is very chemical focused at the present time. Risk quotients are calculated, similar to the approach in ERICA, with dose addition being assumed in order to link exposure to effect. However, rather than looking at single stressors in isolation, the aim is to look at multiple stressors, taking account of all the different interactions that are expected to occur including summations and additions in effects. As such, within the database, information is organized relative to hazards and their modes of action and attempts are made to build bridges between these. The tool developed is called the Source To Outcome Predictor (STOP) which aims to facilitate end-user interaction.

[10] Environmental Pollution 299: 118897.

The graphical user interface that has been developed aggregates and organizes data from multiple stressor exposures as well as from the hazard characterization side using the AOP concept and performs cumulative risk assessment calculations that can be either prospective or retrospective to allow the outcome of different scenarios to be evaluated, such as future accident scenarios. It will also be supportive of mitigation actions to look at the consequence of different actions through, for example, the removal of one or more stressor. It is EFSA compliant and is automation friendly so could be connected to sensors in real time.

The interface is supplied by the risk assessment database on effects. Modelled or measured exposure data are then used for a given site to generate a spatiotemporal consideration of hotspots where threshold exceedance is expected. Once you have this, it’s possible to look at the high risks and concerns and what the reasons for those risks and concerns are such as whether they relate to one or other susceptible species group. The output is therefore a taxa-informed cumulative risk assessment for a given exposure situation. The next step is then to look at the adversity relevant for the given scenario and rank according to the likely effects from the complex mixture, which could be related to mortality, reproduction etc. and efforts are ongoing to supply more data on adversity as it develops, including for the radiation field. Efforts are then made to try to characterize the mechanisms that are behind particular adversities and to rank the mechanisms according to their relevance for the scenario. This enables the key risk drivers to be identified, i.e., the stressors that give rise to the greatest risk. With this available information, laboratory or field studies can then be undertaken to evaluate whether the predictions are in line with what is seen.

A simulation study has been performed on a lake north of Oslo. The simulation involved the derailing of a truck carrying special wastes that included pesticides, chemicals and radioactivity. Background radiation, including UV radiation were also considered as additional possible stressors. The set of stressors was then subject to CRA and a spatial distribution map was generated to identify where thresholds could be exceeded. The temporal aspects were also considered in terms of the time necessary for risks to be reduced to safe levels and to investigate the effects of mitigation measures. It was also possible to identify organisms likely to be affected in the acute phase versus those in the chronic phase and to rank species according to their susceptibility. If the species to be protected are known, it is also possible to then look at the risk drivers for those species. This relies mostly on experimental data, but some predictions for effects can be performed using quantitative structure activity relationships (QSAR) where data are unavailable. If the risk drivers are considered in a cumulative way, it is possible to look at the addition from each stressor and get an idea of the relevance of each pollutant.

Several other case studies are planned to be looked at in the future. Work is also ongoing to investigate how well the complex interactions that occur are being addressed in the CRA approach.

Discussion

The tool is currently at a research level and work is ongoing to gain confidence in the predictions, rather than it being applied as a regulatory tool. However, there has been a lot of regulatory interest but nationally and internationally and there is a large European initiative where CRA is the central focus. It is likely, therefore, that the CRA approach will be more approachable from a regulatory perspective in the future.

5.6 The CONCERT-TERRITORIES project and the management of existing exposure situations

Marie Simon-Cornu (IRSN) presented.

The European project TERRITORIES (To Enhance unceRtainties Reduction and stakeholders Involvement TO wards integrated and graded Risk management of humans and wildlife In long lasting radiological Exposure Situations) was a 3-year research project within CONCERT, the European joint program for the integration of radiation protection research funded by Euratom. The project, which ran from January 2017 to January 2020) involved 11 partners from 8 countries, but connected to a wider network of experts through annual meetings and open events. The outcome from the project includes a publicly available database (available from http://radioecomachine.ciemat.es) as well as numerous published articles and reports. The project addressed long-term exposure situations that are mostly managed as existing exposure situations. Outcomes from the project include recommendations and applied case studies for assessing and managing long-term exposure situations, particularly after (the transition phase of) a nuclear accident or in cases of enhanced natural radioactivity, and a graded and integrated approach with fit for purpose reduction / analysis of uncertainties associated with the evaluation of doses to human populations and wildlife with consideration of uncertainties and involvement of all stakeholders in decision making processes.

The project included several work packages. Work packages 1 and 2 were focused on technical uncertainties and work package 3 on decisional uncertainties. Work package 4 was then focused on dissemination and work package 5 on management of the project.

Work package 1 was led by CIEMAT and was focused on quantifying variability and reducing uncertainties when characterizing radiological exposure of humans and wildlife by making best use of data from monitoring and of existing models and several case studies were considered. Work package 1 produced 4 deliverables:

→ A report describing the TERRITORIES Library Database that provides the data sets acquired throughout the project. Altogether there were seven datasets from five territories, including from two NORM observatories (a Belgian forest and a Polish lake) as well as data modelled or analyzed within the project.

→ Guidance on reducing sampling uncertainties when designing sampling protocols.

→ Guidance on selecting the desirable fit-for-purpose level of complexity for models to be applied in risk assessments. Models were applied to data from 4 sites in order to compare the models. In total, 11 models were applied, but not to all sites. The comparison considered the ability of models to predict measured data and resulted in proposed quantitative indicators for models.

→ Guidance on uncertainty analysis for radioecology models, including parameter and conceptual uncertainties.

The output from work package 1 has been referred to in the SRAs of ALLIANCE and NERIS and has been used in an assessment by Public Health England (PHE) of the risk to people's health from radioactive objects on beaches around the Sellafield site in which guidance for radioecological modelling was applied.

Work package 2 was focused on reducing uncertainties when characterizing exposure scenarios, accounting for human and wildlife behaviors, and integrating social and ethical considerations in the management of uncertainties. The work package was led by PHE and there were two main deliverables. The first deliverable was on exposure scenarios that looked at variability and how to account for the variability in behaviors of humans and biota through case studies. In one study, the focus was on where reindeers spent their time and the ambient dose rate they received. The other case studies looked at high school students in Belarus and the measurement of ambient dose rates around the village in which the students lived as a citizen science project. The second deliverable was focused on more social aspects, including ethical and social considerations around research activities. The citizen science study in Belarus and the Reindeer study have both been mentioned in the NERIS and ALLIANCE SRAs and the output of the work package has also been referred to in the PHE Sellafield study referred to above.

Work package 3 focused on stakeholder engagement for better management of uncertainty in risk assessment and decision-making processes, including remediation strategies and was jointly led by CEP and DSA. Several deliverables were produced, including a synthesis report on decision making strategies, guidance for management of post-accident and NORM scenarios, based on feedback from different case studies. Following the review of different tools and strategies, stakeholder panels were established, and innovative assessment methods (e.g., a serious game) were applied to inform debate and enhance engagement with different stakeholders. As a result of the work undertaken within the work package, several recommendations were made, including for modeling and measurements to be appropriate to the characterization of existing exposure situations, to consider the complexity in assessing radiological exposures to non-human biota, to establish dialogue around the uncertainties and their impact on assessments and to place radiological hazards in the context of the overall hazards. The output from work package 3 has also been referred to in the SRA of ALLIANCE and NERIS and the serious game has been used by the French association of local commissions of information around nuclear associations in a white paper regarding cross border situations. The output has also been used in an IAEA ENVIRONET project and in a new RADONORM project.

Work package 4 on dissemination organized various workshops around uncertainties and communication with stakeholders. A website was also developed and is still accessed by people from around the world.

Overall, the TERRITORIES project has led to practical recommendations around monitoring, uncertainties and the integration of socioeconomic analysis and technical considerations. Throughout the project there was structured dialogue and a series of workshop and there are several examples of the output being used in other projects.

Discussion

Many recommendations from the project have been shared with other countries and there has been positive feedback around interactions between stakeholders. It will be interesting to see in the future whether deliverables continue to be cited by other scientist as this will indicate how well the recommendations have been taken up throughout the radioecological community.

6 Radioecology and Management of Nuclear and other Legacies

6.1 NEA activities related to decommissioning and legacy management, including the Characterization Methodology for Unconventional and Legacy Waste

Rebecca Tadesse (NEA) presented.

The NEA has 34 member countries, which represent around 86% of the worlds installed nuclear capacity. There are currently has 8 technical standing committees, more than 80 working parties and expert groups and 23 international joint research projects. Within the 8 committees are the Radioactive Waste Management Committee (RWMC), focused on the development of strategic policies and best practices in the management of radioactive wastes in all phases, and the recently created Committee on Decommissioning of Nuclear Installations and Legacy Management (CDLM) that aims to develop strategic policies and best practices in nuclear decommissioning and management of legacy facilities. Both of these committees take a holistic approach to the issues by considering regulatory aspects, legal issues, operational safety, and societal, environmental and economic factors. Both technical committees are also supported by two groups – a regulators forum (RF) that brings together regulators to address technical and policy issues, and a forum on stakeholder confidence (FSC) that looks at issues around communicating uncertainties, end states and safety cases and other aspects.

The RWMC has a number of technical groups, including an Integration Group for the Safety Case (IGSC) that considers characterization and performance of different host rocks for repositories as well as operational safety, performance assessments and safety cases. Recently, a new expert group on the application of robotics and remote systems in the nuclear back end has also been formed under the RWMC, which is focused on issues preventing entities from using artificial intelligence and robotics, such as whether there are regulatory issues that need to be addressed. There is also a Working Party on Information, Data and Knowledge Management that aims to address issues around the maintenance of knowledge and transfer of knowledge to the next generation.

The CDLM was created in 2018, with the work program taking around a year to develop. A workshop was held in 2019 at which a list of focus areas was developed by member countries. Currently two working parties have been developed on technical, environmental and safety aspects (WPTES) and on management and organizational aspects (WPMO), which includes an expert group on costing for decommissioning of nuclear installations and legacy management (EGCDL), as well as an expert group on holistic process for decision making on decommissioning and management of complex sites (HDCS). In addition, there is a joint CPD project that has been running for around 15 years. This brings together industry to exchange knowledge around technology and other areas where knowledge sharing would be beneficial. The CPD is a closed group but there is interaction with the CDLM to ensure knowledge is shared.

The WMPO is focused on how to manage programs, ensure cost and funding issues as well as supply chain issues are addressed. Societal impacts and communication are also addressed, along with knowledge management and the education and training of staff.

The WPTES is focused on risk impacts (workers, public and environmental safety), sampling and characterization, decontamination and decommissioning technologies (including robotics), and how to ensure waste streams have appropriate disposal paths, including for chemicals used in decontamination processes.

The mandate for the EGCDL was created in June 2020 and includes:

- fostering exchange of information and experience between members on issues concerned with cost estimation;
- describing good practices in the field of cost estimation for decommissioning and legacy management projects;
- advising the CDLM on major and emerging issues in the area of cost estimation for decommissioning and legacy management; and,
- defining, conducting, and overseeing studies aimed at improving the transparency and reproducibility of cost estimates, including approaches to presentation and reporting estimates.

The HDCS mandate was also created in June 2020, with a kick-off meeting being held in November 2020. The HDCS aims to develop a holistic process for decision-making at complex/legacy sites in order to identify, assess, control and manage risks (including societal, economic and environmental risks) and develop guidelines and identify needed decisions on how to implement the process. The group reports directly to the CDLM. Within the next few years, it is possible a similar group will be created to look specifically at decommissioning processes.

The FSC is largely focused on waste management and recently held, together with the CDLM, a small stakeholders confidence workshop on the decommissioning of nuclear facilities in the UK to look at potential drivers affecting stakeholder confidence. Various stakeholders were present, including regulators, NGOs and the UK Nuclear Decommissioning Authority (NDA). Some of the areas that need to be addressed for decommissioning are similar to those for waste management but there are some differences. Some important aspects to consider are how to ensure affected communities have a voice in the decision-making process and how to ensure loss of income in those communities is addressed. A short publication has been produced from the workshop and is available from https://www.oecd-nea.org/jcms/pl_59337.

An expert group on the characterization of unconventional and legacy waste (EGCUL) is currently supporting Fukushima decommissioning. The mandate of the group is to share state-of-the-art knowledge and experience in characterization on large amounts of unknown waste, discuss relevant issues and challenges around characterization and provide international feedback on Japan's newly developed characterization methodology. The first thing the group did was agree not to develop a precise definition of 'legacy waste' or 'unconventional waste', rather, legacy waste is defined as radioactive waste generated by past activities and not complying with present criteria and unconventional waste is defined as radioactive waste generated in an unexpected situation, such as an accident, and that has unknown properties. Several case studies have been identified, including Fukushima in Japan, a decommissioning and treatment facility in France, Chornobyl in Ukraine and a nuclear site in the UK etc. and the group is looking at each to consider what were the key challenges and lessons learned. Several key challenge areas and lessons learned resulted, including the need for a radioactive waste management framework, including waste classification and categorization and the development of waste acceptance criteria for storage and disposal. End states also need to be defined, which involves considering what can be left behind. The goal is for there to be an appropriate regulatory infrastructure for the operation of a facility, but sometimes criteria may need to be modernized to address new wastes generated because of accidents and consideration needs to be given to the appropriate methods for characterization of such wastes.

Based on the case studies, a characterization roadmap for unconventional and legacy waste has been developed and recommendations and conclusions on international good practices have been developed[11]. These include the need for a clear policy and strategy underpinned by a regulatory framework to

[11] Since the workshop, the EGCUL report has been published by NEA and is available at https://www.oecd-nea.org/jcms/pl_62389/characterisation-methodology-for-unconventional-and-legacy-waste?details=true

implement the policy and the integration of decommissioning and waste management strategies to optimize resources and time. A further recommendation is for a clear and flexible waste classification system and waste acceptance criteria that applies to unconventional and legacy waste that addresses both the radiological and other hazardous content of the waste. It is also important to have a flexible and adaptable sampling methodology and to understand the end state goal prior to undertaking characterization activities.

The EGCUL has identified a number of areas of work for the CDLM to address key topics. A report on how to optimize the management of radioactive waste from decommissioning has also been published that considers the strategic analysis of impacts and how to ensure the different components are addressed.

Discussion

The HDCS has some connection with the working group 1 of the IAEA MODARIA program on NORM and legacy sites. The IAEA is represented at the Committee so there will be the opportunity for issues identified by the working group to be fed into the developing work program.

6.2 Drivers for radioecological research: lessons from decommissioning and legacy management and the outcome of a recent Nordic Workshop

Malgorzata Sneve (DSA) presented.

A virtual Nordic workshop was organized by DSA and CERAD and held in February 2021. This followed from several other workshops organized by DSA including two previous pre-ICRER workshops in Barcelona and Berlin. The latter of these was focused on the topic of radioecology as support to regulatory decision-making. The workshop included discussions around relevant case studies and identification of needs for radioecology and is reported in StrålevernRapport 2018:2, available at https://dsa.no/en/publications. A key conclusion from that workshop was the importance of understanding where the most important uncertainties that lead to regulatory challenges. These challenges include setting levels for releasing contaminated areas from regulatory supervision, demonstrating compliance, regulating for chemicals alongside radioactivity, and addressing uncertainties in a regulatory context (i.e., understanding when uncertainties affect the ability to make robust decisions). Many of these challenges are internationally recognized and have been identified and experience shared through various case studies discussed within international programs and workshops, including several recent NEA activities and a series of DSA-led workshops. A special issue of the Journal of Radiological Protection is also being organized on the topic of decommissioning and legacy sites[12].

The Nordic countries (Norway, Denmark, Sweden and Finland) have a similar nuclear research history that has led to a number of legacy sites, facilities and wastes. The countries have cooperated on nuclear and radiation safety and face common challenges in addressing uncertainties linked to safety assessments. A joint Nordic workshop was therefore proposed by DSA, which was in part triggered by the permanent shut-down of a Norwegian research reactor and a renewed initiative to address the issue of spent nuclear fuel which poses a significant regulatory challenge. The safety and other assessments that will be needed to address the challenges faced will require both technical and scientific input and it was therefore thought that sharing of knowledge and experience with Nordic neighbors would be beneficial. The virtual workshop 'Risk and safety assessments supporting regulatory supervision of decommissioning and waste management for nuclear research and radiation facilities' took place from 9th to 11th February 2021. The key topics for the workshop were:

[12] Since completed - described and with links to individual papers at https://iopscience.iop.org/journal/0952-4746/page/optimisation-of-the-management-and-regulatory-supervision-of-nuclear-decommissioning

- → waste and site characterization;
- → measurements and assessments supporting regulatory approval of decontamination and dismantling activities;
- → atmospheric and liquid radioactive discharges to the environment during operations; and
- → treatment, interim storage and final disposal of solid radioactive waste.

A key focus was on the development and review of safety cases and assessments and the key issues identified by operators and regulators, as well as key uncertainties that affect the assessment conclusions. It is important to recognize that there will usually be a large number of uncertainties and the focus therefore needs to be on those uncertainties that matter in that they affect the ability to make robust decisions. The workshop objectives were therefore to:

- → explore approaches to building a coherent risk and safety assessment framework;
- → identify key scientific uncertainties in safety assessments for decommissioning and waste disposal safety, especially from a Nordic perspective;
- → share research results and develop proposals to reduce uncertainties; and,
- → share experience to improve risk communication

The workshop was attended by more than 50 participants, representing operators, regulators, technical support organizations and the scientific community, primarily from Norway Sweden and Finland. There was a broad range of presentations, that were organized into three sessions:

- → Experience: Encompassing lessons learned from legacy sites, decommissioning and waste management.
- → Methodology: Radiological and other risk assessment methods that support proportionate and optimized management of different hazards and risks.
- → Challenges: Research conducted to reduce scientific uncertainties.

The workshop also included group discussions, which can be challenging when meeting virtually. To address this, questions were presented in advance to allow workshop participants to prepare and to encourage active participation:

- → What are the key contaminants (both radioactive and non-radioactive) from research facility decommissioning and what makes them key?
- → What environmental media / exposure pathways are important for these key contaminants?
- → What site characterization data are important?
- → Are the answers different for current operations and for releases into the far future, e.g., from disposal facilities?

Additional topics were recognized during discussions and collective feedback from the discussion groups was collated.

A report of the workshop has been published (DSA Report 2021: 3) that provided detail of the presentations and discussion. The main conclusions from the workshop were as follows:

- → Key contaminants from research facilities can differ from those associated with commercial reactors and information on characteristics is often lacking and, even for common contaminants, knowledge of behavior can be lacking for Scandinavian ecosystems.

- → Research could be developed to provide necessary knowledge in support of safety assessments. However, there is a tendency to focus on single issues or topics whereas it would be useful to take a cross cutting approach whereby several issues are considered together to find the optimum way forward.
- → The need for a harmonized and proportionate risk management approach to decommissioning, legacy and waste management is commonly recognized but developing and applying such an approach is challenging. For example, decommissioning and legacy sites are often associated with a wide range of radiological, chemical and physical hazards and complex social contexts. Different safety standards may therefore apply and there may be different regulatory authorities. It would therefore be useful to collect experience of approaches that have been adopted or adapted to address these issues, the results of which would support the research supporting the development and application of harmonized and proportionate assessments of risk from different hazards.
- → Consideration needs to be given as to how to carry out effective dialogue between relevant stakeholders that addresses all the different hazards, benefits and disbenefits.
- → There is significant scope to learn from continuing information exchange in decommissioning, site and waste characterization and management, regulatory processes, and stakeholder engagement, to identify common research needs on particular topics, evaluate how to meet those research needs (e.g., with shared technical expertise and resources) and thereby develop necessary skills and competencies.

It is hoped that the report will be used as input to further discussions within NEA and IAEA projects, as well as providing background for DSA, CERAD and others across the Nordic countries in exploring mechanisms for continued sharing of experience and contribute to the development science projects to address key issues and uncertainties.

Discussion

DSA also has a lot of experience in working on legacy issues with Russia, Ukraine and countries in Central Asia. The challenges that are faced are all very similar although the approaches to solving those challenges can be very different. Much can therefore be learned from looking at different sites, the challenges faced and the approaches that have been employed to address those challenges. Practical experience has shown the benefits that can be achieved when those responsible for managing legacy issues sit with scientists to discuss the problems. This has been seen with discussions between Russians and US scientists where solutions were achieved that helped both sides. Cross-border dialogue can therefore also be very beneficial.

The magnitude of uncertainties associated with data and models and how they affect the ability to make decisions needs to be known and experience from real sites has shown that the best approach is for regulators, operators and other stakeholders work closely together to gain a good understanding of the situation and the different approaches that could be used to address the situation. The need for such close cooperation has been recognized internationally as is difficult for a regulator to apply a regulatory regime if they are not aware of the situation at a site and it is those with experience of sites that are contributing to the development of international guidance on how to deal with legacy sites.

It is important to build trust between the different stakeholders at an early stage. By building trust and joint understanding around a situation, the different sides can see common interests and benefits.

6.3 The status of the sunken nuclear submarine Komsomolets in the Norwegian Sea

Justin Gwynn (DSA) presented.

Komsomolets (K-278) was the only Soviet “Mike” class nuclear-powered attack submarine. It was unique in having an outer and inner pressure hull made of a titanium alloy that allowed the submarine to dive deeper than any other submarine (>1000m). The submarine entered service in 1983 and was equipped with two nuclear warheads in the torpedo compartment. It was also equipped with an escape capsule.

The Komsolmolets submarine set sail on its last and final mission in February 1989 with a crew of 69 onboard. On 7th April, the submarine was cruising at a depth of 400 m in the Norwegian Sea when there was a report of a fire in compartment 7, which led to an order to surface and the main ballast tanks were blown. High pressure air in compartment 7 led to a high-pressure blast and the reactor was put into emergency shutdown as the submarine surfaced. Deck tiles over the stern starboard ballast tank peeled off into the water and ventilation lines fed smoke and fumes into other compartments. As the fire died out, pressure in compartment 7 dropped and water started to enter. An evacuation order was given just before the submarine sank. There were 6 crew members still onboard as it sank with 5 reaching the escape capsule, but it wouldn’t release. A violent shock from below then led to the sudden release of the capsule, but 3 of the crew within the capsule were overcome by fumes on the way to the surface. On reaching the surface, the upper hatch was blown off the capsule which killed one of the 2 remaining conscious crew members. There was only 1 life raft for the 53 crew in the water and it inflated upside down. Most crew were without life jackets or survival suits. It was over an hour after the submarine sank before the first help arrived, by which time a further 23 crew had died. Only 27 crew, including the sole survivor from the capsule, survived.

Komsomolets final resting place is 250 km from Bear Island and at a depth of 1700 m. At the time of sinking, the inventory of the reactor is estimated to have been 20 PBq with a further 16 TBq of Pu-239/240 in the nuclear warheads. In 2019, the activity remaining in the reactor was around 3 PBq and was comprised of primarily Cs-137 and Sr-90.

A number of surveys have been made by the Russians to monitor the situation. Surveys in the early 1990s showed that there was damage to both outer and inner pressure hulls and a large hole was present in the forward torpedo compartment. Radioactive release from the reactor was also detected from a ventilation pipe. In 1994, torpedo holes were plugged and large holes were covered in order to reduce flow through the compartments. Further monitoring detected 1 MBq/m^3 Cs-137 in the ventilation pipe, which reduced to 4 kBq/m^3 in the immediate area around the pipe and a release of 500 GBq/yr was estimated. In 2007, a further survey concluded that the rate of release of Cs-137 from the vent pipe had reduced by around 30-fold compared with 1994. The ventilation pipe connects to compartment 5, which Is located to the aft of the reactor compartment. Detection of fission products in the pipe suggest that the reactor was damaged when the submarine sank or when it made contact with the seabed.

Norway has monitored the marine environment around Komsomolets since 1990. Surface sediments collected in 1993 and 1994 contained Cs-134 and elevated concentrations of Cs-137 were detected in bottom seawater in 1991 and 1993. No increased activity concentrations have been detected above values typical for the Norwegian Sea since then. In the period since 2013, Norwegian monitoring has been carried out using an acoustic transponder on sampling gear to allow samples to be collected at precise locations.

In 2019, an expedition was organized under the Norwegian Russian Expert Group for the Investigation of Radioactive Contamination in the Northern Areas, which included a range of participant, including from DSA and CERAD and financed by the Norwegian Ministry of Trade, Industries and Fisheries and through DSA’s funding from the Norwegian Ministry of Foreign Affairs. A key element of the expedition was to deploy a remotely operated vehicle (ROV), connected to the ship by cable. The ROV was fitted with high resolution sonar and video imaging equipment, along with manipulator arms to allow water, sediment and biota samples to be obtained.

The ROV reached the sea floor after around an hour. Visibility was good and tail fin markings were still clearly visible after 30 years. There was evidence of only a light covering of benthic organisms on deck tiles. Overall, corrosion levels were low due to the titanium construction and no structural damage to the stern was evident. The only damage to the stern was the missing tiles, which matches the accounts of witnesses to the surfacing of the submarine during the accident. Whilst damage to the hull was covered in the 1990s, damage to the outer and inner hull could still be seen and the plugs over the torpedo tubes didn't form a complete seal in all places. Significant damage to the lower hull was evident.

One liter water samples were collected from the ventilation pipe and at a distance of 5 m above the pipe. Activity concentrations of Cs-137 and Sr-90 were not unusual. However, on subsequent dives, there were obvious clouds coming from the pipe and water samples were again taken. These samples had higher Cs-137 and Sr-90 concentrations, the highest being 800,000 and 400,000 times greater, respectively, than typical values for the Norwegian Sea. A metal grill next to the ventilation pipe also showed signs of releases that hadn't been reported previously and could equate to releases from the diesel generator. The ratio of Cs-137:Sr-90 in samples matches those predicted for spent nuclear fuel assemblies immersed in seawater.

Only Cs-137 was detected in sediment cores taken from around the submarine and concentrations were within the range of values for samples collected since 1993 and the profiles suggest a low, but increasing flux of Cs-137 to sediments around the submarine. However, at this depth, it is difficult to evaluate the impact of other sources of Cs-137. Samples of biota growing on the surface of the submarine were also taken for analysis. Only Cs-137 was detected in the samples. The concentrations were low, but indicate detectable releases from the reactor.

The findings of the 2019 expedition were consistent with previous Russian expeditions regarding releases of Cs-137 from the ventilation pipe and the releases observed are not expected to have any consequences for the marine environment due to activity concentrations being released, the depth of the submarine, and available dilution. The findings are supported by sediment and biota sample analyses. Furthermore, whilst releases have occurred since the accident, monitoring hasn't detected any unexpected levels of Cs-137 or Sr-90 in seawater or fish in the Norwegian Sea.

Further analysis remains to be completed from the expedition, including analysis of uranium and plutonium in seawater, sediments and biota to determine if releases from the warheads can be detected. No releases have previously been detected, but the 2019 samples should provide a definitive answer. Ongoing analysis will also provide information on any corrosion processes and releases. It is hoped that a full story will be published in 2021/22 and be presented during ICRER 2022.

Regular surface monitoring of Komsomolets will continue and it is hoped that there will be further opportunity to deploy ROVs or a manned submersible that could allow hypotheses as to what is causing the releases and their variability to be tested. Learning around the accident and the ongoing situation will also hopefully provide insights into the fates of other reactors in dumped and sunken nuclear submarines, and into any future accidents involving nuclear propelled vessels.

Discussion

There is not detailed information on the nuclear warheads that were onboard Komsomolets, but they are assumed to be fairly standard. Results from the 2019 expedition may help provide some information.

There are plans for Russians to raise shallower sunk submarines, but at 17,000 m depth, raising of Komsomolets is beyond current technical capabilities. It may be possible to install a plate over the release pipe but there are uncertainties around what would happen as a result. Potentially, this could give rise to a greater release from another point.

6.4 Radioecology and the RadoNorm project

Laureline Février (IRSN) presented.

RadoNorm is the acronym for the project 'Towards effective radiation protection based on improved scientific evidence and social considerations – focus on radon and NORM' that is funded by EC. The project began in September 2020 and has a 5-year duration. The project involves 20 European member states, plus Norway and Switzerland.

Euratom research objectives are to:

- reduce risks from low doses from industrial, medical or environmental exposure;
- maintain and develop expertise and competence in the Community; and
- support the nuclear policies of the EC & European Union.

Refining knowledge on radon and NORM through the RadoNorm project will help meet these objectives. The overall objective is to support European member states and radiation protection authorities in the implementation of the EU BSS by reducing uncertainties in all steps of radiation risk management cycle for radon and NORM exposure situations, providing new research and disseminating the project output to targeted stakeholders. The project provides an umbrella framework for integrating all aspects of radon and NORM protection, including:

- measuring and/or modelling human exposure;
- dosimetry;
- assessment of radiation induced biological effect as well as risks to humans and the environment;
- innovative mitigation techniques and strategies aiming at dose reduction;
- social and economic aspects including communication;
- education and training; and
- dissemination of information and re-use of knowledge.

The project is comprised of several work packages of which three were the focus of the presentation.

Work package 2 is focused on exposure and aims to better characterize the exposure of people (including workers) and biota to radon and other naturally occurring radionuclides. The objectives of the work package are to develop measurement methods and protocols to assess radon and thoron doses, address scientific knowledge gaps on factors and processes impacting radon and NORM transfer and dispersion both indoors and outdoors, and to develop/improve models quantifying radon and NORM transfer, focusing on relevant exposure pathways and spatial and temporal scales. Eight tasks have been developed that are aimed at:

- reducing uncertainties in radon measurements;
- improving the modelling of radon transport in the environment;
- improving the characterization of exposure to radon in buildings;

- improving methods used to identify high indoor radon levels;
- developing an overview of NORM sites and exposure scenarios throughout Europe;
- refining soil to plant transfer factors;
- refining solid-liquid distribution coefficients (Kd); and
- updating approaches for modeling long-term predictions of NORM transfer in the environment.

Work package 4 is focused on effects and risk assessment and aims to address gaps of knowledge in health risk assessment of radon and NORM, acquire new knowledge on biological effects and responses to radon and NORM exposures and their implications for risk assessment and radiation protection of humans and the environment, and reduce existing uncertainties in risk assessment. There are 9 tasks in work package 4:

- interaction between radon and smoking in lung cancer;
- radon related risks other than lung cancer among adults;
- risks associated with radon exposure during childhood (childhood leukemia and brain cancer);
- uncertainties in radon risk assessment due to thoron;
- mechanisms of radiation action in lung cancer among never smokers;
- consideration of various sources of uncertainties in radon induced lung cancer risk inference;
- risks from radon and NORM in drinking water;
- effects and mechanisms of action of combined exposures to radon or NORM and other stressors relevant of true exposure situations of humans and biota; and
- assessment of combined toxicity and cumulative risk.

Various methods will be used, including epidemiological studies, risk modelling, and experimental studies on combined effects under realistic co-exposure conditions leading to proposal of adverse outcome pathways linking mechanisms and effects after co-exposures.

Work package 5 is then focused on mitigation and has the general objective of improving and optimizing radiation protection of workers, the general public and the environment against the harmful effects of radiation caused by the presence of natural radionuclides in natural and work environments by utilizing innovative mitigation techniques and systems. There are two main issues regarding mitigation. The first relates to current requirements on the energy performance of buildings, which affects indoor radon concentrations. There is a need, therefore, to harmonize energy saving with radon mitigation strategies. The second is that mitigation strategies and technologies applied in NORM do not fully reflect the current EU BSS requirements for long-lasting exposure situation and remediation strategies. The main objectives of the work package are therefore to develop innovative mitigation techniques, and provide an optimization of current mitigation systems. Tasks to improve radon mitigation systems aim to take advantage of increased knowledge on radon sources and pathways and radon control systems, including considering modification and optimization of the performance of existing ventilation systems and the application of radon-resistant construction techniques and materials. Information on lessons learned and experience gained in mitigating radon in buildings will also be gathered and analyzed. Work package 5 will also look at the development of NORM residues/waste final treatment strategies, based on preventative actions and mitigation methods, including evaluation of remediation options.

Further information on the RadoNorm project is available from www.radonorm.eu. A network of stakeholders is being built and anyone interested can register their interest on the website.

Discussion

The work on Kd will involve laboratory sorption/desorption experiments and will include consideration of kinetics. Different ways of characterizing in situ Kd's will also be investigated and new models proposed (e.g., the use of the 'smart kd' approach).

No industrial partners are in the project but there are a lot within the stakeholder network and involvement in planned workshops will therefore be an important part of the project. A workshop on NORM in liquid effluents has already been held and the annual meeting for the project was scheduled to take place in September 2021 to which industry stakeholders will be invited.

7 Conclusions from the online event

The online event saw a wide range of presentations detailing new data and knowledge, improved models and methods and the philosophies of human and environmental protection, from a wide range of experts from international organizations, research groups and organizations from around the world. There was an impressive audience with around 450 registered participants from all continents.

From the presentations and discussions, it is evident that international cooperation and joint research is crucial for gaining perspective around radiation protection issues, including exposure of the public, workers and non-human biota. Radioecology has become increasingly important over the years and recent integration activities both within radioecology and with other disciplines have benefitted the global radiation protection community. Many of the successful joint research projects have had an impact in different areas and contexts, such as new research projects, changes to recommendations and principles, as well as legislative changes.

It is increasingly clear that ethical, social and economic aspects need to be addressed alongside radiological considerations, such as evaluations of exposures and effects. There has been a notable shift away from a rigorous technical and scientific approach to radiation protection to programs more focused around affected areas and affected people, with the aim of taking account of the complex interactions between society, economy and the environment. Furthermore, in the case of legacy, decommissioning and other complex situations, a wide range of radiological, chemical and physical hazards need to be addressed, often alongside complex social contexts. As an example, the need for a harmonized and proportionate risk management approach to decommissioning, legacy and waste management was recognized that includes effective dialogue with relevant stakeholders in order to address all hazards, as part of the practical application of the optimization principle.

There has been a shift from anthropocentrism towards ecocentrism, where all complex and interrelated conditions are considered in an integrated manner. Such approaches are evolving but further development is required. Notable areas where further developments are required include ensuring appropriate evaluation of both internal and external dose rates for biota (e.g., appropriately evaluating transfers and uptake to biota and accounting for heterogeneous contamination of the environment) and developing understanding of how biological effects at an individual level will manifest at an ecosystem level. Scientific understanding around how multiple stressors, including radionuclides, interact in the environment also needs to evolve, along with the continued development of approaches to support evaluation of multiple stressor effects.

It is important to ensure that assessment capabilities develop alongside scientific understanding. An example of continued development and enhancement of assessment capabilities is the ERICA assessment tool for evaluating dose rates for non-human biota. The ERICA tool has been applied to planned, existing and emergency exposure situations for the NORM industry, nuclear facilities, decommissioning and radioactive waste management. Substantial development of the ERICA tool over the last year has addressed various user needs and ensured the tools is consistent with scientific developments in the field. The new version of ERICA includes new dosimetry, updated parameter databases and the addition of new functionality such as the ability to evaluate dose rates for noble gases, including radon.

The number of scientific publications in the field of radioecology is increasing but there is also a growing awareness of issues such as bias in preparing publications and in the review process, as well as fake news relating to radiation science. To move forward and address issues, proper hypothesis setting and testing is needed, along with a focus on repeatability of experiments and results. It is also important to encourage the reporting of negative results, as well as greater international scientific exchange and debate around results and emerging theories through consensus conferences and dedicated discussion sessions.

Radioecology has been, and will continue to be, essential in supporting the development and application of radiation protection principles and regulations, including compliance demonstration. There remain, however, a broad spectrum of challenges faced in the field of radioecology and environmental radioactivity that are of great importance and that need to be addressed alongside broader societal issues. It is clear from the presentations and discussions during the event that scientific developments have continued through the Covid-19 pandemic, and continued progress is needed, including continued interaction between the different disciplines and among the science community, operators and regulators to ensure key challenges are identified and solutions to those challenges developed.

Many of the key scientific topical issues and motivations identified during the event will be explored in more detail at physical conference that will take place in Oslo from 4-9 September 2022. The conference will provide an opportunity to meet in person and further discuss radioecology and environmental radioactivity science needs and developments. Further information on the conference is available from www.icrer.org.

Appendix A. Conference programme

Tuesday 29 June

International/Regional & Cooperating Organizations Chairperson: Astrid Liland, DSA	
09:45 – 10:00	Welcome and introduction (Per STRAND, DSA and IUR)
10:00 – 10:30	UNSCEAR 2020: Levels and Effects of Radiation Exposure due to the Accident at the Fukushima Daiichi Nuclear Power Station (Gillian HIRTH, UNSCEAR)
10:30 – 10:40	10 min. break
10:40 – 11:00	Trends in radiocaesium and remaining issues in Fukushima after the 2011 accident, (Hirofumi TSUKADA, Institute of Environmental Radioactivity, Fukushima University)
11:00 – 11:20	Trends in radioecology: last decade through the lens of JER (Che DOERING, JER)
11:20 – 11:30	10 min. break
11:30 – 12:00	IAEA/FAO/WHO Project on Radionuclides in Food and Drinking Water (Tony COLGAN, IAEA)
12:00 – 12:30	Lunch
12:30 – 12:50	Status of Plans for a programme to follow MODARIA II (Joanne BROWN, IAEA)
12:50 – 13:10	Radiation weighting factors for Reference Animals and Plants (Kathryn HIGLEY, ICRP)
13:10 – 13:20	10 min. break
13:20 – 13:50	Feasibility Study on the safe and secure management/disposal of sunken radioactive objects in the Arctic Sea (Alain VAN DEN BRANDE)
13:50 – 14:10	The future of European Radiation Protection Research and the role of the ALLIANCE (Hildegarde VANDENHOVE, SCK CEN)

Wednesday 30 June

Public engagement and risk communication (case studies) Chairperson: Astrid Liland, DSA	
09:45 – 10:00	Introduction and reflections on first day (Astrid LILAND, DSA)
10:00 – 10:30	Monitoring and communication of environmental survey results (Tetsuo YASUTAKA, National Institute of Advanced Industrial Science and Technology)
10:30 – 10:40	10 min. break
10:40 – 11:00	Legacy, Remediation, Waste and Stakeholders – What lessons have we learned? (Marcus GRZECHNIK, ARPANSA)
11:00 – 11:20	Rehabilitation of the Chornobyl affected areas: exploring attitudes of local residents (Yevgeniya TOMKIV, Norwegian University of Life Sciences)
11:20 – 11:30	10 min. break
11:30 – 12:00	Trust, Reproducibility and Sustainability: What can Radioecology learn from COVID-19? (Deborah OUGHTON, CERAD and COMEST)
12:00 – 12:30	Lunch
Ecosystem approach	
12:30 – 12:50	IUR: Ecosystem approach and consensus conferences, an overview (François BRECHIGNAC, IUR)
12:50 – 13:10	Towards a holistic approach to protection of inhabitants of contaminated environments: the role of non-targeted effects (Carmel MOTHERSILL, McMaster University)
13:10 – 13:20	10 min. break
13:20 – 13:50	Applying an ecosystem approach in radioecology: from experimental to field data (Anna-Lea GOLZ, Alfred Wegener Institute)
13:50 – 14:10	Why many Chornobyl radiation effects studies are wrong (Mike WOOD, University of Salford)

Thursday 1 July

Application of radioecology to radiation protection Chairperson: Astrid Liland, DSA	
09:45 – 10:30	Launch of ERICA Tool version 2, Overview (Carol ROBINSON, DSA), including feedback on the ERICA user survey (David COPPLESTONE, University of Stirling)
10:30 – 10:40	10 min. break
10:40 – 11:00	Update of the wildlife transfer database (Nick BERESFORD, UKCEH)
11:00 – 11:20	Cumulative hazard and risk assessment for radioactive and chemical contaminants (Knut Erik TOLLEFSEN, NIVA and NMBU)
11:20 – 11:30	10 min. break
11:30 – 12:00	The CONCERT-TERRITORIES project and the management of existing exposure situations (Marie SIMON-CORNU, IRSN)
12:00 – 12:30	Lunch
Radioecology and management of nuclear and other legacies	
12:30 – 12:50	NEA activities related to Decommissioning and legacy management, including the Characterization Methodology for Unconventional and Legacy Waste (Rebecca TADESSE, NEA)
12:50 – 13:10	Drivers for radioecological research: lessons from decommissioning and legacy management – outcome from Nordic Workshop (Malgorzata SNEVE, DSA)
13:10 – 13:20	10 min. break
13:20 – 13:50	The status of the sunken nuclear submarine Komsomolets in the Norwegian Sea (Justin GWYNN, DSA)
13:50 – 14:10	Radioecology and the RadoNorm Project (Laureline FEVRIER, IRSN)
14.10 – 14.30	Conclusions and Closure (Astrid LILAND and Per STRAND, DSA)

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ICRER pre-conference online event

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