General Environmental Impact Assessment Methodology Approach (Model Development Process) for NORM Sites Working Group

Reference approach for risk and environmental impact assessments necessary for management and remediation of NORM and legacy sites

EMRAS II
Norm and Legacy Working Group

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1 BACKGROUND AND OBJECTIVES

Naturally occurring radionuclides are found throughout the earth's crust, and they form part of the natural background of radiation to which all humans are exposed. Many human activities—such as mining and milling of ores, extraction of petroleum products, use of groundwater for domestic purposes, and living in houses alter the natural background of radiation either by moving naturally occurring radionuclides from inaccessible locations to locations where humans are present or by concentrating the radionuclides in the exposure environment. Such alterations of the natural environment can increase, sometimes substantially, radiation exposures of the public.

There several circumstances in which materials containing natural radionuclides are recovered and processed that may lead to enhanced concentrations in the final products or waste, in such a way that a radiation exposure results in significant dose to the public.

Include reference to UNSCEAR report for summary of natural radiation exposure

The decay chains of some naturally occurring radionuclides are considerably more complex than the decay chains of other radionuclides with regard to the number of decay products and chemical elements involved. However, contemporary methods of risk assessment that estimate doses and risks related to ingestion or inhalation of radionuclides by assuming that decay products produced in the body are redistributed and retained in the body according to the metabolic behaviour characteristic of particular chemical elements take the added complexity into account by using the same methods that are applied to other radionuclides with many fewer decay products.

This is a reasonable point, but a broader point is that radiation protection objectives should not be different (in principle) for NROM and other situations. The safety fundamentals and BSS do not allow for this for example.

Thus, in general, there should be no difference between NORM and other radioactive materials with regard to suitable approaches to estimating doses and risks related to external or internal exposure. However, because naturally occurring radionuclides are ubiquitous in the exposure environment, there might be more opportunity than there is with many human-made radionuclides to use observational data on natural levels in different environmental compartments (such as soil, water, air, plants, and animals) and the fluxes between compartments to calibrate exposure-pathway models for NORM.

On the other hand, the ability to use such natural analogue data for exposure pathway analysis must be tempered by the recognition that the physical and chemical forms of NORM could be substantially different from those for the same

elements in the natural environment. NORM is in the natural environment, the point is that NORM radionuclides occur naturally in many forms; they also occur in many forms due to technological changes made to those radionuclides in the natural environment; and finally the same radionuclides appear in the environment due to the nuclear fuel cycle, further amending the forms and proportions of those radionuclides as they are found in the environment.
In that case, observations on the behaviour of radionuclides in natural systems might not be relevant to the exposure situation of concern.

Mathematical modelling of radionuclide transfer through the environment will always be an important aspect of radiological protection. It is an essential component in predicting doses and risk to individual and populations, and hence in providing an input to decisions on the sitting, design and operational procedures for all type of facility which will or could release radionuclide into environment. ICRP publication 103 tells us specifically not to assess risks to populations. So it may be good to check if IAEA want this... or if they wish to contradict ICRP

Assessment of the radiological impact of planned or existing practices involving actual or potential release pf radionuclides to the environment are largely based on the use of modelling techniques which allow prediction of the relationship between environmental levels and release and the associated radiation dose to man.

Refer to examples from EMRAS I documents, also the set of BIOMASS documents (there were 7 including one on a Ra-226 legacy site in Belgium!). And also the IAEA's ISAM methodology. All are relevant and we want the best bits of each of them in the new guidance we develop here, combined in a way which works well for NORM and Legacy sites. NB we don't want to contradict the waste WG.. except in so far as difference is justified.

Models are imperfect means of representing environmental transfer processes, and it is essential to know the reliability which can be associated with perditions of these models for each every assessment situation. It is also essential to know what level of reliability you need in order to make a decision. This is a very important and neglected issue. You don't know if reliability is good enough if you don't know what reliability you need.

In the environment, radionuclides have many sources and they follow various pathways to reach the man. There are the different sources such as the natural radioactivity in the environment, the controlled releases from nuclear power plants and reprocessing plants, the uncontrolled accidental releases, and the release from deposited waste. Despite the manifold efforts and studies, uncertainty is still inherent to these sources term. Modelling is going to surfer from uncertainty still in the next and further future.

A next step, which is a subject of consideration, is the dispersion after release from whatever source. Three main dispersion pathways may be described: atmospheric dispersion, transfer through the geosphere after any deposition and finally dispersion through the biosphere including terrestrial and aquatic environment.

For a general radiation protection point of view it may good to bear in mind the ultimate goals of all these scientific efforts but a few of them are the most important

- Reliable description of the sequential transfer of radionuclides to the biosphere.

- Adequate estimation of the amount of contamination eventually taken up by man after inhalation or ingestion of radionuclides via different pathways

- Reliable estimation of dose to man and human population brought about different pathways.

This draft document describes the general approach modelling that could be adopted for the assessment of radiological impact of NORM industry **waste** disposal **and legacy site management**.

An integrated methodology is **proposed** and issues **such** as risk, exposure pathways and the plausible scenarios in which the contaminant can migrate and reach the environment and human beings are addressed. A specific example **application** of the procedure is described and results are presented.

(This is what was done by IAEA in BIOMASS, ISAM, ASAM). In the final document they had several examples, and maybe EMRAS can do the same.

The main objective of this document is to present a brief methodology for the long-term prediction of the environmental impact of the NORM situations. With these document is sought to apply the developed methodology during the project BIOMASS to environmental impact assessment of to NORM contaminated situation, where to huge quantities of waste flows dispose in the environment. The opposing studies until the moment in the bibliographical one refer to scenarios where the residuals and the radionuclides are placed and they are liberated by the infiltration.

In some specific situations, remediation action would be taken for radioactive residues from activities and accidents. Indeed, it is not just about waste disposal, the goal of the remedial actions shall be the timely and progressive reduction of the hazard and eventually, if possible, the removal without restrictions of regulatory control from the area. In cases where the removal of control cannot practicably be achieved, at least the unacceptable risks to human health and the environment shall be removed and any restrictions on access to or use of the area and any other restrictions shall be established on the basis of an optimization process.

Whether or not regulate of waste containing elevated levels of radionuclides generated incidentally by industrial processes that are not involved in the nuclear industry or radionuclide industry is an issue currently under discussion at national and international levels. These industries, many of which have been operating for many ten of years, may not see the necessity for additional control, a counter argument is that the health risk associated with a exposure to radionuclides in the waste may be little different to those associated with regulated waste from the nuclear industry.

Several countries have developed separately assessment methodology for NORM waste contaminated site. In some cases they have been developed and implemented methodologies for national agency in other case applications exist as part of the study of specific site situations.

Objectives and Scope

I thought we also want the methodology to apply to contaminated land – legacy sites. It certainly is possible to arrange this, on the source pathway receptor 'model 'that you mention above.

The performance assessment of the NORM waste disposal facility will carry out using the leaching scenario or off-site scenario (considered a normal evolution scenario). This corresponds to the use of contaminated water in the biosphere compartment at the interface with the aquifer, after migration of the radionuclides through the unsaturated and saturated zones.

In the interface between the geosphere and the biosphere there is a well intercepting the radioactive plume, at an off-site location where the concentration is the highest (e.g. at the downstream waste site boundary). Accordingly, the biosphere can be composed of a small farm system where the well water is used for drinking and in the production of vegetables, milk, meat and fish. Once the water is used to irrigate, the public can also receive a dose from accidental ingestion of contaminated soil, re-suspended dust and inhalation, external exposure and radon inhalation.

NORM situations is practised in numerous countries and today many countries consider that it is essential to justify any waste disposal or contamination by showing compliance with the relevant regulatory criteria.

None of this is silly… but it presumes too much of a specific assessment context. At some sites, there will be NO irrigation and the only problem might be radon and dust… not groundwater release at all.

So I would replace this with text from the ToR. Not to re-invent them, but to re-present them and then to extend them according to the suggestions from Malgorzata, sent last Friday.

2 THE METHODOLOGY FRAMEWORK

A brief description of the key aspects of a safety assessment approach is provided. The basic methodological aspects to follow are: (1) context of the evaluation (definition of objectives, safety requirements, radiation protection criteria, etc.), (2) system description. Output from both the assessment context and system description allows the identification and description of the relevant characteristics, events and processes to be included in the scenarios (3) that will be represented in the conceptual model and the associated mathematical model (4). The results of the evaluation permit the analysis of the case suitability, through comparison with the defined radiological criteria. A new iteration of the methodology should be carried out in case that a modification of the system would be needed.

The assessment methodology is based on that outlined by Little et al. 1996, but also taken under consideration recent development in relevant international programmes such as (BIOMOVS, BIOMASS) for the IAEA and BIOMOSA for European Community. The methodology provides a formal procedure for the identification and assessment of impact pathways (pathways through which contaminants may be release and results in a detrimental impact on the environment, including humans). It can be applied to assess short term and long-term impacts to the environment, workers and public.

The proposed methodology framework is presented in Figure 1 and has six primordial steps.

Of course they are sensible and I can see connection to performance assessment methodologies. But I don’t see why we would not use the same steps as in BIOMASS and ISAM. Or present both and then suggest a combination.

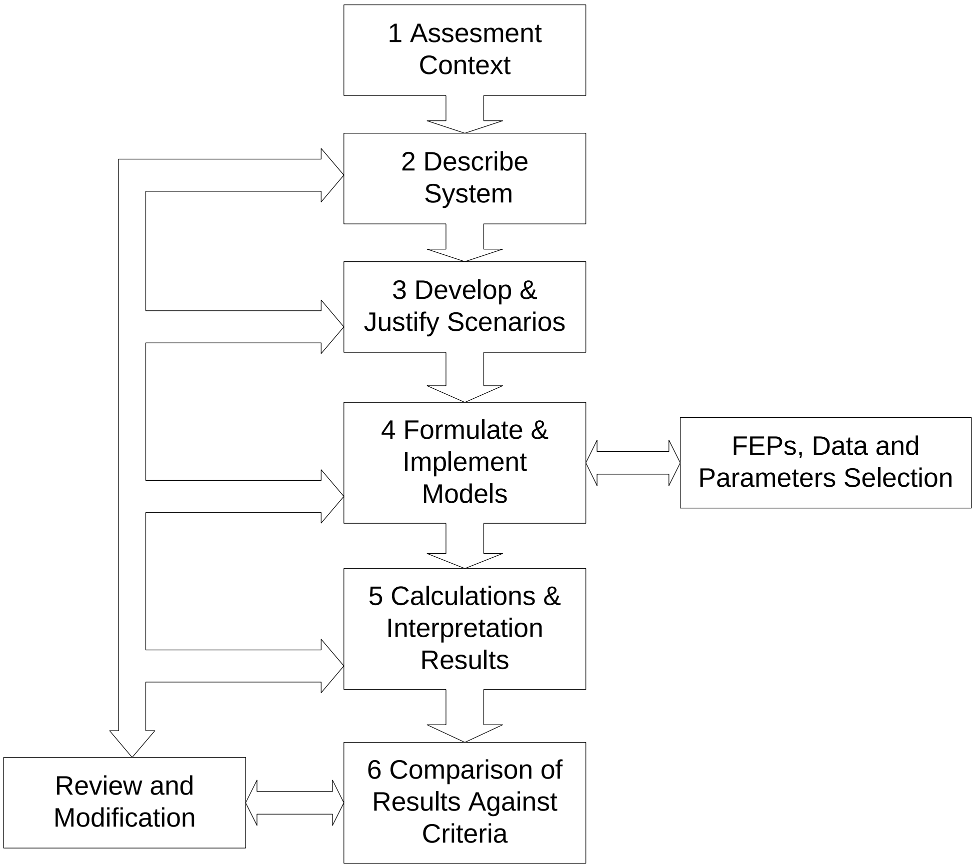

Figure 1. Diagram of the Assessment Approach to used for NORM Situations

2.1 ASSESSMENT CONTEXT

The assessment context answers some fundamental questions, which need to be asked before any assessment is undertaken: What is being assessed; and why is it being assessed? What are the relevant assessment criteria? What are the timescales to be considered?. The main issues of the context are: purpose, safety requirements, radiological protection criteria, assessment end-points, waste properties, and disposal system and time scales of the evaluation.

The background and requirement of the assessment can have an important bearing on how, the range of different environmental features, events and processes that are potentially relevant to the assessment area considered. In particular, the context of the assessment may play a key role in defining the boundaries (both temporal and spatial) components of the system to be represented. Particular issues relevant to definition of the assessment context are the followings.

Assessment Purpose of the evaluation.

The purpose of undertaking and assessment may vary from a simple calculation to support for example remediation actions or disposal concept development, through to a detailed, site specific performance assessment against regulatory criteria in support of a disposal license application.

Assessment Endpoint and Safety Criteria.

The nature of the assessment will tend to reflect the results that it is designed to evaluate. These, in turn, will largely depend on the criteria (regulatory o otherwise) that are adopted to judge the impact of the treatment, reuse or disposal practice. Example assessment end-points include contaminants concentrations in various environmental media (soil, atmosphere and water bodies), contaminants intake rates by humans, radiation doses, and a level of risk of fatal cancer in humans from intake of contaminants. Example criteria include environmental quality standards, human's intake limits, and human health risk limits.

Even though the main role of the safety assessment often relates to the licence application and approval process for radioactive NORM waste (required for regulatory purposes at various stages), one of the most important applications of safety assessment can be to assist in the optimisation and facility design after its concept development and site selection. This can be achieved by carrying out comparative assessments for various combinations of alternative waste packages, disposal modules, and site management and closure measures.

The aim of an assessment is not to predict the disposal system performance, but rather to reach reasonable assurance that it will provide an adequate level of safety, by demonstrating compliance with safety and regulatory requirements. The assessment of regulatory compliance is not limited to numerical assessments of potential dose rates but may also include consideration of: the applicant's commitments and proposed limiting conditions of operation; the applicant's proposed environmental monitoring and survey programme; the ease with which operations can be adjusted to minimise or mitigate potential releases of radioactivity; the past environmental monitoring; and applicant's training and experience.

As an example purpose an assessment end-point, it is proposed that a range of illustrative end points will be considered which will allow an understanding of the radionuclides behaviour in the disposal system. The end points to be considered are: time evolution of flux/concentration at the repository and in the geosphere/biosphere interface; time evolution of concentration of radionuclides in the biosphere; and time evolution of the annual individual effective dose for each exposure pathway; time evolution of total annual individual effective dose summed across all appropriate pathways.

Assessment timescales

If limits are placed on the times scale of the assessment, these may have a significant effect on the way in which issues such as long term environmental change are addressed in the assessment.

Site Context

The general location of the system to be assessed may have an important influence on the likely pathways for release of contaminants to the environments and the extent to which site specific factor can influence the impact of such release. The site location will therefore tend to influence the degree of detail used in representing particular elements of the system to be assessed.

The identification and general description of characteristic climate states relevant to the environmental impact assessment of NORM waste location. Also is important to have data of relevant meteorological factors such as temperature, precipitation, evaporation, wind speed direction and solar radiation.

Another Environmental and Society Assumptions Issues relating to NORM situations

In the choice of the optimized remediation option, a wide variety of factors shall be considered and impacts on health, safety and the environment shall be considered together with technical, social and financial factors. Non-radiological hazards shall be considered in conjunction with the radiological hazards. The objectives of remediation shall be to reduce existing exposures and to avert the potential for prolonged exposures to occur in the future. In particular, the remediation shall be aimed at:

(a) Reducing the doses received by individuals or groups of individuals being exposed;
(b) Averting doses to individuals or groups of individuals that are likely to arise in the future;
(c) Preventing or reducing environmental impacts from the radionuclides present in the contaminated area.

Responsibility for the implementation of remedial actions shall include the preparation of a remedial plan for approval by the regulatory body, the conduct of the remedial work and the management of the waste resulting from the remedial work. The organization to which this responsibility is assigned shall be responsible for all aspects of safety including the performance of a safety assessment and of an assessment of the environmental impact.

For demonstrating compliance of nuclear waste disposal with current radiation protection standards, the radiological impact due to hypothetical releases of radionuclides into the biosphere is the principal safety indicator. However the assessment of the radiological impact to future exposure groups is associated with inherent uncertainties.

Ethical Issues

Long term environmental considerations commonly involve ethical questions. The debate about fairness to future generations has centred on radioactive waste, although concerns about toxic chemical waste can be more relevant as it remains hazardous indefinitely. Time span issues are not limited to waste, but also cover a very wide range of issues that include depletion of natural resources and the effects of global warming, as well as many recent technological and bio-genetic developments. A clear case is the current depletion of natural resources in the earth's crust that involves a fundamental change to our environment.

Regulatory Safety requirements.

At a chosen site location, what assurance is there that the multiple barriers to isolate the radioactive substances will be sufficient under all conceivable circumstances? Tests and measurements can certainly confirm structural integrity, heat resistance and leak tightness in the short term. But long term issues involve developing scenarios and describing processes and conditions that require considerable mathematical models.

The need to regulate **radioactivity** in the environment is a matter of concern to nationals and has been the subject of discussion at a number of international forums. The number of requests from nationals regulatory bodies and expert for assistance on the regulatory issues have increased during the past couple years. The radiation exposure to the public from different industries that use or generate NORM can be significant and needs to be considered as part of the overall radiation protection regime. Many countries have not considered regulation of these industries because of the potential burden this process could have on not only the affected industry, but also the regulatory body. What is needed is a rational, yet effective approach to the regulation of these industries. The processes of exclusion and exemption as defined in the BSS should be clarified as to their application to residues that result from these activities.

The aim of dose environmental impact assessment for NORM waste disposal situations is to demonstrate compliance with the safety requirements, related to human exposure and the environment.

The ICRP recommendations on radiological protection for other situations as disposal of radioactive wastes (ICRP, 1998) suggest that the control of public exposure from waste disposal should be exercised by the use of the constrained optimisation of protection. To allow exposures to multiple sources, the maximum value of the constraint used in the optimisation of protection for a single source should be less than 1 mSv in a year. A value of no more than about 0.3 mSv in a year would be appropriate.

ICRP recommendations (ICRP, 2000) for the assessment of long-lived radionuclides, makes a differentiation in the events that cause the exposure due to natural processes (for which the protection criteria is the individual dose constraint of 0.3 mSv in a year) and the exposures due to human intrusion. For the latter, when the situation results in doses such that intervention would be required based on current criteria (order of 10 mSv/a), it is recommended to take reasonable measures to reduce the probability or limit the consequences.

The critical group is defined, according to the ICRP Publication 77 (ICRP, 1998) as an homogeneous group with respect to the diet and those aspects of behaviour that affect the dose; it is representative of the individual who receives the maximum doses. The characteristics of the hypothetical exposure groups will be defined based on these premises.

Environmental problems associated with NORM

Handling, storage, transportation and the use of NORM contaminated equipment or waste media without controls can lead to the spread of NORM contamination, and result in contamination of areas of land, resulting in potential exposure of the public.

NORM release and disposal options

The objective is to establish safe, practical and cost effective permanent disposal protocols for NORM waste that provide adequate protection to both human health and the environment.

A permanent disposal protocol should be designed to prevent contamination of natural resources such as underground water, or contamination of soil that could in future become residential or agricultural areas even although the area is currently remote or uninhabited.

Methods of NORM disposal currently used are:

- Land based management
- Salt cavern disposal
- Offshore discharge
- Land fill
- Underground injection

The preliminary selection criteria may include:

- Risk
- Technical feasibility
- Cost
- General acceptance (regulatory and public)

Description of disposal methods (American Petroleum Institute, 2006)

Disposal Method	Description
Land spreading	Land spreading involves disposal by spreading sludge and scale on the surface/open lands in an area where NORM was not originally present above background levels.

Land spreading with dilution (land farming)	Land Spreading with dilution involves mixing of the applied NORM thoroughly within the top layer of soil using agricultural equipment in an area where NORM was not originally present above background levels.
Non-retrieved line (surface) pipe	Buried line pipe used at a facility could be abandoned in place after being flushed to remove any oil or gas present.
Burial with unrestricted site use	Burial with unrestricted site use involves burial of NORM with at least 15 feet (4.6m) of cover that is level with the surrounding terrain, minimising erosion potential.
Commercial oil industry waste facility	Disposal in a commercial oil industry waste facility assumes burial with other oilfield wastes where NORM represents less than 7% of the total waste volume.
Commercial NORM waste facility	A NORM waste disposal site is designed to contain NORM for long periods and its control may revert to a national authority for permanent monitoring and restricted future use after closure.
Commercial low level radioactive waste facility	A low-level radioactive waste disposal is defined and licensed under national regulations with numerous protective features and restrictions.
Plugged and abandoned well	Well abandonment operations provide an opportunity to dispose of NORM.
Well injection and hydraulic fracturing	Sludge and scale wastes could be injected or fractured into formations that are isolated geologically and mechanically.
Equipment release to smelter	Smelting may be a viable option for NORM contaminated equipment.

NORM recycling

2.2 SYSTEM DESCRIPTION

The system description forms the basis for identifying the features, events and process (FEPs) and scenarios of importance for the assessment. For an assessment of residue disposal, information should be collated concerning: the disposal facility (waste types, waste form, disposal practices, engineered barriers, facility dimensions); the geosphere (e.g. lithologies, flow and transport characteristics); and the biosphere (e.g. the climate and geomorphologic characteristics, human activities). For an assessment of residue treatment, information collation should focus on the treatment technique and the system into which resultant residues are deposited. While for residues reuse, information collation should focus on the reuse options and the system, which the residues are applied.

A description of how the different NORM situations or system components interact should be provided. It is important to ensure that the data collated are pertinent to the assessment. For the first interaction of the methodology, emphasis should be placed on the collation of existing data rather than collection of new data. For subsequent iterations, the emphasis could move towards collection of new data.

The site characteristics shall be taken into account in the safety assessment. In determining the site characteristics that are important to the safety assessment, the following can be considered: geology, hydrogeology, geochemistry, tectonics and seismicity, surface processes, meteorology and description of human activities.

The site has been sufficiently well characterised, such that the impact of the potential migration of radionuclides from the disposal facility to the environment can be readily assessed. The effective and safe isolation of waste depends on the performance of the overall disposal system; the relative contributions of the different system components will vary depending on the disposal concept and site conditions.

NORM Waste

The residues of NORM industries are recycled/reused or they have to be disposed of. The presence of natural radiation sources can lead to a significant increase in the exposure of workers or members of the public. Therefore these processes cannot be disregarded from the radiation protection point of view.

Some examples for NORM residues are:

- Scales, residues, sludge and wastewater of mineral oil exploration, gas purification and carbon pyrolysis.
- Mining residues
- Contaminations on ferrous scraps and non-ferrous scrap.
- Materials arising from chemical and mechanical surface processing of ferrous scraps and non-ferrous scrap
- Residues, sludge and waste water of ore exploration, e.g. Al, Nb, Ta, Cu, Sn, Zn, REE, Ba …
- Scales, powders, dusts of thermal processes.
- Waste of the phosphate production in particular gypsum.

Source Term

The waste under consideration contains natural radionuclides, some of them with very long high life. The presence of these long life radionuclides in the waste implies that attention should be paid to periods covering several thousand years.

The natural radionuclides present in NORM industry or waste are those of three naturally occurring series, Uranium series (U-238), actinium series (U-235) and the thorium series. These wastes can produce in very large volume's with relatively low specific activities and must be disposed in away to ensure they remain sufficiently isolated as long as necessary to protect the human.

The sheer volume of waste of some NORM industries and Uranium mill tailing, despite the relatively low activity associated with the tailings wastes has engendered a perception that these waste sites pose a serious hazard and potential risk to human health and the environment. The actual risk, of course, depends upon the nature and amount of radioactive materials to which the public can be exposed.

The waste streams that constitute the majority of the waste volume and activity should be identified in terms of specific waste-generating facilities.

Information on the physical, chemical, and radiological characteristics of each waste stream can include: annual volumes, waste class, average concentrations of the principal radionuclides, chemical and physical form, the presence of chelating agents, packaging characteristics, solidification agent, etc.

Limits shall, as necessary, be established for radionuclide inventories and/or concentrations. Long lived alpha emitters, long-lived beta and gamma-emitting radionuclides are subject to limitation, both in the total inventory and in the concentrations as determined by means of a site-specific safety assessment.

From model point of view the source waste characteristics for radionuclide release. Uniform waste is assumed. Radionuclide release is assumed to occur by leaching, with the following hypothesis:

- Wastes are mixed with the excavated native soil, without compactation and available to instantaneous release as soon as getting in contact with the infiltration water. The release is assumed to be in a single location.
- Contaminant solubility limit in the aqueous medium is not considered.
- Care should be taken not to consider the retardation twice. Here, it is included transport calculations.
- In a simplified way, wastes are considered as a homogeneous mixture with unique properties.

If the waste is dispose in some special system, taking into account the waste characteristics, engineered barriers and natural barriers associated with the site, the geosphere and the biosphere, shall provide for the isolation of waste and the limitation of releases of radionuclides required to ensure that the potential impact of waste disposal on humans and environment is within acceptable limits.

Radionuclides

2.3 SCENARIO DEVELOPMENT AND JUSTIFICATION

Relevant pathways of exposure to radiation originating from NORM in process residues and wastes depend on the mode of disposal, the local environment, the demographics of the population in the region and any institutional measures that may be applied to a given site. Disposal practices may be industry specific and may also depend on the state of the development in the industry and the specific socioeconomic circumstances. The vast amounts of NORM which are generated, however, tend to limit the choices for disposal options. Landfill or landspread surface impoundments and surface mounding (waste piles) are the most common forms of waste management for NORM. Sometimes the wastes are covered, but in many cases the NORM containing wastes are disposed of without cover. The disposal method chosen determines the potential for direct exposure to the NORM and also the potential for surface water and groundwater contamination arising from it. In IAEA (TRS 419) provide e perspective on the relationship between different disposal practices an releases.

The scenario development is the preparation of a list of features events and processes (FEPs), which can influence the system, the release, the migration and fate of contaminants within it. All the possible features, events and processes which have been identified then have to be screened in order to reduce the number, which will be assessed in detail. Criteria such as low probability or low impact can be used as screening mechanism. Simple scoping calculations of certain features, events and processes may be used to make preliminary assessment of impacts to aid screening.
Each possible combination of features, events and process can term a scenario. These scenario are identified and the number reducing by grouping them into categories (those with the same impact, those causing pollution of the same media, etc.) Finally those scenarios for which detailed modelling should be undertaken due to their high probability of occurrence, high impact, etc, are identified. Normally the conceptual model for and specific site is based in the fieldwork and the information on previous work made available for the NORM waste emplacement.

Disposal Scenario
Recycling Scenario
Release Scenario

Considerar que hay escenarios disposal and recycling y que los esceanrios estan formados por diferentes pathways.

The major effort in an assessment is to determine what affect the disposed radioactive waste will have on future generations and the environment, and under what future conditions, something that is obviously not known. An approach historically used to circumvent this problem is to collate and screen all currently available information on the characteristics of the waste disposal (e.g., behaviour of people, climate change, geo-hydrological conditions), and any other natural or human induced condition. Personal judgement is then used to generate a number of scientifically sound descriptions, commonly referred to as *scenarios*, of potential future conditions at the site.

Depending on the characteristics of the disposed waste, an environmental impact assessment can be concerned with the impact of the waste on humans and the environment over time scales tens to thousands of years.

The approach commonly followed today in the assessments to address the uncertainties in the future evolution of a waste disposal system, is scenario generation. The main purpose of scenario generation in the assessment of a radioactive waste disposal system is essentially to use scientifically informed expert judgement to guide the development of descriptions of the waste disposal and its potential future behaviour.

The scenario does not try to predict the future; rather, the aim is to identify salient changes, based on analysis of trends, within which variants are explored to investigate the importance of particular sources of uncertainty. The emphasis is therefore on providing meaningful illustrations of future conditions to assist in the decision-making process. Care should be taken to ensure that the selected scenarios provide an appropriately comprehensive picture of the system, its possible evolutionary pathways, critical events and system robustness. In this context, it is extremely important to have a systematic scenario generation approach and to document all steps in the generation of the scenarios.

Scenarios depend on the environment and system characteristics, and on events and processes, which could either, cause initial release of radionuclides from the waste or influence their fate and transport to humans and to the environment. The choice of appropriate scenarios is very important and strongly influences subsequent analysis of the waste disposal system.

These scenarios may vary widely depending on NORM situations and disposal site design and operation, the waste acceptance criteria and site environmental conditions, which are applicable during all periods of the disposal facility life. It may be helpful in developing a suitable list of scenarios to consider the processes and events of natural origin; the processes attributable to waste itself or features of the near surface repository; and human activities. The first step in identifying which of the many features, events and processes (FEPs) is relevant to the safety assessment should be to establish a checklist such as the one shown in Appendix I. The FEPs list used has been developed within the BIOMASS project for IAEA. (IAEA, 2000).

Using the initial FEP list, together with information from the assessment context and system description, some initiating events are considered whilst others are rejected to finally obtain the FEPs list for this specific case. It is important to record the process, the judgements made and the factors considered in the screening. Therefore a well-structured, transparent and comprehensive approach should be used, which will allow the description of the relevant future evolutions as well as the identification of the critical issues.

This first step has allowed the structuring and review of available information, using information from the system description as well as the assessment context.

The second step of the approach is the definition of the most important elements to be considered in the assessment, namely, the waste itself, the barriers and the human access to the site, before defining the states of barrier performance and human behaviour. From the consideration of the screened FEPs List, two groups of scenarios can be developed: the scenario representing the evolution of the system due to natural and internal characteristics and processes, and the second group that are a consequence of external events and processes on the system.

The majority of case of NORM waste disposal is described by a leaching scenario or off-site scenario considering a normal evolution. This scenario correspond to the use of contaminated water in the biosphere compartment at the interface with the aquifer, after migration of the radionuclides through the unsaturated zone and saturated zones. In the interface between geosphere and biosphere there is a well inside the radioactive contamination groundwater plume, at an offsite location downstream waste site boundary (of course where the concentration is higher). In order to model the biosphere normally is consider a agricultural scenario, that is the existence of a farm near the site (at the border using water from a well for (a) ingestion of well water, irrigation and consequently resuspension, inhalation and external exposure to contaminated agricultural soil. Is consider also an consumption of home grown produce, contaminated meet and milk, accidental ingestion of contaminated soil and inhalation of radon and decay product from soil.

2.4 MODEL FORMULATION AND IMPLEMENTATION

Once the scenarios have been developed, their consequences in terms of the assessment context must be analysed. Depending on the nature of scenarios, an appropriate approach for its analysis is chosen. For those scenarios, which are to be assessed qualitatively, it is appropriate to go straight Calculation and interpretation of results. For the scenarios, which are to be quantitatively assessed, the scenarios must be organized into forma that is amenable to mathematical representation. For each scenario, one begins with set of model level assumptions about dimensionality, boundary conditions, features events and processes etc., which comprise the conceptual model. More than one conceptual model may be consistent with the available information for each scenario.

The conceptual model for each scenario is then expressed in mathematical form as a group of algebraic and differential equations to be solved. Yet again, more than one mathematical formulation might be appropriate for the conceptual model considered. These equations and their associate parameter form the basis of the mathematical models.

Solution of mathematical models is usually conducted by implementation in one or more computer tool using analytical or numerical techniques. In order to allow the computer tools to be run, data for the input parameters need to be specific. In specific data, consideration should be given to treatment of uncertainties associated with the parameter values.

After the identification and description of the scenarios to be considered (consistent with the assessment context), the next step in the methodological approach is the development of a conceptual model, starting from the generic list of Features, Events and Processes (FEPs) to be considered, to ensure that no significant issues are ignored in defining the final model and providing traceability and transparency in the biosphere analysis. The conceptual model developed from the screening of the

FEP list for a selected scenario must be represented in terms of mathematical expressions.

The used tool to represents, identification, structuring and ranking the FEPs is named interaction matrix. In this matrix, the main compartments of the scenario are identified and listed along the leading diagonal elements of square matrix. The identified interactions between the diagonal elements occurs in the off diagonal terms. This process is illustrated as example in the next Figure together with clock-wise convention for the influence direction. A more detailed description of the interaction matrix development is given by (reference).

A structured generic Biosphere FEP list was developed during BIOMOVS II project by the Reference Biospheres Working Group [BIOMOVS, 1996]. This list has been updated within the BIOMASS project [BIOMASS, 2003] to reflect the experience gained with the application of the methodology and the need to express intrinsic phenomena relating to the biosphere system in terms of characteristics of the system, rather than the behaviour of radionuclides within the system. It distinguishes also elements of the assessment context from those related to the biosphere system, radionuclide transport and radiation exposure.

The FEP list has a hierarchical structure to facilitate systematic screening. Each of the phenomena associated with the biosphere system description developed for a particular assessment context can be linked to one or more FEPs.

The complete FEP list for biosphere assessment is presented in APENDIX A. The hierarchy of the FEP list is shown by indentation.

Idea is to development FEPs list and interaction matrix for different NORM situations

The prediction of transport of radioactive and non radioactive contaminants from NORM into the surrounding environment require a good understanding of the processes controlling their release and the path ways along which they move. These include release of gases and particular to air, leaching from the waste tailing into groundwater, river and lakes and uptake and distribution in biota, soil and sediments.

The development of the conceptual and mathematical models for each scenario and their implementation in the calculation tools are the tasks that need to be undertaken prior to the quantitative analysis of the scenarios.

The FEP list has a hierarchical structure to facilitate systematic screening. Each of the phenomena associated with the biosphere system description developed for a particular assessment context can be linked to one or more FEPs. In many cases, FEPs do not require characterisation by mathematical expressions. This is because they are not specific to modelling (e.g. those relating to the assessment context), are included through descriptions of the specific scenarios to be modelled (e.g. biosphere system features), are matters of definition that do not require an equation (e.g. annual individual dose), or are represented through the choice of specific parameter values in the expressions that are provided (e.g. consumption and inhalation rates).

To impact assessment the model needs to have enough detail to allow the mathematical development to describe the system behaviour. The conceptual model, hence, can be considered as the set of hypothesis that describe the physical-chemical and mechanical processes that affect the repository and the site behaviour, together with the geometry, structure, properties, initial conditions and boundary conditions of the system. They all form the basis for the development of the mathematical model.

Normally the conceptual model for and specific site is based in the fieldwork and the information on previous work made available for the NORM waste emplacement. This is a reasonable and sensible example, but far too prescriptive for a general methodology.

Mathematical representation of the model

A mathematical model for the release, migration and uptake of radionuclides was developed consistent with the conceptual model. Each process identified in the conceptual model was represented mathematically either implicitly or explicitly. at were then collated from a variety of internationally recognised sources.

The conceptual model represents the system as a set of homogeneous compartments. The mathematical representation of the transport among them is represented by a first order linear differential equation system. The radioactive decay and the transfer processes between compartments are represented as linear processes. Equilibrium in the physical medium is assumed for the concentration calculations in foodstuff.

The biosphere is modelled as a series of compartments in which homogeneous conditions are assumed. Each transfer between compartments is described by a "transfer rate", which represents the fraction of activity in a compartment that is transferred to another per unit of time. In this approach, the variation of the activity of radionuclide *m* in compartment *i*, I^m_i, is expressed as:

$$\frac{dI_i^m}{dt} = -\left[\lambda_r^m + \sum_j \lambda_{ij}\right] I_i^m + \lambda_r^m \cdot I_i^{m+1} + \sum_j \lambda_{ji} \cdot I_j^m$$

where, λ_{ij} is the exchange rate between compartment *i* and compartment *j*, $m+1$ is the parent of radionuclide *m*, and λ_r^m is the decay rate. This representation results in a set of first-order linear differential equations that are solved numerically (Lawson et al. 1985)

Solving equations is very easy these days. I think it is best not to reference specific software packages. Sure I think MABER is very good because it does not assume anything... it just solves equations efficiently. It is not an expert system, it is the opposite..it is a system for experts! RESRAD is more or less the opposite. Both are useful in the right context. Or ecolego... or model maker.

The inter-compartmental transfer rate coefficients (λ_{ij}) from donor compartment *i* to receptor compartment *j* are the mathematical representations of the transfer processes and are computed by:

$$\lambda_{ij} = \frac{1}{V_i} \cdot \frac{F_{ij}^m + K_i^m M_{ij}^m}{\theta_i + (1-\varepsilon_{t,i})\rho_{t,i} K_i^m} = \frac{F_{ij}^m + K_i^m M_{ij}^m}{V_i(\theta_i + \rho_b K_i^m)}$$

where,

F^m_{ij}	liquid phase transport ($m^3\ y^{-1}$),
M^m_{ij}	solid phase transport ($kg\ y^{-1}$)
K^m_i	solid/liquid distribution coefficient ($m^3\ kg^{-1}$)
θ_i	moisture content (-)
$\varepsilon_{t.i}$	total porosity (-)
$\rho_{t,i}$	grain density ($kg\ m^{-3}$)
ρ_b	bulk density ($kg\ m^{-3}$)
V_i	donor compartment volume (m^3).

Mass balance is represented by matrices for the water and solid material fluxes from compartment *i* to compartment *j* (respectively denoted by F_{ij} ($m^3\ y^{-1}$) and M_{ij} ($kg\ y^{-1}$). Radionuclides in any compartment are represented as in solution in the water or sorbed onto the solid material in the compartment. The partitioning is modelled by use of the solid-liquid distribution coefficient K_i (Bq kg^{-1} per Bq m^{-3}).

In this approach, to characterise the inter-compartment transfers it is necessary to characterise the mass balance scheme for solute and solids. This is good and true for advective transport, but is not correct for diffusive transfer between compartments. So it should be presented as a good example, but then refer to the CIEMAT document on mathematical representation of processes, and/or various of the BIOMASS documents (Agüero et al. 2005, BIOMASS 6).

In the APENDIX B, the items of the list of FEPs are completed with their definitions and mathematical expressions, where appropriate. The framed texts are the definitions given in the original list in BIOMASS (BIOMASS, 2003). The parameters in the mathematical expressions are accompanied by their dependences in brackets and are listed and defined in chapter III. In many cases, FEPs do not require characterisation by mathematical expressions. This is because they are not specific to modelling (e.g. those relating to the assessment context), are included through descriptions of the specific scenarios to be modelled (e.g. biosphere system features), are matters of definition that do not require an equation (e.g. annual individual dose), or are represented through the choice of specific parameter values in the expressions that are provided (e.g. consumption and inhalation rates).

Quantification of model parameter

They're various parameters and assumptions defining radionuclide behaviour that are frequently part of model descriptions that require constrains. While these must generally be determined for each particular site, laboratory experiments must also be conducted to further define the range of possibilities and the operation of particular mechanism.

In a model uses a compartimental approach. An ecosystem is described as a set of compartments in equilibrium linked together by some ways of transfers. Ways of transfer are chosen to correspond to human radiological highest exposure (external exposure, inhalation and ingestion). The assumption that radionuclides only follow these ways of transfer is made usually, when an operator makes an environmental and health impact assessment, the choice of the compartments and the way of transfer is made after a study of the ecosystem that has to be modelled. But the transfer factors values are often generic; they are issued from international compilation of experimental data measured on various conditions. Finally, values can be the same for all sites and context.

2.5 CALCULATION AND INTERPRETATION OF RESULTS

Once the computer tool is prepared with the necessary input data, the analyses can be run. It is important to ensure that the results generated are consistent with the assessment end-point of interest (for example intakes rates, risk, and environmental concentrations) to facilitate comparison. These results are used to judge the designs ability to meet the radiological standards for long-term protection of the public, establish by the governmental authorities.

2.6 COMPARISON OF RESULTS AGAINST CRITERIA

Once calculated, the results should be compared with applicable criteria and associated end-point from the assessment context. The assessment context will include regulatory criteria and may also include other indicator against which results can be compared. If the results exceed the associated limits, then the causes exceedance have to be investigated and, if appropriate, action taken. A further iteration through the entire methodology or components of the methodology might be required.

The level of detail incorporated in the applications of this methodology depends on a variety of factor such as the resources available, the level of under standing of the system to be assessed and its process, and the perceived severity of the existing or potential problems. The methodology should be seen as being able to be used at range of different level of detail. Furthermore it should be not seen as a once through process, but as an iterative procedure, each iterations taking account of changes in conceptual assumptions and data values arising from the previous iteration. Iteration might require the repetition all the steps or just particular steps in the methodology.

As a first iteration in the process, screening calculations will be performed in order to identify with contaminants will give more significant impact in the environment as well as in the humans. For these purposes, very simple models wee used and also, with a high degree of simplifications in the assumptions for the conceptual model.

3 APPLICATION OF METHODOLOGY TO REAL ASSESSMENT CASE

Real scenarios from EMRAS I
Possibility of have example of central Asian republics
Uranium extraction facilities in Canada

I present during the meeting an example of Radiological Assessment of an Area with Uranium Residual Material

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APENDIX A

Table 1. List of FEPs

1 Assessment Context
1.1 Assessment Purpose
1.2 Assessment Endpoints
1.2.1 Annual Individual Dose
1.2.2 Lifetime Individual Dose
1.2.3 Annual Individual Risk
1.2.4 Lifetime Individual Risk
1.2.5 Collective Dose/Risk
1.2.6 Dose to Non-human Biota
1.2.7 Modification of the Radiation Environment
1.2.8 Fluxes
1.2.9 Non-radiological Endpoints
1.2.10 Uncertainties and/or Confidence
1.3 Assessment Philosophy
1.4 Repository System
1.5 Site Context
1.6 Source Term
1.6.1 Geosphere/Biosphere Interface
1.6.2 Release Mechanism
1.6.3 Source Term Characteristics
1.7 Time Frames
1.8 Societal Assumptions
2 Biosphere System Features
2.1 Climate
2.1.1 Description of Climate Change
2.1.2 Identification and Characterisation of Climate Categories
2.2 Human Society
2.3 Systems of Exchange
2.3.1 Environment Types 2.3.1.1 Natural and Semi-natural Environments 2.3.1.1.1 Agricultural Environments 2.3.1.1.2 Urban and Industrial Environments
2.3.2 Ecosystems 2.3.2.1 Living Components of Ecosystems 2.3.2.2 Non-living Components of Ecosystems
3 Biosphere Events and Processes
3.1 Natural Events and Processes
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- 3.1.2 Environmental Dynamics
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    - 3.1.2.2 Seasonal Variability
    - 3.1.2.3 Interannual and Longer Timescale Variability

- 3.1.3 Cycling and Distribution of Materials in Living Components
    - 3.1.3.1 Transport Mediated by Flora and Fauna
        - 3.1.3.1.1 Root Uptake
        - 3.1.3.1.2 Respiration
        - 3.1.3.1.3 Transpiration
        - 3.1.3.1.4 Intake by Fauna
        - 3.1.3.1.5 Interception
        - 3.1.3.1.6 Weathering
        - 3.1.3.1.7 Bioturbation
    - 3.1.3.2 Metabolism by Flora and Fauna
        - 3.1.3.2.1 Translocation
        - 3.1.3.2.2 Animal Metabolism

- 3.1.4 Cycling and Distribution of Materials in Non-living Components
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        - 3.1.4.1.1 Evaporation
        - 3.1.4.1.2 Gas Transport
        - 3.1.4.1.3 Aerosol Formation and Transport
        - 3.1.4.1.4 Precipitation
        - 3.1.4.1.5 Washout and Wet Deposition
        - 3.1.4.1.6 Dry Deposition
    - 3.1.4.2 Water-borne Transport
        - 3.1.4.2.1 Infiltration
        - 3.1.4.2.2 Percolation
        - 3.1.4.2.3 Capillary Rise
        - 3.1.4.2.4 Groundwater Transport
        - 3.1.4.2.5 Multiphase Flow
        - 3.1.4.2.6 Surface Run-off
        - 3.1.4.2.7 Discharge
        - 3.1.4.2.8 Recharge
        - 3.1.4.2.9 Transport in Surface Water Bodies
        - 3.1.4.2.10 Erosion
    - 3.1.4.3 Solid-phase Transport
        - 3.1.4.3.1 Landslides and Rock Falls
        - 3.1.4.3.2 Sedimentation
        - 3.1.4.3.3 Sediment Suspension
        - 3.1.4.3.4 Rain Splash
    - 3.1.4.4 Physicochemical Changes
        - 3.1.4.4.1 Dissolution/Precipitation
        - 3.1.4.4.2 Adsorption/Desorption

3.1.4.4.3 Colloid Formation
3.2 Events and Processes Related to Human Activity
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3.2.2 Physical Changes 3.2.2.1 Construction 3.2.2.2 Water Extraction by Pumping 3.2.2.3 Water Recharge by Pumping 3.2.2.4 Dam Building 3.2.2.5 Land Reclamation
3.2.3 Recycling and Mixing of Bulk Materials 3.2.3.1 Ploughing 3.2.3.2 Well Supply 3.2.3.3 Other Water Supply 3.2.3.4 Irrigation 3.2.3.5 Recycling of Bulk Solid Materials 3.2.3.6 Artificial Mixing of Water Bodies 3.2.3.7 Dredging 3.2.3.8 Controlled Ventilation
3.2.4 Redistribution of Trace Materials 3.2.4.1 Water Treatment 3.2.4.2 Air Filtration 3.2.4.3 Food Processing
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4.1 Human Habits
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4.1.3 Location
4.1.4 Diet
4.2 External Irradiation
4.2.1 External Irradiation from the Atmosphere
4.2.2 External Irradiation from Soils
4.2.3 External Irradiation from Water
4.2.4 External Irradiation from Sediments
4.2.5 External Irradiation from Non-food Products
4.2.6 External Irradiation from the Flora and Fauna

4.3 Internal Exposure
4.3.1 Inhalation
4.3.2 Ingestion 4.3.2.1 Drinking 4.3.2.2 Food 4.3.2.3 Soil and Sediments
4.3.3 Dermal Absorption

APENDIX B

ASSESSMENT CONTEXT

The circumstances in which a biosphere model is to be developed and used.

Assessment Purpose

The underlying reason for developing a biosphere model and/or carrying out a biosphere assessment. Example assessment purposes include:

- Demonstration of compliance with regulatory requirements
- Formulation of regulatory guidance
- Contribution to public confidence
- Contribution to confidence of policy makers and the scientific community
- Guide research priorities
- Proof of concept
- Guide to site selection and approval at later stages in repository development
- System optimisation.

Assessment Endpoints

The required format of the assessment results, expressed as a calculated radiological impact or in other terms.

The ICRP defined the basic quantities for dosimetric purposes in [ICRP, 1991].

The *effective dose*, E, is the sum of the weighted equivalent dose in all the tissues and organs of the body. It is given by the expression:

$$E = \sum_T w_T \cdot H_T = \sum_T w_T \sum_R w_R \cdot D_{T,R} \qquad \textbf{(1.)}$$

where,

w_T weighting factor for tissue or organ T
H_T equivalent dose in tissue or organ T
w_R radiation weighting factor
$D_{T,R}$ average absorbed dose from radiation type R in tissue or organ T.

The *committed effective dose* is the effective dose integrated over time τ following an intake of radioactive material.

The *collective dose* is the measure of the radiation exposure in a population. It has been defined as:

$$S = \int_0^\infty E \cdot \frac{dN}{dE} dE \quad or \quad \sum_i \overline{E}_i \cdot N_i \qquad (2.)$$

where,
$\overline{E}_i$ is the mean effective dose to population subgroup *i*
N_i is the number of individuals in the subgroup *i*.

Risk means the mathematical expectation of the magnitude of the undesirable consequence, i.e. the product of the probability and the consequence of the event.

ICRP is mainly concerned with two quantifiable risk quantities, namely:

P_i is the probability of each harmful effect *i*. The effects have to be specified, e.g. lethal cancer or curable cancer, severe hereditary harm, *etc.*
W_i is the consequence if the effect occurs. The consequence can be described in a variety of ways, indicating the severity of the effect and the distribution in time. The mathematical expectation of consequence is:

$$\overline{W} = \sum_i P_i \cdot W_i \qquad (3.)$$

where the summation is over all harmful effects of relevance.

Annual Individual Dose

The radiation dose to a person, incurred over a year (usually taken to mean the committed dose from exposure over a year).

Lifetime Individual Dose

The radiation dose to a person, accumulated over their lifetime.

Annual Individual Risk

The radiological risk to a person, averaged over a year.

Lifetime Individual Risk

The radiological risk to a person, accumulated over their lifetime.

Collective Dose/Risk

The radiation dose or radiological risk integrated over an exposed population.

Dose to Non-human Biota

The radiation dose to organisms other than man.

Modification of the Radiation Environment

The concentration and/or distribution of repository-derived radionuclides in environmental media.

Fluxes

The release rate of radionuclides into, or through, parts of the biosphere.

Non-radiological Endpoints

Biospheric consequences of disposal unrelated to radioactivity.

Uncertainties and/or Confidence

An estimate of the confidence that can be attached to the quantitative value of a given endpoint.

Assessment Philosophy

The underlying approach adopted towards the management of uncertainties within the assessment.

Repository System

The type of disposal facility to be addressed in the assessment calculation.

Site Context

A ‘broad-brush’ description of the physical features of the present-day biosphere in the general location where future releases may occur.

Source Term

The release of contamination into the biosphere from the repository system.

Geosphere/Biosphere Interface

The interface between biosphere and geosphere domains in a decoupled system model.

Release Mechanism

The mechanism for transferring radionuclides (and other contaminants) from the geosphere to the biosphere. Example release mechanisms include:

- Groundwater release to land and surface water bodies *via* natural aquifer discharge
- Groundwater release *via* extraction of well water
- Gaseous release
- Release of solid materials as a result of human intrusion or natural erosion

Source Term Characteristics

Basic attributes of the source term from the geosphere to the biosphere, including:

- Radionuclide and other hazardous materials content
- Physical and chemical properties of the release

3.1 Time Frames

Identification of the time periods for which biosphere modelling is required.

3.2 Societal Assumptions

Broad hypotheses regarding the way in which representative future biospheres are presumed to be exploited by man.

4 BIOSPHERE SYSTEM FEATURES

A description of the biosphere system(s) assumed to be representative of future environmental conditions at the site(s) of interest.

Climate

A description of the way in which climate is represented in the biosphere assessment.

Description of Climate Change

The approach taken to considering the potential impact of changing climate.

Identification and Characterisation of Climate Categories

The identification and general description of characteristic climate states relevant to the assessment. Relevant characteristics include temperature, precipitation, wind speed and direction and solar radiation.

Human Society

A description of the role of human actions in defining the local biosphere. Principal features of human society relevant to the description of the biosphere system include:

- Community structures that determine human influence on the environment (e.g. through industry, agriculture, urbanisation)
- The exploitation of biosphere resources (e.g. water bodies, land, natural flora and fauna)
- The extent of import and export of resources to/from the domain of the biosphere system.

Systems of Exchange

The identification of environmental systems and their arrangement in the landscape.

Environment Types

Identification and description of features of the landscape to be addressed in the biosphere assessment.

Natural and Semi-natural Environments

Environments that are not significantly, or are only partially, influenced by human activities.

Agricultural Environments

Terrestrial regions intensively exploited for food as pasture and arable land.

Urban and Industrial Environments

Environments exploited by humans in which habits, diet and exposure are significantly different from the agricultural environment.

Ecosystems

Communities of living organisms and their habitats.

Living Components of Ecosystems

Specification of the living components of the assumed biosphere system.

Non-living Components of Ecosystems

Specification of the non-living components of the assumed biosphere system.

5 BIOSPHERE EVENTS AND PROCESSES

Phenomena, whether natural or artificial, that influence, or may influence, the dynamics of the biosphere system or the behaviour of trace materials in the biosphere.

Natural Events and Processes

Natural phenomena that could be involved in the dynamics of the environmental system or in the fate of trace materials.

Environmental Change

> Natural phenomena causing lasting change to the basic properties of the biosphere system, modifying the situation represented in the assessment.

See Annex II, for implications of environmental changes on the geosphere-biosphere interface zone.

Physical Changes

> Long-term physical changes in environmental media; e.g. changes in their dimensions or physical properties.

Chemical Changes

> Long-term chemical changes in environmental media.

Ecological Changes

> Ecological successions caused by natural perturbations to the foodweb *etc.*

Environmental Dynamics

> Natural phenomena causing temporal variability in systems of exchange within an otherwise constant biosphere system.

Diurnal Variability

> Cycling in properties of the biosphere system on a period of 24 hours.

Seasonal Variability

> Changes in properties of the biosphere system due to natural variability of solar radiation, temperature, precipitation, wind speed and direction through the year.

Interannual and Longer Timescale Variability

> Variability in properties of the biosphere system with periodicity greater than a year.

Cycling and Distribution of Materials in Living Components

Natural phenomena causing temporal variability in systems of exchange within an otherwise constant biosphere system.

Transport Mediated by Flora and Fauna

The movement of materials within the environment caused by plants and animals.

Root Uptake

Uptake of water and nutrients from soil solution and soil particles by absorption and biological processes within plant roots.

This process is influenced by the physical and chemical characteristics of the radionuclide, the soil properties and the plant species. For long-term assessment modelling it is appropriate to use the soil-to-plant transfer factor approach. This transfer factor relates the activity in edible parts (Bq kg^{-1}) to the activity in soil (Bq kg^{-1}). It is important to specify whether calculations are based on wet or dry weight of soil and plants [IAEA, 1982], [IAEA, 1994].

Respiration

Uptake (release) of gases from (to) the atmosphere by plants.

Transpiration

Transfer of water from the soil to the atmosphere by transpiration in plants

See Annex I, for a mathematical description.

Intake by Fauna

Consumption and inhalation of materials by animals, birds, fish, *etc*. Includes:

- Food consumption (plant and animal foodstuffs)
- Aerosol inhalation
- Soil consumption
- Sediment consumption

Interception

Interception of incident rainfall, aerosol, suspended sediment *etc.* by plants and animal surfaces.

For terrestrial vegetation the intercepted fraction is:

$$I = 1 - e^{-\mu \cdot Y_{veg}} \qquad (4.)$$

where,

μ [RN, veg][1] coefficient of interception for the vegetation ($m^2\,kg^{-1}$)

Y_{veg} [climate, veg] density of above-ground standing biomass ($kg\,m^{-2}$)

Weathering

Materials captured by interception may subsequently be lost from plant and animal surfaces because of wind, rain, volatilisation, *etc*.

Weathering of the intercepted amount of a radionuclide on vegetation is represented by the term:

$$f_w = e^{-l_w \cdot t_w} \qquad (5.)$$

where,

f_w	fraction of the initially intercepted activity that remains
l_w [climate, RN, veg]	removal rate of radionuclides deposited on vegetation surfaces by weathering processes (y^{-1})
t_w [climate, veg]	time between irrigation and harvest (y)

The weathering process is taken to apply only after irrigation has ended.

An alternative for calculating the radionuclide concentration in pasture, represents weathering with the term l_w^{-1}. This assumes that irrigation and weathering are occurring simultaneously and continuously so that the assumed activity on the plant at the time of harvesting is the average over the year. This also assumes that the irrigation process has been ongoing for a period that is long compared with l_w^{-1}.

Bioturbation

The redistribution and mixing of soil or sediments by the activities of plants and burrowing animals.

The bioturbation transfer rate due to terrestrial animals is represented as:

$$\lambda_{bio} = bio \qquad (6.)$$

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[1] The dependencies of the parameters are indicated by the descriptors in parentheses. Their meanings are: RN=radionuclide and its chemical form, veg=vegetation type, climate=climate state, sedim=sediment type, soil=soil type, aqu=aquifer, water=water body, age=population age group, animal=animal group, met.proc=method of processing.

where,

bio [soil, animal]	transfer rate of solid materials due to terrestrial animals (y^{-1})

In lakes and rivers, the bioturbation transfer rate (y^{-1}) is described by:

$$\lambda_{bio} = \frac{(R_{sed} - 1)}{R_{sed}} \frac{B}{d_{sed}^{2}} \qquad (7.)$$

where,

R_{sed} [sedim]	retardation coefficient for sediment (-)
B [sedim]	diffusion transfer rate due to bioturbation ($m^2\ y^{-1}$)
d_{sed} [sedim]	depth of sediment compartment (m)

The retardation coefficient term (R) relative to the contents of the pore water for a general compartment *i,* is calculated using the following equation:

$$R = 1 + \frac{(1-\varepsilon_{t,i})\rho_i}{\theta_i} K_{d,i} \qquad (8.)$$

where,

$\varepsilon_{t,i}$	total porosity of compartment *i* (-)
ρ_i	grain density of solids in compartment *i* ($kg\ m^{-3}$)
$K_{d,i}$	solid/liquid distribution coefficient of compartment *i* ($m^3\ kg^{-1}$)
θ_i	moisture content of the compartment *i* defined as a fraction of the total volume of the compartment (-)

Metabolism by Flora and Fauna

The processes occurring within an organism by which materials are transported and accumulated through the organism or transported and liberated from the organism.

Translocation

The internal movement of material from one part of a plant to another.

The translocation factor can be quantified as the ratio of the activity in the edible parts at harvest (Bq kg^{-1}) to the activity retained on one m^2 of foliage at the time of deposition (Bq m^{-2}), [IAEA 1994]. The degree of translocation depends upon the nature of the plant and the chemical properties and form of the contaminant.

Animal Metabolism

The derivation and use of energy and biochemical processing of other materials from ingested substances, involving the transfer of trace materials present in animal fodder (or other ingested and inhaled material) to body tissues.

Cycling and Distribution of Materials in Non-living Components

Natural processes giving rise to the movement of materials within the environment.

Atmospheric Transport

Natural transport processes within the atmosphere.

Evaporation

Emission of water vapour and other volatile materials from a free surface at a temperature below their boiling point.

See Annex I for a mathematical description of the process.

Gas Transport

Convection and diffusion of gases and vapours in the atmosphere.

Aerosol Formation and Transport

Suspension and transport of solid materials in the atmosphere typically as a result of wind action. A special example of aerosol formation is that arising from the burning of materials in a fire.

Resuspension is often modelled by use of a resuspension factor K_t (m^{-1}) defined as the ratio of the activity in air (Bq m^{-3}) to that in the surface deposit (Bq m^{-2}). The process is influenced by factors such as the soil type, texture and moisture, the vegetation cover and the wind speed.

For an equilibrium situation, the resuspension rate λ_{res} can be expressed as:

$$\lambda_{res} = K_t \cdot v_d \qquad (9.)$$

where,

K_t [climate, soil, RN, veg] resuspension factor (m^{-1})

v_d [climate, RN] deposition velocity (m y^{-1})

The long-term resuspension factor for a single acute deposition event can be described by a time-dependent function, [IAEA, 1992]:

$$K_t = a \cdot e^{-b \cdot t} + c \qquad (10.)$$

where,
a [climate, RN] initial value of the resuspension factor (m^{-1})
b [climate, RN] rate of decrease of the resuspension factor (y^{-1})
c [climate, RN] long-term resuspension factor (m^{-1})

Precipitation

Rain, snow, hail etc. as part of the natural hydrological cycle.

Washout and Wet Deposition

The removal of gaseous or particulate material from the atmosphere by precipitation, causing deposition of material onto surfaces.

Dry Deposition

The removal of gaseous or particulate material from the atmosphere as a result of interception and gravitational settling.

Water-borne Transport

Natural transport processes within water courses

Infiltration

The downward movement of water from the surface into the soil.

See Annex VI, for a description of the soil water balance.

The downward transfer rate of a radionuclide due to infiltration λ_{inf}, is defined as:

$$\lambda_{\mathrm{inf}} = \frac{r + Irr + cap - ET - S}{R_{soil} \cdot d_{soil} \cdot \theta_{soil}} \tag{11.}$$

where,

r [climate]	annual precipitation rate (m y^{-1})
Irr [climate, veg]	irrigation rate (m^{3} m^{-2} y^{-1})
cap [soil]	capillary rate (m y^{-1})
ET [climate, veg]	annual evapotranspiration rate (m y^{-1})
S [soil]	throughflow losses rate from surface soil (m y^{-1})
R_{soil} [RN, soil]	retardation coefficient for soil (-)
d_{soil} [soil]	depth of the soil compartment (m)
θ_{soil} [soil]	water filled porosity (-)

Percolation

Downward (or sub-horizontal) movement of water, with dissolved and suspended materials through soil and sediment materials towards the water table.

Downward movement
For modelling purposes, this process is considered as downward percolation from the deep-soil compartment to the water table (see Annex VI):

$$\lambda_{per} = \frac{I + D - cap - B}{R_{soil} \cdot d_{soil} \cdot \theta_{soil}} \tag{12.}$$

where,

I [soil]	infiltration rate (m y^{-1})
D [soil]	discharge rate (m y^{-1})
cap [soil]	capillary rate (m y^{-1})
B [soil]	discharge from deep soil (m y^{-1})
R_{soil} [RN, soil]	retardation coeff. of deep soil compartment (-)
d_{soil} [soil]	depth of the deep soil compartment (m)
θ_{soil} [soil]	moisture content of deep soil compartment (-)

Sub-horizontal flow between two soil compartments

$$\lambda_{sub} = \frac{\phi_{sub}}{R_{soil} \cdot \theta_{soil} \cdot V_{soil}} \tag{13.}$$

where,

ϕ_{sub} [soil]	volume of sub-horizontal flow between soil compartments ($m^3\ y^{-1}$)
R_{soil} [RN, soil]	retardation coeff. of deep soil compartment (-)
θ_{soil} [soil]	moisture content of deep soil compartment (-)
V_{soil} [soil]	volume of the deep soil compartment (m^3)

Capillary Rise

Upward movement of water through soil layers above the water table as a result of capillary forces related to evaporation and transpiration.

$$\lambda_{cap} = \frac{I + D - P - B}{R_{soil} \cdot d_{soil} \cdot \theta_{soil}} \qquad (14.)$$

where,

I [soil]	infiltration rate ($m\ y^{-1}$)
D [soil]	discharge rate ($m\ y^{-1}$)
B [soil]	discharge from deep soil ($m\ y^{-1}$)
P [soil]	percolation from deep soil ($m\ y^{-1}$)
R_{soil} [RN, soil]	retardation coeff. of deep soil compartment (-)
θ_{soil} [soil]	moisture content of deep soil compartment (-)

Groundwater Transport

Transport of water, with dissolved and suspended materials in saturated porous media.

There are three main mechanisms by which contaminants are transported in groundwater: advection, molecular diffusion and kinematic dispersion.

Advection is the phenomenon in which dissolved substances are carried along by the movement of fluid displacement. The velocity of fluid displacement depends on the hydraulic conductivity, kinematic porosity and hydraulic gradient of the aquifer. The velocity of movement of the dissolved substance is reduced by sorption to the solid phase.

The transfer rate due to advection is:

$$\lambda_{ij} = \frac{\upsilon_i}{R_i L_i} \qquad \mathbf{(15.)}$$

where

$$\upsilon_i = \frac{K_{h,i}\dfrac{\partial h}{\Delta x}}{\varepsilon_{c,aqu}} \qquad (16.)$$

υ_i [aqu]	mean linear velocity (m y^{-1})
R_i [RN,aqu]	retardation coefficient for aquifer (-)
L_i [aqu]	length of donor compartment *i* in the direction of the advective flow (m)
$K_{h,i}$ [aqu]	hydraulic conductivity (m y^{-1})
$\frac{\partial h}{\Delta x}$ [aqu]	hydraulic gradient (-)
$\varepsilon_{c,aqu}$ [aqu]	kinematic porosity of the aquifer (-)

Dispersion coefficients in contaminant transport models are used to represent diffusion as well as dispersion processes. *Molecular diffusion* is a physical phenomenon determined by the thermal movement of contaminant molecules. This results in the transfer of contaminants from zones of high concentration to zones of low concentration. *Kinematic dispersion* is a mixing phenomenon linked to the heterogeneity of the microscopic velocities inside the porous medium on whatever scale they are observed.

To model the diffusion and dispersion processes between two compartments two fluxes must be used: a "forward", λ^f, and a "backward" flux, λ^b. The equations used are:

$$\lambda_{ij}^{f} = \frac{\alpha_L \upsilon_i}{R_i L_i \Delta x} \qquad \textbf{(17.)}$$

$$\lambda_{ji}^{b} = \frac{\alpha_L \upsilon_i}{R_j L_j \Delta x} \qquad \textbf{(18.)}$$

where,

α_L [aqu]	longitudinal dispersivity coefficient (m)
R_i, R_j [RN, aqu]	retardation factor of compartment *i, j* (-)
L_i	length of donor compartment *i*
L_j	length of receptor compartment *j*
Δx	length for the calculation of the hydraulic gradient (m)

The total flux of each donor compartment can then be calculated by: *Advective flux of donor + Forward dispersive flux from donor - Backward dispersive flux from receiver.*

For definition of the compartments needed to model the porous media see Annex III.

To represent aquifers in the biosphere it is necessary to make some hydrological modelling assumptions, which are described in Annex IV.

Multiphase Flow

Combined flow of different fluids and/or gases in porous media.

Surface Run-off

A fraction of incident precipitation may be transferred directly from land to surface waters by overland flow, without entering the soil column. This includes delayed runoff (e.g. as a result of snow melt)

Discharge

The release of groundwater into the surface environment.

Recharge

The percolation of incident precipitation and other surface waters to groundwater systems.

Transport in Surface Water Bodies

Movement of materials dissolved and suspended in water by advection and diffusion in water bodies.

The transfer rate of radionuclides from a water compartment to the next water compartment is given by:

$$\lambda_A = \frac{\phi_w}{V_i} \qquad (19.)$$

where,

ϕ_w[water]	rate at which water is discharged from one water compartment to the following (m^3 y^{-1})
V_i [water]	volume of the donor water compartment (m^3).

The movement of radionuclides from the sediment compartment to the surface water compartment is given by:

$$\lambda_{up} = \frac{\phi_{sed}}{R_{sed} \cdot \theta_{sed} \cdot V_{sed}} \qquad (20.)$$

where,

ϕ_{sed} [sedim]	rate of movement of water from the sediment compartment to the surface water compartment of the water body ($m^3\ y^{-1}$)
R_{sed} [sedim]	retardation coefficient for sediment (-)
θ_{sed} [sedim]	volumetric fractional water content of the sediment compartment of the water body (-)
V_{sed} [sedim]	volume of the sediment compartment of the water body (m^3)

Erosion

Erosion caused by rainfall, surface run-off, river water and occasional floods which can lead to the transport of superficial materials and plants in water courses.

For modelling purposes, the transfer rate due to erosion, λ_{se}, y^{-1}, is given by:

$$\lambda_{se} = \frac{E_{se}}{(1 - \varepsilon_{t,soil}) \cdot \rho_{soil} \cdot d_{soil}} \qquad (21.)$$

where,

E_{se} [climate, veg, soil]	transfer of solid material from the surface soils to the local watercourses ($kg\ m^{-2}\ y^{-1}$)
$\varepsilon_{t,soil}$ [soil]	total porosity of the topsoil compartment (-)
ρ_{soil} [soil]	grain density of the soil ($kg\ m^{-3}$)
d_{soil} [soil]	depth of the topsoil compartment (m)

Solid-phase Transport

Natural transport processes causing movements of solid materials between environmental media.

Transfer of detritus to the local watercourse

A proportion of the plants grown on an area will be lost to the local watercourse due to the movement of detritus. The transfer rate of radionuclides from an area to the local watercourse due to the loss of this detritus is given by:

$$\lambda_P = \frac{f_{prod} \cdot (TF_{veg} + S_{veg}) \cdot y_{veg}}{(1 - \varepsilon_{t,soil}) \cdot \rho_{soil} \cdot d_{soil}} \qquad (22.)$$

where,

f_{prod} [climate,veg]	fraction of primary productivity lost as detritus to the local watercourse (-)
TF_{veg} [RN,veg,soil]	soil-to-plant transfer factor defined on a fresh weight plant and dry weight soil basis (Bq kg^{-1} plant per Bq kg^{-1} soil)
S_{veg} [climate,veg,soil]	soil contamination on the vegetation (kg dry weight of soil per kg fresh weight of vegetation)
y_{veg} [climate, veg]	annual production of biomass of vegetation (kg m^{-2} y^{-1})
$\varepsilon_{t,\,soil}$ [soil]	total porosity of soil (-)
ρ_{soil} [soil]	grain density of the surface soil compartment (kg m^{-3})
d_{soil} [soil]	depth of the soil compartment (m)

Landslides and Rock Falls

Overland transport of solid material by landslides and rock falls.

Sedimentation

Gravitational settling and deposition of suspended particles within water bodies to form sediments.

Sedimentation in the water bodies:

$$\lambda_{sed} = \frac{K_{d,part} \cdot sed}{d_{water} \cdot (1 + K_{d,part} \cdot m_{susp})} \qquad (23.)$$

where,

$K_{d,\,part}$ [RN, sedim]	distribution coefficient for suspended particles (m^{-3} kg^{-1})
sed [water,sedim]	sedimentation rate (kg m^{-2} y^{-1})
d_{water} [water]	water body depth (m)
m_{susp} [water,sedim]	concentration of suspended material in the water body compartment (kg m^{-3})

Advection of bed sediments

The transfer rate of radionuclides due to the advection of the bed sediments (y^{-1}), is given by:

$$\lambda_{drag} = \frac{K_{d,sed}\ q_{sed}}{R_{sed} \cdot \theta_{sed} \cdot V_{sed}} \qquad \textbf{(24.)}$$

where,

$K_{d,sed}$ [RN, sedim]	distribution coefficient of the bed sediment ($m^3\ kg^{-1}$)
q_{sed} [water,sedim]	transfer of sediments across the compartment boundary ($kg\ y^{-1}$)
R_{sed} [sedim]	retardation coefficient for sediment (-)
θ_{sed} [sedim]	volumetric fractional water content of the sediment compartment of the water body (-)
V_{sed} [sedim]	volume of the bed sediments (m^3)

Burial of bed sediments

The transfer rate that describes the transport from the surface sediment to buried sediment (y^{-1}), is given by:

$$\lambda_{bur} = \frac{sed}{SM_{sed}} \qquad \textbf{(25.)}$$

where,

***sed* [water,sedim]**	**sedimentation rate ($kg\ m^{-2}\ y^{-1}$)**
SM_{sed} [water,sedim]	surface sediment mass per unit of area ($kg\ m^{-2}$).

Sediment suspension

Erosion of bed sediments from surface water courses by the action of flowing water.

Transfer from sediment to the water compartment due to resuspension.

$$\lambda_{resp} = \frac{res \cdot A_{sed}}{V_{sed} \cdot \rho_{sed}\,(1 - \varepsilon_{t,sed})} \qquad (26.)$$

where,

res [water,sedim] suspension rate of the sediment in the water body (kg m^{-2} y^{-1})
A_{sed} area of the sediment (m^2)
$\varepsilon_{t,sed}$ [sediml] total porosity of the sediment compartment (-)
ρ_{sed} [sedimentl] grain density of the sediment (kg m^{-3})
V_{sed} [sedim] volume of the sediment compartment (m^3)

Rain Splash

Localised transport of soil material to other media (e.g. onto plants) caused by the energy of incident rainfall.

Physicochemical Changes

Chemical and physical processes causing changes to the nature of materials present within the environment.

Dissolution/Precipitation

Processes by which material in the solid phases is incorporated into the liquid phase, and *vice versa*. Affected by local Eh, pH, solubility limits and the presence of other chemical species.

Adsorption/Desorption

Sorption and/or adhesion of a layer of ions from an aqueous solution onto a solid surface and subsequent migration into the solid matrix (and the reverse process).

Colloid Formation

Complexation of materials to form colloids.

Events and Processes Related to Human Activity

Human activities that result in an alteration of the biosphere system and/or contribute to the cycling of materials within the system.

A process that would modify the concentration in soils is cropping of the yield of plants. The activity from soil that is taken up by the plants and does not return to the soil through the plant decay, is removed by cropping and, therefore, it is lost from the system. The rate constant for removal is given by:

$$\lambda_c = \frac{f_{crop} \cdot (TF_{veg} + S_{veg}) \cdot y_{veg}}{(1 - \varepsilon_{t,soil}) \cdot \rho_{soil} \cdot d_{soil}} \qquad (27.)$$

where,

f_{crop} [veg]	fraction of crop removed in cropping (-)
TF_{veg} [RN,veg,soil]	soil-to-plant transfer factor defined on a fresh weight plant and dry weight soil basis (Bq kg^{-1} of plant per Bq kg^{-1} of soil)
S_{veg} [climate,veg,soil]	soil contamination on the vegetation (kg dry weight of soil per kg fresh weight of vegetation)
y_{veg} [climate, veg]	annual production of biomass of vegetation (kg m^{-2} y^{-1})
$\varepsilon_{t,\ soil}$ [soil]	total porosity of soil (-)
ρ_{soil} [soil]	grain density of the surface soil compartment (kg m^{-3})
d_{soil} [soil]	depth of the soil compartment (m)

Chemical Changes

Chemical phenomena related to human activity that can cause significant change to the biosphere system, modifying the situation represented in the assessment.

Artificial Soil Fertilisation

The import of artificial fertiliser to enhance crop productivity.

Chemical Pollution

Human activities with a significant impact on the chemistry of ecosystems.

Acid Rain

Acid precipitation or deposition capable of causing acidification in soil and water bodies.

Physical Changes

Physical phenomena related to human activity that can cause lasting change to the biosphere system, modifying the situation represented in the assessment.

Construction

The excavation of foundations and other structures, and building of surface features, causing gross movements of solid materials and/or changes to natural water flow patterns.

Water Extraction by Pumping

Extraction of water from surface water courses or wells, causing alteration to natural water potentials.

Water Recharge by Pumping

The recharge of groundwater systems by pumping.

Dam Building

The construction of engineered structures in order to retain surface waters.

Land Reclamation

The draining of areas that were formerly marshland or covered by rivers, lakes or the sea.

Recycling and Mixing of Bulk Materials

Activities that artificially enhance natural transport processes within the biosphere.

Ploughing

Agricultural practices enhancing the mixing of upper soil horizons.

Well Supply

Extraction and use of water from an aquifer.

Other Water Supply

Abstraction of water from surface water bodies in the local biosphere.

Irrigation

Use of abstracted water to supplement natural supplies to gardens and/or agricultural crops.

The transfer rate to soil due to irrigation can be expressed:

$$\lambda_{irr} = \frac{Irr}{V_{irr}} A_{soil} (1 - I_{veg}) \qquad (28.)$$

where,

V_{irr}	water volume extracted for irrigation (m^3), see Annexes IV and V.
A_{soil}	area of the soil compartment (m^2)
I_{veg} [RN, veg]	interception fraction (-)

Recycling of Bulk Solid Materials

The re-use of crop residues, manure, ashes or sewage sludge on land in order to recycle nutrients or to act as mulch.

Transfer of ash to another soil

The transfer rate of radionuclides from one area to another due to the amendment of ash after burning biomass crops is given by:

$$\lambda_{ash} = \frac{f_{ash} \cdot \left(TF_{veg} + S_{veg}\right) \cdot y_{veg}}{(1 - \varepsilon_{t,soil}) \cdot \rho_{soil} \cdot d_{soil}} \qquad (29.)$$

where,

f_{ash} [veg]	fraction of primary productivity in the cropped area that is burnt multiplied by the fraction that is transferred as ash following burning (-)
TF_{veg} [RN, veg, soil]	soil-to-plant transfer factor (Bq kg^{-1} of vegetal per Bq kg^{-1} of soil)
S_{veg} [climate,veg,soil]	soil contamination on the vegetation (kg dry weight of soil per kg fresh weight of vegetation)
y_{veg} [climate, veg]	annual production of biomass of vegetation per unit of area (kg m^{-2} y^{-1})
$\varepsilon_{t,soil}$ [soil]	total porosity of the soil (-)
ρ_{soil} [soil]	grain density of the soil (kg m^{-3})
d_{soil} [soil]	depth of the soil compartment (m)

Artificial Mixing of Water Bodies

Enhanced mixing of lake and other surface waters as a direct, or indirect, effect of human actions.

Dredging

The removal of sediments from lakes, rivers, estuaries or harbours, either to provide materials for soil improvement or simply to maintain transport channels in the water body.

$$\lambda_{dred} = \frac{dred \cdot A_{soil}}{(1 - \varepsilon_{t,sed}) \cdot \rho_{sed} \cdot V_{sed}} \qquad (30.)$$

where,

dred	mass of sediment transferred from the water body to the surface of the soil compartment expressed per unit area of soil (kg m^{-2} y^{-1})
A_{soil} [soil]	area of the surface soil to which the transfer occurs (m^2)

$\varepsilon_{t,sed}$ [sedim] total porosity of the sediment (-)
ρ_{sed} [sedim] grain density of the sediment (kg m^{-3})
V_{sed} [sedim] volume of the sediment compartment of the water body (m^3)

Controlled Ventilation

Actions taken to enhance (or reduce) the mixing of air in enclosed spaces.

Redistribution of Trace Materials

Activities that change the natural physical and chemical composition of biosphere products.

Water Treatment

Processing of water supplies (filtering, chemical treatment, storage, *etc*.) to make then suitable for drinking water or other uses.

Air Filtration

The enhanced removal of aerosols and gases from air supplies.

Food Processing

Actions taken in the preparation of foods that may modify the constituents of what is finally consumed.

After processing the activity in a consumption product is reduced by a factor:

f_{cook} [RN, product, met.proc] fraction of activity in the product after food processing (-)

6 HUMAN EXPOSURE FEATURES, EVENTS AND PROCESSES

Human habits and activities involving possible radiological exposure (internal or external) from as a result of living in a contaminated environment.

6.1 Human Habits

A general description of the influences of human behaviour on exposure to contaminated materials.

Resource Usage

The exploitation of potentially contaminated resources (natural and other) by population groups present within the biosphere system.

Arable Food Resources

Food products obtained from arable farming and/or gardening within the biosphere system. Types of product include:

- grain (wheat, rice, *etc*.)
- root vegetables
- leaf vegetables
- legumes
- fruit vegetables
- fruit and nuts

Animal-derived Food Resources

Food products obtained from livestock farming within the biosphere system. Types of product include:

- meat and offal (cow, sheep, pig, horse, goat, poultry)
- milk (cow, sheep, goat, horse)
- eggs
- fish

Fodder Products

Food products – especially pasture – cultivated or naturally available within the local biosphere that are intended for consumption by livestock.

Natural Food Resources

Food products obtained by gathering natural resources. Types of product include:

- fruit and nuts
- fungi
- fish
- game birds and animals

Non-food Uses of Biosphere Products

Resources obtained from the biosphere system that have non-food uses. Relevant products/uses include:

- construction (wood, soil, sediments, rocks, other plant materials)
- tools (wood)
- energy (wood, peat, waste products)
- furniture (wood, animal products, plant materials)
- clothing (animal and plant products)
- cosmetics (plant products, soils and sediments)

Water

Exploitation of biosphere water resources in domestic supplies - particularly as drinking water for humans and their livestock.

Storage of Products

Storage of biosphere products before use and/or consumption.

Location

The time spent by an individual at different locations within the biosphere system.

Diet

Consumption rates of different food products.

6.2 External Irradiation

Exposures to contaminated sources resulting in doses incurred via external irradiation.

External Irradiation from the Atmosphere

Exposures to radioactive gases, vapours and aerosols present in the atmosphere.

The annual individual dose to humans from external irradiation from a contaminated cloud is given by:

$$D_{cloud} = C_{top-soil} \cdot DCC_{cloud} \cdot m_{dust} \cdot OF_{ext} \cdot 24 \cdot 365 \qquad (31.)$$

where,

D_{cloud} [RN]	external dose for irradiation from a cloud (Sv y^{-1})
$C_{top-soil}$	concentration in the top soil (Bq kg^{-1})
DCC_{cloud} [RN, age]	dose conversion factor for external irradiation from a contaminated cloud (Sv h^{-1} per Bq m^{-3})
m_{dust} [climate,soil,veg]	quantity of dust particles in air (kg m^{-3})
OF_{ext} [climate,age]	occupancy time in the area (-)
24·365	conversion from h to y

External Irradiation from Soils

Exposures to radioactive materials present in soils

The annual individual dose to humans from external irradiation from soil during occupancy of the soil compartment is given by:

$$D_{soil} = C_{top-soil\cdot} \cdot \rho_{b,soil} \cdot DCC_{soil} \cdot OF_{ext} \cdot 24 \cdot 365 \qquad (32.)$$

where,

D_{soil} [RN]	external dose for irradiation from the soil (Sv y^{-1})
$C_{top-soil}$	concentration in the top soil (Bq kg^{-1})
$\rho_{b,soil}$ [soil]	soil bulk density (kg m^{-3})
DCC_{soil} [RN, age]	dose conversion factor for exposure to soil contaminated to a depth of 15 cm (Sv h^{-1} per Bq m^{-3})
OF_{ext} [clim,age]	occupancy time in the area (-)

External Irradiation from Water

Exposures to radioactive materials present in water – e.g. during fishing, bathing.

The annual individual dose to humans from external irradiation from immersion in water is given by:

$$D_{bath} = C_{river} \cdot DCC_{bath} \cdot OF_{bath} \cdot 24 \cdot 365 \qquad (33.)$$

where,

D_{bath} [RN]	external dose for immersion in water (Sv y^{-1})
C_{river}	concentration in river water (Bq m^{-3})
DCC_{bath} [RN, age]	dose conversion factor for immersion in water (Sv h^{-1} per Bq m^{-3})
OF_{bath} [climate, age]	occupancy time for bathing (-)

External Irradiation from Sediments

Exposures to radioactive materials present in the sediments – e.g. during fishing or handling of fishing nets.

The exposure to contaminated sediments is calculated in the same way as the external irradiation from soil.

External Irradiation from Non-food Products

Exposures to radioactive materials present in building materials, furniture, clothing, cosmetics, medical applications *etc.*

Calculations would be scenario specific.

External Irradiation from the Flora and Fauna

Exposures to radioactive materials present on plant surfaces or animal hides.

Calculations would be scenario specific.

6.3 Internal Exposure

Intake of contaminated materials resulting in doses incurred via internal irradiation.

Inhalation

Incorporation of radioactivity into the body in the form of aerosols, vapours or gases as a result of breathing.

The annual individual dose to humans from the inhalation of dust during occupancy of the soil compartment is given by:

$$D_{inh} = C_{top\text{-}soil} \cdot DCC_{inh} \cdot m_{dust} \cdot BR \cdot OF_{inh} \qquad (34.)$$

where,

D_{inh} [RN]	committed dose for inhalation (Sv y^{-1})
$C_{top\text{-}soil}$	concentration in the top soil (Bq kg^{-1})
DCC_{inh} [RN, age]	dose conversion factor for inhalation (Sv Bq^{-1})
m_{dust} [climate,soil,veg]	quantity of dust particles in air (kg m^{-3})
BR [age]	breathing rate (m^3 y^{-1})
OF_{inh} [climate,age]	occupancy time in the area (-)

Ingestion

Incorporation of radioactivity into the body in water or other contaminated substances by ingestion.

Drinking

Ingestion of drinking water, milk, water-based drinks, plant-derived drinks, water used in cooking.

The annual individual dose from the consumption of water is given by:

$$D_{ing-water} = C_{well} \cdot DCC_{ing} \cdot ING_{water} \cdot f_{filter} \qquad (35.)$$

where,

$D_{ing\text{-}water}$ [RN]	committed dose for water ingestion (Sv y^{-1})
C_{well}	concentration in well water (Bq m^{-3})
DCC_{ing} [RN, age]	dose conversion factor for ingestion (Sv Bq^{-1})
ING_{water} [age]	ingestion rate of water (m^3 y^{-1})
f_{filter}	fraction of activity in filtered water (-)

Food

Ingestion of foods derived from:

- plants
- fungi
- meat and offal
- dairy products
- fish
- eggs

The calculation of the individual dose through this pathway takes into account the ingestion of vegetable and animal products.

The concentration of a radionuclide in vegetable products includes the contributions from root uptake, external contamination due to deposition of re-suspended particles from the soil, and external contamination from irrigation:

$$C_{veg} = \frac{(TF_{veg} + S_{veg}) \cdot C_{soil}}{(1 - \varepsilon_{t,soil}) \cdot \rho_{soil}} + \frac{I_{veg} \cdot Irr \cdot C_{water}}{Y_{veg} \cdot l_w} \qquad (36.)$$

where,

C_{veg}	concentration in vegetation (Bq kg^{-1})
C_{soil}	concentration in soil (Bq m^{-3})
C_{water}	concentration in water (Bq m^{-3})
TF_{veg} [RN, veg, soil]	soil-to-plant transfer factor (Bq kg^{-1} of vegetal per Bq kg^{-1} of soil)

S_{veg} [climate,veg,soil]	soil contamination on the vegetation (kg dry weight of soil per kg fresh weight of vegetation)
$\varepsilon_{t,soil}$ [soil]	total porosity of the soil (-)
ρ_{soil} [soil]	grain density of the soil (kg m^{-3})
I_{veg} [RN, veg]	interception fraction (-)
Irr [climate, veg]	irrigation rate (m^{3} m^{-2} y^{-1})
Y_{veg} [climate, veg]	standing biomass of the vegetation (kg m^{-2})
l_w [climate, RN, veg]	removal rate of radionuclides deposited on vegetation surfaces by weathering (y^{-1})

The concentration in fodder is expressed as:

$$C_{fodd} = \frac{(TF_{veg} + S_{veg}) \cdot C_{soil}}{(1-\varepsilon_{t,soil}) \cdot \rho_{soil}} + \frac{I_{veg} \cdot Irr \cdot C_{water}}{Y_{veg} \cdot l_w + 365 \cdot SD \cdot ING_{fodd}} \quad (37.)$$

where,

C_{fodd}	concentration in fodder[2] (Bq kg^{-1})
SD	density of animals grazing in the area (m^{-2})
ING_{fodd} [climate, animal, fodder]	ingestion rate of fodder by the animal (kg d^{-1})

The parameters TF_{veg}, I_{veg}, S_{veg} and Y_{veg} in this formula applied to pasture, grass and other fodder crops. Note that this equation combines internal and external contamination of plants. This is appropriate for fodder, as no food processing is involved prior to consumption that would result in preferential removal of the external contamination.

For terrestrial animals, the calculation of the concentration in animal products takes into account the consumption of fodder, water and soil:

$$C_{prod} = \left(C_{fodd} \cdot ING_{fodd} + C_{water} \cdot ING_{water,anim} + \frac{C_{soil} \cdot ING_{soil,anim}}{(1-\varepsilon_{soil,t}) \cdot \rho_{soil} + \theta_{soil} \cdot \rho_w} \right) \cdot CF_{prod,ing} + \\ + \left(BR_{anim} \cdot OF_{anim} \cdot C_{air} \right) \cdot CF_{prod,inh} \quad (38.)$$

where,

C_{prod}	concentration in animal product (Bq kg^{-1})
C_{fodd}	concentration in fodder (Bq kg^{-1})
ING_{fodd} [climate, animal, fodder]	ingestion rate of fodder (kg d^{-1})
C_{water}	concentration in water (Bq m^{-3})

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[2] "fodder" refers to the all components of the animal diet (fodder crops, cultivated grass, mixed pasture....) derived from the contaminated area.

$ING_{water,anim}$ [climate, animal]	rate of ingestion of water by the animal (m^3 d^{-1})
C_{soil}	concentration in soil (Bq m^{-3})
$ING_{soil,anim}$ [climate, animal]	rate of ingestion of soil by the animal (kg d^{-1})
$\varepsilon_{t,soil}$ [soil]	total porosity of the soil (-)
ρ_{soil} [soil]	grain density of the soil (kg m^{-3})
θ_{soil} [soil]	moisture content of deep soil compartment (-)
ρ_w	density of water (kg m^{-3})
$CF_{prod,ing}$ [RN, product]	accumulation factor for animal product due to ingestion (d kg^{-1} w.w.)
BR_{anim} [animal]	breathing rate of the animal (m^3 h^{-1})
OF_{anim} [animal,climate]	occupancy time of the animal in the area (h d^{-1})
C_{air}	concentration in air (Bq m^{-3})
$CF_{prod,inh}$ [RN, product]	accumulation factor for animal product due to inhalation (d kg^{-1})

The concentration in the air is calculated as:

$$C_{air} = \frac{C_{soil}}{(1-\varepsilon_{t,soil})\cdot\rho_{soil}}\,\frac{R_{soil}-1}{R_{soil}}\cdot m_{dust} \qquad (39.)$$

where,

C_{soil}	concentration in soil (Bq m^{-3})
$\varepsilon_{t,soil}$ [soil]	total porosity of the soil (-)
ρ_{soil} [soil]	grain density of the soil (kg m^{-3})
R_{soil} [RN, soil]	retardation coefficient for soil (-)
m_{dust} [climate,soil,veg]	quantity of dust particles in air (kg m^{-3})

In equation 40, the soil ingestion term is expressed as wet weight soil. In practice, soil ingestion rates of both humans and animals are often expressed on a dry weight basis, as a consequence of the techniques used to estimate the amounts ingested. If this is the case, then the denominator term $(1 - \varepsilon_{t,soil})\cdot\rho_{soil} + \theta_{soil}\cdot\rho_w$ should be replaced by $(1 - \varepsilon_{t,soil})\cdot\rho_{soil}$.

For aquatic animals, the concentration can be expressed as:

$$C_{aqu} = C_{water}\cdot CF_{aqu,anim} \qquad (40.)$$

where,

C_{water}	concentration in water (Bq m^{-3})
$CF_{aqu,anim}$ [animal]	concentration factor for the aquatic animal (m^3 kg^{-1})

The annual individual dose due to consumption of vegetable products is then expressed as:

$$D_{ing-veg} = \sum_{veg} C_{veg} \cdot DCC_{ing} \cdot ING_{veg} \cdot f_{cook} \qquad (41.)$$

where,

$D_{ing\text{-}veg}$	committed dose for ingestion of vegetal products (Sv y^{-1})
C_{veg}	concentration in vegetation (Bq kg^{-1})
DCC_{ing} [RN, age]	dose conversion factor for ingestion (Sv Bq^{-1})
ING_{veg} [climate, age]	ingestion rate of product (kg y^{-1})
f_{cook} [RN, product, met.proc]	fraction of activity in the product after food processing (-)

The consumption of animal products results in:

$$D_{ing-anim} = \sum_{anim} C_{prod} \cdot DCC_{ing} \cdot ING_{prod} \cdot f_{cook} \qquad (42.)$$

where,

$D_{ing\text{-}anim}$	committed dose for ingestion of animal products (Sv y^{-1})
C_{prod}	concentration in animal product (Bq kg^{-1})
DCC_{ing} [RN, age]	dose conversion factor for ingestion (Sv Bq^{-1})
ING_{prod} [climate, age]	ingestion rate of animal product (kg y^{-1})
f_{cook} [RN, product, met.proc]	fraction of activity in the product after food processing (-)

Soil and Sediments

Ingestion of soil either inadvertently (e.g. with food products) or deliberately (pica).

The annual individual dose to humans due to the ingestion of soil is given by:

$$D_{ing-soil} = ING_{soil} \cdot DCC_{ing} \frac{C_{soil}}{(1-\varepsilon_{t,soil}) \cdot \rho_{soil} + \theta_{soil} \cdot \rho_{w}} \qquad (43.)$$

where,

$D_{ing\text{-}soil}$ [RN]	individual dose for ingestion of soil (Sv y^{-1})
ING_{soil} [age]	ingestion rate of soil (kg y^{-1})
DCC_{ing} [RN, age]	dose conversion factor for ingestion (Sv Bq^{-1})
C_{soil}	concentration in soil (Bq m^{-3})
$\varepsilon_{t,soil}$ [soil]	total porosity of the soil (-)
ρ_{soil} [soil]	grain density of the soil (kg m^{-3})

θ_{soil} [soil] moisture content of deep soil compartment (-)
ρ_w density of the water (kg m^{-3})

As with equation 40, the soil ingestion term is expressed as wet weight soil. In practice, soil ingestion rates of both humans and animals are often expressed on a dry weight basis, as a consequence of the techniques used to estimate the amounts ingested. If this is the case, then the denominator term $(1 - \varepsilon_{t,soil}) \cdot \rho_{soil} + \theta_{soil} \cdot \rho_w$ should be replaced by $(1 - \varepsilon_{t,soil}) \cdot \rho_{soil}$.

Dermal Absorption

Incorporation of radioactivity into the body as a result of the absorption of contaminated substances through the skin.

This is unlikely to be of importance except for H-3.