Technical University of Denmark

Nuclear Safety Research and Facilities Department annual report 1999

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Publication date:
2000

Document Version
Publisher's PDF, also known as Version of record

Risø-R-1162(EN)

Nuclear Safety Research and Facilities Department Annual Report 1999

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Risø National Laboratory, Roskilde, Denmark
April 2000

Abstract The report presents a summary of the work of the Nuclear Safety Research and Facilities Department in 1999. The department´s research and development activities were organized in two research programmes: “Radiation Protection and Reactor Safety” and “Radioecology and Tracer Studies”. The nuclear facilities operated by the department include the research reactor DR 3, the Isotope Laboratory, the Waste Management Plant, and the educational reactor DR 1. Lists of staff and publications are included together with a summary of the staff´s participation in national and international committees.

Front cover:
In an EU project on submarine groundwater, Risø analyses radium and radon in seawater and sediments. The picture shows sediment sampling from the German research vessel F/S Alkor in the Western Baltic on a sunny December day.

ISBN 87-550-2659-1; 87-550-2660-5 (Internet)
ISSN 0106-2840
ISSN 1398-9189

Information Service Department, Risø, 2000

Contents

1 Introduction

On January 1, 2000, the Nuclear Safety Research and Facilities Department was divided into two departments: 1) the Nuclear Safety Research Department carrying out research and development and the tasks applied health physics and emergency preparedness, personnel dosimetry, environmental monitoring, industrial dosimetry, and isotope and irradiation services, and 2) the Nuclear Facilities Department operating the research reactor DR 3, the educational reactor DR 1, and the Waste Management Plant, and carrying out the task NTD silicon. Hence, this annual report is the last one covering the combined Nuclear Safety Research and Facilities Department.

In 1999 the department's research and development activities were organized in two research programmes: "Radiation Protection and Reactor Safety" and "Radioecology and Tracer Studies". The research subjects include dosimetry, optically stimulated luminescence, natural radioactivity, emergency preparedness, contamination physics, reactor safety, radioecology, aquatic tracers, radioecological models, radioanalytical chemistry, and radioactive waste.

The research and development work of the department is carried out in close co-operation with Danish and foreign universities and research institutes and also with the Danish nuclear and radiation protection authorities. The department participates in national and international research programmes including some European Commission programmes and the Nordic Nuclear Safety Research Programme.

This report presents a summary of the work of the department in 1999 with an emphasis on the results of the research and development activities. Lists of staff and publications are included together with a summary of the staff´s participation in national and international committees.

2 Radiation protection and reactor safety

The Radiation Protection and Reactor Safety programme carries out research and development in the fields of radiation protection, dosimetry, and reactor safety in order to contribute to the protection against the harmful effects of ionising radiation and to ensure a proficient co-operation with private enterprises and authorities in the field of nuclear technology.

The main fields of dosimetry research in 1999 concerned beta-dosimetry, retrospective dosimetry, industrial dosimetry, and internal dosimetry. Retrospective dosimetry based on optically stimulated luminescence has also applications in dating of artefacts and sediments.

Natural radioactivity is a factor to be considered in radiation protection, but it is also a useful tool as natural tracers in air and water.

In the field of emergency preparedness Risø is leading a Nordic Nuclear Safety Research project, NKS/BOK-1, consisting of six sub-projects focusing on measurement quality and strategies, countermeasures and emergency exercises.

Contamination physics covers both theoretical and technological questions concerning the characterisation and possible reduction of a radioactive contamination in the wake of a nuclear accident. The methods have been applied and a wealth of experiences have been achieved during work in areas in the CIS countries affected by the Chernobyl accident.

In the field of reactor safety the decommissioning of the DR 2 reactor has become a major project. Risøs expertise in calculation of neutron activation of reactor components is used in this work as well as in calculations for the Swedish Forsmark reactors. The work on the coolability of the melted core of the TMI reactor is near its conclusion. It may offer an explanation why the melted core did not compromise the integrity of the reactor vessel.

2.1 Dosimetry

Beta spectroscopy

Beta spectroscopy is a valuable tool for radiation protection in the assessment of beta doses to tissue surfaces. Information on beta spectra at the working place is useful for the design of appropriate shielding and for the evaluation of the radiation risk from exposure of the skin. In particular, in accident situations where high doses to the skin may occur, knowledge of the beta spectra is necessary for the determination of the dose at different depths of the skin.

The development and construction of a beta telescope spectrometer, carried out as part of a three-year EU research project, was completed in 1999. The aim of the work was to achieve a flexible, portable survey instrument to be used under normal working conditions as well as for radiological accident situations. The three silicon detectors arranged in a telescope set-up enables the spectrometer to identify electron and photon spectra separately from mixed beta/photon radiation fields (Figure 2.1). The software development was made with the LabVIEW™ system (National Instruments). It includes the capability of evaluating absorbed dose rates from the measured beta spectra, features for displaying and analysing the measurement data, and the control and display of a variety of operational parameters.

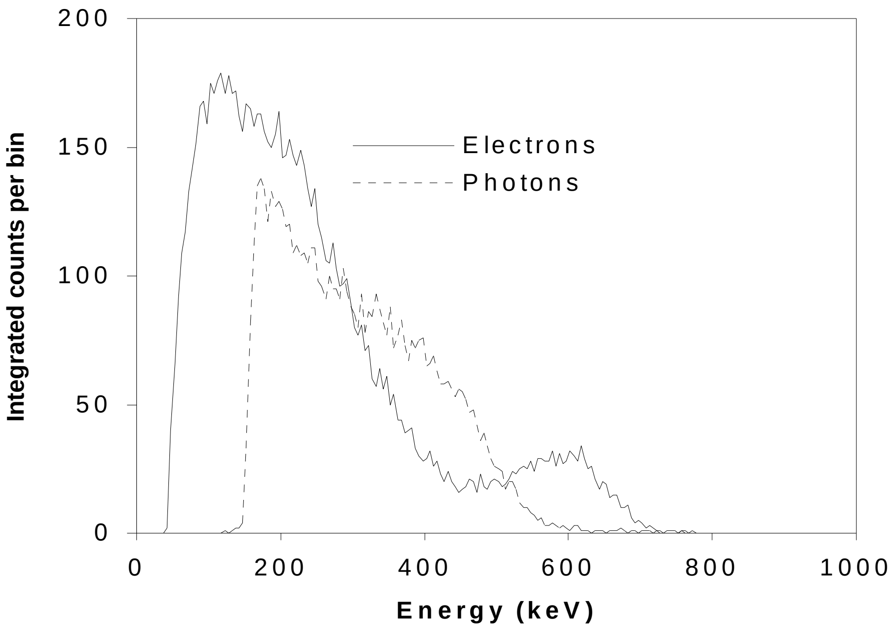

Figure 2.1. Beta and photon spectrum of a 10 mm diameter, 3.7 MBq ^{137}Cs source covered by a 1 mg/cm^2 Mylar foil measured at a distance of 100 mm by the spectrometer.

The capability of the spectrometer to measure beta spectra as well as to determine beta dose rates from mixed beta/photon radiation fields was confirmed by a number of experimental data. However, a relatively high noise level for the thin front detector of the telescope has restricted the photon rejection capability. The development of a second improved spectrometer version was therefore initiated.

Harmonisation and dosimetric quality assurance in individual monitoring

Risø has contributed to the working group, set-up by EURADOS in December 1996, entitled "Harmonisation and Dosimetric Quality Assurance in Individual Monitoring for External Radiation". The work was completed in 1999. The principal objectives were to consolidate the quality of individual monitoring using personal dosimeters and to facilitate harmonised procedures within EU. The results and recommendations of the group will be published as three reports in Radiation Protection Dosimetry.

Quality assurance in diagnostic radiology

Risø participated in a EU working group concerning criteria and protocols for dosimetry laboratories concerned with diagnostic radiology. The aim of the work was to improve the quality assurance in diagnostic radiology and thereby reduce radiation doses for exposed patients. The work was completed in 1999 by the preparation of an EU report.

Calibration of gamma-cells

Three gamma-cells for blood irradiation, two at Odense University and one at Novo Nordisk, have been re-calibrated. All results showed good agreement with previous calibrations.

Dosimetry for Radiation Sterilisation of Medical Devices

The EU supported project on "Dosimetry for Radiation Sterilisation of Medical Devices" was concluded with the publication of "Guidelines for Calibration of Dosimeters for use in Radiation Processing" (CIRM-29, NPL, UK). The project was based on a collaboration between Risø and National Physical Laboratory, UK, (NPL). It concerned documentation of the dosimetry capabilities of European irradiation facilities, in particular those that irradiate for sterilisation of medical devices. The documentation was provided through intercomparisons involving mailed dosimeters measured at Risø and NPL. The second intercomparison, carried out in 1998-99, showed agreement for both gamma and electron facilities generally within +/- 5%, but also that significant dosimetry errors (>10%) might occur. The results of the intercomparisons will be published in Radiation Physics and Chemistry.

Accreditation for High Dose Measurements

This EU supported project concerns the establishment of documentation for Eastern European high dose measurement laboratories, that will allow them to seek accreditation as calibration laboratories. A series of intercomparisons have been carried out in collaboration with NPL, UK, to document the measurement capability of the laboratories. In addition workshops on quality documentation has been organised.

Intercomparison exercise on internal dose assessment

Determination of internal doses, i.e. doses due to radionuclides in the body, is an essential part of radiation protection of workers who may be exposed to intakes of radionuclides. Within the European EULEP/EURADOS programme (4th Framework Programme) an intercomparison programme was organised. 50 institutions from 18 European and 5 other countries participated. Considerable differences were found for calculated intakes and doses, mainly due to differences in the interpretation of data and the use of different dosimetric models. For each case, the results were within one or two orders of magnitude. The results from Risø were in most cases within 10% of the geometric mean of the results in the specific cases. Results from all participating laboratories are presented in Figure 2.2 for a case with unknown time of intake and way of intake of ^{239}Pu. The result from Risø is numbered 15.

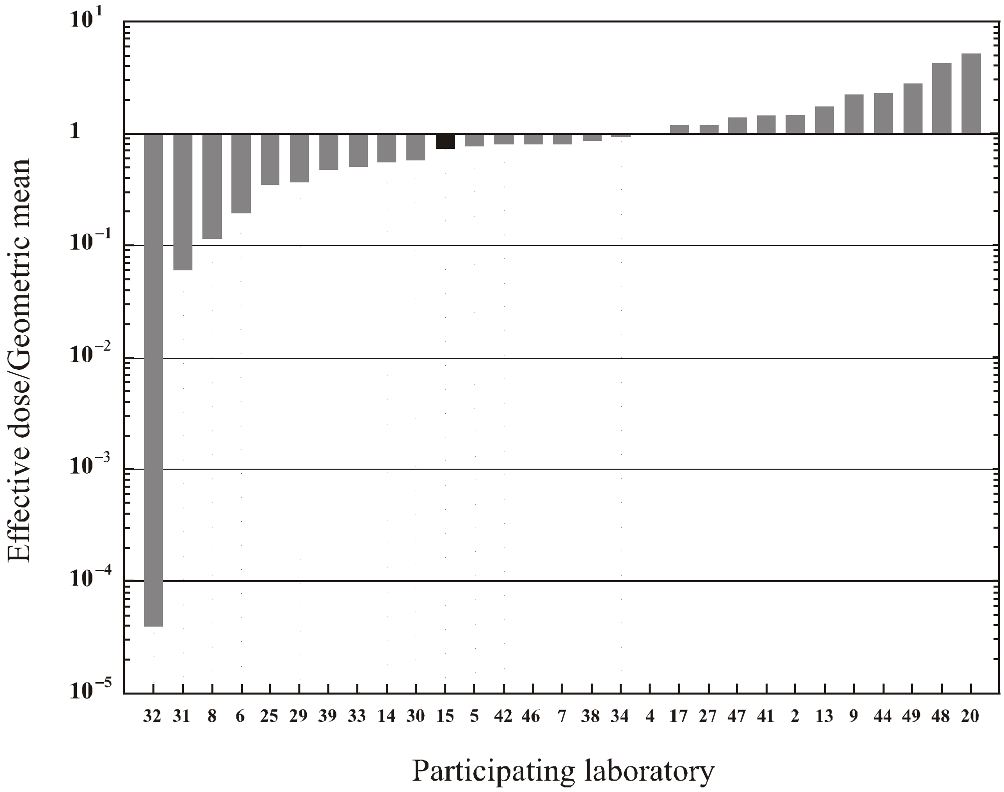

Figure 2.2. Internal dose calculation from intake of 239Pu with unknown time of intake and way of intake (case 7). Laboratory 32 was not included in the geometric mean.

Uncertainties in determination of intakes and doses

Whole-body measurements on personnel at the nuclear facilities at Risø have revealed body content of the radionuclides ^{51}Cr, ^{60}Co, ^{65}Zn, ^{124}Sb, ^{131}I, ^{137}Cs, and ^{203}Hg. For these radionuclides the uncertainties on the calculated intakes and resulting doses have been investigated. The most important contributors to these uncertainties are lack of knowledge on the time elapsed after intake and the route of intake. Less important are lung deposition, lung clearance, breathing mode and activity mean aerodynamic diameter. The uncertainties introduced by the latter are, however, comparable to or larger than the uncertainty on the activity measurement in a whole-body counter.

Determination of ^{131}I in thyroid after accidents

In case of a major nuclear accident it is very important to be able to detect intakes of iodine. Whole body counters are the most reliable in detecting iodine in the thyroid, but only a few whole body counters in the Nordic countries are calibrated for iodine in the thyroid. As part of a project sponsored by the Nordic Committee for Nuclear Safety Research (NKS) a thyroid-phantom has been made. Different Nordic laboratories, including Risø, have used this phantom to calibrate their whole-body counter for iodine in the thyroid.

Whole-body counting of many people after a nuclear accident is a rather difficult task. As an alternative, the use of ordinary hand-held instruments has been investigated. This investigation shows that about 25 kBq of ^{131}I in the thyroid can be detected qualitatively and about 100 kBq of ^{131}I quantitatively by the most sensitive of Risø's hand-held instruments, provided that no other radionuclides are present in form of contamination or other intakes. An uptake of 100 kBq of ^{131}I in the thyroid will give a committed effective dose of about 7 mSv.

2.2 Optically stimulated luminescence

Optically stimulated luminescence (OSL) is a physical phenomenon found in several natural materials which can be utilised to measure radiation doses. OSL arises from the recombination of charge which has been optically released from electron traps within a crystal. The electron population in the traps is the result of irradiation of the material, and thus the OSL intensity is related to the absorbed radiation dose. For experimental convenience OSL emitted during recombination of the de-trapped charges is usually measured in a spectral region different from that of the exciting photons. The OSL signal during exposure to the stimulation light is observed to decrease to a low level as the trapped charge is depleted (decay curve). The physical principles of OSL are thus closely related to those of the thermoluminescence (TL) method. An immediate advantage of OSL over TL is that OSL is normally measured at or close to room temperature and thus results in less alteration of the crystal – i.e. it is less destructive. OSL also measures only the component of the trapped electron population that is most sensitive to light. In geological dating, this is important because this component is most likely to be emptied (or "reset") during transport prior to deposition and burial.

The most frequently used natural minerals in OSL dosimetry are quartz and feldspar. Dating of archaeological and geological materials depends on the fact that, when mineral grains are concealed from daylight by burial, they begin to accumulate a trapped electron population. This results from exposure to the ionising radiation emitted by the decay of naturally occurring radionuclides present in the deposit. Some of the radioactivity is contained within the grains, but especially in quartz, the radiation dose is derived almost entirely from the surrounding material. If the flux of ionising radiation is constant, then the burial time of the grains can simply be determined by dividing the total dose that gave rise to the trapped electron population stored in the grains during burial by the dose rate.

Recently, luminescence techniques similar to those used in dating have been adopted for retrospective dose assessment i.e. reconstruction of radiation doses received by the general population after nuclear accidents. Typically, radiation doses are determined using luminescence measurements carried out on quartz and feldspar samples extracted from bricks, tiles, pottery, or porcelain items collected in contaminated areas such as Hiroshima and Chernobyl.

Blue LED stimulation

Three new optical stimulation systems have been developed for the commercially available Risø TL/OSL reader. The first is a blue (470 nm) light emitting diode (LED) array, developed in response to requests for a more intense monochromatic and convenient light source than the usual broad-band spectrum filtered halogen lamp. The blue LED array delivers up to 30 mW/cm^2 to the sample and it stimulates quartz OSL about 3 times faster than the broad-band source.

IR laser diode stimulation

The second stimulation systems is a 1 W solid state infrared (IR) laser diode assembly (830 nm) which provides more than one order of magnitude greater stimulation power (400 mW/cm^2) than a conventional IR LED array. This not only allows the more complete stimulation of the feldspar signal, but also provides a much more sensitive test of feldspar contamination in quartz extracts. The IR laser diode is integrated with the blue LED clusters in a single flexible OSL unit. During an automatic sequence the stimulation source may be software selected, the stimulation power varied over its entire range, and the sample held at any temperature up to 700^{o}C.

Single grain OSL attachment

The third new stimulation systems is an attachment designed to make it practical to measure the OSL signal from of large numbers of single grains using a standard Risø luminescence reader. The new system (see Figure 2.3) is based on a 10 mW 532nm Nd:YVO_4 solid-state diode-pumped laser. The power of the laser beam is controlled by attenuation in a rotating variable neutral density filter. After attenuation, the beam is focussed to a 20 µm diameter spot, and its entry into the measurement chamber is controlled by an electro-mechanical shutter. The beam can be directed to any position within the measurement chamber with a precision better than 3 µm using two moveable mirrors. Grains are mounted on an aluminium disc having a nine by nine matrix of holes, each holding one grain. The measurement of a large number of grains in a sample makes it possible to establish the distribution of single-grain signals and subsequently to determine the OSL signal which represents the grains that are correctly reset.

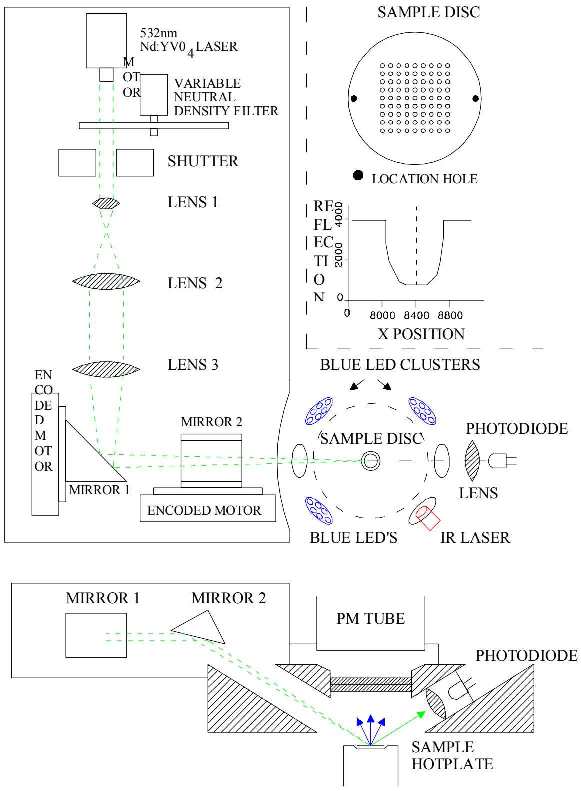

Figure 2.3. Scematic diagram of the single grain laser OSL unit. The sample disc and an example of a reflected locating hole profile are also shown.

Portable OSL reader for UV dosimetry

Field measurement of UV radiation has become important due to the continued depletion of the ozone layer. The use of OSL techniques with highly sensitive phosphors like Al_2O_3:C has provided a very flexible tool for measuring UV exposure over short periods (minutes) in the field. A portable OSL reader was developed and tested at Risø in collaboration with Oklahoma State University. This apparatus uses blue (or green) light emitting diodes as the stimulation light source. The whole system is powered from, and controlled by a laptop computer via a DAQ board allowing operation over longer periods in the field. In addition to UV dosimetry, the portable reader can be used for measuring the environmental dose rates in connection with retrospective dosimetry and dating.

Software modifications

Significant additional software modifications include facilities to (i) linearly vary the stimulation power of both blue diodes and the IR laser during stimulation (linearly modulated OSL), (ii) monitor the dark count (including phosphorescence) immediately before and after stimulation, and (iii) reduce the heating rate to as low as 0.01 $^{o}C\ s^{-1}$.

Comprehensive descriptions of these features were presented at the International Luminescence Dating Conference in Rome, September 1999, and published in Radiation Protection Dosimetry.

2.3 Natural radioactivity

National survey of radon in houses

Radon (radon-222) causes a dominant part of the life-time radiation dose for most persons in Denmark as well as in many other countries. Radon is generated in the ground and enters the house by small (but persistent) flows of soil gas. This can cause an increased level of indoor radon. In Denmark, houses with an annual level above 1000 Bq/m^3 have been found. This is of concern because radon is believed to increase the risk of lung cancer. The authorities now recommend that minor actions are taken in houses with levels above 200 Bq/m^3. For houses with levels above 400 Bq/m^3 more efficient actions should be considered.

Radon in the indoor environment depends on many factors among which the radium content of the soil beneath the house and the ability of the soil to conduct gas flow are some of the more important. This means that different geological areas tend to have different mean indoor radon concentrations, and it is therefore useful to map indoor radon levels. To this end, a new national survey has been carried out by the Danish Institute of Radiation Hygiene (SIS), Geological Survey of Denmark and Greenland (GEUS), and Risø. Measurements have been conducted in more than 3000 houses, and the analysis of the data is now completed. An important parameter is the fraction of houses with radon levels above 200 Bq/m^3 in each of the 275 municipalities. To obtain the most accurate estimates, a statistical model has been developed and tested. The model is based on a transformation of the data to normality and on analytical (conditionally) unbiased estimators of the quantities of interest. Bayesian statistics is used to minimize the effect of small sample size (typically there is only 10 measurements in each municipality). In each municipality, the correction depends on the fraction of area where sand and gravel is a dominating surface geology. The uncertainty analysis is done with a Monte-Carlo technique. Another aspect of the survey concerns the analysis of how indoor radon relates to geology, house construction, and other factors. A comprehensive report on the survey will be published in 2000.

Radon as a tracer of sub-marine groundwater

Natural radioisotopes may be excellent tracers of transport processes in the environment. In the EU project, Sub-Gate, Risø utilizes radon-222 and radium-226 as tracers for sub-marine groundwater inflow to Eckernförde Bay in the western Baltic Sea. The method is based on the observation that groundwater tends to be enriched in radon and radium. Hence, sufficient sub-marine groundwater inflow will increase the level of these isotopes in a localized region compared with (for example) open-sea levels. On July 13-14, 1999 water samples were collected at 31 positions in the bay. For each position, two 5L samples were taken: one close to the seafloor and another close to the surface. The samples were analyzed for radon-222 and radium-226 in the laboratory. The results are shown in Figure 2.4. For radium-226, no significant difference were found between surface and bottom layers. In comparison, radon-222 showed significant differences from position to position and between surface and bottom levels: The bottom levels are much higher (and more variable) than surface levels. One reason why radon-222 is probably a much better tracer than radium-226 comes from the difference in half-lifes: 3.8 days for radon-222 and 1600 years for radium-226. This means that radon-222 can not easily be mixed over a larger region, and any point-specific supply (such as supply of sub-marine groundwater through vents in the seafloor) will only influence the region near the source. For radium-226, radioactive decay is not an important loss mechanism, and the supply may influence a wider area.

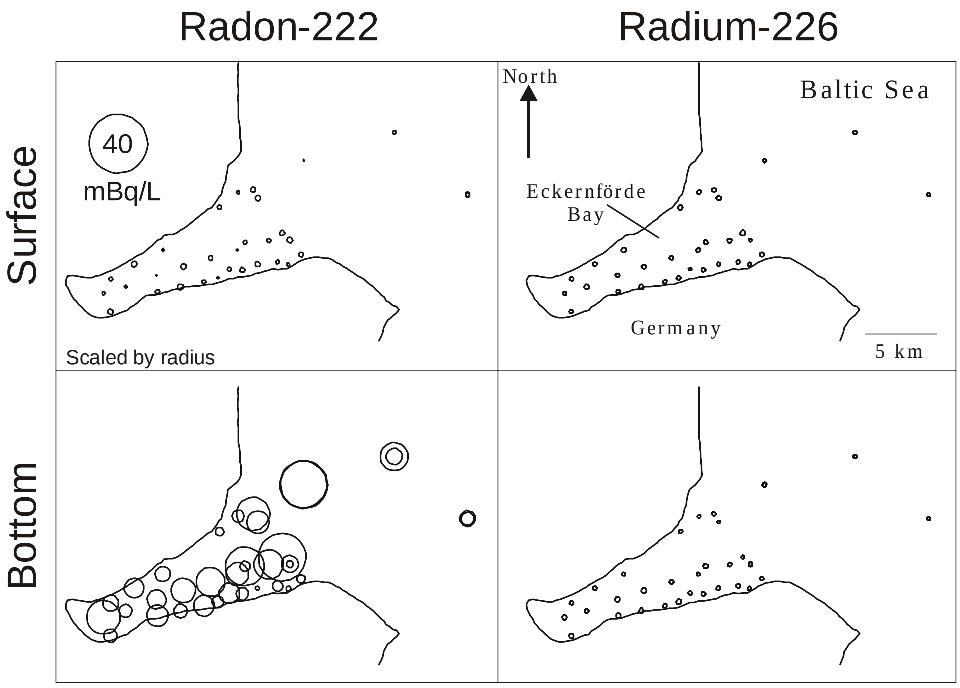

Figure 2.4. Radon-222 and radium-226 measurements in Eckernförde Bay in the western bay.

2.4 Emergency preparedness

Nordic Nuclear Safety Research

Risø is leading a Nordic Nuclear Safety Research project, NKS/BOK-1, on nuclear emergency preparedness. The project consists of six sub-projects, listed as quality assurance in laboratory measurements, measurement strategies and mobile measurements, field measurements and data assimilation, countermeasures in agriculture and forestry, emergency monitoring in the Nordic and Baltic Sea countries, and emergency exercises.

Special emphasis has been devoted to the project on quality assurance in laboratory measurements, in which an international intercomparison exercise on radioactivity measurements was conducted, and to the project on measurement strategies and mobile measurements. In the latter, a large exercise, RESUME-99, for carborne gamma-ray spectroscopy (CGS) was conducted at Gävle, Sweden where contamination levels of cesium following the Chernobyl accident are still high. The exercise focused on data acquisition and processing for emergency preparedness purposes.

In the RESUME-99 exercise, a new CGS system that was constructed at Risø in 1998 was tested. The system, consisting of a NaI detector connected to a multichannel analyzer and a GPS (Global Positioning System) receiver, was shown to be useful for environmental monitoring of radioactivity, especially for emergency preparedness purposes.

Radiological consequence analysis of a new low-level radioactive waste deposit

A radiological consequence analysis was performed for a new low-level radioactive waste deposit at the OKG Nuclear Power Plant at Oskarshamn, Sweden. The analysis was carried out for normal operating conditions, in case of human intervention long time after the deposit is closed, and for hypothetical accident scenarios. The accident scenarios consisted of a fast leaching scenario in which activity was discharged into the hydrological environment, and an accident in which a rapidly burning fire in the deposit caused dispersion of activity into the atmosphere. Both accident scenarios were found to give rise to doses of the order of 4 μSv to individual members of a critical group. The doses are dominated by external radiation from the discharges.

2.5 Contamination physics

Contamination physics research at Risø is conducted in challenging areas on the crossroads between several traditional research areas, such as health physics, aerosol physics, soil physics and assessments and countermeasures concerning pollution in an integrated environment.

Through often multi-disciplinary research projects carried out over the years expertise has been developed in many areas of work, each comprising elements of laboratory work, field work, theoretical calculations and modelling.
Some main activities in 1999 were:

Application of contaminated biomass in safe energy production in Belarus

The Chernobyl accident led to a radioactive contamination of large forest areas in Belarus. Risø has participated in a Danish-Belarussian-American collaborative project to investigate the feasibility to apply biomass removed from the contaminated Belarussian forests in safe energy production in a specially designed power plant. An implementation of the concept studied has the potential to improve on the local energy production deficiency in Belarus and at the same time to reduce radiation doses to people living in or near the contaminated forest areas. Harvesting the contaminated forest would also make it possible to rise new less contaminated forests where the wood could be used as timber.

The success of the combustion project greatly depends on the ability to retain the contamination in relatively small volumes of ash, which can be safely stored. A test was therefore conducted to determine the likely releases to the atmosphere in the biomass energy production process. The test was carried out in Rechitza, Belarus at a commercial-scale combustion facility equipped with the type of filter that could be applied in the recommended power plant. It was found that about 99.5% of the radioactive contamination in the flue gas created by the combustion process was removed by the filter system and thereby the stack release was reduced by a factor of 200. According to modelling, this implies that 100 years operation of power plants fired with an annual total of 1,000,000 tonnes of biomass would result in less than one case of fatal cancer in the populace.

Decision maker guidance in urban contamination emergencies

A PC software has been developed by Risø and the Swedish NFI for implementation by the Swedish Emergency Management Agency (Räddningsverket) in the Swedish emergency preparedness. This programme is a tool, which can be applied by local decision-makers in case of a nuclear emergency in an urban area. The user is guided through a sequence of information screens, which help to choose the right countermeasures for the particular situation. The first part can be regarded as a user's manual, including an introductory section on radiation terms, and is also addressing important issues such as social and psychological factors.

The consequence assessment calculation part gives information on how to measure the degree of contamination in the area. From these measurements the potential radiological impact can be assessed. Based on the calculated radiation doses to the inhabitants it can be evaluated if an intervention is cost-effective seen strictly from a radiation protection viewpoint. Even if this is not the case it may still be carried out due to non-radiological aspects.

The last part contains an example of application of the programme for a hypothetical situation. This part indicates how also non-radiological aspects may be incorporated in the formation of an optimised clean-up strategy.

Radiation dose due to deposition to skin and clothing

Deposition on skin of radioactive particles can cause β-doses to the skin. Similarly, deposition of radioactive particles on skin, hair and clothing may cause γ-doses to the body. These contributions have so far largely been ignored in calculations of doses from radioactive releases. Recently, however, it has been realised that dose contributions from deposition of radioactive particles can be substantial.

Through an EU contract, Risø has in collaboration with Imperial College in London investigated the processes governing the doses received from radioactive contaminant deposition to the human body. This includes assessment of both deposition of particles of different sizes and the natural removal of particles from human body surfaces.

The main experimental technique applied involves the release and subsequent deposition on volunteers in test rooms of particles of different sizes labelled with stable isotopes with a very low natural abundance. These carefully chosen isotopes can, subsequent to deposition on a test surface (e.g., a filter paper or a piece of cloth), be bombarded with neutrons in a research reactor. The result of this is the creation of radioactive isotopes, which emit characteristic gamma rays, from which the amount of deposited tracer labelled particles can be determined.

Modelling has shown that gamma doses received after the Chernobyl accident from deposition of particularly elemental iodine and radiocaesium were significant, even in comparison with gamma dose contributions from environmental contamination, in some areas of the CIS countries, where deposition took place in absence of precipitation. The modelling also shows that the corresponding beta doses may in some cases have given rise to significant skin cancer risk.

Restoration of contaminated land

When old nuclear facilities are decommissioned it is also required to restore the sites if contamination has been dispersed or if radioactive residues are contained by methods which may be unreliable for long-term storage. Restoration of such sites is often very expensive and a robust and transparent decision-aiding methodology is necessary. The RESTRAT-project under the Fourth Framework of the Nuclear Fission Safety Programme has addressed the major aspects of the restoration of different types of sites. This project has been completed in 1999. The partners involved in the project were the Research Centre SCK•CEN, Belgium (co-ordinating the work programme), Westlakes Scientific Consulting, UK, Forschungszentrum Rossendorf, Germany, Studsvik Ecosafe, Sweden, and Risø National Laboratory. Five typical example sites have been studied: the Drigg low-level waste disposal site in UK, the Ravenglass Estuary in UK, the Molse Nete River in Belgium, the Ranstad uranium tailing site in Sweden, and the Lake Tranebärssjön in Sweden. Generic compartment schemes have been developed for each example site. As an example, Figure 2.5 shows the generic compartment scheme for a low-level waste disposal site.

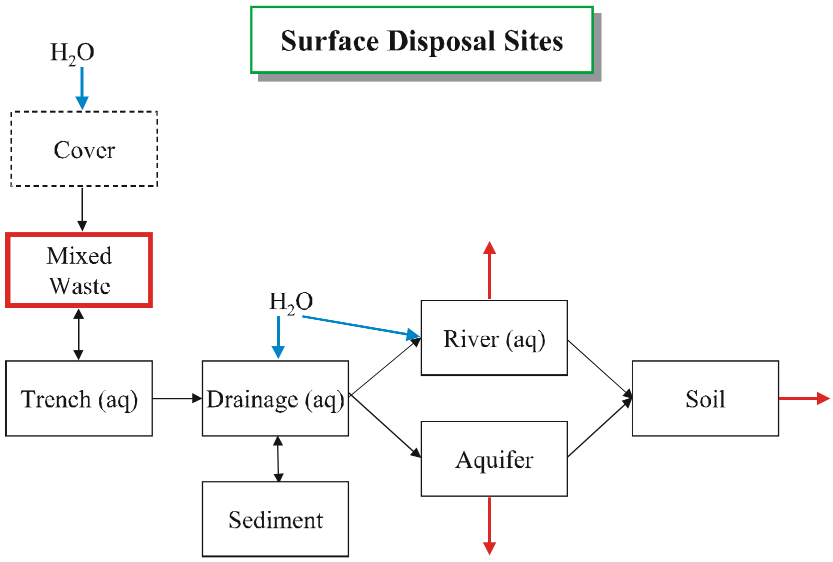

Figure 2.5. Generic compartment scheme for surface disposal sites.

The restoration techniques, which can be applied to a contaminated site, will depend upon a number of factors. These include the scale of the contamination problem, the contaminated medium, the radionuclides involved, the location of the contaminated site with respect to the local population, and the location of the contaminated site with respect to a suitable waste repository. Four major categories of restoration techniques have been included in the project: source removal, separation, containment, and immobilisation.

Detailed studies of the cost and efficiency for several sub-sets of these major categories are included in the project. Different remediation measures have been evaluated for the five example sites. The evaluation has been based upon (a) justification of the measures by trade-off between avertable collective dose and monetary costs, (b) compliance with the recommended clean-up criteria from the IAEA, and (c) optimisation of scores for the different remediation measures using multi-attribute utility analyses.

A manual has been published in which a detailed description of the methodology has been given and how it has been applied to the example sites. The manual contains CD-ROMs with databases on restoration techniques, their costs and efficiencies as well as software for dose calculations and multi-attribute ranking of restoration options.

2.6 Reactor safety

Decommissioning of research reactors

The DR 2 project which aims at determining the residual activity in the various parts of the DR 2 reactor and planning the future dismantling work has continued during the year. The ”Safety Documentation for the DR 2” including a proposal for ”Conditions of Operation” and the ”Description of the DR 2-project” were completed and submitted firstly to the Safety Committee at Risø and secondly to the Danish regulatory authorities. The approval of the project with revised ”Conditions of Operation” was received at the end of the year.

The project has progressed by measurements of the activity in the reactor tank. The activity, mainly ^{60}Co, was measured through a hole in the concrete plate, which covers the top of the tank. The measurements showed an activity around 60 GBq. In addition, the activity was estimated by calculations, indicating a value of 4 GBq. Considering the approximations involved, the difference is hardly surprising and only more accurate measurements of the individual stainless steel components in the tank can give the correct value. However, it seems quite obvious that the remaining activity is modest. It is expected that the reactor can be opened in the beginning of 2000.

Nordic project on Nuclear Possible Risks from Areas close to the Nordic Countries

The project is carried out as part of the Nordic Nuclear Safety Research Programme (NKS). The project will assess the potential risks which eastern nuclear facilities may present to the Nordic countries in case of accidents. The facilities included in the studies are the Kola, the Leningrad, and the Ignalina nuclear power plants, the ship reactors in icebreakers and submarines and the storage facilities for spent fuel and radioactive waste.

A first step in the project is the establishment of a database, which contains information on these facilities and the risks, they represent. The database is under preparation. Later workshops and seminars will be held. A member of the reactor safety group is a sub-leader of the project.

Investigation of criticality accidents

A study has been made of 74 criticality accidents, described in the literature. It is characteristic for this type of accidents that they involve the use of nearly pure fissile materials, that they occur during non-routine operations and that they are due to human errors. They have primarily occurred in criticality facilities, in reprocessing plants and in submarine reactors. Only 2 of the 74 accidents involved power reactors (a military reactor and Chernobyl-4). Almost all of the accidents have occurred in USSR/Russia and in the USA, and many have been connected to military activities. The number has been decreasing with time. During the last ten years there were only 3 accidents, two in Russia and one in Japan.

Nuclear power review

The Nuclear Knowledge Preparedness Group whose members come from the Risø National Laboratory, the Nuclear Office of the Emergency Management Agency and the Technical University of Denmark published in the beginning of 1999 its fifth annual report on the international status of nuclear power. The report is written in Danish. The purpose of the report is to keep politicians, civil servants and the media informed about the general trends of the nuclear power development in the world.

The group arranged two seminars covering presentations on nuclear developments, in particular those related to reactor safety. Examples of subjects covered are the risk of recriticality after a loss-of-coolant accident, cooling of a melted core, and the future of the Barsebäck nuclear power plant.

Core meltdown and coolability

Within the Nordic Nuclear Safety Research Programme (NKS), a computer program simulating the in-vessel lower head coolability in the Three Mile Island (TMI) accident has been developed. The aim of the work has been to describe the thermal history of the TMI core melt accident with a model which is a more realistic approach than the highly hypothetical gap model by Henry and Dube used in the MAAP program.

The new model is based on thermal cracking of the growing crust surrounding the hot molten debris after its relocation from the core region to the bottom of the water-filled reactor vessel. Cooling is provided by water percolation against the escaping steam into the fractures, which in turn are propagated into the debris due to the cooling. For the sake of simplicity, the model is divided in two parts, a slab model of the top crust and a spherical model of the lower head.

In its present state, the applied heat conduction model is limited to purely radial conduction. Angular conduction terms are being implemented to make the model truly two-dimensional. The model is then expected to be applied for parametric investigations of the influence of the system pressure, debris mass, composition dependent thermal properties and vessel wall thickness.

Calculation of neutron doses to reactor components.

In order to assess the radiation damage and the induced activity in a reactor one has to know the neutron doses received by the various reactor materials and components. The induced activity is particularly important to know when planning the dismantling and subsequent disposal of a reactor installation.

Calculation of such neutron doses were performed earlier for the Forsmark 1 reactor and more recently for the Forsmark 3 BWR by means of a Monte Carlo code (MCNP4A). Three different methods for representing the heterogeneously arranged materials in the core have been used. The first method was used for the Forsmark 1 calculations. The fuel rods were represented by an amount of iron, which gave the same total absorption cross section as the fuel rods. We denote this approach the FE-method.

The second method was used for the Forsmark 3 calculations. The fuel rods were represented by a 'fuel isotopic vector', where the fuel isotopes (^{235}U, ^{238}U,^{239}Pu, etc.) were present in the true relative proportions, but with concentration adjusted such that the resulting flux distribution was as close as possible to the flux distribution in the heterogeneous case. This approach is called the FUELVECTOR-method.

The third method was also used for the Forsmark 3 calculations. The fuel rods were represented by the 3 isotopes whose concentrations were adjusted to yield absorption cross sections in 3 selected energy ranges (thermal, intermediate and fast neutrons) similar to the heterogeneous case. This approach is called the ^{135}Xe, ^{238}U, and ^{16}O method.

The 3 methods were compared to a heterogeneous Monte Carlo calculation for a limited but representative geometry, where each fuel rod was modelled in detail. The flux variation in the fast energy range is shown in Figure 2.6, which demonstrates, that the methods 2 and 3 give very satisfactory agreement with 'reality', while the FE-method displays significant discrepancies at some distance from the core.

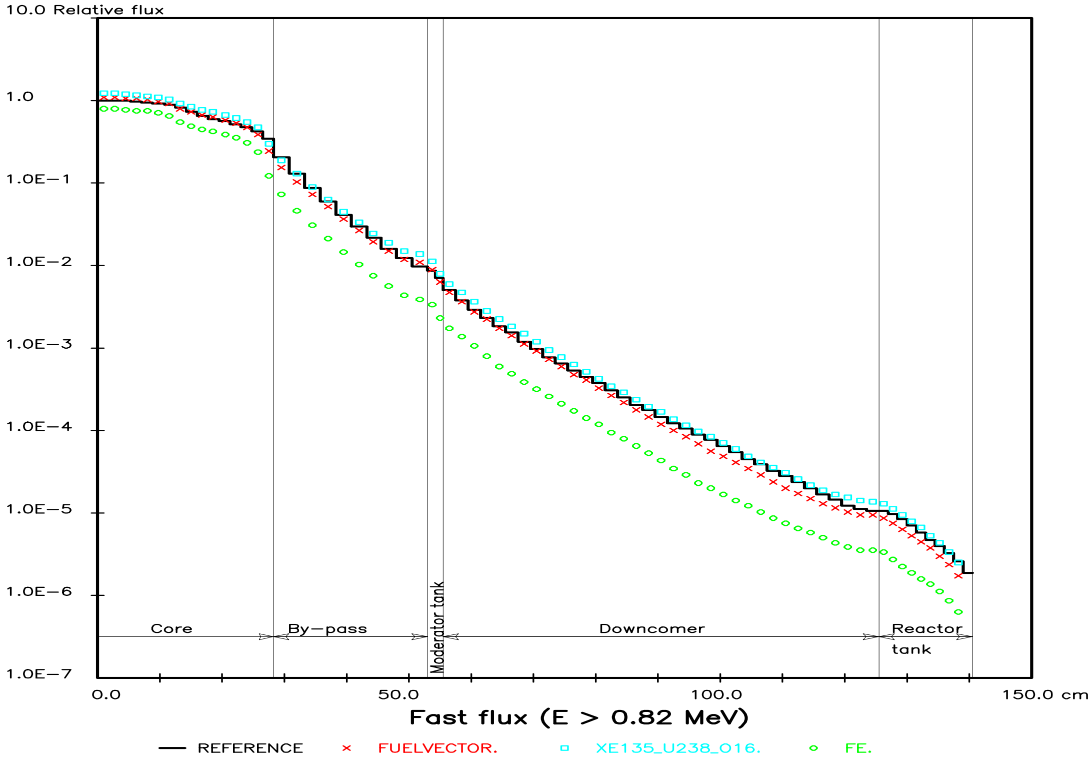

Figure 2.6. Fast-flux variation with distance from the core center calculated by three different approximations. For comparison the reference curve shows a Monte Carlo calculation, where each fuel rod is modelled in detail.

3 Radioecology and tracer studies

The aim of the programme on Radioecology and Tracer Studies is to strengthen the nuclear research at Risø within the fields of chemistry and biology with special emphasis to improve our understanding of the biogeochemical behaviour in the environment of radioactive as well as stable elements. Furthermore, the purpose is to use radioecological principles and measurement techniques including neutron activation analysis and mass spectrometry to solve general environmental problems. The programme maintains the professional standard and the international relations considered important for radioactive waste management. It is an obligation of the programme to maintain and develop a radioecological expertise in order to assist the Danish nuclear authorities and industry with advice and laboratory assistance. The programme is deeply involved in international co-operation both in a Nordic (NKS), European (EU) and global (IAEA) context.

Some important achievements in 1999 are listed in the following.

Internal projects and key areas:

- Using the Sellafield discharge to the Irish Sea of ^{99}Tc as tracer in Danish waters
- Comparing and reporting results of methods for analysis of ^{237}Np by alpha and mass spectrometry
- Implementing the technique for the analysis of ^{129}I by neutron activation analysis

Co-sponsored projects:

- Determining radium and radon as tracers in seawater using a new radon emanation facility
- Finalising the sampling programme on flue-gas particles from Danish power plants
- Comparing the ECOSYS radioecological model with Danish fallout data
- Participating in EC projects on certification of reference materials
- Finalising investigations of concrete barriers in EC project on radioactive waste
- Reporting Risø's experience with disposal of low-level radioactive waste

Commercial activities:

- Performing gamma-spectrometric analyses of foodstuffs and issuing certificates for industry for export purposes
- Performing neutron activation analyses for the investigation of Menke's and Wilson's diseases.

3.1 Radioecology

Monitoring of environmental radioactivity in Denmark is a national obligation, which is carried out by Risø. The obligation is due to the Euratom Treaty and the Helsinki Convention.

The Euratom Treaty (European Atomic Energy Community) signed in 1957 specifies in Article 35 the following: "Each Member State shall establish the facilities necessary to carry out continuous monitoring of the levels of radioactivity in the air, water and soil and to ensure compliance with the basic standards. The Community shall have the right of access to such facilities so that it may verify their operation and efficiency."

The Helsinki Convention of 1974, issued to protect the marine environment of the Baltic Sea, was the first international agreement to cover all sources of pollution, both from land and from ships as well as airborne. The governing body of the Convention is the Helsinki Commission – Baltic Marine Environment Protection Commission – also known as HELCOM. The present contracting parties to HELCOM are Denmark, Estonia, European Community, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. The Convention calls for prevention and elimination of pollution caused by harmful substances (including radioactivity) from all sources. Since 1985 Risø has attended to the HELCOM recommendation 18/1 on monitoring of radioactive substances in the Baltic Sea.

Figure 3.1. The large precipitation collector (10 m^2) at Risø. The Waste Treatment Plant is seen in the background.

Figure 3.2. Sampling of water from Roskilde Fjord.

3.2 Aquatic tracers

Sellafield Tc-99 in Danish waters

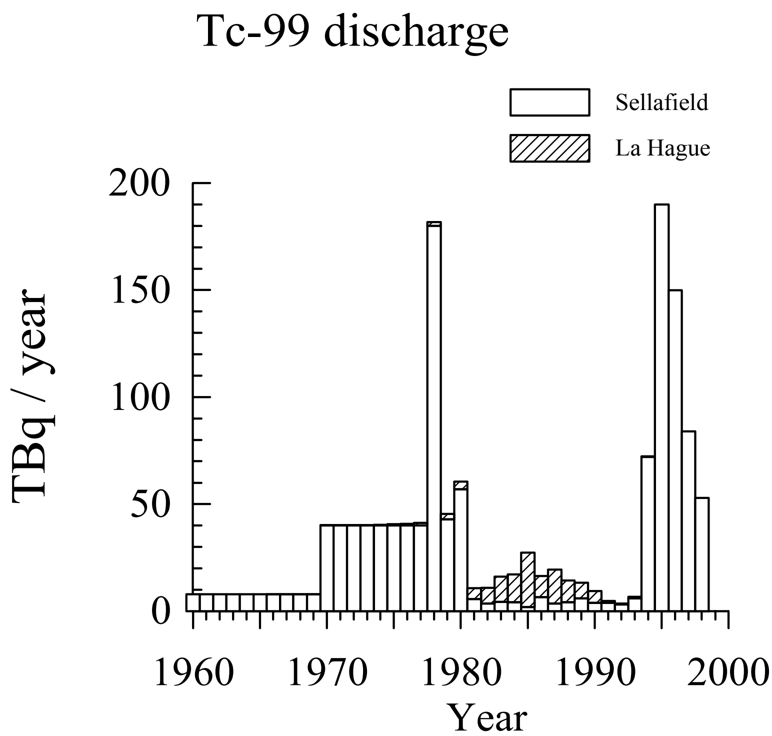

Figure 3.3. Annual discharges of technetium-99 to the marine environment from Sellafield and La Hague.

The discharges of ^{99}Tc from Sellafield increased dramatically late in1994 when the new Enhanced Actinide Removal Plant, EARP, started operation (Figure 3.3). Earlier studies based on ^{137}Cs discharges indicate a 4-year transport time from Sellafield to the inner Danish waters, the Kattegat and the Belt Sea.

Figure 3.4 shows the concentrations of ^{99}Tc in Danish waters from June 1999, i.e. 4 years after the peak 1995 discharge. The North Sea water spiked with ^{99}Tc is flowing in along the bottom. The concentration gradually decreases towards the Baltic. In the surface layer, the out-flowing Baltic water is low in ^{99}Tc, and the increasing surface water concentrations going from the Baltic towards the North Sea is caused by a gradual entrainment of in-flowing bottom water into the out-flowing surface water.

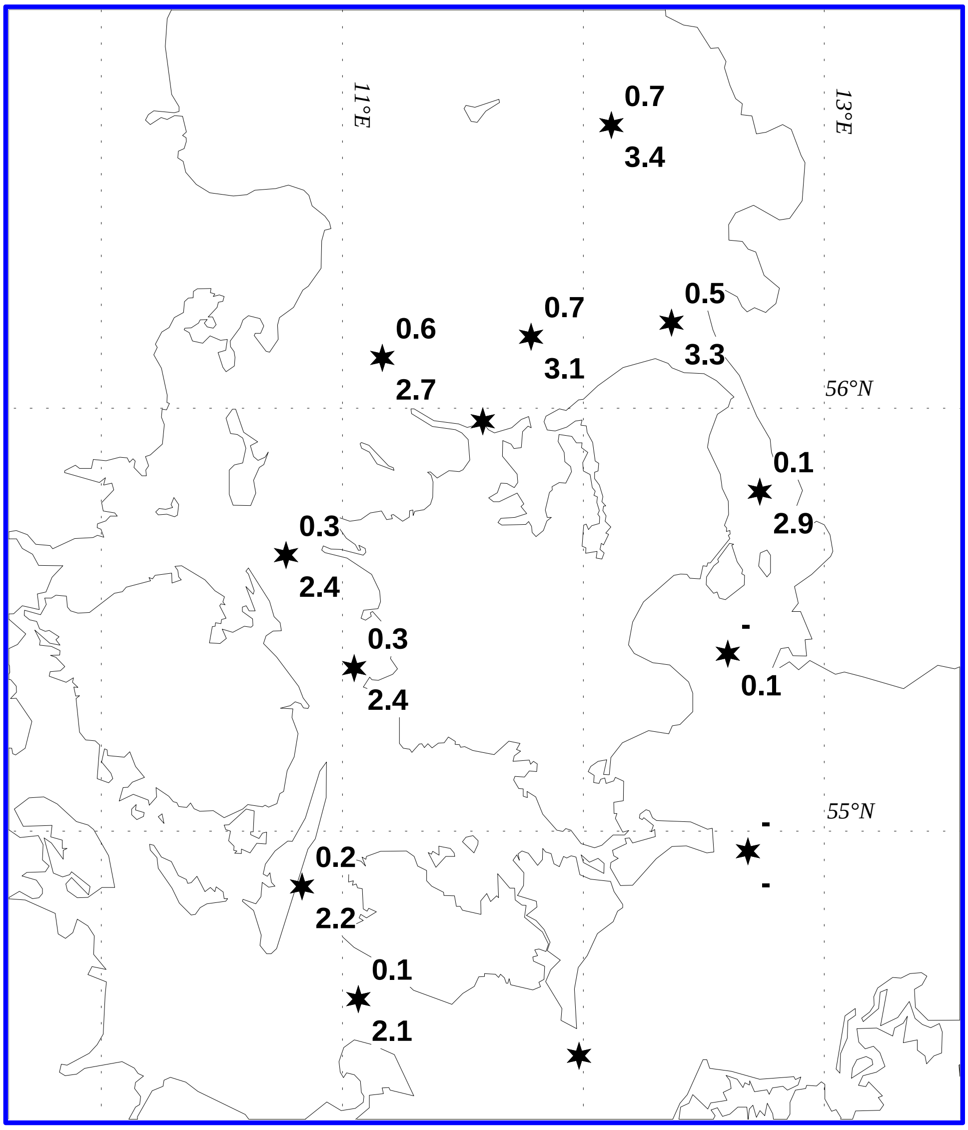

Figure 3.4. Technetium-99 (Bq m-3) in inner Danish waters, June 1999. : sampling points, upper number: surface water, lower number: near bottom water, -: below detection limit.

Participation in Tundra Northwest 1999, the joint Swedish expedition

During two summer months in 1999, ph.d.-student Mats Eriksson participated in a joint Swedish expedition called "Tundra Northwest 1999" (TNW-99) to the Canadian arctic onboard the Canadian icebreaker Louis S. St-Laurent together with 70 scientists. The purpose of the expedition was to explore the tundra ecology. The work was multi-disciplinary and divided in five themes:

A. Interactions between plants, herbivores, and predators

B. Biodiversity in the arctic tundra

C. Migratory birds in the arctic environment

D. Freshwater ecosystems in the High Arctic

E. Climatic change and pollution in the Arctic tundra.

Furthermore, a group studied marine fish and mammals.

The Risø task was, within themes D and E, to study man-made and naturally occurring radionuclides over this area. Of special interest was the study of re-mobilization mechanisms of the actinide elements in lake sediments during an-oxic conditions. Most of the high arctic lakes are small, shallow and oligotrophic. The food web is well defined and simple, so these lakes are excellent ponds for the study of the transfer of radionuclides through the food chains. A further goal was the study of sedimentation processes in these lakes. From analyses of the naturally occurring radionuclide ^{210}Pb, sedimentation rates were determined and used for dating of sediment cores.

The groups were located in separate camps on the tundra and the sites were chosen individually. The Risø camp was always situated nearby a lake. All the scientific equipment and personal belongings were transported by helicopters from the ship to a shore-based camp and back again after 36 hours. On the site, the camp members worked closely together to be able to perform field experiments and sampling during the 36 hours stop. The fresh-water camp collected sediments, water, plankton, fish and organic carbon from the water. During the first leg (the expedition was divided in two legs) 9 sites were visited through the so-called "North West Passage". During the whole expedition many animals in this region were observed (musk ox, polar bears, 6 different species of whales, caribou and many birds). More information about the expedition is available from the Swedish polar research web page:

http://www.polar.kva.se/tnw99/index.html.

Figure 3.5. The expedition at the magnetic North Pole, 1999-08-21, on Ellef Ringnes Island (78.4° N, 103.5° W).

3.3 Radioecological models

Risø has collected data on environmental radioactivity in Denmark since the late 1950's covering abiotic samples, vegetation, foodstuffs and humans. This collection has generated time series of data that illustrate the transfer of anthropogenic radioactivity through foodchains to the Danish population from a variety of sources including fallout from atmospheric nuclear weapons testing and from the Chernobyl accident, and discharges from European nuclear reprocessing facilities. The information obtained from the analysis of these data is useful in connection with predicting radiological consequences from potential nuclear accidents involving radioactive contamination of the Danish environment and for identifying effective countermeasures.

The radioecological sensitivity is a useful concept for characterising the transfer of radioactive contamination to different environmental compartments including man. The time-integrated dose rate to man is the relevant end point of a radiological assessment. Therefore, the radioecological sensitivity is defined as the time-integrated concentration in an environmental sample from a unit ground deposition (e.g. Bq y kg^{-1} per Bq m^{-2}).

The data on environmental radioactivity were analysed with different radioecological models, traditional UNSCEAR models and more recent dynamic models, in order to obtain numerical values of radioecological sensitivities and to provide a comparison between models.

The work is part of the NKS/BOK-2.1 project on Important Nordic Food Chains aiming at characterising radioecological sensitivity and variability across the Nordic countries.

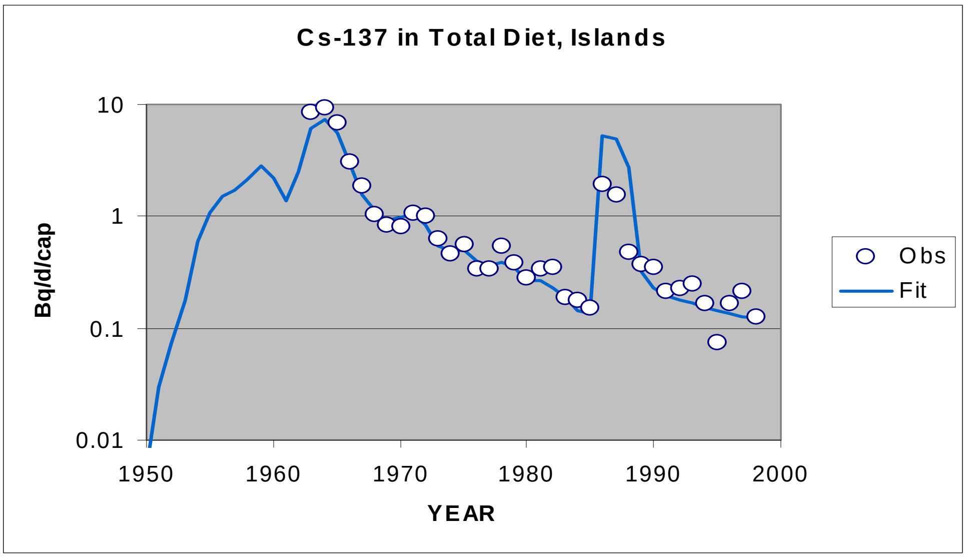

Figure 3.6. UNSCEAR model fitted to data on 137Cs in total diet from Funen and Zealand.

Traditional radioecological models of the UNSCEAR type were applied to time series of Danish data on ^{90}Sr and ^{137}Cs in grass, milk, beef and diet covering four decades. The models fit the data very well for ^{90}Sr for the entire period, but for ^{137}Cs the models generally perform somewhat poorer from 1986 and onwards. The reason for this is the different transfer through the environment particularly in 1986 and 1987 of Chernobyl radiocaesium compared to that from nuclear weapons testing. This difference is caused mainly by different seasonal modes of deposition. But overall, the models reproduce the data quite well. The radioecological sensitivity of the Danish diet for the transfer of ^{90}Sr and ^{137}Cs through Danish foodchains is found to represent an average individual intake of 3 Bq ^{90}Sr and 5 Bq ^{137}Cs for a ground deposition of 1 Bq m^{-2} when no countermeasures are applied.

Dynamic radioecological models do not reproduce the fallout data better than the traditional models. But the general features of the dynamic models make them suited for prediction of radiological consequences of routine and accidental releases in areas where limited radioecological data are available.

3.4 Radioanalytical chemistry

The work on radioanalytical chemistry is focused on developing high-quality and well-documented reference methods and using these to determine trace elements in materials from the environmental, medical and industrial field. Environmental and biological materials represent the majority of samples analysed. Using instrumental neutron activation analysis Risø has participated in the certification of several biological reference materials (mussel tissue, aquatic plant and tuna muscle) and a polymeric reference material for the European Commission under the Standards, Measurements and Testing Programme in co-operation with Mermayde in the Netherlands.

Since spring 1999 Risø has participated in an EU-project concerning the certification of a road-dust reference material for platinum, palladium and rhodium used in catalytic converters for cars. Risø analyses the dust for content of platinum using radiochemical neutron activation analysis.

An international co-operation between the University of Helsinki, the St. Petersburg University and Risø concerning the clean-up of soil polluted with heavy metals using plants (bioremediation) was started in June 1999. The Council of Nordic Ministers supports the project.

Risø and the John F. Kennedy Institute, Copenhagen, co-operate on determination of copper in chorionic villi (placenta) samples for the diagnosis and verification of Menke's disease.

Pharmaceutical products, ashes and polymeric materials from industrial customers have been investigated for their content of trace elements.

Sampling and elemental analysis of flue gas particles

Since 1998 Risø has sampled and analysed flue gas particles. Collaboration between Risø, DTU, FLS Miljø A/S and the Danish power plants has been carried out in a project supported by the Ministry of Environment and Energy. The project has run for two years and measurements have been made at four power plants: Enstedværket, Avedøreværket, Asnæsværket and Nordjyllandsværket. At each power plant measurements have been made at three locations in the off-gas system: 1) upstream from the filter, 2) between the filter and desulphurisation plant, and 3) in the stack.

Risø has sampled particles in the stack and determined the elemental composition of the particulate matter using neutron activation analysis. The particle sample collection in the stack comprised sampling of total-dust on plane filters and size-fractionated sampling using Berner Low Pressure Impactors, BLPI. Equipment for isokinetic sampling was developed according to German Standards (VDI 2066). Impactor sampling was applied to in-stack isokinetic conditions and to extracted dried cooled flue gas.

The experience gained during the above project enabled Risø to test a pilot bag house filter facility in Rechitza in Belarus. The Danish Ministry of Environment and Energy supported this test. The pilot plant was a part of the Chernobyl Bio-energy project described elsewhere in this report. Figure 3.7 shows results from size-fractionated particle samples obtained with the BLPI. The samples were analysed for mass and ^{137}Cs activity. It is noted that both distributions are bi-modal, and that the mass distribution has a maximum in the coarse fraction whereas the ^{137}Cs activity has its maximum in the fine fraction. This is caused by evaporation of caesium during combustion. When the flue gas cools caesium condenses again. This occurs faster in the fine-particle fraction, since small particles have a larger surface-to-volume ratio than larger particles. It was concluded from the test that the operation of the bag house filter facility is satisfactory, from both technical and radiological points of view.

In late 1999 an investigation of the bag house filter at Rudkøbing Kraftvarmeværk was carried out for Fynsværket A/S. This was an interesting chance to test a Danish bag house filter after the experience in Russia. The facility manufactured by Simatek A/S proved to be very efficient and the emission mass concentration was actually lower than that found in outdoor air in Denmark.

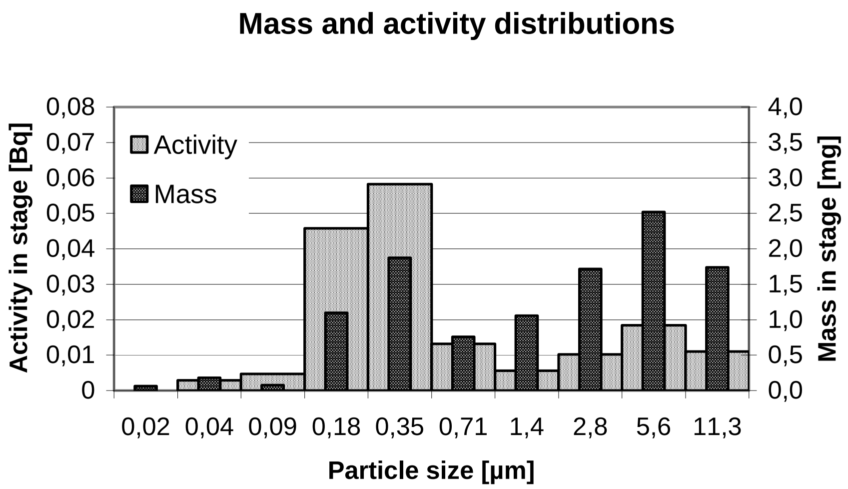

Figure 3.7. Mass and activity distributions from flue gas particles sampled 16 June 1999 at the Rechitza saw mill. The samples were taken after a pilot scale bag house (about 6 m^3 air sample volume) and represent actual release conditions.

Iodine-129 in seaweed from Klint, Utsira, Bornholm, Roskilde Fjord and NW Greenland

Concentrations of ^{129}I and ^{127}I were determined by neutron activation analysis in archived seaweed samples from Klint in the Kattegat, Bornholm in the Baltic Sea, Roskilde Fjord, Utsira on the Norwegian coast and NW Greenland. The analytical results (Figure 3.8) indicate that the ^{129}I levels in all locations investigated are one to three orders of magnitude higher than the fallout background and strongly dominated by the discharges from the reprocessing facilities at La Hague and Sellafield. The $^{129}I/^{99}Tc$ ratio is a more sensitive index compared to ^{129}I alone and used to estimate the origin and transit times of ^{129}I. Transit times of ^{129}I are estimated to be 1-2 years from La Hague to Klint and Utsira and 9-14 years to NW Greenland. Transfer factors for the transport of ^{129}I from La Hague are calculated to 54×10^{-15} y/m^3 to Klint, 60×10^{-15} y/m^3 to Utsira and 1.2×10^{-15} y/m^3 to NW Greenland. Based on the calculated transit times, transfer factors and annual discharge data of radionuclides from the reprocessing facilities, the variations of ^{129}I concentrations and $^{129}I/^{99}Tc$ and $^{129}I/^{137}Cs$ ratios are modelled.

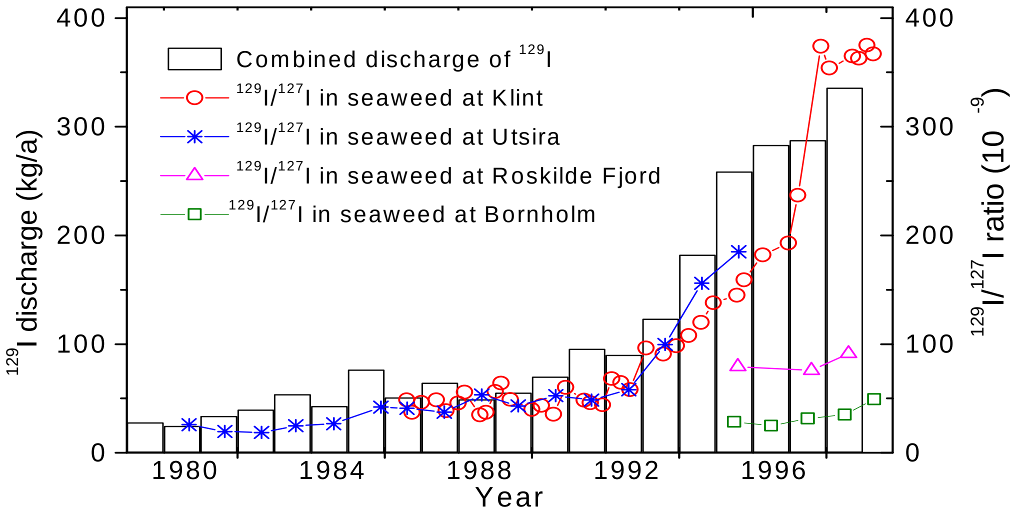

Figure 3.8. Ratios of $^{129}I/^{127}I$ in seaweed from various locations and the combined discharges of ^{129}I from La Hague and Sellafield shown by time of discharge and sampling. The combined discharge is calculated by assuming that the Sellafield discharge reaches thelocations two years later than from La Hague.

Chemical speciation of ^{129}I in seawater and its potential utilisation for biogeochemical cycle study of stable iodine in the ocean

The chemical speciation of iodine plays a central role in determining its marine geochemical cycle. Although much effort has been devoted, the data on the mass transfer of iodine among geochemical reservoirs are still too fragmentary to construct a reliable marine geochemical cycle of iodine. The main reason is the difficulty with characterising the origin and conversion of various chemical species of iodine. Isotopic tracers are excellent for characterising the origin of chemical species of elements. Iodine-129 discharged from the European reprocessing facilities, Sellafield and La Hague, provides a unique field tracer for the investigation of marine geochemical cycle of stable iodine in the natural environment. The investigation involves determination of the concentrations of different species of ^{129}I, as well as stable iodine in seawater and their variation with location and depth.

A method for the determination of ^{129}I and ^{127}I in iodide and iodate species in seawater has been developed based on radiochemical neutron activation analysis and pre-separation by ion exchange. With this method, as low as 3×10^{-13} g/L ^{129}I and 1.0 µg/L ^{127}I can be determined. Seawater samples collected in the Kattegat and the Baltic Sea were analysed for ^{129}I and ^{127}I in iodide and iodate species and total inorganic iodine. The possibility of using this method to study the geochemical cycle of iodine in the ocean was investigated. The preliminary results indicate that ^{129}I discharged from reprocessing facilities can be used as a tracer to investigate the transport, dispersion and mixture of water masses.

3.5 Radioactive waste

Staff from the Waste Management Plant have through many years contributed to international studies of long term properties of conditioned radioactive waste and barrier materials used in repositories. The work is carried out as part of the Radioecology Programme but is also important for the practical waste management described in Section 4.4.

Most of the work is carried out within the EU Fission Research Programme or the Nordic co-operative programme NKS. Contributions to safety assessment of a surface disposal facillity for very low level waste at the Swedish nuclear power plant Oskarshamn was a new topic in 1999.

Cemented waste and concrete barriers

The experimental work within a three year EU contract concerned with pore systems, leaching behaviour and influence of various types of defects on transport behaviour in cemented waste or concrete barriers was finalised. A tendency to slow clogging of the pore system in highly permeable cementitious backfills such as for example the Nirex NRVB material was demonstrated. This may be important for safety assessment because prevention of releases of gasses produced by corrosion or biological processes could lead to undesirable pressurisation in disposal facilities. Some additional work on transport of radioisotopes (europium, uranium) through cracks in concrete was carried out. It was again demonstrated that a covering layer of calcite precipitated on the inside of such cracks from a flow of calcium bicarbonate containing water was preventing effective retention of the radioisotopes. Under the circumstances the thin calcite layer has self-repairing properties and functions as an effective barrier against contact between the solution in the crack and the high pH environment in the pores of the cementitious material. The effect was demonstrated for ordinary cement mortar like in construction concrete, as well as for highly porous backfill. In the later case the calcite precipitation may result in closure of relatively wide cracks. In ordinary mortar the limit for crack closure is about 0.3 mm.

The pseudo 2-dimensional CRACK2 numerical model of precipitation of calcite in cracks in concrete is now finalised. It describes the pore system and the macro-chemistry, including correction for diffusion potential of simultaneous migrating ionic species, together with the behaviour of one or two radioisotopes present in the concrete or entering with calcium bicarbonate containing solution. Parameter studies have shown that assumptions about initial and final porosity of the calcite layer are important for the distribution of precipitate inside the crack. A Risø-report describing the mathematics and presenting some calculation examples is written but has not yet been published.

Results from the cement studies was presented at a Nordic conference on ordinary uses of concrete (where crack behaviour also is important) and again at the Luxembourg conference summarising results from EU research programme on radioactive waste management.

Bituminized waste materials

There is considerable international interest for the Risø experimental and modelling work performed in previous years under EU contracts. An updated summary was presented at a bitumen workshop in Prague in 1999. Many of the ideas are taken up and carried on especially in France. A description of the modelling principles has been written, but lack of time has so far prevented publication. Some further development of the models is expected in 2000.

Contributions to the NKS programme

A programme on measurement of low contents of radioisotopes in steel and aluminium from reuse has been initiated. A description of Danish experience with the upgrading of old waste units have been written for use in a Nordic description of such problems. One in the series of Nordic meetings discussing use of Environmental Impact Statements in connection with disposal of radioactive waste was held at Risø in August 1999. The contribution from Denmark was mainly examples from outside the nuclear field, but the Risø work for OKG was also shortly presented.

Source terms for use in low level disposal

A request by OKG (the Oskarshamn nuclear power plant in Sweden) to make a safety assessment of an intended extension of the existing surface disposal facility for very low level waste, led to the development of a simple numerical model describing degradation of waste units and percolation of rainwater in such waste disposal mounts. Various release scenarios were investigated and the resulting doses calculated in cooperation with other members of the staff of the department.

4 Nuclear facilities and services

4.1 Research reactor DR 3

DR 3 is a heavy-water moderated and cooled nuclear research reactor, which has been in operation since 1960. It was originally built as a material testing reactor, but today it is used as a multipurpose research reactor. The operation cycle is 4 weeks, of which 23½ days is continuous operation and 4½ days is shut down. The vertical experimental facilities comprise 13 tubes in the core, 50 mm diameter, and 14 tubes in the D_2O and graphite reflectors with sizes ranging from 10 to 18 cm in diameter. Four tubes, 18 cm diameter, pass horizontally and tangentially to the core. These facilities were intended for loop experiments, but turned out to be excellent beam ports. Two beam ports are supplied with thermal neutrons from a water scatterer; two others are supplied with cold neutrons from a 38K cold hydrogen neutron source.

Six three-axis spectrometers and a Small Angle Neutron Scatterer (SANS) instrument are supplied by the neutron beams from the four beam ports belonging to the tangential 18cm diameter tubes. One of the cold source beam ports is connected to a building outside the reactor hall, by means of a neutron guide tube. The monochromatic cold neutron flux at the sample position is: $7 \cdot 10^6$ n cm^{-2} s^{-1} (E_n = 5 meV). Two of the three-axis spectrometers are multipurpose instruments with a high degree of flexibility, facilitated by five different detector arms which can be attached or detached in less than one hour.

Neutron scattering is an important technique for the study of large molecules such as polymers and biological molecules and for the study of superconductivity and magnetism in high-temperature super-conductors. These are examples of recent applications of the beam facilities of DR 3. DR 3 is appointed as a European Large-Scale Facility and the neutron beam instruments are intensively utilized by researchers from Risø and from other EU-countries.

Neutrons from DR 3 are also used for activation analysis, isotope production and transmutation doping of silicon. These activities are described in sections 3.4, 4.2 and 4.3.

The reactor was kept in operation at 10 MW for 6203 hours, corresponding to 73% of the year. The reactor was closed down for repair on November 26 owing to a leakage in the drain pipe.

4.2 NTD silicon

Neutron Transmutation Doping of silicon takes place in seven irradiation facilities in the reactor DR3. Five facilities are placed in vertical positions, three in the heavy water and two in the graphite, and two facilities are placed in horizontal positions in the heavy water.

The project to change the control system in the oldest horizontal facility continues, the new control system includes modern instrumentation and Windows based software. The project has been delayed due to abolition of the engineering and computer department. It is now in progress and will be finished at the end of 2000.

As NTD-Silicon moved offices to the reactor DR 3 a new data handling system was implemented to improve and rationalise the administrative procedures. The database system includes all known information on the silicon crystals - before and after irradiation - and provide the instructions, control sheets and certificates needed during and after the irradiation process.

The Quality Manual and the related books (approx. 150 documents) have been reviewed as part of the ongoing process of improving the quality system and subsequently converted to MSWord.

All elements in our quality system have been reviewed by The Danish Standard Association for compliance with the standard DS/EN ISO 9002. After auditing the certificate was renewed.

The production of NTD-silicon has increased in the second half of 1999, specially irradiation of 5” silicon, and there will be a demand for more 5” facilities.

4.3 Isotope Laboratory

The Isotope Laboratory is classified as a Nuclear Installation. It includes the Basic Irradiation Service and the activation analysis staff from the Radioecology and Tracer Studies programme, that jointly utilizes the irradiation facilities in the reactor DR 3.

Basic Irradiation Service

This section continues to fulfil our commitment to cover all needs for neutron irradiated materials for technical and scientific purposes in Denmark. The Isotope Laboratory is responsible for the production of radioactive isotopes and other radioactive materials for industry, hospitals and research institutions. The major part of the deliveries to domestic as well as foreign customers is unprocessed irradiations from dedicated reactor irradiation facilities. All radioactive materials needed for Risø’s own research are delivered as ready-to-use preparations.

A total of 1217 irradiations were carried out for use by Risø and 33 different external customers in Denmark, Finland, Norway, Sweden, Germany, Italy, U.K., Slovakia and Switzerland. This is an increase of 12% from last year in spite of the fact that there has been a five week unscheduled reactor shut down.

The number of customers is still increasing as 5 more are using the irradiation facilities compared to 1998. Altogether 95 shipments of other radioactive products were sent to a variety of institutes, industry and hospitals.

For research applications at Risø, 98 irradiations were performed and 128 deliveries of radioisotopes in specially prepared forms were made. This represents an increase of almost 40% compared to 1998. For educational purposes 624 solid radioactive sources were supplied to the Nordic countries.

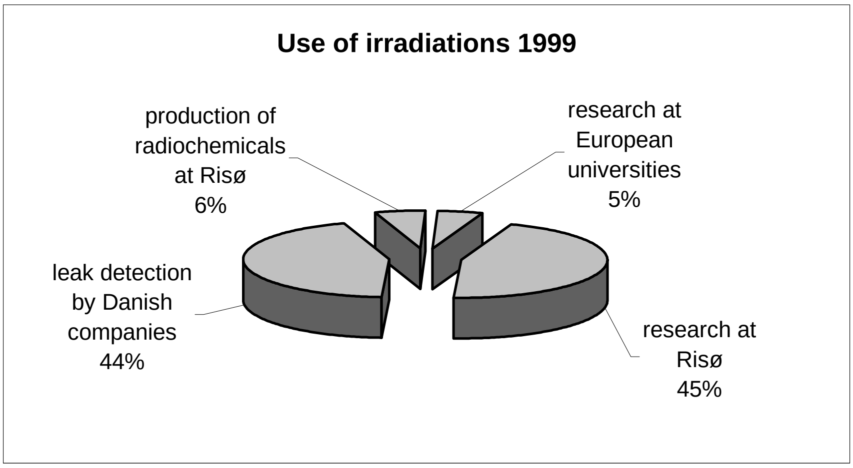

Figure 4.1. The figure shows the distribution of the irradiations between the different applications.

4.4 Waste Management Plant

The Waste Management Plant is responsible for the collection, conditioning and storage of radioactive waste from the laboratories and nuclear facilities at Risø and from other Danish users of radioactive materials. Collection of chemically toxic waste, purification of ordinary sewage water and laundering and decontamination work are other obligations. The staff takes part in international committee work, notably within EU, and in research activities as described in Section 3.5.

Radioactive waste

Low-level liquid waste is purified by distillation. After control for β-activity the distillate is released to Roskilde fiord via the ordinary sewage purification system. The total gross-β release in 1999 was 55 MBq corresponding to <1 % of the permitted activity. A considerable part is natural ^{40}K in the sewage with minor contributions of other isotopes from the 1190 m^3 distillate and other sources. In 1999 about 30 000 GBq tritium was released with sewage water. This is considerably higher than usual, and is due to various operational problems at the DR 3 reactor. Tritiated water cannot be retained by the water purification system, but fortunately the dose from a given amount of tritium is rather slight. In addition 4 GBq ^{14}C as carbon dioxide and 0.5 MBq of gross-β as particulates were released with the off-gas from the plants.

The concentrate from the process was evaporated to dryness in the small bituminization plant. The content of β-activity stored in this form was only 1.0 GBq. Experience from 30 years operation of this plant was presented at a bitumen workshop in Prague.

The facilities at Risø are also used to store radioactive waste from other Danish users of radioisotopes. The service is provided on a commercial basis. About 2.4 t out of the total 7.6 t of low-level solid waste was of external origin. This waste contained about 150 GBq radioisotopes with half-life longer than 1 year, mostly in form of sealed sources.

The number of drums transferred to the storage hall for low-level waste was 81 including 8 which had been stored temporarily for decay in a shielded facility at the Waste Management Plant. The storage hall now contains 4587 drums and has a remaining capacity sufficient for 5 to 10 years. The air-dryer installed in 1998 has been found able to prevent the previously observed condensation on the surface of the drums when the weather change from cool to warm and moist conditions. Unfortunately some drums with old evaporator concentrate shoved renewed tendency to leakage. The activity contents in this type of drum is slight and the leakage of no direct safety concern, but the salt solution may corrode other drums standing below and in general damage the appearance of the store.

As the final step in a long process the crushed concrete from demolition of the old silos used previously for storage of drums with low-level waste was declassified and use as inactive fill material in the area were the silos had been standing previously. An application for declassification of the area has been sent to the nuclear safety authorities. A summary of the experience gained in the drum transfer project was presented at the ENS-Topseal conference in October 1999.

Plans for a minor extension of the storage capacity in the facility intended for waste with high radiation level were accepted by the authorities. The construction work will be carried out early 2000.

The storage facilities at Risø are only for temporary use, and so far no planning for actual disposal has been made. However, late in 1999 some preparatory work for a policy concerning disposal and decommissioning was initiated.

Relevant information about the various waste types and possible disposal concepts have been collected previously in connection with research projects. A review of proposals concerning disposal of tailings and remaining ore from the uranium extraction pilot plants operated at Risø in the early 1980's is being written.

Inactive systems

The sewage purification plant with nitrogen removal is now 3½ years old. The system has operated quite satisfactory in 1999 where the plant treated 55000 m^3. The mean concentrations in the effluent was 3.9 mg (total) N/L, 2.2 mg P/L and 2.9 mg BOD/L where the permissible weighed mean concentrations are 6 mg N/L and 15 mg BOD/L (organic components expressed as biological oxygen demand).

The collection of chemically toxic waste and transfer for treatment at Kommunekemi, decontamination of protective clothing, and the ordinary laundry facilities were operated as previously.

5 Other tasks

5.1 Applied health physics and emergency preparedness

The major task for the Section of Applied Health Physics is primarily radiation protection of Risø employees including radiation hygiene surveillance, professional advice and teaching in radiation protection for staff members at the nuclear facilities. A kaleidoscopic summary of the work on radiation protection is given below.

Surveillance programmes

The programme includes radiation and contamination surveillance of working operations at the nuclear facilities where personnel is or can be exposed to radiation and contamination. The γ-radiation levels at different locations are measured daily and surface and air contamination are analysed from smear and air samples. Air contamination is also measured continuously at central working places. System samples from reactor DR 3, *e.g.* the primary cooling system, are analysed by γ-spectroscopy. X-ray and laser equipment is inspected once a year. The overall surveillance programme for 1999 includes about 85,000 measurements and analyses.

Radiation environment at DR 3

As a supplement to the routine health physics monitoring programmes a special measurement programme has been implemented to obtain more detailed information on the radiation levels in the reactor hall and on the relative importance of the different sources of radiation. The programme included three sorts of measurements: dose measurements with an extra set of thermoluminescence dosimeters, a set of continuous measurements of γ-dose rate at selected places and spot measurements with handheld instruments around the spectrometers (TAS). The major contributor to the γ-radiation fields is the neutron guide tube for the source of cold neutrons and operation of the triple axis spectrometers for neutron physics research.

Neutron exposure of a step motor

A surprisingly high content of ^{60}Co (7 MBq) was found in a step motor that had been used at a Triple Axis Spectrometer (TAS) at reactor DR 3. The step motor is shown in Figure 5.1.

The step motor was separated into parts and the activity content in each part was measured by γ-spectroscopy. Most of the activity was found in the rotor magnet material. A neutron activation analysis was carried out to determine the element composition more precisely. The content of ^{59}Co in the rotor was found to be approximately 14% by weight. It has been concluded from the investigations that the step motor has been exposed to a thermal neutron fluence rate of the order of $10^7\ n_{th}\cdot cm^{-2}\cdot s^{-1}$ for a longer time period in a monochromator arrangement at a triple axis spectrometer.

This has led to a general recommendation on allowable impurity concentrations in materials that might be exposed to neutrons at triple axis spectrometers at DR 3.

Figure 5.1. Step motor used in a triple axis spectrometer at Reactor DR 3.

Release of slightly contaminated steel

A pilot uranium production plant at Risø has been dismantled. During operation more than 2,000 metres (9,700 kg) of steel pipes were contaminated at the inner surfaces with uranium and decay products of the uranium and thorium series. During dismantling, a 20 cm piece of the steel pipe was removed for each 100 metres interval and analysed for activity content by γ-spectroscopy. The total amount of activity in the pipes has been estimated from the measurements to be about 7 MBq out of which 3 MBq is ^{226}Ra and 2.5 MBq $^{230+232+234}$Th. The radiological consequences of an unconditional release of the steel pipes outside Risø have been studied. Several exposure scenarios have been investigated, including public exposure from a deposit at a dump and worker exposure from smelting the pipes at a steel plant. Even with very conservative assumptions the annual individual doses to the public would be less than a few μSv per year and the individual doses to the workers engaged in the smelting of the pipes less than a few tens of μSv. The authorities gave permission to release the pipes for smelting but the company in question declined to receive the pipes. The pipes are now stored at Risø together with uranium tailings from the dismantled plant.

Emergency response preparedness

The emergency preparedness service for the Danish Emergency Management Agency (DEMA) includes operation and maintenance of the permanent measuring system, which was installed after the Chernobyl accident to detect low levels of airborne activity within a few hours. If the system alarm is triggered specialists on call are called in to investigate whether it is a system error or due to a real increase of the environmental radiation level.

The permanent measuring system

Central computers at DEMA and Risø collect data on an hourly basis from gamma monitoring stations placed at eleven different locations in Denmark. Each station contains a high-pressure ionisation chamber, a gamma spectrometer with NaI-detector, equipment for measurement of precipitation and temperature and a microcomputer for data collection and communication with the central computers. All eleven stations have continued to operate smoothly in 1999 with only a limited number of technical malfunctions, primarily transmission errors. To assist harmonization an intercomparison exercise was carried out during May/June 1999 at the Risø Natural Environmental Radiation Measurement Station in Denmark and at the PTB underground laboratory for dosimetry and spectrometry (UDO) in Germany. The intercomparison was organised by a EURADOS working group. The system used in the Danish PMS was tested together with systems from six other European countries. Tests included (for example) certified sources in the field and a simulated plume. The results are still under review by the organisers of the exercise.

Re-sampling of γ-spectra for the PMS system

Data from the Danish measurement stations in the permanent measuring system (PMS) are transmitted as electronic telegrams. Each telegram contains a NaI-spectrum of 256 channels. The software developed for the stations in the eastern countries (PMS-E) operates with spectra of 512 channels. In order to use this software in the Danish PMS it is necessary to convert the PMS-telegrams to PMS-E format and the applied algorithm has been documented in 1999. The algorithm creates a spectrum, which is distributed of 512 channels in the new spectrum (re-sampling) with the same spectrum integral as that of 256 channels.

Normalised standard γ-spectra for the PMS system

Standard γ-spectra for the radionuclides ^{40}K, ^{222}Rn + daughter products and ^{232}Th + daughter products have been determined based on measured spectra on one of the eleven Danish permanent measurement stations. The difference between the integrated spectra collected over 256 channels is calculated with and without the presence of the radionuclides. Sources containing ^{40}K and ^{232}Th (fertilisers) were placed in different distances from the ionisation chamber and the NaI-detector. Measurements in periods with heavy rain and without rain, respectively, were used to determine the standard spectrum for ^{222}Rn + daughter products. Measurement series of up 80 hours have been applied and the integral of the spectra calculated. For the same time periods the average air kerma was measured at the high-pressure ionisation chamber of the system, also with and without the presence of radionuclides. The air kerma difference has been normalised to the corresponding difference between the integral of the standard spectra (after re-sampling) for each of the radionuclides for conversion of the measured integral spectra into kerma and individual doses.

5.2 Personnel dosimetry

Risø's personnel dosimetry service covers the individual monitoring of the personnel at Risø. Only persons actually involved in radiation work are equipped with a personal dosimeter. In areas where the use of personal dosimeters are not required, the radiation levels are controlled through an extensive area-monitoring programme using thermoluminescence (TL) dosimeters.

During 1999 a total of 729 persons were monitored out of which 133 received external doses above the registration level at 0.2 mSv and 46 received internal doses from intake of tritiated water. The total external collective equivalent dose to the monitored personnel was 157 mSv, while the internal collective dose was 13 mSv.

The main statistics of the dosimetry service for 1999 are shown Figure 5.2.

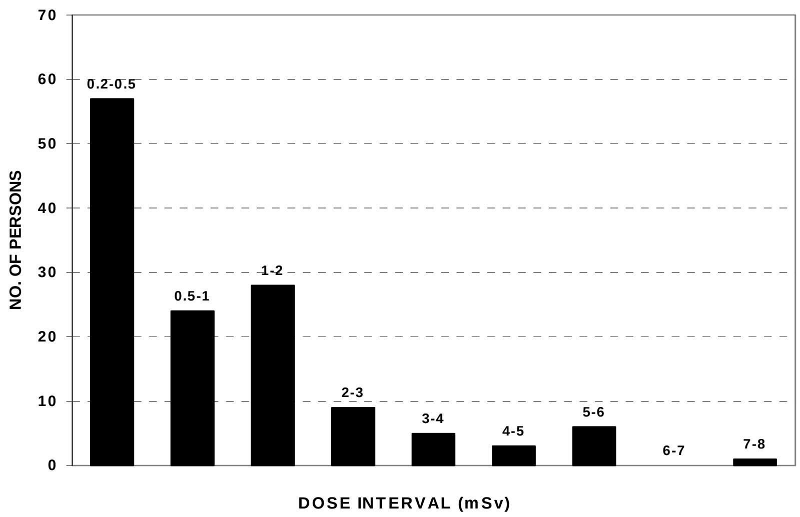

Figure 5.2. Distribution of whole-body doses (effective doses) in 1999.

5.3 Environmental monitoring

The department is responsible for the monitoring of radioactivity in the environment at Risø. The programme carried out for this purpose comprises routine monitoring of air, precipitation, sediments, seawater, grass, sea plants, milk and wastewater from the Waste Management Plant. The samples are measured for γ-activity, tritium, and gross β-activity. External γ-radiation is monitored at 25 locations around Risø.

The results are reported semi-annually in the Risø-I-Report series "Radioactivity in the Risø District". The results from the latest report January-June 1999 show that the mean concentrations in air were 0.41 μBq m^{-3} of ^{137}Cs, 3.1 mBq m^{-3} of ^{7}Be, and 0.20 mBq m^{-3} of ^{210}Pb. The average external background dose rate on the Risø site measured by TLD was 128 nSv h^{-1}, which is somewhat higher than the background dose rate of 88 nSv h^{-1} from the area around Risø. The additional dose rate on the Risø site is due mainly to the Waste Management Plant. None of the measured levels are of any concern from a radiological protection point of view and the levels are similar to those observed in 1998.

5.4 Industrial dosimetry

The activities of the accredited Risø High Dose Reference Laboratory (HDRL) were increased in 1999, with 88 dose measurement reports and 74 dosimeter certificates being issued. This reflects the growing need for documentation of industrial radiation processes, in particular radiation sterilization of medical devices, as required by the directives of the EU, and outlined in international standards.

The dose measurement reports mainly concern dose mapping in products that shall be radiation sterilized. The measurements are carried out in cooperation with the customers, and they are used to determine the irradiation parameters that shall be used for effective sterilization of the products.

In this context we arranged three courses in 1999 on “Validation and Process Control for Electron Beam Sterilization” with 15 participants from 10 countries.
We participate actively in the ongoing revision of the radiation sterilization standards (ISO 11137 and EN 552) through membership of the relevant working groups. The head of HDRL is convener for the European working group, EN/TC 204 WG2, on radiation sterilization.

Radiation Physics and Chemistry

The head of HDRL is editor-in-chief for Radiation Physics and Chemistry (Elsevier). This is a main journal for publication of articles on radiation processing.

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7 Education

7.1 External teaching

Lectures on radiation protection and emergency response preparedness have been given at a one-week course at Forschungszentrum Karlsruhe. The course entitled *RODOS-3 - Computer Based Training Course: Decision Support for Off-Site Emergency Management in the Later Phases of a Nuclear Accident* was a part of the European Radiation Protection Education and Training (ERPET) programme.

Reactor physics lectures at the Technical University of Denmark

The department runs a reactor physics lecture course for engineering students at the Technical University of Denmark at Lyngby.

The course comprises lectures on principles and design of nuclear reactors, interaction between neutrons and nuclei, neutron behaviour in nuclear reactors, criticality conditions for reactors, and determination of reactor physics parameters for thermal reactors and their variation with time.

The course is a prerequisite for the reactor physics lab course at the DR 1 reactor (see below).

Courses at the DR 1 reactor

The DR 1 reactor has been used almost exclusively for educational purposes. About 40 high school classes have carried out one-day or half-a-day experiments at the reactor. The total number of high school pupils visiting DR 1 in 1999 was about 500.

A number of students from the Technical University of Denmark have participated in the reactor physics lab course at DR 1. During this course they have carried out experiments at the reactor over a period of three weeks. Examples of the experiments performed are:

- Determination of the temperature, power, and bubble coefficients of the reactor
- Neutron activation analysis
- Measurements of neutron cross sections
- Neutron radiography
- Health physics experiments
- Core flux distribution

7.2 External examiners

Damkjær, A. Examiner in physics at the University of Copenhagen and at the Technical University of Denmark.

Fynbo, P.B. Examiner in physics at the University of Odense.

Højerup, C.F. Examiner in reactor physics at the Technical University of Denmark.

Jacobsen, U. Examiner in isotope techniques at the Technical University of Denmark.

7.3 Internal teaching

The Section of Applied Health Physics has given lectures and courses in radiation protection for Risø staff members. The following lectures been presented in 1999:

Periodic internal courses

- eight introduction courses for new Risø-employees
- course on health physics for 11 Risø-staff members, 8 persons from private companies seeking authorisation to work with radioactive substances and 9 laboratory technician trainees
- introduction course on working conditions in radiation and criticality areas for 18 external employees working at Risø

Education of new staff members

- two specialised courses for new engineers at reactor DR 3
- two specialised courses for supervisors at reactor DR 3
- specialised course for a new deputy director
- specialised course for new guards
- education of a new health physics technician started in 1999

Re-training of staff members

- two specialised courses for staff members at reactor DR 3
- specialised course for staff members in the Technical Department

8 Committee memberships

8.1 National

The advisory committee on protection measures in the case of accidents in nuclear facilities (§ 9 stk 2)
C.F. Højerup and B. Majborn
(E. Nonbøl and P. Hedemann Jensen, substitutes)

The coordination committee of the Emergency Management Agency and Risø National Laboratory
B. Majborn and P. Hedemann Jensen

The coordination committee for nuclear safety in Central and Eastern Europe (Ministry of Foreign Affairs)
B. Majborn

The advisory coordination committee for research in environmental medicine (Ministry of Health)
B. Majborn

The Board of the Danish Nuclear Society
B. Majborn and M. Bagger Hansen

Danish National Council for Oceanology
H. Dahlgaard

8.2 International

European Union

Consultative Committee Euratom - Fission
B. Majborn

External Advisory Group Euratom - Fission
S.P. Nielsen

Technical Experts on Radiation Protection Dosimetry
P. Christensen

Technical Experts on Environmental Radiation Monitoring
L. Bøtter-Jensen

EURADOS working group 2. Skin Dosimetry
P. Christensen

EURADOS working group 12. Environmental Radiation Monitoring
L. Bøtter-Jensen

Article 31 Group of Experts, Euratom Treaty
P. Hedemann Jensen

Articles 35 and 36 of the European Treaty (Environmental Monitoring)
S.P. Nielsen

Article 37 Group of Experts, Euratom Treaty
S.P. Nielsen

National Correspondents on Assistance and Emergency Planning in the Event of a Nuclear Accident or Radiological Emergency
F. Nielsen

Working Party set up by the EU Article 31 Group of Experts to develop European criteria on clean up of contaminated land
P. Hedemann Jensen

Working Party on Criteria for Recycling Materials from the Dismantling of Nuclear Installations
M.S. Carugati

ACPM for the Community Plan of Action in the Field of Radioactive Waste
K. Brodersen

Scientific Committe of STORM (Simplified Test on Resuspension Mechanisms)
P.B. Fynbo

Group for Nuclear Safety Research Index, NSRI
E. Nonbøl

OECD/NEA

Committee on Radiation Protection and Public Health (CRPPH)
P. Hedemann Jensen

Nuclear Science Committee
C.F. Højerup

NEA Data Bank Executive Group
C.F. Højerup

CSNI (NEA) Committee on the Safety of Nuclear Installations
P.B. Fynbo

Principal Working Group 4, PWG 4
P.B. Fynbo

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L. Bøtter-Jensen

Radiation Protection Dosimetry
L. Bøtter-Jensen

Analytical Letters
B. Rietz

Nuclear Europe Worldscan
K. Hjerrild Nielsen

Other Committees

The Board of the Nordic Nuclear Safety Research Programme, NKS
B. Majborn

The Board of the Nordic Society for Radiation Protection
A. Aarkrog (President), A. Damkjær (Executive secretary) and
J. Søgaard-Hansen

Baltic Marine Environment Protection Commission Helsinki Commission (HELCOM), Group of Experts on Monitoring of Radioactive Substances in the Baltic Sea (MORS)
S. P. Nielsen

Working groups within IAEA to prepare Safety Requirements and Safety Guides on contaminated environments
P. Hedemann Jensen

ICRP Task Group to prepare recommendations on protection of the public in situations of chronic exposures
P. Hedemann Jensen

International Solid State Dosimetry Organization
L. Bøtter-Jensen

Standing Committee for the International Solid Sate Dosimetry Conferences
L. Bøtter-Jensen

European Atomic Energy Society (EAES) Working Group
B. Majborn

European Atomic Energy Society (EAES). Research Reactor Operators Group
H. Floto

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H. Floto

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Bibliographic Data Sheet **Risø-R-1162(EN)**

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Nuclear Safety Research and Facilities Department
Annual Report 1999

Edited by B. Majborn, A. Damkjær, P. Hedemann Jensen, S.P. Nielsen and E. Nonbøl

ISBN	ISSN
87-550-2659-1; 87-550-2660-5 (internet)	0106-2840 1398-9189

Department or group	Date
Nuclear Safety Research and Facilities Department	April 2000

Groups own reg. number(s)	Project/contract No(s)

Pages	Tables	Illustrations	References
58		17	

Abstract (Max. 2000 characters)

The report presents a summary of the work of the Nuclear Safety Research and Facilities Department in 1999. The department´s research and development activities were organized in two research programmes: “Radiation Protection and Reactor Safety” and “Radioecology and Tracer Studies”. The nuclear facilities operated by the department include the research reactor DR 3, the Isotope Laboratory, the Waste Management Plant, and the educational reactor DR 1. Lists of staff and publications are included together with a summary of the staff´s participation in national and international committees.

Descriptors INIS/EDB

INTERNATIONAL COOPERATION; PROGRESS REPORT; RADIATION PROTECTION; RADIOACTIVE WASTE MANAGEMENT; RADIOCHEMISTRY; RADIOECOLOGY; REACTOR PHYSICS; REACTOR OPERATION; REACTOR TECHNOLOGY; RESEARCH PROGRAMS; RISOE NATIONAL LABORATORY

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