

Protection of the Abiotic Environment

R. Michel¹, K.-E. Huthmacher², H.-H. Landfermann²

¹Center for Radiation Protection and Radioecology, University Hanover, Herrenhaeuser Str. 2,
D-30419 Hannover, Germany. E-mail: michel@zsr.uni-hannover.de

²Federal Ministry for the Environment, Nature Conservation and Reactor Safety, P.O.Box 12 06 29,
D-53048 Bonn, Germany

Abstract. Environmental protection against the dangers arising from ionizing radiation, radioactive materials, and other harmful substances is more than to avoid acute dangers or risks for humans or for non-human living organisms. To allow for a sustainable development the abiotic part of the environment must not be neglected in concepts of environmental protection. The environmental impact of some selected long-lived anthropogenic radionuclides is used to exemplify adverse effects for which a unified approach is needed. To this end, indicators are needed for the assessment of the human impact on the abiotic environment which allows to compare different human actions with respect to sustainability and to choose appropriate measures in the competition for a sustainable development. Such indicators have to account for the dynamics of the different environmental compartments. Using the long-lived radionuclides ¹⁴C, ³⁶Cl, ⁸⁵Kr, and ¹²⁹I as examples, the importance to consider dynamical models and ecological lifetimes in quantifications of the human impact on the environment is emphasized. Particular problems arise from the natural occurrences and variability of radionuclides and other harmful substances. Suitable indicators for the assessment of human impact on the abiotic compartments air, water, and soil are discussed.

1. Introduction

In order to comply with a sustainable development future concepts for the protection of the environment against the dangers of ionizing radiation and radioactive substances have to consider the environment as an entity and must include aside of the living environment also the abiotic environment, i.e. the compartments atmosphere, hydrosphere, and geo-, or at least, pedosphere. As concepts of the protection of soil, water, and air, this is already commonplace practice in environmental protection approaches which are in place for non-radiological emissions.

ICRP stated in a recent draft to ICRP 91 [1] that „...*any framework for environmental protection that is developed for radiation therefore needs to acknowledge and accommodate the principles outlined above, and needs to be compatible with other environmental protection approaches that will be in place for non-radiological emissions ...*“. But, then the commission limited the scope of its future concept of environmental protection to that of the living environment saying that „...*abiotic components are considered in terms of their impact on biota, but the ethical issue raised by the mere presence of radionuclides in abiotic components, independent of possible effects, is beyond the scope of this report.*“

These two statements are in severe contradiction and the first one violates today's principles of environmental management and assessment of environmental risks. The ICRP approach is not sufficient to represent a conceptual framework of radiological protection of the environment. The limitation to the living environment is an approach that gives just an *a posteriori* justification of the earlier statements of ICRP 60 [2] that the environment is protected when man is protected. The ICRP has recognized the concepts discussed and partially already used in other fields of environmental protection such as sustainability, biological resources, and biodiversity, but the ICRP approach is not compatible with these concepts. In order to comply with a sustainable development one has to develop a concept for the protection of the environment against the dangers of ionizing radiation and radioactive substances which considers the environment as an entity and which includes aside of the living environment also the abiotic environment, i.e. the compartments atmosphere, hydrosphere, and geo-, or at least, pedosphere. Such a system of environmental protection against the dangers of

ionizing radiation and radioactive substances should generally be discussed in the context of protection against other harmful substances as e.g. non-radioactive chemicals or other pollutants. This is necessary to allow comparisons with respect to the choices of policies in the context of sustainable development.

To this end, indicators are needed for the assessment of the human impact on the abiotic environment which allows to compare different human actions with respect to sustainability and to choose appropriate measures in the competition for a sustainable development. Such indicators should not only consider the radiation exposures of man and of other living species. Also the human impact on the abiotic part of the environment by releases of radioactivity has to be accounted for. As for other environmental pollutants (e.g. heavy metals) the establishment of meaningful indicators in the context of radiological protection is not trivial and should be performed under consideration of the international discussions. Possible ways of assessing the abiotic environment are exemplified and some considerations for suitable indicators are presented. Radiological protection should become a consistent part of a general scheme of the protection of the environment. Indicators for sustainability should take into account the dynamics of the abiotic compartments of the environment and should be likewise applicable to radioactive and non-radioactive environmental pollutants.

In this contribution, the needs to revise the ICRP policy and to consider the protection of the abiotic environment in the system of radiological protection are discussed. With the goal of a sustainable development, environmental protection is more than to avoid acute dangers or risks for humans or for non-human living organisms. The precautionary principle requires to consider man-made changes of the environment as adverse effects before they become harmful or risky and to choose policies which minimize the human impact on the environment. Examples for human environmental impact, which – at least at the time being – are not directly of radiological relevance but rather represent adverse effects by changing the environmental radioactivity, are the emission of Kr-85 in the atmosphere and the release of long-lived radionuclides from human practices, such as H-3, C-14, Cl-36, Tc-99, I-129, Cs-135, and some long-lived actinides, into atmosphere or hydrosphere and their subsequent local or global dispersion. For these cases, internationally accepted measurable quantities and criteria are still missing.

2. Sustainable Development and Human Environmental Impact

At the conference of the United Nations on the environment and development in Rio de Janeiro in 1992, a framework was set for the elaboration of concepts for the establishment of a sustainable development with the Agenda 21 [3]. In chapter 40 of the Agenda 21 the development and application of measurable quantities and assessment criteria is demanded by which the national and international developments can be assessed with the goal to comply with a sustainable development. The United Nations established a Commission on Sustainable Development which developed a set of 134 indicators for sustainability; see e.g. [4]. This set of indicators was further elaborated and assessed with respect to their applicability until the 2nd world summit in Johannesburg 2002 by 22 testing countries. In particular indicators for environmental development, which allow assessing the tolerance of the environment against harmful substances and the vulnerability of the environmental items to be protected, are of interest. That means quantities have to be defined which characterize sustainability.

Mere protection concepts to avoid acute dangers are no longer sufficient to satisfy the needs for the actual international discussions in environmental protection. The concepts also have to be applicable to the demands of sustainability. With respect to the status of the abiotic environment the radiological aspects should be assessed in close connection with the status of other non-radioactive harmful substances and should allow for a generalization with the goal of a consistent concept of environmental protection.

The protection of air, water, and soil against pollution with harmful substances is a legal issue for non-radioactive substances. Examples for such non-radioactive pollutants are heavy metals from mining, milling, and use of combustibles, CO₂ emissions from using fossil fuels, application of pesticides and

fungicides and routine or accidental releases of harmful chemicals and, last but not least, from the final disposal of waste. We shall not discuss non-radioactive pollutants further in this paper, but we want to stress that a system of environmental protection is needed which consistently is applicable to radioactive and non-radioactive harmful substances. It must be cover their normal use, routine and accidental releases and the disposal of wastes and residues.

We shall concentrate in this paper on long-lived radionuclides in the environment and on some aspects which have to be considered when developing indicators quantifying the state of the environment. Both, natural and man-made radionuclides make their ways through the environment from sources to sinks. Sinks are those compartments where radionuclides are caught and stay confined until they decay. Geological formations, deep ground and sea water, or deep sea sediments can act as sinks as long as they have negligible exchange rates with other environmental compartments over the lifetime of the respective substance. In contrast to stable harmful substances, radioactive decay acts similar to a sink ultimately removing radionuclides from any compartment. The abiotic compartments air, water, and soil as they are considered in today's environmental concepts do not act as sinks since they are in direct exchange among each other and the biotic compartments.

Man-made long-lived radionuclides are released to the environment by explosions of nuclear weapons, nuclear installations under normal operation and during incidents and accidents, as a consequence of the clearance of radioactive materials and of the disposal of radioactive waste. Some of these radionuclides occur also naturally, for instance as cosmogenic radionuclides or as products from spontaneous fission. Also natural primordial radionuclides and their progeny are set free from their geological occurrences by human action and can lead to enhanced environmental radioactivity levels. One has to mention here releases of natural radionuclides to the environment from all types of mining and milling of mineral resources, from work activities, and even from disposal of non-radioactive materials. The problem to deal with enhanced concentrations of natural radionuclides is that there is a large natural variability and that they are also present in air, water and soil as a consequence of natural weathering and transport processes.

For all these cases, internationally accepted measurable quantities and criteria are still missing. Indicators are needed which allow to distinguish between natural occurrence and variability, on the one hand, and man-made enhancements, on the other, and which provide a basis for a judgment about the consequences of human action. The precautionary principle requires that such indicators are applicable at low environmental concentrations before harmful effects in biota occur. Even if a radioactive environmental pollution does not produce a significant radiation exposure to biota, the question must be answered whether man should to change the environment in a sustainable way.

3. Long-Lived radionuclides in the Environmental

There are many examples for human environmental impact which – at least at the time being – are not directly of radiological relevance but rather represent adverse effects by changing the environmental radioactivity. We shall exemplify them for the cases of the radionuclides ^{14}C ($T_{1/2} = 5\,730\text{ a}$), ^{36}Cl ($T_{1/2} = 300\text{ ka}$), ^{85}Kr ($T_{1/2} = 10,76\text{ a}$), and ^{129}I ($T_{1/2} = 15.7\text{ Ma}$) released by atmospheric nuclear explosions and from the nuclear fuel cycle. These examples exhibit different degrees of complexity of their environmental behaviour which have to be taken into account in assessing their environmental impact. Similar adverse effects do exist for the man-made radionuclides ^3H , ^{99}Tc , ^{135}Cs , some long-lived actinides, and for natural radionuclides set free by work activities and practices.

By atmospheric explosions of nuclear weapons large amounts of fission products, actinides and activation products have been released into the environment between 1944 and 1963 when the large number of atmospheric test explosions was terminated by the Test Ban Treaty. Subsequent, atmospheric tests added just marginally to the anthropogenic input. These releases led to increasing human radiation exposure which world-wide reached 8 % of the global average natural exposure of

2.4 mSv per year in 1963 [5]. Today, the exposure due to radionuclides from the past nuclear explosions is below 10 μ Sv per year [6] and no longer radiologically significant.

^{36}Cl was produced by oceanic nuclear weapons tests which resulted in activation of ^{35}Cl in seawater. Information on the annual fall-out of ^{36}Cl was preserved in archives like ice cores and sediments. In Fig. 1 the annual fall-out of ^{36}Cl is shown as exhibited by the investigation of an ice-core from the Fiescherhorn in Switzerland. ^{36}Cl is also a naturally occurring cosmogenic radionuclide being produced a. o. via spallation reactions on atmospheric argon. Fig. 1 shows an increase of the ^{36}Cl fall-out by more than two orders of magnitude due to atmospheric explosions of nuclear weapons compared to the pre-nuclear value. In the atmosphere, ^{36}Cl is quickly attached to aerosols and cleared from the troposphere. The decline of ^{36}Cl fall-out rates over 25 years back to pre-nuclear values reflects the stratosphere-troposphere exchange with a residence time in the stratosphere of 2 years [7] and aerosol deposition in the troposphere with time scales between 2 weeks and 1 month. Thus, in spite of its long physical half-life, its atmospheric concentrations are completely exclusively ruled by relatively short ecological lifetimes.

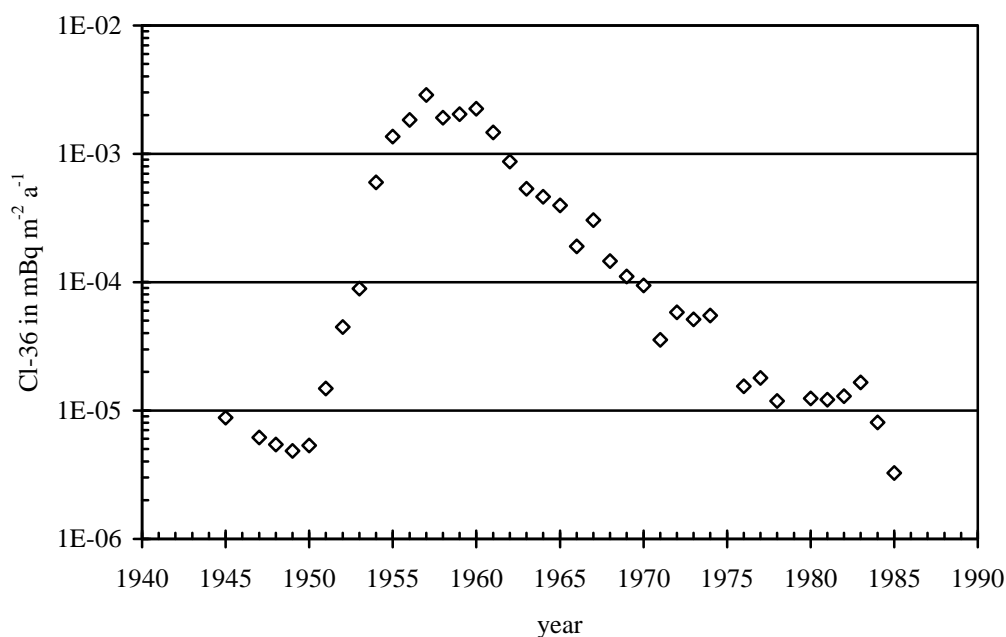


Fig. 1. Annual fall-out of ^{36}Cl ($T_{1/2} = 300$ ka) in the Fiescherhorn ice core [7].

A more complicated example is ^{14}C ($T_{1/2} = 5730$ a) which involves in addition to atmospheric mixing and clearance the entire natural CO_2 cycle; see [8, 9] for detailed descriptions and references. Also ^{14}C occurs naturally as a cosmogenic radionuclide produced by secondary galactic neutrons via the reaction $^{14}\text{N}(p,n)^{14}\text{C}$; by the same reactions it is produced in atmospheric nuclear explosions. The global natural ^{14}C inventory is about 70 t of which the ocean contains about 90 %, the terrestrial biosphere about 8 % and the atmosphere 2 %. This ^{14}C is just a minute part of the free global carbon inventory of the atmosphere, the biosphere and soils and of the ocean of 44.4×10^3 Gt. Most of the terrestrial carbon, i.e. about $60 \cdot 10^6$ Gt rests in sediments.

By the atmospheric nuclear weapons tests 2.2 t (85 000 TBq) of ^{14}C were produced in the atmosphere. In Fig. 2 the bomb peak of ^{14}C in atmospheric carbon is shown in $\Delta^{14}\text{C}$ units. These units are per mil deviations of a measured isotopic ratio $\Delta^{14}\text{C}$ from a standard $^{14}\text{C}/\text{C}$ atomic ratio of 1.2×10^{-12} . The standard $^{14}\text{C}/\text{C}$ ratio is equivalent to the specific activity of atmospheric CO_2 in 1850 of 0.226 Bq per gram carbon. The natural ^{14}C abundances cause a human exposure of about 12 μ Sv per year.

There are natural variations of the ^{14}C activity of atmospheric carbon due to changes in production rates and in the global carbon cycle. According to the analysis of tree rings they amounted to about 150 per mil during the last 12 ka. High $\Delta^{14}\text{C}$ values of +100 per mil were observed shortly after the last ice age 7 000 BC which decreased to a minimum value of -20 per mil around 500 AD. Then, $\Delta^{14}\text{C}$ increased again up to the onset of industrialization which by massive combustion of fossil fuels diluted the atmospheric carbon with ^{14}C free CO_2 and thus lowered the $\Delta^{14}\text{C}$ values: the so-called Suess effect.

The atmospheric explosions overruled the Suess effect completely and caused an increase of the ^{14}C specific activity of atmospheric carbon by up to 1000 per mil (Fig. 2). The ^{14}C bomb peak shows small differences between the northern and southern hemispheres due to the time required for global mixing of atmospheric CO_2 with the bomb ^{14}C which was mainly set free on the northern hemisphere. In spite of the long half-life of ^{14}C , the specific activity of atmospheric carbon declines strongly by ^{14}C uptake by the oceans and the biosphere, the turnover times being of the order of 10 years and 15 years, respectively. Finally, it will decay in the sinks of the deep ocean, sediments and dead organic matter and the atmospheric carbon will return to its natural specific activity.

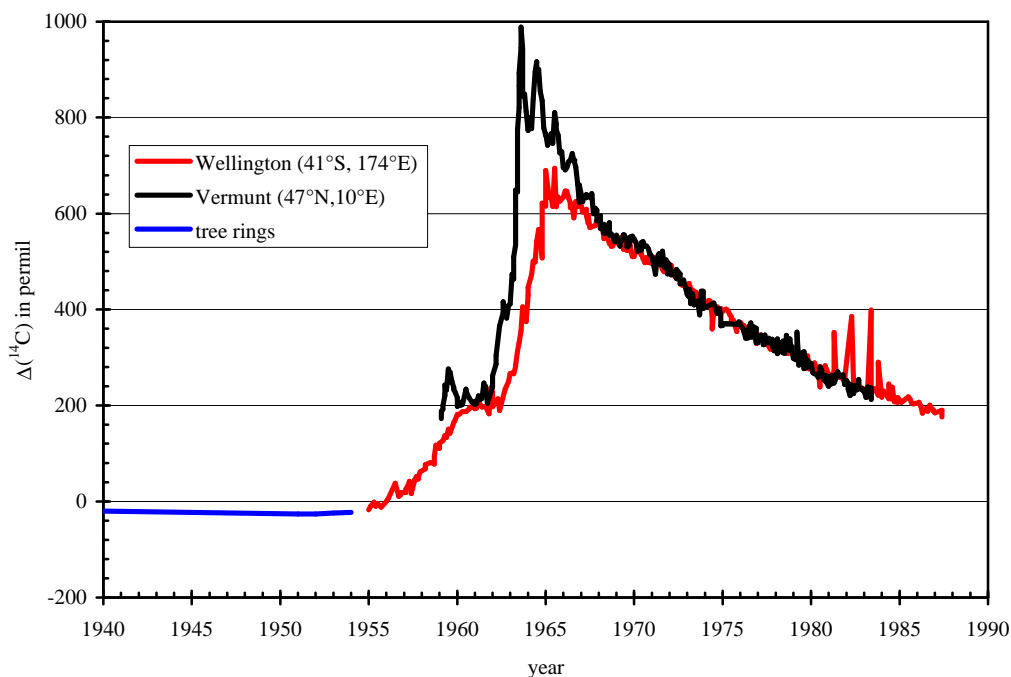


Fig. 2. ^{14}C ($T_{1/2} = 5736$ a) in atmospheric CO_2 [9].

^{14}C is also routinely released from nuclear power plants. In the 1980s, emission of ^{14}C from nuclear power plants was estimated to be 40 % of the natural production rate. But their consequences remain within the natural variability of ^{14}C abundances. They are even somewhat counterbalanced by a release of 5 Gt per year of dead carbon from burning fossil fuels [10]. Small changes of environmental ^{14}C levels can be observed in tree rings in the nearest proximity of nuclear power plants. In 2000, UNSCEAR [6] estimated an equilibrium exposure of $1 \mu\text{Sv}$ per year if the present use of nuclear energy is continued over long time-scales.

The third example of environmental radioactivity deals with the fission product ^{85}Kr . Though having a much shorter half-life of 10.76 a, its abundances in the atmosphere have been changed by human practices. ^{85}Kr is set free in the nuclear fuel cycle during the reprocessing of spent fuel. Since these emissions are presently not of radiological relevance no efficient measures are taken to prevent the

atmospheric contamination. The concentrations of ^{85}Kr in the troposphere do not show a “bomb peak” but a continuous increase demonstrating that its production in nuclear explosions is by far outweighed by releases from reprocessing plant. Since there are no sinks for ^{85}Kr , the time dependence of its concentrations in the atmosphere is exclusively ruled by atmospheric mixing and by the balance between emission rate and physical decay rate.

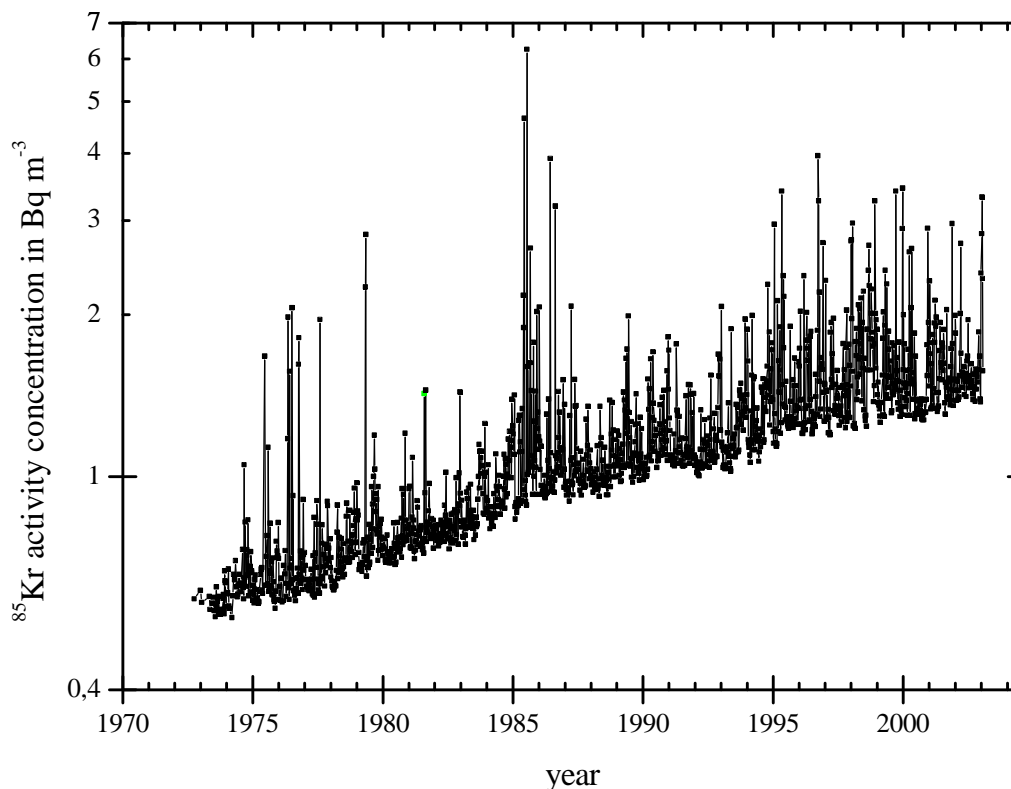


Fig. 3. ^{85}Kr ($T_{1/2} = 10,76$ a) in air at the Schauinsland/Freiburg/Germany [11, 12].

The last example is ^{129}I ($T_{1/2} = 15.7$ Ma), which is naturally produced by cosmic ray interactions with xenon and by spontaneous fission of uranium. For details and references see [13, 14]. The total natural inventory was estimated to be 50 000 kg (327 TBq) of which only 263 kg (1.7 TBq) is in the natural free ^{129}I inventory of atmosphere, hydrosphere, pedosphere, and biosphere. The environmental, ^{129}I is mixed with stable ^{127}I of the global iodine cycle. Since the half-life of ^{129}I is with 15.7 Ma much larger than the oceanic mixing time of 40 ka the oceanic mixed layer and the deep ocean are naturally in equilibrium with an $^{129}\text{I}/^{127}\text{I}$ ratio of $(1.3 \pm 0.3) \times 10^{-12}$. But, these isotopic ratios have been changed by atmospheric nuclear explosions and emissions from reprocessing plants in a sustainable way. Up to the year 2000, the European reprocessing plants emitted about 3500 kg (23 TBq) ^{129}I . The atmospheric explosions of nuclear weapons added 43 kg of ^{129}I (0.28 TBq) and the Chernobyl accident 2 kg (6.5 GBq) to the free ^{129}I inventory.

Fig. 4 shows the dependence on time of the $^{129}\text{I}/^{127}\text{I}$ isotopic ratios in precipitation in Germany and Switzerland and in water from the North Sea; [13-15] and references therein. The precipitation data do not show a bomb peak but a continuous increase which, after a short peak due to the Chernobyl accident in 1986, levelled off at isotopic ratios of about 10^{-6} , six orders of magnitude higher than the natural ones and nearly as high as those measured in water from the North Sea at the German coast. The latter is directly affected by the liquid discharges from La Hague which are transported through the channel along the coast line.

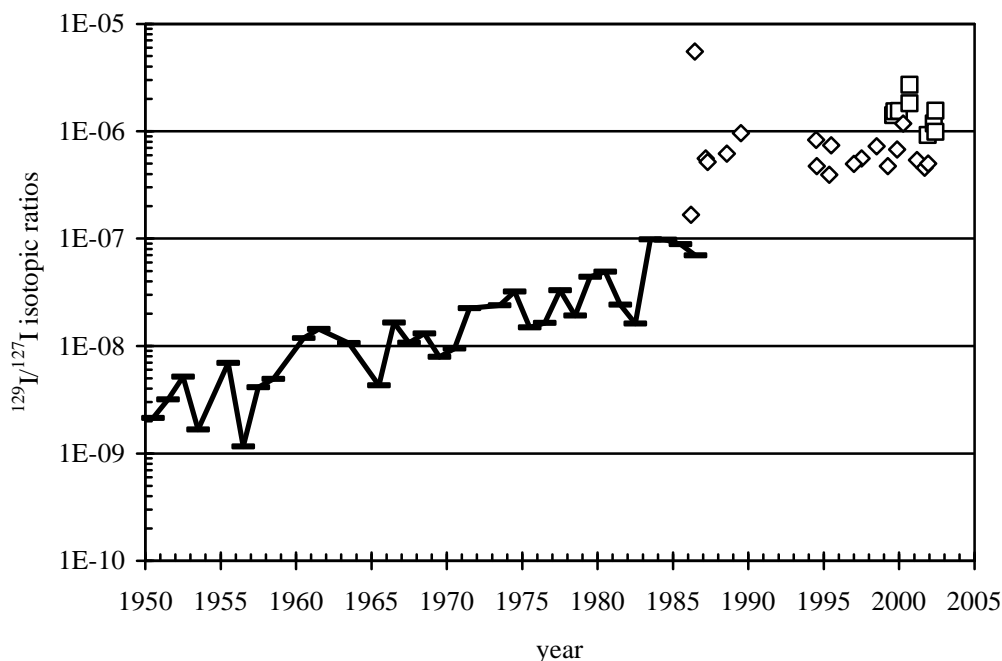


Fig. 4. $^{129}\text{I}/^{127}\text{I}$ isotopic ratios in natural waters from Germany and Switzerland. The solid line represents data from the Fiescherhorn ice core, diamonds rain from Germany and Switzerland and squares seawater from North Sea. For references see [13-15].

As a consequence of the releases from the European reprocessing plants stable and radioactive iodine isotopes are in disequilibrium in all the abiotic and biotic environmental compartments in Western Europe. Iodine from precipitation is accumulated in soils, transported by surface water, infiltrating groundwater and makes its way into the biosphere. In soils the man-made ^{129}I was observed to a depth of 2.5 m [16], in groundwater to an infiltration depth of 10 m [15]. In the soils, modern iodine is mixed with pre-nuclear one. As a consequence, the $^{129}\text{I}/^{127}\text{I}$ isotopic ratios in surface soils range from 2.1×10^{-7} to 1.7×10^{-9} and in surface water from 2.2×10^{-6} to 1.7×10^{-8} in Northern Germany. In the biosphere, $^{129}\text{I}/^{127}\text{I}$ isotopic ratios between 5.1×10^{-7} and 2.8×10^{-9} reveal the influences of wet and dry deposition, of transfer from soils to roots and of exchange with surface water.

Except for the closest vicinities of the reprocessing plants, ^{129}I does not cause a relevant radiation exposure. In Germany, average $^{129}\text{I}/^{127}\text{I}$ isotopic ratios of 1.1×10^{-8} in human thyroid glands [14] are equivalent to an annual radiation exposure due to ^{129}I of about 5 nSv. Though this exposure is surely not of radiological relevance, the changes of the natural $^{129}\text{I}/^{127}\text{I}$ isotopic ratios by up to six orders of magnitude in atmosphere, hydrosphere, pedosphere and biosphere of Western Europe represent an adverse environmental effect of high ecological complexity which has to be considered in the context of the sustainability of human actions.

The four examples of adverse effects in the abiotic environment presented in this chapter make it evident that only dynamic models can adequately describe the behaviour of harmful substances in the environment. They show that ecological lifetime, sizes of reservoirs and complex transport and exchange processes have to be taken into account if environmental impact has to be quantified by indicators of sustainability.

4. Indicators of a Sustainable Development

A number of indicators have been proposed: The degree by which radiation exposures are in compliance with dose limits, the average exposure to Rn-222 in homes, and the activities of long-lived radionuclides in air, water, and soil. However, these indicators do not cover all relevant endpoints. Rn-222 exposure in homes addresses an aspect of human well-being and is not a relevant indicator for the abiotic environment. The activity concentrations in air, water, and soil are more generally suitable for a quantification of the state of the environment though they are mostly used in terms of predicting the exposure of living organisms with respect to potential hazards or health risks.

To assess the impact on the environment of such substance, their amounts released to the environment (soil, water and air as compartments to be protected) appear to be better measures than the activity concentrations $C(t)$ in a compartment. However, the absolute releases do not take into account the dispersion in the environmental compartments and the dynamics of these departments. Therefore, better indicators of sustainability are the changes of the concentrations or specific activities of harmful substances in the relevant compartments weighed by the probability that they are removed from the respective environmental compartment. Consider to this end a simple single compartment model in which a substance is increasing the concentration at a rate R_{in} by releases into the compartment and in which the substance disappears with a probability I . Then the concentration $C(t)$ can be described by

$$\frac{dC(t)}{dt} = R_{in} - I \times C(t) \quad (1)$$

with I being the effective decay constant in this compartment. The effective decay constant I is describing two effects. First, the physical (or chemical) decay of the substance and, second, the ecological decay, i.e. the probability for the substance to be removed from the compartment by environmental transport processes.

$$I = I_{phys} + I_{ecol} \quad (2)$$

The physical and ecological decay probabilities are measures of the physical mean lifetime $1/I_{phys}$ and of the ecological mean lifetime $1/I_{ecol}$ in the respective compartment.

It has to be noted that transport means here the transfer into another environmental compartment which either can be a real sink in which the substance is no longer regarded as harmful or relevant or a compartment in which the consequently changing concentrations have to be further considered, e.g. with respect to an exposure via another exposure path.

It is trivial that the concentration $C(t)$ will decrease exponentially if there is no input (release).

$$C(t) = C(0) \cdot \exp(-I \times t) \quad (3)$$

But it is important to consider that $1/I$ is a measure of the mean time during which the substance is of relevance in the considered compartment.

Therefore, an indicator for sustainability could be

$$I = \frac{1}{I} \times \frac{dC(t)}{dt} \quad (4)$$

It is the rate at which the concentration of a potentially harmful substance $C(t)$ in a compartment is changing multiplied by its mean time of relevance $1/I$. This approach holds for radioactive and stable substances, independent whether activity concentrations or element concentrations are used. The

examples of in the previous chapter emphasized the importance to consider the dynamics of environmental compartments. These dynamics are taken care of by the indicator given in equation 4.

This quantity allows for an individual judgment about the different environmental compartments. Negative values are indicating improvements, positive values point to increases of the environmental burden. Actual exposures of humans or of non-human species can be easily derived in this concept since an exposure E to a harmful substance during a time span between t_0 and t_1 is given by summing up the exposures via the compartments i

$$E(t_0, t_1) = \sum_i DF_i \cdot \int_{t_0}^{t_1} \frac{dC_i(t)}{dt} dt \quad (5)$$

making use of aggregated dose factors DF_i which describe the exposure in the environmental compartment i per unit concentration of the substance. Likewise, risk assessments can be performed by weighing an indicator I with relative or absolute risk factors for a particular endpoint. The potential indicator according to equation 4 is an example for discussion pointing to the relevance of the dynamics of the system environment.

Independent of their final formulation such indicators are needed as a quantitative basis in the competition for sustainable development. At present, they can be developed without giving already the final answers with respect to constraints or limits. But, they can serve as a basis for a system of minimization and optimization in environmental protection taking into account the precautionary principle. Tasks in which they are needed are e.g. the bookkeeping of emissions and of the input into the oceans within the OSPAR convention [17] in the context of the Sintra Statement [18], the distinction of the input in the hydrosphere of natural radionuclides by natural weathering from that originating from human practices or work activities. They can be used to address the question of sustainability in the context of the clearance of long-lived radioactive materials from practices and of the release of residues containing elevated levels of long-lived natural radionuclides from work activities. Further, they can provide the tools to compare different options of human action and their inferred risks in the final disposal of conventional and radioactive wastes.

It is evident that the development of internationally acceptable goals, criteria and finally constraints or limits based on doses or dose rates for the living environment and on activity concentrations for the abiotic environment is extremely difficult. It will take a long time to succeed. In spite of these difficulties one should at least try to develop indicators for the quantification of the radiological status of the abiotic environment. ICRP should consider taking the lead in future-oriented discussion of a comprehensive environmental protection.

5. CONCLUSIONS

There is a need for indicators to quantify the human impact via natural and man-made radionuclides on the abiotic environment, i.e. air, water, and soil. Such indicators have to be consistently applicable to radioactive and non-radioactive substances. According to the precautionary principle, the system of protection should work even at such low concentrations or concentration changes which are not relevant with respect to significant biological endpoints. This is necessary for discussions in the the context of competition for sustainability.

As exemplified for selected cases of long-lived anthropogenic radionuclides in the environment, it is not sufficient to base such indicators merely on emissions, emission rates, or concentrations in environmental compartments. Such indicators have also to account for the dynamics of the environment and transport processes between the relevant compartments. The ecological life-times have to be considered in quantifying both the environmental impact on air, water, and soil and the potential hazard of harmful substances to the biosphere

ICRP should take an active role in the development of operable indicators for sustainable development. Such indicators should not only consider the radiation exposures of man and of other living species. Also the human impact on the abiotic part of the environment by releases of radioactivity has to be accounted for. As for other environmental pollutants (e.g. heavy metals, CO₂, organics) the establishment of meaningful indicators in the context of radiation protection is not trivial and should be performed under consideration of the international discussions. Radiological protection should become a consistent part of a general scheme of the protection of the environment. Indicators for sustainability should take into account the dynamics of the abiotic compartments and should be likewise applicable to radioactive and non-radioactive environmental pollutants.

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