Radioecology is primarily concerned with the transport of radionuclides in the environment, and the effects of environmental radioactivity on plants and animals. Its development as a discipline was motivated by the production and testing of nuclear weapons and by accidental environmental releases of radionuclides (for example, the Windscale, Three Mile Island, Kyshtym and the Chernobyl accidents). In radioecology, data and models are used to estimate radionuclide activity concentrations in water, soils, and plant or animal food products in order to calculate the intake of radionuclides, resulting doses, and ultimately the correlation of dose estimates with health effects on human beings and biota. Investigations in radioecology might include aspects of field sampling, designed field and laboratory experiments and the development of predictive simulation models. This multi- and interdisciplinary science combines techniques from some of the more basic, traditional fields, such as physics, chemistry, mathematics, biology, and ecology, with applied concepts in radiation protection.

A number of measurement quantities and units have evolved in radioecology; in addition, other quantities, derived from basic measurements and experiments, have been devised. Some of these quantities and units are rather unique to radioecology; others have been borrowed from more traditional disciplines. In general, there has been very little consistency in the use of symbols, names, dimensional units, and precise definitions of numerous quantities because the work has been conducted by people from different disciplines and countries, and the material is published in a large variety of scientific journals. This situation can lead, and has already led, to confusion and sometimes misinterpretation.

In December 1995, an ICRU report committee was established charged with the development of a report designed to improve sampling strategies and techniques in radioecology. The committee, sponsored by Commission members Hans-Georg Menzel and Herwig G. Paretzke is chaired by F. Ward Whicker (Colorado State University, USA); committee members are Marian Scott (University of Glasgow, Scotland), Philip Dixon (Iowa State University, USA), Kurt Bunzl (GSF-Research Center for Environment and Health, Germany), Steve Sheppard (ECO matters Inc., Canada), and Gabriele Voigt (GSF-Research Center for Environment and Health, Germany). The development of the report was motivated largely by the fact that some studies in radioecology, especially those involving both field sampling and laboratory measurements, have not paid adequate attention to the problem of obtaining representative, unbiased samples. This can greatly affect the quality of scientific interpretation, and our ability to use the information to manage the environment.

The drafting of the report was initiated in September 1996 in Glasgow, Scotland and subsequent drafting sessions have been held in Munich, Germany, and in Fort Collins, Colorado (USA) in 1998. An additional meeting of the drafting committee was held in Bad Honnef in November 1997 during an international workshop entitled Measuring
In the original outline of the sampling report, it was envisaged that an appendix defining quantities, units, and terms used in radioecology would be included. It became apparent from discussions at the Bad Honnef workshop, that such an appendix might serve a broader audience. As a result, it was proposed that it should be published as a separate report and this idea was endorsed by ICRU. Therefore, a separate report entitled Quantities, units, and terms in radioecology has been prepared.

The primary goal of that document is to describe, in more detail, the quantities normally used in radioecology. The descriptions and dimensions of the units are provided, and special conditions or dependencies that must be specified for some quantities to be fully understood are given. One example of how the different terms are treated is given below.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>rate coefficient, or rate constant</td>
</tr>
<tr>
<td>Units</td>
<td>per time</td>
</tr>
<tr>
<td>Must specify</td>
<td>underlying model (e.g., first order), process, processes summed, donor and receptor compartments, direction</td>
</tr>
<tr>
<td>Dependencies</td>
<td>time; environment; chemical, physical, biological, social state</td>
</tr>
<tr>
<td>Other Symbols</td>
<td>lambda</td>
</tr>
</tbody>
</table>

Description: Most often a first order rate coefficient, defined as a fractional transfer per unit time, and constant in the sense that it is constant with respect to mass. As a first order k, it is the mass action transfer, where transfer rate is dependent upon the product of k and the mass being transferred. However, it is not constant with respect to any other variable, and so the term rate coefficient is suggested when it is necessary to avoid misinterpretation of the term constant. It may apply to a single process or an aggregation of first order processes. It is not a zero order rate coefficient, which instead is a flux.
It is hoped that this effort will lead to more uniformity of use, and less confusion in general. In addition, a general glossary of scientific terms that are often used in radioecology is given in a number of appendices which provide common and scientific names of a few selected plant and animal species, soil types classification etc.; references to more complete and authoritative species lists are also provided.

The draft report has been reviewed by a number of members of the International Union of Radioecologists, and their comments have been largely incorporated (see UIR Newsletter, No 31, July-Sept., 1998). The final report should be ready for submission to the Commission in 1999.

A second report entitled *Sampling for radionuclides in the environment* addresses the more statistical aspects of sampling strategies. The first issue of concern is the variation frequently observed in measurement of which the causes in radioecological data are attributable to both measurement errors and 'natural environmental variation' and this is addressed in the first chapter of this second report. The quantification of the latter source of variation and its implication for sampling strategies is treated in detail. The representativity of samples and clear guidelines for adopting different sampling approaches are discussed taking into account practical constraints such as time and costs or other physical limitations.

The second chapter introduces general sampling concepts and emphasises the importance of adopting a systematic approach, based on four steps, to arrive at the appropriate sampling scheme. Throughout the report, the emphasis has been on using examples to illustrate the processes by which the sampling design is constructed. It was decided that, since general statistical details (formulae) for specific sampling designs can be found in the literature, the report should concentrate on concepts but that illustrations of the use of statistical techniques should, however, be included in case studies where appropriate.

Subsequent chapters deal with specific sampling objectives and through case studies illustrate the basic steps in designing a sampling strategy to meet the stated objectives; key points in the decision making process are highlighted. Each chapter demonstrates how the statistical design requirements are influenced by practical constraints (for example cost, sampling and analysis methods), gives guidance on potential pitfalls and provides references to useful literature. The final sections of the chapter conclude with examples of 'what if' situations, mainly dealing with practical difficulties in satisfying the statistical design (typically inability to collect the samples), discusses the implications for analysis, and provides some guidelines on how to respond to such practical difficulties.

**Chapter 2: General sampling concepts.**

Within radioecology, there are many specific objectives which can be identified. These include: inventory estimation, impact assessment (including long-term monitoring), model testing, measurement of fluxes/transport, estimation of mean, and distributional quantities, identification of hot spots and/or hot particles, estimation of background
levels, assessment of remediation programmes, measurement of concentration factors and mapping. The choice of sampling method must be determined by the objective in mind and the environmental context of the problem. This chapter presents a step by step approach to ensuring that the objective is clearly stated and that all known factors are accounted for.

The approach is outlined as follows: first, it is fundamental that the objectives and questions to be answered be clearly and precisely defined. Next the target population and its spatial and temporal extent must be identified. The environmental context of the problem also introduces important information to be considered in the choice of the sampling design. Finally, it is important, as part of the data quality statement, to ensure that the sampling design is fully documented.

The chapter lays out the basic rules for inference and the key concept of representativity before presenting a brief discussion of a large number of sampling designs. Finally, practical concerns of numbers of samples required to meet the objectives and issues of compositing and pooling are discussed. 'How many samples?' is perhaps one of the most commonly asked but most difficult questions to answer. The report presents the formal approach which should be followed, identifying the other key pieces of information required to answer the question. In subsequent chapters, this issue of sample numbers is addressed again.

The next four chapters deal with more practical issues under a number of sampling objectives.

Chapter 3: Determining the average, a proportion, the maximum or other percentile of the distribution.

This chapter focuses on three common objectives and uses them as a means of introducing three sampling methods: simple random sampling, stratified random sampling and systematic sampling. These three methods are some of the most widely used sampling designs and each section in the chapter uses an extensive case study to work through the steps laid out in Chapter 2, before introducing specific details of the sampling methods, including evaluating the number of samples required and any practical difficulties which could be encountered in putting the sampling design into practice. The final section of the chapter introduces some less widely used sampling designs, including quadrat, two-stage and double sampling.

In the past few years, the spatial and temporal nature of problems within radioecology has been increasingly relevant. When designing a sampling scheme, the use of information on soil types, boundaries, land-use, production rates and information on the target communities etc., and their changes with time may be important. The application of GIS (Geographical Information Systems) and geostatistical methods especially in the development of Environmental Decision Support Systems are included in this second report. Specifically, chapters 4 and 5 address these and related issues.
Chapter 4: Radionuclide mapping and Chapter 5: spatio-temporal problems

Spatial problems are discussed in Chapter 4, where sections cover estimating the spatial average, mapping the entire area, locating hot-spots and finally the use of GIS systems. As always, a number of case studies are used to illustrate the main points in each section. Two of the more difficult concepts necessary for this chapter are spatial variation and dependence. The chapter first discusses some of the commonly used sampling schemes (systematic and random sampling) before introducing model based schemes, based on geostatistical principles.

Chapter 5 considers a variety of problems which can be classed as temporal or spatio-temporal and also their different characteristics. Five main classes of problems are defined, before a number of sampling designs for use in temporal problems are introduced. There are also sections on sampling to detect impact (environmental impact assessment) and on the design of monitoring networks (which of course has strong links to the work described in chapter 4).

When dealing with the spatial and temporal nature of much radioecological sampling, issues which must be considered include the choice and definition of appropriate spatial and temporal scales which impacts on the type of design used (e.g., the use of systematic grids) and the usefulness of prior information and pilot studies.

Although chapters 4 and 5 introduce more technical material, the underlying approach taken is still similar to that adopted in the simpler situations, the scientist must still clearly identify the objectives and the target population, including the spatial and temporal extent of the population.

Spatial and temporal scale, choice of sampling grid and sampling intensity

Three aspects of spatial scale - the extent of the area, the size of the sampling unit and the sample spacing are important.

The extent of the area to be sampled defines the population to which inferences will be made. This will be defined by the context and purpose of the study. The range of the physical limits could extend from, at one extreme, locating hot particles on a leaf to, at the other, mapping Chernobyl fallout over Europe. The boundaries and limitations of the area to be sampled should, of course be clear and explicit.

For continuous sampling media such as soil, air, water or time, the size of the sampling unit - called the support - should be chosen to average out uninformative small-scale variation and to be meaningful on the scale of the information to be mapped. The sampling scale should reflect the way in which the sample population is effectively sampled by the consumer. Sampling with too small a spatial support loses meaningful patterns. Sampling with too large a support may hide meaningful variation.
For spatially integrating systems (such as a mobile gamma spectrometer), the spatial support of the detector is also a key factor to be considered in the sampling design and the analysis of the results.

These considerations extend to the time frame. All sampling takes place in the time domain, and it may be necessary to incorporate the time interval into the specification of the support. For example, a very short sampling interval would be required for monitoring cyanide, where short-term exposure to high concentrations would be lethal. However, for monitoring particulate matter in air, a longer interval might be required in order to average out the effect of transitory events such as the exhaust from a passing vehicle.

In both spatial and temporal problems, the concept of the periodicity of the system being studied is also important and prior information concerning the periods or cycles is essential to ensure that the sampling is appropriate (inappropriate sampling can result in confounding between the period of the sampling and the period of the system).

Although sampling grids and sampling intensity may be prescribed on statistical grounds according to some notion of optimality, they must also be practical. For example, during a nuclear incident some compromise must be reached between the ideal sample coverage to give a true statistical picture of land contamination, and the need to gather larger numbers of samples as rapidly as possible, though these might represent a more restricted population. The difficulty then arises of extrapolating such information to the total population. Where such sub-sampling is logistically necessary it is essential for the circumstances to be fully reported. Inferences with respect to the total area should then take into account prior knowledge that may support the assumption that non-sampled areas are similar to sampled areas.

Use of prior information and pilot studies

Broadly, two types of prior information (i.e., information collated and evaluated prior to the main study) are often useful. In many cases, the existence of prior information has broadly been defined as the environmental context of the problem.

Firstly there may be prior knowledge about the nature of the problem and the underlying physical / chemical / biological processes. This kind of information leads to a refinement of the context of the problem, to a clearer identification of what needs to be modelled or estimated, and to practical, efficient and effective sampling schemes. A simple example is exploiting information about local land practices when considering exposure via milk consumption of radionuclides deposited to land.

The second type of prior information is used when defining the population to be sampled, i.e., the spatial boundaries, restricted areas (which may lead to a difference between the target population and the sampled population), the sampling unit, the sampling protocol, the measurement method and so on.
When designing the sampling scheme and particularly when calculating the number of samples required, it will be necessary to have some information about the likely distribution of observations and the magnitudes of their variances. This information may come from desk or pilot studies, and is essential for designing an effective sampling scheme that will ensure that the objectives of the study are likely to be met. Although prior information and pilot studies are particularly mentioned in the context of spatial and temporal problems, they also have applications in other, earlier problems.

Further specific problems in environmental sampling, including estimation of concentration ratios, and location of hot particles are also considered. These are the topics of Chapter 6.

Chapter 6. Concentration ratios and hot particles

Chapter 6 deals with two particular topics; it does not introduce any new sampling strategies, but rather considers possible approaches to achieving the specific objectives of finding hot particles and estimating their density and distribution and the estimation of concentration ratios, which are summary quantities much used in radioecological models.

Hot particles

The presence of hot particles in the environment (in the air, in the terrestrial environment, in the aquatic environment) has to be considered when estimating the radiation exposure of the population after a fallout event. This section differs from that on locating hotspots discussed in Chapter 4 only on spatial scale; a hot spot has a much larger spatial dimension that a hot particle, and it is typically assumed that, in total, the hot particles make up a very small percentage of the total so that different sampling strategies may be more appropriate. The environmental context of the problem also plays a particularly important role.

The sampling objectives may include obtaining information about the size distribution, the activity distribution, and the radionuclide composition of the hot particles in air, soil and the aquatic environment. In addition, it may be important to have information on the depth distribution of the hot particles.

The spatial boundaries of the study also need to be defined, depending on the contamination and extension of the plumes, the type of land use, the extent of fishing areas, population patterns and densities.

Temporal boundaries may be determined by considering the need for rapid information on air quality after an accident. It is known that hot particles are not stable in a natural environment, hence, it might be necessary to assess their presence periodically or after special events, e.g., after a flood.
Concentration ratios

Concentration ratios for a given radionuclide in two environmental compartments are required for various models that describe the corresponding short- and long-term behaviour. Typical examples for these ratios are: soil/plant; plant/animal; water/ aquatic biota; soil/air; or soil/solution.

Also, there may be interest in detecting differences in ratios between different habitats or at different times in the same habitat.

For example, for $^{137}\text{Cs}$ in plant/$^{137}\text{Cs}$ in soil, information of the following types will be needed: $^{137}\text{Cs}$ activity concentration in plants and soil, their time dependence, type of plants, depth distribution of $^{137}\text{Cs}$ in the soil, distribution of roots (vertical and horizontal), spatial distribution of plant species, and spatial distribution of $^{137}\text{Cs}$ in the soil.

For such an example, boundaries would also be needed to define the target population from which representative samples will be collected:

- spatial boundaries (e.g., area of pasture with typical land management practice).

- temporal boundaries (e.g., length of vegetation period, seasons, such as spring, summer, autumn).

Two possible approaches to the estimation of ratio values are considered. If paired data, e.g., $^{137}\text{Cs}$ in plant and $^{137}\text{Cs}$ in soil can be measured, then it is possible to calculate for each sampling point the concentration ratio CR.

In many cases it will not be possible to collect paired data. A typical example would be the plant/soil CR for trees, where it is impossible to sample the soil in the root zone, or the plant/soil CR for mushrooms, because these species can take up radionuclides via their mycelium from locations many meters away from where the fruit body was collected. In this situation, we can estimate the mean plant activity concentration (e.g., for $^{137}\text{Cs}$) and divide it by the mean $^{137}\text{Cs}$ soil activity concentration to estimate the mean CR. This situation, however, creates problems in the inference concerning the CR value due to lack of information on the covariance between the concentrations in the two compartments. One possible solution to this problem is to divide the sampling area into various strata that have different mean $^{137}\text{Cs}$ activity concentrations in the soil, and estimate for each stratum the mean $^{137}\text{Cs}$ activity concentration in plant and the corresponding mean value for the soil. A scatter plot of these two quantities may give some information on the degree of their association and on the soundness of the underlying assumption of a linear relationship (through the origin) between plant and soil activity concentrations.

The final chapter summarises the work, and emphasises that in the approach presented throughout the report there exists an iterative and exchange process between radio-
ecologists and statisticians which results in a cost-effective, practical experimental design compatible with detecting a defined effect.

At present, the second report on Sampling for radionuclides in the environment exists in draft form, but its final version will be presented to the ICRU at the end of 2000.