



Compliance monitoring for remediated sites



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FOREWORD

Throughout the world, many countries have experienced problems associated with pollution of the environment. Poorly managed practices in nuclear fuel cycle, medicine, industry, weapons production and testing, research and development activities, as well as accidents, and poor disposal practices have produced a large array of radioactively contaminated facilities and sites. Structures, biota, soils, rocks, and both surface and groundwaters have become contaminated with radionuclides and other associated contaminants, a condition that raises serious concern due to potential health effects to the exposed human populations and the environment.

In response to the needs of its Member States in dealing with the problems of radioactive contamination in the environment, the IAEA has established an Environmental Restoration Project. The principal aspects of current IAEA efforts in this area include (1) gathering information and data, performing analyses, and publishing technical summaries, and other documents on key technical aspects of environmental restoration; (2) conducting a Co-ordinated Research Project on Environmental Restoration; and (3) providing direct technical assistance to Member States through technical co-operation programmes. The transfer of technologies to Member States in need of applicable methodologies and techniques for the remediation of contaminated sites is a principal objective of this project.

This report focuses on compliance monitoring of remediated sites, as well as on the planning and management options to accomplish this task. To ensure that restored sites can be released for future use, compliance of residual radioactivity with cleanup criteria must be verified. Thus, post-cleanup monitoring must be carried out.

The IAEA expresses its thanks to all those involved in the preparation of this publication. The IAEA officer responsible for this report was D. Stritzke of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

Past poor radioactive waste management and disposal practices, intentional or accidental spills of radioactive substances and other incidents involving radionuclides at nuclear installations or other user establishments, e.g. hospitals, industry and research facilities, have led to significant radioactive contamination at sites in many countries.

Atmospheric atomic weapon tests and major nuclear accidents, such as Chernobyl, are another source of radioactive contamination. These events have led to radioactive fallout over much larger areas beyond the original site, which has made difficult the overall characterisation and restoration of contaminated land. A good overview on environmental restoration of nuclear testing sites worldwide is given in Ref. [1].

Another source of environmental contamination is represented by old, mostly out of operation factories, which manufactured radioactive materials when either radiation protection criteria were not as stringent as today or the harmful effects of radioactive materials were not appreciated, e.g. radium in luminising facilities. These factories were often located close to large population centres and caused contamination of urban areas.

Radioactive contamination can also result from human activities, such as conventional ore mining and ore processing, e.g. copper ore mining or phosphogypsum production, during which natural radionuclides can concentrate in uncontrolled areas at levels beyond the limits set by national authorities.

The migration of the contamination through numerous environmental pathways can represent hazards to the health of human populations and the environment. The characterisation and subsequent restoration of these contaminated sites will reduce undue exposure of human populations to radiation. The IAEA has published numerous documents dealing with planning, monitoring and implementation of cleanup techniques for sites which have undergone an accident, or ceased normal operations and had to be decommissioned and released for unrestricted or restricted use. Those of particular relevance are the technical reports and documents dealing with cleanup of large areas contaminated as a result of a nuclear accident [2, 3], monitoring programmes for unrestricted release [4, 5] general aspects of decommissioning [6, 7] and land restoration [8].

In the USA, the US Nuclear Regulatory Commission, has published a series of reports [9–13] providing valuable information on the various aspects of the final radiological surveying of restored sites.

To ensure that restored sites can be released for future use, compliance of residual radioactivity with cleanup criteria must be verified. Thus, post-cleanup monitoring must be carried out, based on a plan with the following objectives:

- Any area with residual contamination must be identified and the nature, quantity, and distribution of the radioactivity determined;
- Where contamination is present, it must be shown, through an assessment, that radionuclide dispersion and migration, will not have deleterious effects on the population and the environment;

- The plan shall consider appropriate further action, if compliance with cleanup criteria cannot be confirmed.

Post-cleanup characterisation of a site to be released for future use will consist of several key activities:

- definition of an appropriate strategy;
- planning and management of a post-cleanup monitoring;
- site monitoring;
- assessment; and
- reporting of results obtained.

1.2. OBJECTIVE

The objective of this publication is to provide guidance to those responsible for post-restoration monitoring of contaminated sites in order to protect the public from exposure to residual radioactive materials. The guidance relates, in general, to the planning, performing and assessing of post-cleanup monitoring with subsequent validation of compliance with cleanup criteria. It may also be useful for any regulatory authority in verifying whether an optimum strategy and appropriate individual steps were selected to fulfil the post-cleanup characterisation task.

This report provides guidelines for developing a comprehensive and economically sound approach to fulfil the above task.

Specifically, this technical report is aimed to foster consolidation and dissemination of information on the practical experience gained by various Member States in the post-cleanup characterisation of restored sites.

1.3. SCOPE

Radioactive contamination of the environment can occur for many reasons. For sites where there was a risk of immediate or deleterious effects to the population and the environment from such contamination, cleanup should be undertaken to reduce these risks to acceptable levels. For purposes of this document, post-restoration monitoring applies to any such site which has been restored. Contamination of uranium mining and milling sites and contamination of buildings and equipment during decommissioning of nuclear facilities are not considered in this report. They are dealt with in other IAEA publications [14, 15].

The specification of cleanup criteria for the release of sites for restricted or unrestricted future use, should be defined by appropriate national authorities. Such specifications are not within the scope of this report. Detailed descriptions of monitoring techniques, environmental pathway studies and dose assessments can be found in other relevant literature [4, 6, 13, 16].

1.4. STRUCTURE OF THE REPORT

The report is structured as follows: Section 2 discusses the selection of an optimum post-restoration monitoring strategy. It briefly describes the scanning techniques available and provides information on required analyses and sensitivities. Planning and management aspects are discussed in Section 3 and include the organisational structure of project teams with

responsibilities of various bodies involved, the health and safety aspects and information on the overall project costs. Section 4 provides information on sampling and measurement techniques applicable to post-restoration monitoring activities. Quality assurance issues are outlined in Section 5. Section 6 discusses the verification of compliance with the cleanup criteria. It provides a general overview of tests which may be used to ascertain the degree of confidence, which can be placed in the results. Section 7 provides a short summary of the report and the principal conclusions drawn.

The report is supplemented with references, appendices and annexes, which summarise international experience on the subject. A list of drafting and reviewing bodies is added.

2. DEFINITION OF A STRATEGY FOR POST-RESTORATION SITE CHARACTERISATION

2.1. THE REMEDIATION PROCESS

The remediation of a contaminated site includes the planning and integration of a number of key tasks. Depending on the size of the project, some or all of the following tasks may be undertaken. A flowchart showing the key stages in the remediation and release of a potentially contaminated site is given in Fig. 1. The first stage is usually an awareness of possible contamination. This may be based on historical records, knowledge of the types of processes carried out on the site, the practices prevalent at the times the site was operational, evidence from sites with similar histories or even public memory and concerns. A preliminary assessment of the site, possibly including site characterisation, is then carried out with a conservative dose and risk evaluation. On completion of this stage, a decision should be made on whether remedial action will be required for the site to meet the defined criteria [17, 18].

If the criteria are not met, the next stage is usually a more detailed and complete characterisation. Characterisation is performed to obtain the necessary data for identification of possible exposure scenarios with impact modelling and to undertake a detailed assessment. If results confirm that action is required, possible intervention options are identified. These are then compared and a final selection is made on the basis of an optimisation study. This final selection includes remediation techniques to be used, management and disposal of waste and the remaining risks. The remediation is then implemented [19]. Finally, post-restoration monitoring is necessary to determine whether the criteria and other remediation goals have been achieved. If they have not been achieved, an analysis of the failure should be made by the party responsible for the contamination on the site. The options are then to perform further remediation, further characterisation or, subject to regulatory approval, to change the planned use of the site. There may be restrictions on the use of the site and a licence may be required. Requirements for ongoing monitoring will normally be defined by the regulatory authority. All operations should be performed under an appropriate quality assurance programme. The following sections define strategies for post-restoration monitoring.

2.2. ENVIRONMENTAL RISK ASSESSMENT

Environmental risk assessment is the basis for all remediation measures of contaminated sites. It is needed to identify existing and potential future radiological risks to those living at the site or in its vicinity.

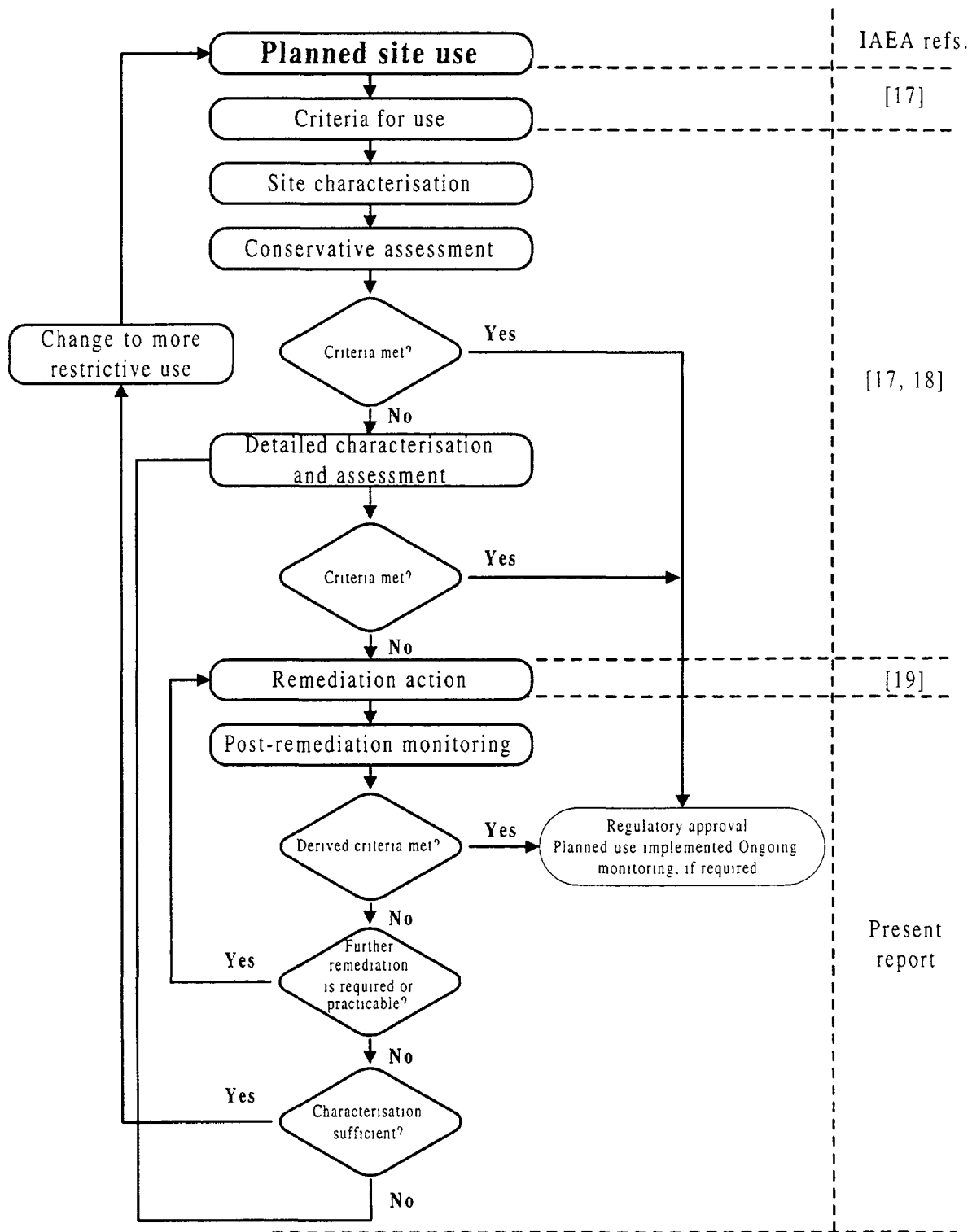


FIG. 1. Key stages in remediation and release of contaminated sites.

Radioactive materials released from a contamination may be dispersed within the site or off-site. They may be present in the air, surface or subsurface soils, surface waters and groundwater, as well as in the flora and fauna. They can migrate through various pathways to reach and thus expose humans.

To assess the potential impact of these contaminants on workers and the general public currently living nearby or who in the future could use the site for housing, etc., different exposure scenarios need to be considered. The development of such scenarios is based on modelling of radionuclide migration and dispersion will normally have been undertaken in the site remediation process as part of the determination of the restoration criteria for acceptable levels of residual risk.

Typical scenarios are:

- residential scenario, which assumes construction of a house on site, farming or gardening and consumption of the field products, e.g. vegetables, fruit, meat. This could result in exposure of individuals through inhalation of contaminated air during excavation works, long-term exposure to contaminated soil and ingestion of contaminated food;
- groundwater scenario which may sometimes be combined with the residential scenario. This assumes use of groundwater from a well on the site for drinking purposes. The resulting exposure is through the ingestion of contaminated water;
- other relevant scenarios include recreation, such as bathing, fishing, hunting and playing on the site or inadvertent intrusion, for example, for collection of lost buried objects.

Notwithstanding the importance of particular scenarios for any specific site, the radiological impact assessment should cover all the likely pathways and exposure situations that may arise from the proposed use.

Potential impacts can be calculated using various models and computer codes. The quality of the resulting assessment is strongly dependent on the quality of input data. If post-restoration monitoring is carried out long after the restoration, insufficient data may be available. The necessary information may therefore need to be gathered from later investigations.

2.3. POST-RESTORATION MONITORING STAGE

The final stage in the restoration of any contaminated site is the post-restoration monitoring stage. Normally, this stage would be planned from the outset as an integral part of the overall site restoration plan. As such it will be refined in the light of information gathered in earlier stages. However, in some cases it can be a stand-alone step. This could occur when the final monitoring is carried out a long time after completion of the remedial works or when this monitoring is carried out independently of the restoration team, as on behalf of regulatory authorities.

The key actions in the post-restoration monitoring stage are:

- (a) the responsible party (a State organisation or a private owner) shall appoint the project manager for the work and define his responsibilities;

- (b) the project manager shall be responsible for selecting an optimum strategy for the post-restoration monitoring. This will involve obtaining the prior agreement of the regulatory authority on the restoration criteria, background levels and sampling design to be used;
- (c) the project manager shall be responsible for developing a plan for all activities necessary to implement the optimum strategy;
- (d) the project manager shall establish a team of specialists and perform the work according to the plan;
- (e) if the restoration criteria are not met or if compliance with the restoration criteria cannot be demonstrated, the owner should perform an analysis of the reasons for failure. Adequate corrective measures should then be taken;
- (f) after all work is done, a final report shall be prepared and submitted to the appropriate regulatory authority for approval. The regulatory authority may conduct its own checks;
- (g) if it is demonstrated that the site conditions comply with the criteria, the project may be terminated after regulatory acceptance. This could involve issuing a licence, in which conditions, including ongoing monitoring and restrictions, on future use of the site, are stipulated;
- (h) the final decision may be supplemented by a public presentation of the results. This will enable all stakeholders, e.g. representatives of the owner, the regulatory authority, local organisations, and public interest groups, to view the results of the project.

2.4. CHOICE OF AN OPTIMUM STRATEGY

The project manager must consider and have some basic information about the following in order to produce the optimum strategy:

- knowledge of all involved parties and all applicable regulations;
- the restoration criteria and the final licensing condition;
- planned use of the site;
- details of the remedial works undertaken;
- availability of any documents that may be relevant to performing the radiological monitoring.

This information is needed to:

- limit the extent of the monitoring by selecting those methods that are most appropriate to past, present or future radiological activities conducted at a site;
- prevent redundancy in measurements or locations to be monitored; and
- provide information to facilitate or supplement the radiological monitoring.

Examples of pertinent information that might be required are:

- relevant historical documents of radiological activities at a site;
- results of previous aerial or ground level radiological monitoring;
- documents of land ownership;
- maps, diagrams and photographs;
- geological, hydrological, topographical and meteorological data; and
- relevant private or state activities that are planned for the site.

This information may be obtained from previous or current site owners, official documents, or other reputable sources. The information may prove valuable for preparation of the overall plan, since it can substantially influence the extent and intensity of monitoring efforts.

Relevant factors also include:

- the availability of financial resources and the influence of each task on the overall costs (cost structure of each task);
- capacity of the organisation of the owner to perform all work or whether it will need help of external suppliers. For example, if the monitoring plan requires subsurface investigations, it may be necessary to secure the services of a specialist drilling subcontractor;
- knowledge of available sampling and measuring techniques.

Based on this information, the project manager will optimise his strategy by making choices on the following:

- the type of scanning to be applied to post-restoration monitoring of the remediated sites, depending upon the overall character of the site, nature and distribution of contamination, and the criteria to be met. Some scanning types are briefly mentioned in Section 2.5. More information on individual types is given in Section 4;
- agreement with the regulators on the background levels which would characterise the area (see Section 2.6). These background radiation levels may be collected from various sources. They can be obtained by consulting an appropriate reputable document or historical readings could be taken during the pre-operational radiological monitoring of the site. It is important to decide whether this type of information should rely on historical data, result from previous characterisations or whether new measurements should be provided before or concurrently with the ongoing monitoring;
- the project manager shall select, with respect to site-specific conditions, the optimum sampling and measurement programme. He will also define the required measurement sensitivity in consultation with the regulatory authority. More information on this aspect is provided in Sections 2.7 and 6 and Appendix C; and
- Together with the quality assurance (QA) officer, the project manager will decide on QA procedures (Section 5).

2.5. MONITORING MEASUREMENTS

Comprehensive post-restoration monitoring should provide information that the radiological conditions of the site comply with the cleanup criteria and that no further restoration activities are required. Sufficient measurements, including scanning, and samples need to be taken from the area of interest in order to characterise the radiological condition of the site, including the boundaries of contamination.

The results can then be assessed, supplemented possibly by calculations of the potential residual doses to the affected population. Finally a report can be submitted to the regulatory authorities to confirm that the site can be released for the planned use.

If, however, significant contamination is found to remain, additional measurements may be necessary to determine:

- the radioisotopic composition of the remaining contamination;
- its aerial and vertical extent and location, i.e. three-dimensional spatial distribution;
- an estimate of the volume of contaminated material still remaining;
- the degree of contamination relative to background levels;

- the potential for off-site migration of contaminants;
- estimates of the potential doses to the reference groups.

The monitoring usually consists of the following activities:

1. scanning of the site to locate any residual contamination;
2. systematic radiation measurements and sampling to determine radiation levels on site, so that long-term radiation doses to humans can be estimated;
3. additional sampling and measurements where residual contamination was observed during scanning to determine the identity of the contamination, to further define the areal extent and magnitude of contamination and to determine if radiation levels exceed appropriate criteria;
4. subsurface investigations, potentially including drilling, logging, geophysical investigations and sampling, to determine the vertical extent of contamination and any relevant underground structure, and
5. taking other measurements and samples, such as from groundwater, sediments, vegetation, on and off site, to determine the potential for off-site migration.

2.6. DETERMINATION OF BACKGROUND LEVELS

Cleanup criteria for contaminated sites are presented invariably in terms of the excess of radiation or activity levels above the prevailing background. Hence, it is necessary to determine the local background radiation levels to provide a baseline for comparison with measurements and data collected at a site. Pre-existing background data are used if available and are supplemented by new measurements and sampling as required. In determining background it is necessary to acknowledge that the site and its surroundings could have been impacted by industrial operations on the site. This may have led to low but enhanced levels of certain radionuclides above the original background levels. Remediation to the original background levels could be costly, if the areas involved are large. Therefore, it is important that for each type of measurement or sample taken when monitoring, a comparable reference background radiation level should be determined and used.

Background radiation is the natural radiation in the region in question plus that part of artificial environmental radiation which can be regarded as a normal part of the living environment in the region. Background levels within buildings may differ from those in open land areas, because of the presence of naturally occurring radionuclides in construction materials and the shielding effect that construction materials can provide. Reference levels for indoor background radiation can often be determined by measuring similarly constructed buildings in unaffected regions.

Although no minimum number of background measurements and samples of each type is specified, the number of measurements should be sufficient to achieve the data quality objectives. The background levels are to be compared with total radiation or activity levels in order to determine the net residual on-site activity. Thus the background levels need to be determined with a detection sensitivity and accuracy at least equivalent to those of the values from which they will be subtracted. This can be achieved using the same instruments and techniques, as are used in assessing the final site conditions.

The background levels should be presented in the radiological monitoring report and contained in the discussion of the monitoring results.

2.7. SAMPLING DESIGN CONSIDERATIONS

The degree of certainty required in compliance decisions will influence the number of samples/measurements to be taken and their locations. To determine the type, quantity and quality of samples/measurements required, a structured planning process, such as the data quality objectives (DQO) process [20], can be used to plan the study. The DQO process is a 7-step planning process. It is based on the scientific method, that is used to establish criteria for data quality and developing the sampling and measurement design, i.e. number and field location of samples and measurements. The level of effort associated with DQO planning is based on the complexity of the study. Use of the DQO process can improve the sampling and measurement effectiveness and efficiency. Hence compliance decisions, made with the use of statistical tests and detector scanning, can be defended more readily. The process can also reduce the cost of the sampling and measurement programme by reducing unneeded or overly precise data.

There are a number of different types of sampling and measurement programmes or designs that may be used. They include:

- **complete sampling/measurement:** measuring at every location or all of the material within the given area;
- **sampling/measurement based on judgement:** choosing to measure at locations known historically or on the basis of expert opinion to be special, i.e. generally the most contaminated;
- **simple random sampling/measurement:** choosing the sampling locations randomly throughout the area such that all locations have the same probability of being chosen;
- **stratified random sampling/measurement:** choosing samples randomly but at different spacing for different parts of the area. This depends on some historical knowledge, and
- **systematic sampling/measurement:** choosing the first sample randomly and others at a specified spacing.

Complete sampling will clearly give the most comprehensive information on the site. However, this can be very expensive and a high proportion of this information can be obtained with much less sampling. The other kinds of programmes sample less completely and give less perfect knowledge about the site. Sampling based on judgement makes use of prior knowledge about the site and may result in the minimum level of effort. However, it will not be reliable if the prior knowledge is incomplete or erroneous. Decisions based on such sampling are a matter of professional judgement.

In situations where complete sampling is not practical and sampling based on judgement is not reliable, quality decisions can still be made efficiently. To do this the samples or measurements are made at locations selected on a triangular or square grid pattern or randomly. Descriptions of different random sampling schemes and the key considerations in their selection have been reported [20, 21, 22].

In more complex sites, a first step in developing an integrated sampling, measurement and scanning design for surface soil or the surface of walls, floors and ceilings of buildings is to classify the site into areas. This can be done, taking into account contamination potential, whether the residual radionuclide concentrations are likely to be uniformly distributed or small areas of elevated contamination are likely to be present. Information obtained from preliminary monitoring concerning the heterogeneity of the radionuclide contamination over

space, including the potential for small areas of elevated concentrations, is crucial for classifying areas. The following three classes are used in [23]:

- Class 1 Areas:** Areas that have or had prior to remediation, a potential for radioactive contamination or known contamination. Areas containing contamination in excess of the compliance criteria prior to remediation should be classified as Class 1 areas.
- Class 2 Areas:** Areas that have, or had prior to remediation, a potential for radioactive contamination or known contamination, but are not expected to exceed the compliance criteria value.
- Class 3 Areas:** Any impacted areas that are not expected to contain any residual radioactivity, or are expected to contain levels of residual radioactivity at a small fraction of the criteria value.

Class 1 areas have the highest potential for contamination and therefore receive the highest level of monitoring effort, followed by Class 2 and then Class 3. For example, it is recommended in [23, Table 5.9] that Class 1 areas are monitored 100% over structures and land areas. Class 2 areas would be monitored from 10% to 100%. Scans in Class 3 Areas are to be conducted on the basis of judgement. Both Class 1 and 2 areas have samples collected and direct in situ measurements conducted on a triangular or square grid pattern. Class 3 areas may have direct measurements made at randomly selected locations. Reference [23] may be consulted for additional information on scanning design.

If the area being evaluated for compliance with criteria values is large, the area may be divided into relatively small units for monitoring. If this is done, then a separate decision may be made for each unit based on samples and measurements made on a grid system as well as radiation scanning, all conducted within the unit. The size of the monitoring units may be determined, based on classification (Class 1, 2 or 3), exposure pathway modelling assumptions and site-specific conditions. Portions of the site with different classifications should not be included in the same monitoring unit.

The sensitivity required of detectors for scanning surface soils in situ for small areas of elevated radionuclide concentrations, i.e. hot spots, must also be determined. The grid spacing may be reduced and samples and measurements may be made on the new spacing if necessary. The number of samples and direct measurements that should be collected is discussed more fully in Appendix C.

3. PLANNING AND MANAGEMENT OF POST-RESTORATION MONITORING

3.1. PRELIMINARY ACTIVITIES

Development of the monitoring plan will be the responsibility of the project manager. The plan will be organised into discrete steps to ensure an orderly progression of work and minimise costs. Upon completion of each step, the project manager proceeds to the next step and co-ordinates subsequent activities. The different steps in development of the plan are shown in Figure 2.

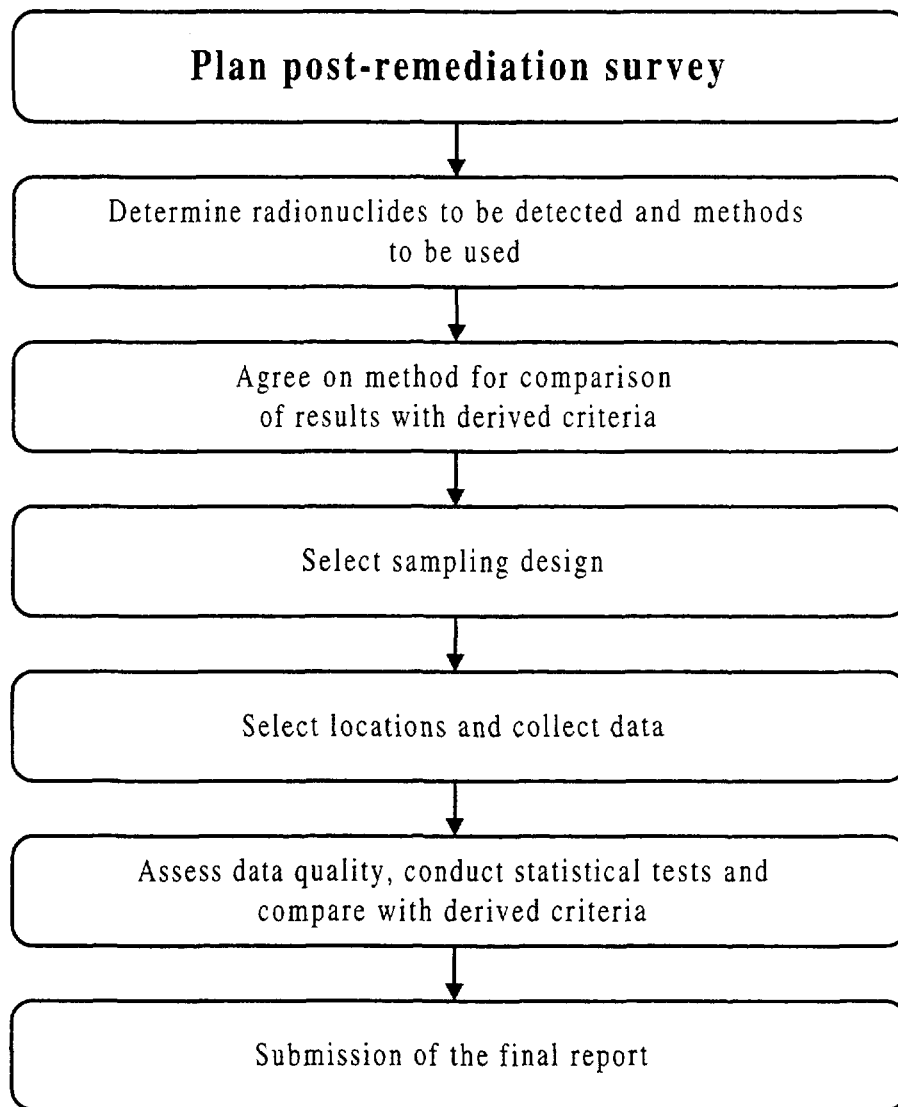


FIG. 2. Development of the monitoring plan.

The first step consists of reviewing records and any other information relevant to the site involved, i.e. the pre-restoration monitoring results including the type and levels of contamination found, the restoration activities performed and the residual contamination that might be anticipated. Results of previous radiological monitoring provide a basis for subsequent decisions.

Upon completion of the post-restoration radiological monitoring, a report will be prepared and submitted to the appropriate regulatory authority. This will document all pertinent information gathered during the monitoring process. It is intended for use by the regulatory authority, contractors, property owners and/or appropriate public bodies. The report may include estimates of potential residual doses to the public and critical groups. It will also include conclusions drawn from monitoring information including any recommendations for further remediation or ongoing monitoring.

In any remediation project, potential doses are determined by gathering appropriate data regarding on-site conditions and usage, as well as obtaining sufficient radiological

measurements to determine average and maximum radiation levels. Thus the potential for radiation exposure to site occupants is determined. By knowing the various exposure pathways from specific radionuclides, the likely occupancy factors and radiation levels, long-term radiation doses to these occupants can be estimated. If the results of the post-remediation monitoring deviate from the assumptions made for the original dose and risk assessment, another assessment based on new data may be necessary.

3.2. PLAN DEVELOPMENT

The radiological monitoring plan summarises pertinent information about a site to be monitored and presents a detailed description of the methods to be used.

Planning activities should include:

- (a) summary of all pertinent historic data about the site concerned (Section 2.1);
- (b) identification of key radionuclides, their pathways and the contaminated media (Section 2.2);
- (c) specification of cleanup criteria agreed with or imposed by the regulatory authority, with details of their conversion into measurable quantities, i.e. dose rates, specific activities, that should be used to demonstrate compliance (Sections 2.7, 3.5);
- (d) identification of the type of measurements and samples needed.
- (e) selection of appropriate instrumentation/measurement methods to be used to estimate the radioactivity present in the environmental media (Section 4);
- (f) establishment of personnel requirements, types of expertise and level of training needed in order to conduct measurements (Sections 3.2, 3.3);
- (g) definition of comprehensive QA programme (Section 5) including documentation;
- (h) assessment of potential health and safety hazards and specification of procedures, etc., for eliminating or minimising such hazards;
- (i) establishment of statistical tests to demonstrate compliance with the criteria and ALARA requirements (Section 6);
- (j) assessment of measurements as the plan is executed (Section 6);
- (k) identification of reporting procedures (Section 3.8); and
- (l) identification of formats for preliminary and final reports (Appendices A and B).

3.3. ORGANISATIONAL STRUCTURE, ROLES AND RESPONSIBILITIES

A well planned post-restoration monitoring programme will require a clear strategy and a team capable of fulfilling the planned task. The programme plan will address issues, such as worker and environmental protection, preparation of detailed plans, time schedules, field work, training and other technical and administrative aspects. To implement the plan, appropriate personnel need to be recruited and assigned responsibility for the key functions. Specialists should be selected with the appropriate technical and professional skills and knowledge, coupled with relevant practical experience.

A typical organisation chart on such a team is given in Figure 3. One typical example of organisational issues in a remediation project is given in Ref. [24].

Interactions with regulators and other relevant outside parties will be decided on a case by case basis. The project manager is responsible for defining internal roles, responsibilities and interactions, as shown in Figure 3.

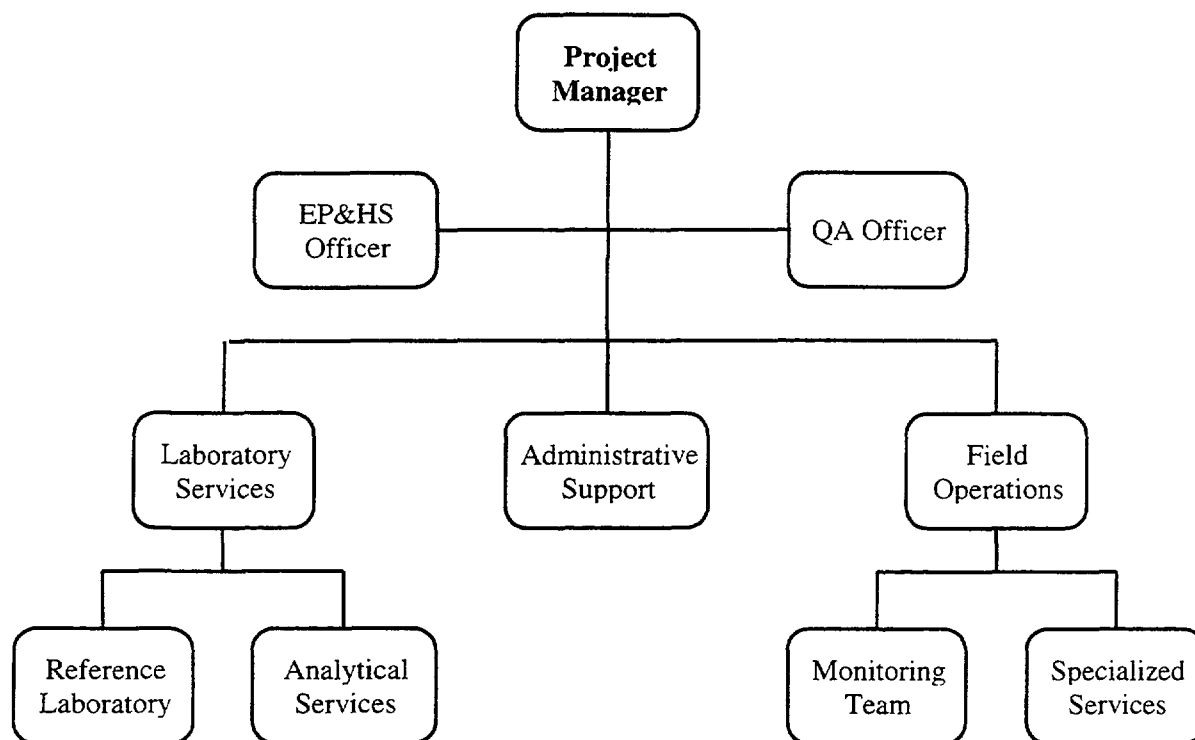


FIG. 3. Organisational chart for post-restoration monitoring team.

The first step is to identify and appoint a qualified project manager, who would act on behalf of the owner and be in charge of all aspects of the programme. The owner, however, still remains legally responsible for achieving the final decision on the future use of the site.

The project manager is responsible for the preparation and execution of the plan, and appoints key staff, defines their job specifications and identifies work responsibilities.

The monitoring team should include staff having the required skills, qualifications and experience necessary for the task to be undertaken. Training programmes should be established to ensure that the staff are appropriately qualified. Records should be kept to demonstrate that the training has been completed. It may be advantageous to recruit personnel from amongst employees, who have participated in site characterisation activities, in order to gain the maximum benefit from past experience.

The QA officer reports to the project manager on all QA aspects of the programme. These include appropriate record-keeping, such as storage of all field data, training records, etc. The environmental protection and health and safety officer will be responsible for all aspects of health and safety and environmental impact associated with the field workers. This will include estimation and measurement of doses and dose rates to workers and the general public. Duties will also include assessment of doses potentially incurred by the population through various environmental pathways and comparison of results obtained with the prescribed cleanup criteria.

The field measurements of radiological parameters and sample collection will be the responsibility of the chief of field operations. Some field work, particularly if it involves subsurface sampling requiring specialised drilling and coring, may have to be done by external contractors. In all cases adequate training must be given.

The laboratory measurements will be the responsibility of the Chief of Laboratory Services. Laboratory services may have to be subcontracted. Ideally, these should be provided by an experienced, reputable laboratory capable of analysing all required characteristics of supplied samples.

3.4. CONTRACTORS

Post-restoration characterisation can require the use of a range of specialist personnel and equipment for particular tasks. Frequently such skills will not be available within the main restoration contractor's organisation and they will need to be provided by suitably qualified and experienced external contractors. Examples of tasks which might be undertaken by such contractors include special radiochemical analyses, subsurface sampling and characterisation involving drilling and geophysical investigations. Such sub-contractors need to be recruited against a list of specifications that define the work to be undertaken, contractor qualification requirements, applicable quality assurance standards and systems, etc. Clearly defined interfaces need to be specified for interactions among sub-contractors, the project team and other involved parties, such as the owner and regulatory bodies, to ensure efficient management of the sub-contractors tasks.

3.5. INTERACTIONS WITH EXTERNAL STAKEHOLDERS

The owner and project manager will be responsible for defining roles and responsibilities for external interactions. External interactions include those with local, regional and state authorities, applicable regulatory bodies, academic institutions and various public interest groups. Whether the owner, project manager or both assume responsibility for external interactions should be decided "a priori", and will likely vary with the local situation. In many cases, it will be helpful to develop an external communications plan which would clearly describe the roles, responsibilities, accountabilities and authorities involved.

3.6. HEALTH AND SAFETY

As with earlier stages in the site restoration process, the post-restoration monitoring should be planned and maintained to ensure adequate protection of the health and safety of the workers and others both on- and off-site. Residual levels of radioactivity during the post-restoration monitoring should be below the criteria.

The main health and safety issues during the final monitoring are likely to be the common industrial hazards found at construction sites. These include excavations, enclosed work spaces, sharp and falling objects (drop hazards) and potentially exposed services, e.g., electrical, gas and water supplies. The plan for monitoring should, therefore, include requirements and procedures for eliminating and minimising such potential safety hazards.

3.7. COSTS

The cost of post-restoration monitoring depends upon the type and number of measurements and number of samples requiring analysis. The cost of monitoring a large, complex site will greatly exceed that for a small site, which handled small quantities of a limited number of radionuclides.

Major costs can be attributed to labour and materials. Additionally, services such as analytical measurements, drilling and coring, aerial land monitoring and travel expenses could constitute a significant cost.

A time schedule for the entire post-restoration monitoring programme is necessary to estimate the total costs of the project. Each task of the project should be included in the schedule and the associated costs should be estimated separately.

As an example, the effort required to monitor a half hectare (5000 m²) site without buildings might be in the range of 1–6 person•weeks. A site of the same size with structures may require more than twice as much effort, particularly if alpha measurements are required [8].

Materials required to perform a post-restoration monitoring include sampling tools, sample containers, plastic bags, signs, labels, photographic films, protective clothing, etc. It is difficult to estimate the costs for a typical monitoring programme, because costs depend on the number and types of samples. However, other costs will far exceed the costs of materials. An error in estimating material costs will have little bearing on the total estimated cost for monitoring.

Purchase of instrumentation to perform radiological monitoring and analyse samples would require a large capital outlay. For a large, complex site, the following instrumentation and equipment may be required:

- airborne instruments;
- portable monitoring instruments;
- automated monitoring systems;
- laboratory detectors and electronics;
- sample analysis system;
- sample preparation equipment; and
- miscellaneous supplies and equipment.

In some cases, setting up on-site or mobile laboratories can be useful.

The cost for obtaining surface soil samples largely reflects the cost of the labour used. A relatively minor investment will cover the cost of sampling tools. Obtaining subsurface samples requires additional effort and expenditure. If depths below 3-5 m have to be sampled, a motorised drilling rig will usually be required.

Occasionally, it is necessary to drill through asphalt, concrete or some other barrier to reach soil that needs to be sampled. Such drilling requires specialised equipment and costs are considerably higher than for soil sampling alone. In addition, holes drilled in such barriers will usually require infilling so as to restore the surface. This will generally increase the total costs for this sampling.

Analytical costs are a major expense and are subject to a great variability, depending on the type of analysis, the number of samples and the level of radioactivity to be assayed. Analysis of a sample for a single radionuclide may present little difficulty, while analysis of the same sample for a large number of radionuclides would be difficult and, consequently, expensive.

Part of the samples taken may have to be treated as radioactive waste. The costs for handling, storage and management of these wastes will have to be charged to the project.

After a site has been monitored and samples collected and analysed, the data must be evaluated and presented in a report which documents the findings. The labour associated with interpreting the data and preparing the report has to be completely evaluated. In addition to the costs of labour, those of materials, such as paper and film, and services, such as typing, printing and copying, should be added.

3.8. REPORTING

Upon completion of the radiological monitoring, the owner will prepare and submit a preliminary report to the regulatory authority, summarising significant findings. The purpose of this report is to give the regulators an opportunity to examine the initial findings from the monitoring, provide feedback on the interpretation of results and to agree on any necessary further work and/or interpretation before submission of the final report. The size of the report may vary, but it should contain the necessary text, figures (including details and a general view of the site) and any pictures that support the findings. Pertinent historic data, such as previous monitoring or certifications, should be referenced or appended to the report. The report should be prepared consistent with local requirements. As an example it could be divided into sections including: Introduction, Site Description, Monitoring Strategy, Design, Procedures, Results, Conclusions, Recommendations and Appendices.

The owner will also be responsible for preparing a comprehensive final radiological monitoring report to present the complete monitoring results and all information and data relevant to past and present radiological conditions of a site.

Examples of formats and contents of radiological monitoring reports are presented in the Appendices A and B [25].

4. MONITORING TECHNIQUES (MEASUREMENTS AND SAMPLING)

4.1. GENERAL

Post-restoration monitoring is performed to detect and quantify any residual contamination and to compare the results with the remedial goals and criteria. It may be carried out using field radiation measurements and by collecting samples with subsequent laboratory analysis. The field measurements may be carried out during scanning, at discrete locations or by means of aerial or ground based (mobile) automated monitoring systems. In the case of laboratory measurements, the frequency, location and technique of sampling need to be considered in addition to the capabilities of the laboratory.

Instruments and methods to be used for these purposes can be selected using the strategy presented in Fig. 4.

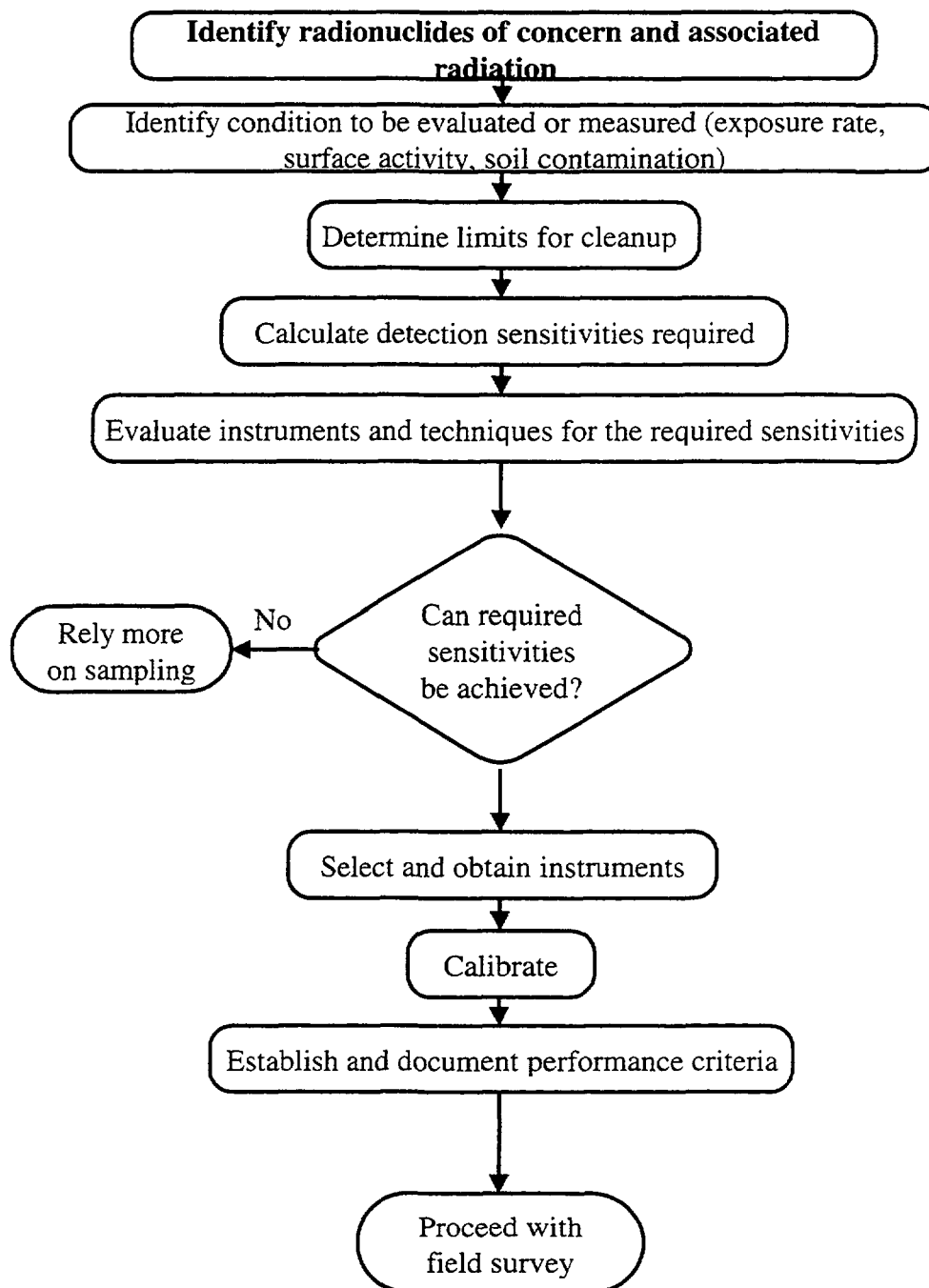


FIG. 4. Strategy selection.

4.2. IN SITU RADIATION MEASUREMENTS

4.2.1. Scanning

In scanning radiation detection instrumentation is moved continuously to measure the radiation levels of a surface. It may be performed easily for gamma radiation and with more effort for alpha, beta, beta-gamma and low-energy X radiation. The type of measurement, suitable instrumentation and the specific methodology for performing the measurements can be selected after consideration of the type of radioactive contamination present, the instrumentation available and the degree of surface coverage needed to meet the objectives of the monitoring plan.

Scanning is performed by moving the monitoring probe over a surface, whilst observing or recording the instrument response. The monitoring method must be carefully selected for specific conditions. The monitoring characteristics are defined, based on required detection probabilities, source strength and instrument performance. The detector output and hence the sensitivity depend directly on the scanning rate. The magnitude of this relationship should be known as contaminated material could be missed, if the rate of scanning is too rapid.

During scanning to identify and delineate contamination, the probe should be kept close to the surface. Any observation of significant changes in ambient radiation levels, either visually in the instrument ratemeter or, more typically, in the pitch of audio response in the instrument headphones, should be noted or registered automatically. These radiometric anomalies can be investigated further using additional local measurements and sampling to define the extent and magnitude of contamination. Scanning intended to measure potential radiation dose is performed with the probe at a known distance from the source in order to be representative for the dose.

As scanning requires the operator to observe and interpret instrument response, it can lack objectivity. Scanning is used to gather general radiation information in areas and to delineate 'hot spots'. As it does not always correlate locational data with measurements, it may lack reproducibility. To overcome this deficiency, either location parameters should be recorded with each measurement or measurements may also be taken at discrete, defined locations. This may be improved using automated monitoring systems.

4.2.2. Measurements at discrete locations

Measurements at discrete locations refer typically to the recording of radiation measurements at points on a predefined sampling grid. Such a grid should be referenced to a known geographical location. The operator holds the detector at the measurement location for a fixed period of time. The detector is commonly an instrument that integrates the counts over the selected time. Increasingly, these instruments have the capacity to store results for later computer processing. When averages over several days or months are needed, integrating dosimeters can be left at the measuring location to be collected after the integration time. This applies in particular to radon exhalation monitoring at locations with uranium or radium contamination.

4.2.3. Automated monitoring systems

Large quantities of data may be generated during monitoring and sampling activities. Three kinds of information are generated for each measurement made: the measurement itself, the location of the measurement and supporting QA information. Traditionally measurements have been recorded manually by marking at the proper location on a map or monitoring form. Data identifying instruments used, their calibration and the measurement date are normally included along with the signatures of the persons making and approving the measurements. Generally, about as much time is taken to record the data as is used to make the measurements.

Some techniques have been developed to speed up this process [26, 27]. New instruments are able to record measurement data directly into a computer or to store it for later computer processing. Some systems enable simultaneous recording of location and measurement. An example, using a vehicle-mounted scintillator with a global positioning radiometric scanner system is given in Ref. [28].

4.2.3.1. Aerial monitoring

Aerial monitoring is conducted for a variety of scientific objectives. For purposes of post-restoration monitoring, the following applications can be considered:

- high altitude aerial photography;
- multispectral photography;
- large area radiological mapping;
- multispectral aerial scanning; and
- airborne gas and particulate sampling.

Aerial photography can help to document a general overview of large restored areas. Although various aerial techniques have been used in the case of nuclear accidents, radiological mapping and/or scanning can also be a useful tool for monitoring large contaminated areas which have undergone restoration. Such monitoring is conducted usually in the first stages of the overall post-restoration monitoring. The objectives are to provide a general overview of the site condition and provide preliminary results to focus further land-based monitoring.

A portable data acquisition and real-time analysis system which displays to the operator all required radiation and system information in real time performs the data collection, data analysis, data display, position and steering calculations and data recording.

The monitoring can be carried out using either fixed wing aircraft or helicopters. The latter have the advantages of being able to traverse the area more slowly and at a lower and more accurately controlled height. Thus they provide greater sensitivity and accuracy, but generally at greater cost.

4.2.3.2. Ground based (mobile) monitoring

Several automated ground-based monitoring systems have been developed for the collection of radiation data. These systems generally collect discrete measurements with a near 100% coverage of the scanned area.

Ground based automated systems typically use NaI(Tl) gamma scintillators in conjunction with data handling systems capable of correlating count rate data with appropriate location information. Variants of automated monitoring systems have been developed using on and off road vehicles, push carts and back packs to house instrumentation in order to monitor all types of terrain.

A mobile system may identify radiometric anomalies by comparing the instantaneous count rate information with a background level established for the area being scanned. Various methods of data analysis are used to discriminate in favour of radionuclide contaminants of concern. These include multichannel analysis capabilities and statistical analysis of the input data. Documentation of monitoring results is typically in the form of strip charts, contoured areal plots or computer-generated data summaries.

Mobile scanning requires that the vehicle travel speed and source-to-detector distance be optimised to achieve the desired sensitivity and monitoring coverage.

Key operational considerations are:

- scanning speed (0.8 to a few km/h)
- scanning swath (0.5 to several meters)
- estimated minimum detectable activity
- manpower.

Scanning speeds and other parameters can be changed to decrease the time required to scan the areas or to increase detection probability. Other types of detectors, such as intrinsic germanium detectors can be used. These are capable of detecting low energy photon radiation, such as that associated with ^{241}Am . They are also more suitable for spectral analysis.

Sodium iodide (NaI) detectors are widely used in detecting naturally occurring radionuclides and transuranics. ^{226}Ra has only a small gamma peak at 186 keV which is difficult to measure, but the NaI detectors can count radon daughter gamma peaks related to ^{226}Ra . Radon is a gas. The fraction of its decay-products which remain in the soil depends on the relative rates of its diffusion out of the soil and decay to daughters. The emanation rate from the soil depends on several factors including soil moisture, source depth distribution, soil Rn emanating fraction, barometric pressure, soil density and composition. Calibration of the detectors must take these variables into account so that Rn daughter gamma peaks can be accurately related to ^{226}Ra soil concentration under field conditions.

Mobile monitoring systems have the advantages of providing rapid scanning, automatic monitoring of location, 100% coverage of verified area with audible evidence of presence, automatic mapping of location, radiation level and standards conformance data at any time during or after scan. Electronic storage and processing of data can increase objectivity in interpretation. They are much less affected by operator perception and are capable of determining gradual changes much more efficiently. The mobile scanner can be used for final verification to demonstrate that restored sites are clean to the required level of assurance. These systems have a potential use to detect subsurface material through multichannel analysis or hydraulically driven probes and include a 3D plotting capability to display subsurface contours.

These techniques do not completely replace laboratory analyses, but reduce the quantity of the latter required. Laboratory analyses can take both considerable time, e.g. one or more weeks, for testing and return of data, and be expensive relative to labour costs. Hence, their use should be optimised. Their samples would require digging and special shipping and handling considerations.

4.2.4. Instruments

Various detection instruments are available to measure contamination. They differ in many respects, including detector area, mechanism of detection, sensitivity to radiation, data handling features and the ability to measure various types of radiation separately or concurrently. Brief characteristics of the individual techniques for in situ monitoring are summarised in Tables I–III (from [13], converted to SI units).

TABLE I SIMPLE MONITORING INSTRUMENTS

Application	Detector	Characteristics	Remarks
alpha emitters	proportional - various window sizes	0.4 to 3 Bq/100 cm ² sensitivity for scanning	sensitivity depending on type of surface
	scintillation	3 Bq/100 cm ² sensitivity for scanning	sensitivity depending on type of surface
beta emitters	proportional - various window sizes	3 Bq/100 cm ² sensitivity for scanning	sensitivity depending on beta energy
	Geiger-Mueller	3 Bq/100 cm ² sensitivity for scanning	sensitivity depending on beta energy
gamma emitters	Geiger-Mueller	measurement at 50% above background (50-100 nSv/h)	better sensitivity with time integration
	proportional	measurement at 50% above background (50-100 nSv/h)	better sensitivity with time integration
	scintillation	measurement at 50% above background (50-100 nSv/h)	better sensitivity with time integration

Note These instruments can be used for scanning or in a time integration mode for increased precision during direct measurements

TABLE II RADIATION DETECTORS FOR EXPOSURE RATE (OR DOSE RATE) MEASUREMENTS

Application	Detector	Characteristics	Remarks
active	pressurised ionisation chamber	<100 nSv/h sensitivity	high precision
	Geiger-Mueller	100 nSv/h sensitivity	energy compensation needed
	proportional	100 nSv/h sensitivity	energy compensation needed
	scintillator	<100 nSv/h sensitivity	dual phosphor or tissue equivalent for flat energy response (used in current mode)
passive	thermoluminescence dosimeter	<50 nSv/h in 1 month	good for wide area deployment
	film badge	100 µSv/month	sensitivity not sufficient for background measurements
	electret ionisation chamber		measures radon as well
active/passive	electronic dosimeter		good for personal monitoring

TABLE III. FIELD RADIATION DETECTORS FOR NUCLIDE-SPECIFIC MEASUREMENTS

Application	Detector	Characteristics	Remarks
alpha emitters	sealed, large-area proportional counter	Minimum detectable activity (MDA) of 0.3 Bq/g or 2 Bq/100 cm ²	used as X ray spectrometer
	FIDLER (Field Instrument for Determination of Low Energy Radiation)	MDA of 70 Bq/100 cm ² for Pu mix	can be used for scanning, detects X rays
	array of Si or Ge crystals	MDA of 0.03 Bq/g for Pu mix in 1 hour	detects X rays or 60 keV line from ²⁴¹ Am
beta emitters	scintillating fibres	MDA of 0.2 Bq/g for ⁹⁰ Sr in 1 minute	provides some nuclide/energy discrimination
gamma emitters	NaI gamma spectrometer	10 × 10-cm crystal measures background nuclide concentrations in minutes	low energy resolution
	Ge gamma spectrometer	larger types can measure 0.004 Bq/g in 10 minutes	high energy resolution

Detectors to measure **alpha and beta** radiation — thin-window GM tubes have only 10–30% efficiency for medium-energy beta particles and allow measurements at or below 5000 Bq/100 cm². To measure alpha radiation alone or clearly separate alpha and beta radiation, pulse ionisation chambers, proportional counters or scintillators should be used. The type of surface, surface roughness, humidity and permeation depth influence the detection efficiency.

One development, known as LRAD (long-range alpha detection), detects alpha radiation by collecting the ions generated in air. The technique is reliable for contamination down to 50–70 Bq/100 cm², but the sensitivity can be increased by using a large-area detector (1 m²). Such detectors have been reported to have a statistical error of 0.08 Bq/g for the top 30 µm of soil and 5-min counting time [29].

Another development is the position-sensitive proportional counter (PSPC) which, instead of extracting the signal from one end of a collector, collects signals from both ends and can indicate the position of the particle [30].

For **gamma** measurements, plastic scintillators are widely used because their costs are significantly lower. Plastic scintillators are largely unable to distinguish effectively between gamma rays of different energies. Hence, the technique is most applicable, where only one or two emitting gamma isotopes are likely to be present. NaI detectors provide the highest sensitivity and can readily detect down to less than 0.04 Bq/g for ⁶⁰Co or ¹³⁷Cs. However, hyperpure Ge detectors provide much higher resolution of gamma energies. Some of these detectors were integrated together with a collimator in a scanning instrument allowing detection of hot spots in a complex area. The instrument is placed some meters away from a structure or building and by tilting and swivelling the detector head a two dimensional image of radiation intensity can be generated. For low energy X rays, the detection efficiency is influenced by the type of surface, surface roughness and penetration depth.

Dose rate measurements in the 1–2000 $\mu\text{Sv/h}$ range can be made using various detectors. The most reliable are portable ion chambers and compensated GM detectors, which are sensitive enough to detect radiation exposure rates below 0.2 $\mu\text{Sv/h}$. The high-pressure ionisation chamber is most efficient, but is heavy and bulky, so limiting portability. The portable NaI scintillation detector (sometimes referred to as a micro-R-meter) is much smaller, but is energy dependent and generally responds at low energies (less than 200 keV).

Neutron measurements are useful for determining the amount of fissile material and transuranium elements present. The techniques are much more sensitive than gamma measurement techniques for the same isotopes because both the energy and intensity of the gamma ray emissions are often too low and are absorbed in the material.

Measurement of fast neutron coincidences is very useful for determining a number of transuranics, including most notably Pu. By combining these with gamma measurements, the whole spectrum of actinides and transuranics can be determined.

4.2.5. Spectroscopic monitoring (nuclide specific measurement)

Portable gamma spectrometers can be used to determine radionuclide specific contamination in soils by in situ measurements. Spectroscopic instruments find application in measurements at discrete locations, in scanning, in automated monitoring systems and in borehole logging. Both germanium and sodium iodide detectors have gained widespread use for site characterisation work. In situ gamma spectroscopy measurements are typically used to augment soil sampling programmes, reducing the overall number of samples required. The measurements may provide immediate estimates of the contamination and, as laboratory tests are lengthy and costly, in situ spectroscopy may give advantages.

Spectroscopic monitoring can be used at several levels of complexity. The most simple will be a back-pack NaI-detector and the more complicated would be systems combining different detectors with sophisticated software. Figure 5 shows the schematic layout of one of the latter instruments with NaI and Ge detectors.

Spectroscopy systems are able to determine depth profiles of the contamination in the soil to a certain degree [31].

4.3. SAMPLING AND LABORATORY MEASUREMENTS

4.3.1. Media sampling techniques

During post-restoration monitoring, most samples taken to verify compliance with the cleanup criteria are solids and liquids. Air samples are usually taken to detect hazardous or toxic chemicals. Radiological air samples are taken for worker protection purposes and to evaluate the remaining risk of exposure of the public due to resuspension of contamination. However, air/gas sampling may also be necessary to verify that contaminants in ambient air at the site boundary are consistent with emissions data and compliant with regulations.

Sampling liquids in surface waters, wells, water impoundment's, etc., is generally straightforward because liquids are homogeneous or can be made so by stirring or sparging. Even when this is not practical, samples can be taken from different areas and depths to assess the variation within the medium. Composite samples can be taken to assess the average

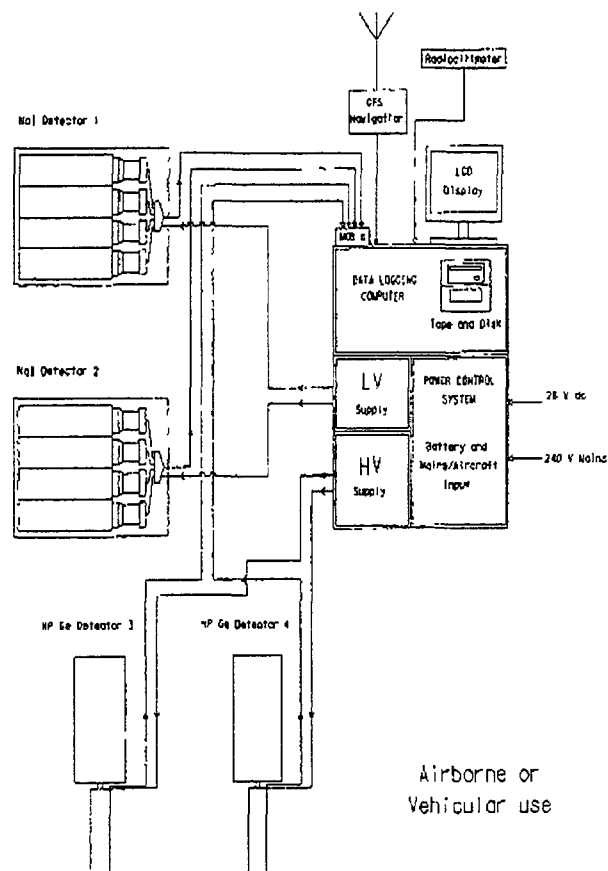


FIG. 5. Environmental gamma-spectrometer.

composition. Liquids can be sampled using various equipment, including weighted bottles, grab samples, syringe samplers, dippers, pumps or remotely operated submersibles (for pond-floor sludges).

Solids sampling is more complex, as the physical form and characteristics of the solids may vary considerably, i.e. the solids may be viscous or sticky, granular or monolithic. In the case of monolithic solids, the sample must be cut out or otherwise removed from its environment. Sampling techniques need to be selected on a case by case basis, because the needs and techniques are so varied. Some techniques commonly used for sampling solids are:

- auguring with sampling from the flights (for soils);
- hollow-stem auguring and split spooning (for soils);
- core drilling (for concrete and rock);
- core drilling or trepanning (for metals);
- shovelling or scooping (for granular material);
- scraping (for surface layers);
- collecting drilling debris (for concrete or metal); and
- using a trier (for soil and sticky solids).

Other measurements, samples, and/or methodologies may be required to fulfil the design objectives of the radiological monitoring. Some of these will be required for determining long

term health effects to the public from environmental pathways. The measurement or sample type selected is specific for the site, the radionuclide and for the radiation dose of concern. These activities should be selected during the preparation for the radiological monitoring or as extraordinary conditions arise during the monitoring. Often these samples or measurements are collected to indicate potential migration of contaminated material from a site.

Measurements may include:

- radon flux rates and exhalation monitoring [32];
- alpha or gamma spectrographs of surfaces, air or liquids to identify the type of contamination;
- alpha, beta or gamma activity in drains, pipes or equipment;
- chemical, hydrological or meteorological conditions on or near a site.
- long-lived radionuclide content in the air or airborne particulate samples;
- alpha, beta or gamma activity of particles in water samples;
- alpha, beta or gamma activity of radionuclides present in building equipment, construction materials or process product;
- radionuclide content of off-site water and sediment samples from sources of standing or running surface water; and
- radionuclide content of samples from the food chain, e.g. vegetation, dairy or poultry products, fruits and meats.

The purpose, methods used and results of these samples and measurements should be reported or referenced in the monitoring report.

4.3.2. Sampling frequency and location

If a grid system has been established over an area, discrete radiological measurements or samples may be taken at the grid points. These measurements can provide definitive radiation levels at precisely defined locations. Furthermore, if the distribution is normal they permit the calculation of mean radiation levels within a given area by averaging individual measurements. The variance about the estimated mean will depend on the degree of heterogeneity remaining. These values can then be used for comparison with other areas or to estimate potential doses to people occupying that area. Grid point measurements may include alpha, beta, beta-gamma, low-energy X ray and gamma radiation. Samples taken typically include soil and routine surface smears. The type of measurement, suitable portable instrumentation and specific methodology to perform the measurement should be selected on the basis of the type of radioactive contamination present, the instrumentation available and the objectives of the monitoring plan in relation to the cleanup criteria.

The grid point measurements may be taken by placing the instrument at the appropriate distance above the surface, taking a discrete measurement for some time interval (e.g. instantaneous, 10 s or 60 s) and recording the measurement. If samples are to be taken, they should be obtained as near to the grid point as is reasonably achievable. They should then be labelled appropriately and removed for the required analyses.

Composite samples may be proposed to characterise the average conditions in a medium at a location rather than the variation within the medium. They may also be taken to enhance the local representativeness of samples or to optimise the number of laboratory analyses made. Examples of compositing techniques are available. To prepare composite samples:

- the medium should be thoroughly mixed;
- samples taken from different parts of the medium should be appropriately composited; and
- proportionate amounts of solids and liquids should be obtained.

At locations where anomalous radiation levels are observed or suspected, additional radiological measurements and samples may be taken on the basis of professional judgement. The purposes of these measurements and samples are to further define the areal extent of potential contamination and to determine maximum radiation levels within the area. Those measurements may include alpha, beta, beta-gamma, low-energy X ray and gamma radiation. However, at these locations these measurements may also be supplemented with other types of measurements, such as radon flux or gamma spectrographic measurements. Air, water, soil and smear samples may be taken at these locations; samples of vegetation and sediments and radon flux measurements. Such measurements and samples are obtained in the manner specific to the monitoring plan. The locations are selected to define best the areal limits of the anomalous radiation levels. All sample and measurement locations and results are recorded. The type of biased measurements and samples taken and the methodology used to perform those activities should be properly selected within the limitations of instrumentation, site conditions and monitoring objectives.

4.3.3. Laboratory capabilities

In the field, a material can be directly sampled and measured, whereas the analysis in an off-site laboratory utilises sophisticated and often large equipment and/or detailed laboratory procedures. The detection limit for a radionuclide can depend strongly on the activity of other radionuclides present in the sample, the background of the counting installation and the counting times, sample volumes and chemical treatment used. A review of the limits for qualitative detection and quantitative determination can be found in Ref. [33]. Examples of laboratory analyses applicable to a post-restoration project are shown in Table IV. In this table examples of laboratory detection capabilities for individual determinations are summarised as well. These estimated lower limits apply if background, counting time and sample volume have the values as stated in the table. To illustrate the influence of the activity of the sample on the detection limit for gamma spectroscopy: the detection limit for ^{60}Co in a sample (0.25 dm³) with no other activity present is 0.13 Bq, in a sample with a small amount of other activity present it is 3 Bq and if the other activity of the sample is high, the detection limit for ^{60}Co rises to 35 Bq, almost 300 times higher than in the blank sample.

There are possibilities for enhancing the indicated detection limits. However, the consequence is that the number of samples which the laboratory can measure in a given time may decrease. The corollary is that, if a very low detection limit is not needed, sample throughput may be increased.

In some circumstances a mobile or field laboratory may be used to minimise the need to transport samples or to initially screen the samples.

4.3.4. Subsurface measurements and samples

Subsurface investigations consist of measurements and samples taken beneath the ground or floor surface. The purpose of these investigations is to locate subsurface contamination and define its depth distribution. These investigations can be conducted by excavating the floor or

TABLE IV. EXAMPLES OF LABORATORY RADIATION DETECTION METHODS IN AQUEOUS SOLUTIONS

Method	Isotope	Background [cpm]	Counting time [min]	Sample volume [dm ³]	Estimated lower limit [mBq/dm ³]
ZnS scintillator	gross alpha	0.06	200	0.2	22
alpha-spectrometry (PIPS) with chemical treatment	Am, Cm, Np, Pu, ²¹⁰ Po, U, Th	0.00024	1440	1	0.5
beta proportional counter 100 cm ²	gross beta	4	500	0.2	100
beta proportional counter with chemical treatment	⁹⁰ Sr- ⁹⁰ Y	0.3	240	1	10
	⁴⁵ Ca	0.3	240	1	20
	³⁶ Cl	0.3	240	1	10
	⁹⁹ Tc	0.3	240	1	20
Liquid scintillation	³ H	4	200	0.01	5000
	¹⁴ C	7	200	0.01	2500
	⁶³ Ni	5	200	0.05	500
	⁹⁰ Sr- ⁹⁰ Y	10	200	1	30
	⁴⁵ Ca	10	200	1	30
	³⁶ Cl	10	200	1	30
	⁹⁹ Tc	10	200	0.1	300
gamma and X ray spectrometry germanium detector	⁶⁰ Co	low	900	0.25	3000
	¹⁰⁶ Ru	low	900	0.25	13000
	¹³⁴ Cs	low	900	0.25	1600
	¹³⁷ Cs	low	900	0.25	1500
	²²⁶ Ra	low	900	0.25	3000
	²²⁸ Ra	low	900	0.25	5000
Lucas method [34]	²²⁶ Ra	0.06	900	0.5	0.7

ground surface by trenching, auguring, coring, shovelling or other means to depths that are either below a contaminated soil layer, i.e. beneath anthropogenic filling activities, or until a natural sealing formation is reached. The subsurface investigations may include logging or scanning of the vertical surfaces with alpha, beta, beta-gamma, low-energy X ray and shielded or unshielded gamma radiation detection instrumentation including spectrometers.

Excavated material or material from the sides of the vertical walls may be sampled for radionuclide analysis. Water or air in the excavation hole may also be sampled for radionuclide content. The number of excavations and the type of measurements or samples to be obtained with appropriate specific methodology will be selected, based on the type of contamination present, limitations in field conditions, type of instrumentation available and objectives of the monitoring plan.

4.4. CALIBRATION

Calibration is the comparison of the measurement of an instrument with a standard in order to report or eliminate by adjustment any deviation in the accuracy of the item being compared. Instruments used both in the field and in the laboratory must have known and recorded

calibrations. The method of calibration should be according to accepted procedures. Standard reference materials and instruments should be traceable to certified primary standards. The limitations of the calibration must be clarified, so that the limitations of the instruments are known. Operational checks following approved procedures will be applied to check operation between calibrations. Verification of the check procedure may be part of the calibration procedure.

5. QUALITY ASSURANCE

5.1. GENERAL INFORMATION

Assurance of the quality of data obtained and used during any final monitoring of remediated areas is critical for ensuring and demonstrating that cleanup criteria have been met. If the monitoring results have significant regulatory or health and safety ramifications, the monitoring must be subject to the highest quality assurance (QA) standards. If this is not the case, the quality requirements may be less stringent. The objective of QA is to provide confidence in the measurement, sampling, analysis, interpretation and use of data generated for this purpose. This is to be done on a cost effective basis that will not compromise public health and safety. Such quality assurance systems should accord with international standards, e.g. Refs [4, 35].

Quality assurance should start with the original programme design and be maintained at each significant step through to the final decision on whether to release the site totally or in part for unrestricted or restricted use. An effective quality assurance programme will define the data quality objectives of the monitoring. This will then determine the monitoring design to a significant extent.

The first step in developing the QA system for the post-restoration monitoring project will be to appoint a QA officer. He should report to the project manager on quality performance and issues within the project. He will be responsible for ensuring that all QA objectives are met. The QA officer will approve all procedures and working instructions. He will review through surveillance and internal audits all aspects of the monitoring against such defined procedures, in order to ensure that the project's quality objectives are met. This will include review of selected field and analytical data. The QA officer should approve the quality of data before they are used to test whether the cleanup targets have been met.

The project manager will develop a comprehensive QA programme for the project. This will include:

- organisation and structure. This will define the management roles and responsibilities of all key personnel in the project;
- qualifications and training. This will define the necessary qualifications, training and experience for all key personnel in the project;
- design control. This will cover the monitoring design and modifications;
- procurement control. This will cover the selection and purchase of any equipment, materials and services used for monitoring, including subcontractors;
- selection, calibration and maintenance of equipment and materials. This will cover all equipment, which can affect the quality of data produced, and procedures to be used with that equipment;

- verification and validation methods. These will apply to all data, procedures and methods of analysis and interpretation. They will be applied to ensure that all procedures, etc., are appropriate for the tasks being undertaken. In addition, they will confirm correct implementation, in order to ensure that the results obtained are fit for purpose;
- non-conformance and corrective action. This will detail methods and procedures to be used to report and handle any non-conformance's and corrective actions;
- record systems. This will include the safe, proper keeping of all key records, both during and after the project. It will include sample management with chain of custody documentation; and
- auditing. This will include both internal and external checks and audits to be undertaken to confirm that all procedures, etc., are being implemented correctly.

Selected aspects are discussed in more detail below.

5.2. QUALIFICATIONS AND TRAINING

The qualifications required by key post-holders in order to fulfil satisfactorily their functions and administrative responsibilities should be clearly defined. Staff should then be selected with the appropriate qualifications and experience for the tasks which they are to undertake. They should receive or have appropriate training to qualify in the procedures being performed. The extent of training and qualifications should be commensurate with the education, experience and proficiency of the individual and the scope, complexity and nature of the activity. Records of training, including testing to demonstrate qualification, should be maintained.

5.3. DESIGN CONTROL

This will particularly cover the design of the sampling plan for the site. Guidance on design procedures are given in Section 2.7. This aspect of QA focuses on control of that design procedure. It will include documentation of the design principles for the monitoring, details of the methodology and calculations used to determine appropriate number and location of samples. Measuring techniques and any variants resulting from preliminary monitoring, etc., will be included.

5.4. PROCUREMENT CONTROL, INCLUDING SUB-CONTRACTOR SERVICES

Specifications will need to be prepared for any equipment, materials and external services required. These will include any tasks to be undertaken by subcontractors. The extent of subcontractors' use will depend on the availability of resources within the owner's organisation, but could include specialised sampling, analysis, etc. The specifications should define the necessary expertise, experience and capabilities required of the subcontractor for each task. All subcontractors selected and used should be appropriately qualified against these specifications.

5.5. SELECTION, CALIBRATION AND MAINTENANCE OF EQUIPMENT AND MATERIALS

Appropriate instrumentation should be selected for each of the necessary measurements. This selection should be made by specialists appropriately qualified and experienced. The energy response of each type of instrument should be known, so that they can be applied

appropriately to different radiation fields. Once selected, detailed procedures should be used for operating, checking, calibrating and handling of the instruments. Inadequately calibrated instruments could lead to either categorising an area as still contaminated or acceptably clean, when in fact the converse is true. Generally, calibration procedures will be available from the instrument supplier or literature. However, where necessary, new procedures may need to be prepared by appropriate specialists. Test results should be documented and evaluated to ensure that the test requirements have been met. To ensure accuracy, instrumentation should be controlled, calibrated, adjusted and maintained as prescribed at given intervals or prior to use, using traceable standards. In this context, inter-comparison studies between laboratories undertaking these analyses can be beneficial.

5.6. MEASURING, SAMPLING AND ANALYTICAL METHODS

For post-restoration monitoring, the QA requirements are those necessary to ensure that the results of the measurement or analysis are an accurate description of the material or area measured. This assurance can be provided by verifying that:

- the samples are representative of the property and location to be measured;
- the samples are collected properly;
- the analysis result is assigned to the proper sample;
- the correct measurement/analysis was performed;
- the measurement/analysis achieves the desired accuracy; and
- the measurement/analysis achieves the desired precision.

To ensure that a sample is collected properly, it is necessary to use appropriate sampling equipment and containers. Samples should be collected according to a workplan. They should be preserved and stored in accordance with defined procedures.

To ensure that the results are assigned to the proper sample measurement, a chain-of-custody process should be established for each sample. This may include appropriate labelling, field-book notations, records, packing lists for transportation, laboratory verification of receipt and sample tracking during analysis.

To achieve the desired accuracy, it is important to ensure that:

- analytical procedures are carefully selected;
- all instrumentation used during the analyses is maintained according to manufacturer's instructions and calibrated according to approved procedures; and
- during the analysis, replicate, reference and blank samples are taken and verified and split samples are checked independently, ideally by a separate laboratory.

Periodic assessment of measurement quality and performance and system audits should ensure that the desired precision is achieved.

5.7. RECORD SYSTEMS

Documentation is a major and key part of any QA programme. Proper and accurate documentation is the main route by which regulatory authorities may verify the results obtained by the site owner or its contractors. A formal document management system is required and should be set up, if an existing system is not used.

Documentation should include details of all the steps in the post-restoration monitoring programme as described in Section 2.3. This will include sufficient information on the site, including its location, layout, history and important events, sampling strategy, measurements made and all calculations supporting planning, assessment and implementation. These will enable re-evaluation of the monitoring at future dates, if required.

The records may contain the following information, where applicable:

- (a) for in situ measurements and samples: location, date, results of dose rate, surface contamination, mass radioactivity;
- (b) for laboratory analyses: concentration of the specific nuclides;
- (c) for all measurements and samples: names of the operators, samplers and analysts with their certifying signatures, instrument specifications and calibration data, laboratory name, analytical procedure and standards used;
- (d) for all results: definition of detection limits and associated significance levels, measurement uncertainty, name and signature of person verifying the results; and
- (e) evaluation and assessment procedures: models, hypothesis and parameters used.

Within the QA/QC programme, internal audits, review and, if necessary, repeated analyses for questionable data should ensure the validity of the results. Records which are in active use should remain under direct control of a designated individual. Inactive records should be protected from loss or destruction by storage in access-controlled areas or files and in facilities with fire protection. It is also recommended that duplicate copies (microfilm, computer disc, photostats, etc.) of critical data be produced and stored in a separate location. The entire documentation should be stored for a defined period of time, which should be specified in the Document Record Plan. This time period should be, at a minimum, that specified by regulatory authorities.

6. VERIFICATION OF COMPLIANCE WITH THE CLEANUP CRITERIA

Compliance with the cleanup criteria should be verified statistically (decision rules) using the data obtained from an integrated sampling and measurement programme conducted for the site. This section provides an outline of the role of statistical tests to evaluate whether a remediated site complies with its cleanup criteria. More information can be found in Appendix C and one example of application is given in Appendix D.

Compliance with the cleanup criteria can be verified starting from two different hypotheses. These are that:

- the site is assumed to comply with the criteria, unless the data are sufficiently convincing that it does not; or
- the site is assumed not to comply with the criteria, unless the data are sufficiently convincing that it does.

A choice of hypothesis should be made from the outset of the post-restoration monitoring programme. Separate statistical tests exist for both, but the requirements for measurements and sampling may differ.

The tests may also vary, depending on whether the radionuclide of concern is present in the background or not. This will be particularly relevant for sites contaminated with natural radionuclides, such as uranium and radium. The tests will also vary, depending on the probability distribution of the data.

The type of statistical test chosen should be taken into account when deciding on the number of measurement points and samples and their locations. If hot spots are present, more comprehensive surface scanning may be necessary to be sure that small areas with elevated activity will still satisfy the criteria (Appendix C).

7. SUMMARY AND CONCLUSIONS

The purpose of this report is to provide guidance to those responsible for post-restoration monitoring of contaminated sites in order to protect the public from exposure to residual radioactive materials. The guidance relates, in general, to the planning, performing and assessing of post-cleanup monitoring with subsequent validation of compliance with cleanup criteria. It will also be useful for any regulatory authority in verifying whether an optimum strategy and appropriate individual steps were selected to fulfil the post-cleanup characterisation task.

This report provides guidelines for developing a comprehensive and economically sound approach to fulfil the above task. Specifically, it is aimed to foster consolidation and dissemination of information on the practical experience gained by various Member States in the post-cleanup characterisation of restored sites.

It starts with a discussion of the key factors to be considered in selecting an optimum post-restoration monitoring strategy. It briefly describes the monitoring techniques available and provides information on required analyses and sensitivities. Planning and management aspects are discussed, including the organisational structure of project teams with responsibilities of various bodies involved. Information is provided on sampling and measurement techniques applicable to post-restoration monitoring activities. The key role and issues of quality assurance are outlined. The use of statistical techniques and analysis for planning post-restoration monitoring surveys, demonstrating compliance and quantifying the degree of certainty in that compliance is described with supporting examples in appendices.

The report concludes that:

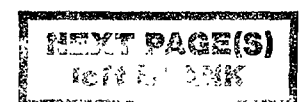
- (a) post-restoration monitoring is an integral part of the overall strategy and approach in the remediation of any contaminated site. It should therefore be planned ideally into that strategy from the outset in order to be achieved in the optimum manner;
- (b) such cleanup criteria should be used for both the remediation works and the post-restoration monitoring as can be readily and directly measured in the field to verify that they have been achieved acceptably;
- (c) statistical methods may be used effectively in both the planning of the optimum post-restoration surveys and as part of the process of verifying compliance with restoration criteria. They can provide justifiable quantitative estimates of the confidence levels to be placed in the attainment of the cleanup criteria.

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APPENDICES A-C



Appendix A

PRELIMINARY RADIOLOGICAL MONITORING REPORT FORMAT

I. Introduction

In this section the purpose of the monitoring should be described and when and by whom it was conducted, including subcontractors. The processes conducted at the site or associated with site contamination should also be described. Ideally, the material processed at the site, its sources and its destination should be included as well as any records of previous monitoring or decontamination efforts. The location of any equipment or decontamination and/or process residues should be reported.

All reports should contain a map with enough detail that the facility can be located accurately, e.g. on a published street map.

II. Site Description

The site should be briefly described in its present condition and information provided on the use of the grounds, buildings and any equipment used. In addition, information regarding occupancy of the buildings and grounds (especially for any contaminated areas) should be presented. Any known planned changes or anticipated future uses of the site should be outlined. It would also be desirable to describe the environs of the site, i.e. neighbouring properties.

A diagram of the facility could be included, if it would aid in the description of the site. Owners and/or company contacts and those assisting in the monitoring effort should also be mentioned.

III. Description of Monitoring Procedures and Results

The monitoring equipment and methods should be described briefly at the start. This section should then emphasise the results rather than procedures. Radiation levels at the site should be summarised and background levels nearby. Diagrams should be included showing areas of the buildings or ground monitoring. Detailed measurements should be placed on the diagram of the facility or in a table referenced to the diagram. Similar reporting procedures should be followed for soil and water samples, including comparison to background concentrations.

IV. Conclusions and Recommendations

This should summarise the findings and recommendations of the monitoring contractor. The following questions should be answered:

- Was any contamination found? If so, how does it compare to standards?
- Is there any foreseeable present or potential future health hazard?
- Is any additional monitoring required? If so, why?
- Do any conditions at this site require special consideration?

Sites to be monitored will usually fall into two categories, those requiring comprehensive monitoring (contaminated or possibly contaminated sites) and those requiring no additional monitoring (radiologically clean sites or controlled/licensed sites). Situations may arise where the preliminary monitoring identifies a very isolated spot of contamination, such as in a drain.

If this occurs, the Monitoring Manager should carefully assess the need for additional work, determine if the history suggests possible hidden contamination and if any additional useful data would be obtained through comprehensive monitoring. The contractor should indicate in the report if a comprehensive monitoring would not produce useful information and recommend remedial action to remove the contamination.

Appendix B

COMPREHENSIVE POST-REMEDIAL ACTION RADIOLOGICAL MONITORING REPORT FORMAT

I. Summary

A brief, executive summary should be prepared, including overall summary tables for indoor and outdoor monitoring results. It should include a statement about exposure evaluation results.

II. Introduction

This should include:

- the purpose of monitoring;
- when the monitoring was conducted and by whom;
- a brief history of the site, or if it is a vicinity property, a history of the associated candidate site including process history, if appropriate. This should be prepared only using published or well documented information; and
- a description of property, including area maps, site-scaled drawings and photographs. Care is needed here not to divulge the site location or ownership, if these are sensitive. If appropriate, codes can be used for all references to site location as needed.

III. Monitoring Methods

This section should include and/or reference appendices or documents that give:

- details of the monitoring plan
- details of the monitoring instrumentation and sample analysis methods employed.

IV. Monitoring Results

Subsections should discuss results for each measurement type. Data should be summarised in terms of range, average and maximum levels observed. Appropriate figures and detailed data tables should be referenced. For on-site measurements, comparison to normal background levels should be mentioned. In addition, specific requirements for each section are as follows:

A. Background Radiation Levels

- A brief description of areas and results included in background determination should be presented or referenced. Background values used should be stated.

B. Indoor Monitoring Results

- Measurements of external radiation levels;
- Sampling results;
- Radon and radon daughter measurements;
- Subsurface investigations: Reference to appended borehole logs; and
- Other samples: Tap water (if on a private well), drain residues, wood, etc.

C. Outdoor Monitoring Results

- Measurements of external radiation levels;
- Surface sampling results;
- Subsurface investigations: Reference to appended borehole logs; and
- Other samples: borehole water, vegetation, etc.

V. Applicable Radiation Guidelines

The guidelines attributed to the appropriate regulatory authority should be summarised as well as the primary regulations applying to the site. A summary table should be given of guidelines and an appendix, including complete citations. Results of the radiological monitoring should be compared with appropriate criteria.

VI. Significance of Findings

The introductory paragraph of this section should state that, based on the results of the monitoring, the following information can be derived:

- Extent of contamination - The areal extent of contamination, indoors and outdoors, should be shown graphically and discussed. A table of contaminated areas (referenced to the figure) should give a breakdown of the estimated area involved, depth of contamination in each area and total volume of material present above the applicable guidelines.
- Evaluation of radiation exposures - The basis for evaluation should be summarised with the assumptions used and the preliminary calculated estimate of the increased risk to individuals on site. The detailed exposure evaluation appendix should be referenced.

VII. References

VIII. Appendices

- Definitions and units of measurements;
- Monitoring plan (reference if appropriate);
- Instrumentation/analysis methods (reference if appropriate);
- Applicable radiation guidelines;
- Auger-hole logging graphs;
- Evaluation of radiation exposures; and
- Pertinent data and/or results of other investigators.

Appendix C

VERIFICATION OF COMPLIANCE WITH THE CLEANUP CRITERIA

The verification of compliance with the cleanup criteria value should be conducted using appropriate statistical tests (decision rules) that use data obtained from an integrated sampling and measurement programme conducted for the site. This section provides guidance on how to use statistical tests to evaluate whether a remediated site complies with post-remediation cleanup criteria.

Hypotheses tested

Statistical tests are used to determine with a known level of certainty whether a given assumption about the state of the site is correct. The assumption could be that the site complies with the cleanup criteria, i.e. it is “clean”. Alternatively, the assumption could be the converse, i.e. the site does not meet the cleanup criteria, so that significant contamination remains.

A statistical test is conducted to decide whether or not to reject a stated null hypothesis, denoted by H_0 , in favour of a stated alternative hypothesis, denoted by H_a . The null hypothesis is a statement about the data summary parameter, e.g. the mean of the specific activity of the contaminant in the soil, being used by the statistical test to make a decision. The alternative hypothesis statement is the opposite of that in the null hypothesis. Reference [C-1] uses the following hypotheses:

H_0 : The site is not in compliance with the criteria value

H_a : The site is in compliance with the criteria value

The statistical test will reject H_0 and thus implicitly accept H_a if the data are sufficiently convincing that H_0 is incorrect. The burden of proof is on showing that the H_a is more plausible than H_0 . Otherwise H_0 will be accepted as being true. Alternatively, H_0 and H_a could be interchanged:

H_0 : The site is in compliance with the criteria value

H_a : The site is not in compliance with the criteria value

With this approach, the site is assumed to comply with the criteria value unless the data are sufficiently convincing that the site does not comply. The statistical test computations depend on whether the H_0 states that the site is in compliance or not in compliance. Hence, it is important at the beginning of the study to determine how H_0 and H_a should be stated. However, the statistical tests in Ref. [C-1] are only appropriate when the H_0 states that the site does not comply.

Background concentrations

A question that must be resolved before an appropriate statistical test can be selected is whether the radionuclide of concern is present in background. If not, then a statistical test should be selected that will compare the site data with the fixed criteria value (limit) to make the decision. The Sign test and the one-sample t test are two possible tests for this situation [C-2, C-3]. If the radionuclide is present in background, then a different type of test is required; one that compares the site data with the background data. Tests that may be applicable for this case are the two-sample t test and the Wilcoxon Rank Sum (WRS) test [C-2, C-4].

Probability distributions of data

An important consideration in selecting a statistical test is the shape of the data distribution for the radionuclide of interest for the site. The data may be adequately characterised (modelled) by the symmetric normal distribution. In this case the one-sample t test [C-3] may be used to test for compliance, if the radionuclide of interest is not present in background. Alternatively, the data may be better modelled by the skewed (unsymmetrical) log normal distribution. In that case, if the radionuclide is not in background, Land's method for computing confidence limits on the lognormal mean is one possible testing approach. More generally, if the data can be shown to be well characterised by a specific distribution, then the statistical test that is appropriate for the particular distribution can be determined. For that reason, it is important to use graphical plots (such as probability plots) and statistical tests (such as the Shiparo-Wilk test) to try and determine which distribution is appropriate. Such methods are discussed in [C-5]. When an appropriate distribution (model) cannot be identified, then statistical tests that are valid for any distribution may be used. Such tests are known as nonparametric or distribution-free tests. The Sign test (MARSSIM 1997) may be used when the contaminant is not present in background and the data are not normally distributed or the distribution is unknown. The nonparametric WRS test can be used, if the distribution is non-normal or unknown and the contaminant is present in background. Table 2.3 in Ref. [C-1] lists alternative tests to those mentioned here. For each test the following information is provided in Table 2.3: the distribution model needed to apply the test, the type of test (parametric or distribution-free), a reference where the test is discussed in detail, and the advantages and disadvantages of the test.

Number and location of samples

The number of locations sampled at the site depends on the particular test that is selected. This in turn, depends on whether the radionuclide is present in background. Once a particular type of test is selected, then formulas are available for computing the number of samples. For example, the formulas for the WRS and Sign tests are given by Equation (5-1) and Equation (5-2), respectively, in Ref. [C-2].

The formulas for determining the number of samples contain parameters whose values must be specified. Two important parameters are the probabilities that can be tolerated of the test giving the wrong decision. Two incorrect decisions can be made: (1) a Type I decision error, which is made when the H_0 is rejected by the test, but H_0 is really true, and (2) a Type II decision error, which is made when the H_0 is accepted when it is really false. Unless the true levels on radionuclide concentrations are all less than or all greater than the compliance criteria, there is always some probability of making Type I and Type II errors. This occurs for two reasons. Firstly there is the variability in the true radionuclide concentrations over the site. Secondly there is uncertainty in the measurements obtained in the analytical laboratory or made by detector instruments. *Hence, it is important to specify the acceptable probabilities of making Type I and Type II decision errors. This is needed to specify the level of uncertainty that, can be accepted, in deciding whether to reject H_0 and consequently accept H_a .* Appendix D in [C-1] provides additional discussion of decision errors.

Another important parameter in the formulas for computing the required number of samples is the total variance of the radionuclide data for the monitoring unit being studied. This includes the variability of true concentrations over space and due to the uncertainty of the sample handling and measurement process. It is important to obtain a good estimate of the total

variance because the number of data required by the statistical test increases with the total variance of the data. The estimate of total variance may be obtained by conducting a preliminary and relatively small study at the site. This could use the same sampling and measurement procedures as for the main study. A preliminary study in which perhaps 10 to 20 samples are collected for the purpose of estimating the variance may be appropriate in most cases. Also, information about variance may be available from studies conducted at the site prior to or during remediation.

The final parameter required is the critical difference between the site data summary parameter (e.g., the mean) and the compliance criteria which has to be detected by the statistical test. If the radionuclide is not in background, then the difference between the site summary parameter and the fixed criteria value should be specified. If the radionuclide is present in background, then the difference between the two summary parameters (e.g., the means of the site and background populations) should be specified.

It is generally recommended [C-2, C-6] that samples should be collected within the monitoring unit (and from background if necessary) in a triangular or square grid pattern over the site. These systematic patterns provide uniform coverage of the site. They are also more efficient than random sampling designs for detecting small areas of elevated radionuclide concentration. The triangular or square grid should be laid out starting at a randomly located point within the monitoring unit.

Detecting hot spots

The number of samples determined as above are appropriate for cases where contamination is approximately uniformly distributed over the monitoring area. However, the distance between samples located in a triangular or square pattern may be too large to detect small areas of elevated radionuclide concentrations of concern. Hence, as discussed in Section 2, systematic measurements and sampling, in conjunction with surface scanning, should be used to obtain adequate assurance that small areas of elevated radioactivity will still satisfy the criteria value. To achieve this added assurance, the grid spacing may have to be reduced and additional sampling and scanning conducted. If the Class 1, 2, and 3 classification is used [C-1], additional direct measurements and samples on a grid of smaller spacing need only be considered usually for Class 1 monitoring units. This is because Class 2 and Class 3 monitoring units are not expected to contain small areas of elevated concentrations.

Procedure have been reported for determining if in situ scanning techniques have sufficient sensitivity to detect an area of elevated activity significantly above the compliance criteria value. The grid spacing could be reduced and additional measurements and samples collected on the new grid system, if the detector does not have the necessary sensitivity. The monitored area would not comply if any scan measurement exceeds an elevated measurement comparison (EMC) criteria value. The latter would be larger than the criteria value used in the statistical tests. This is explained in more detail in Annex I, Section IV.3.2.

REFERENCES TO APPENDIX C

- [C-1] US NUCLEAR REGULATORY COMMISSION, Multiagency Radiation Survey and Site Investigation Manual (MARSSIM). NUREG-1575, EPA 402-R-97-016, Washington, DC (1997).
- [C-2] US NUCLEAR REGULATORY COMMISSION, A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys, NUREG-1505, Washington, DC (1997).
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- [C-4] US ENVIRONMENTAL PROTECTION AGENCY, Statistical Methods for Evaluating the Attainment of Cleanup Standards, Volume 3, Reference-Based Standards for Soils and Solid Media, EPA 230-R-94-004, Office of Policy, Planning and Evaluation, Washington, DC (1994).
- [C-5] US ENVIRONMENTAL PROTECTION AGENCY, Guidance for Data Quality Assessment, Practical Method for Data Analysis, EPA QA/G-9 QA96 Version, EPA /600/R-96/084, Quality Assurance Management Staff, Washington, DC (1996).
- [C-6] US ENVIRONMENTAL PROTECTION AGENCY, Guidance for the Data Quality Objectives Process, EPA/600/R-96/055, EPA QA/G-4, Final Quality Assurance Division, Washington, DC (1994).

ANNEXES I–XI

CASE HISTORIES OF NATIONAL EXPERIENCE

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Annex I

UNITED STATES OF AMERICA

FINAL STATUS SURVEY USING MARSSIM SURVEY METHODOLOGIES AT THE CUSHING REFINERY SITE IN OKLAHOMA

I. INTRODUCTION

This annex describes the MARSSIM (Multiagency Radiation Survey and Site Investigation Manual) [I-1] methodology for conducting final status surveys during decommissioning. The methodology is described for the final status survey that was conducted at the Cushing Refinery site near the City of Cushing in the State of Oklahoma, USA [I-2]. That survey was conducted to demonstrate the feasibility of implementing the MARSSIM methodology at a site contaminated with thorium. The MARSSIM is a consensus document that was developed by the major US Federal agencies [US Nuclear Regulatory Commission (NRC), US Department of Energy (DOE), US Department of Defense (DoD) and the US Environmental Protection Agency (EPA)] that are responsible for radioactive cleanups. The NRC has announced that the MARSSIM will supersede NUREG/CR-5849 [I-3] as an acceptable process for conducting final status surveys during decommissioning.

Kerr-McGee Corporation (KMC) operated an oil refinery at the Cushing site from 1956 to 1972. The KMC Cushing site, which encompasses approximately 178 hectares, is located two miles north of the City of Cushing. From 1962 to 1966, KMC used part of the Cushing site to process natural thorium and natural, depleted, and enriched uranium. In April 1966 KMC reported to the U. S. Atomic Energy Commission (AEC) that all special nuclear material had been transferred from the Cushing site to KMC's new Cimarron facility in Crescent, Oklahoma and that all Cushing buildings in which licensed activities had been performed were cleaned and decontaminated. The AEC conducted a close-out survey of the Cushing facility in July 1966.

KMC performed characterisation surveys and remediation for a large portion of their site. Land areas slightly contaminated with thorium were selected for this demonstration of the MARSSIM methodology. The thorium chain appeared to be in equilibrium with ^{232}Th .

II. MARSSIM SURVEY DESIGN

II.1. Introduction

The MARSSIM stresses the use of data quality objectives (DQOs) and the DQO process [I-4] to develop a final status survey design. The objective of a final status survey is to demonstrate that residual radioactivity levels meet the release criteria. MARSSIM also recommends the use of nonparametric statistical methods, in particular the Wilcoxon Rank Sum (WRS) test (discussed below) and the Sign test. Unlike the parametric methods used in NUREG-5849 [I-3], nonparametric methods do not require that the distribution of the data be normal. Also, when the data distribution is not normal, the WRS test frequently has greater power to detect non-compliance with compliance criteria than the t test used in NUREG-5849. The WRS test can also be used when the data set contains a few (no more than 40%) "less than MDC" (minimum detectable concentration) measurements. The MARSSIM survey design process (Fig. I-1) begins with identifying contaminants and determining the derived concentration guideline levels (DCGLs).

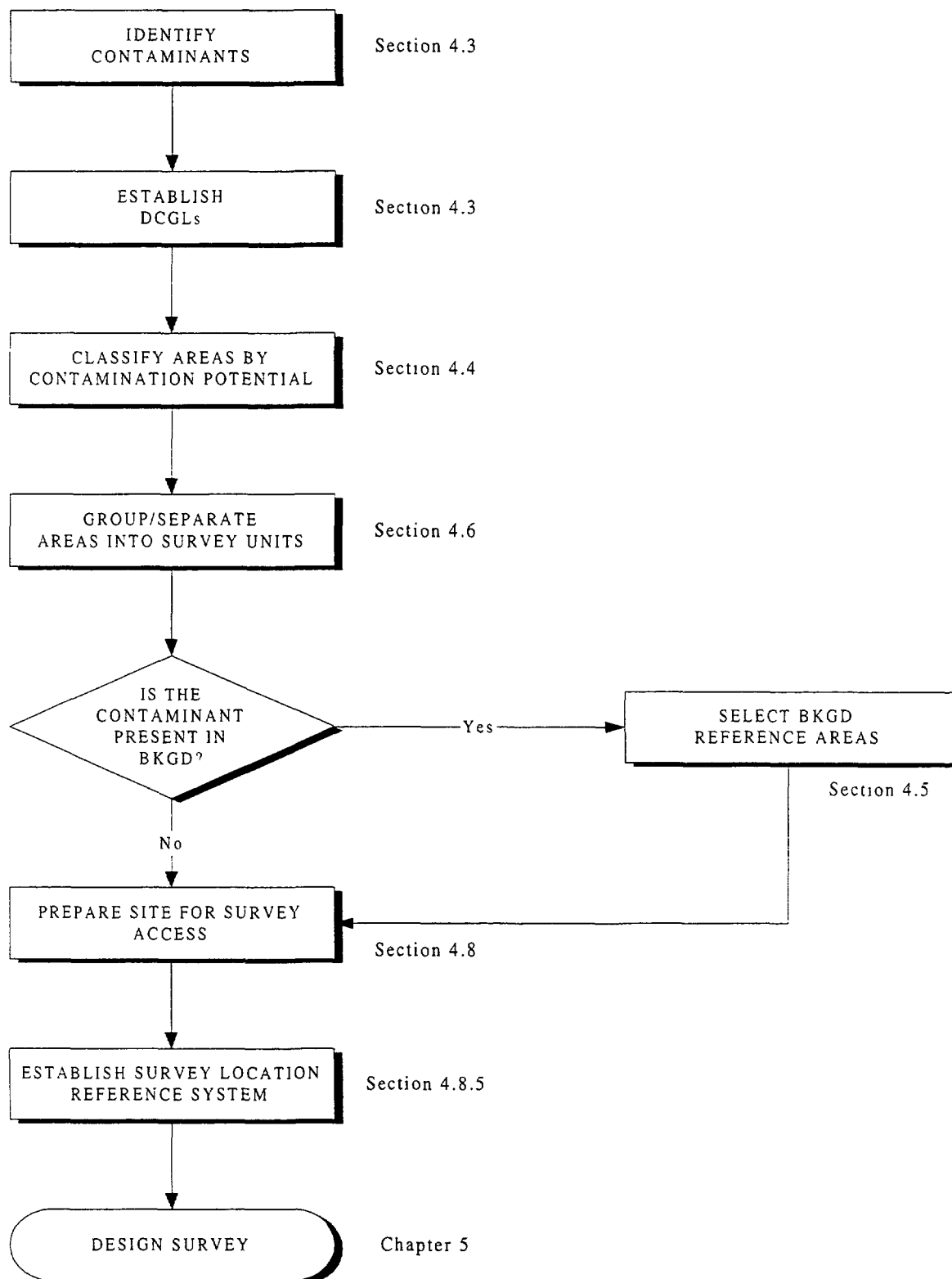


FIG. I-1. Sequence of preliminary activities leading to survey design (NRC 1997a). Note: the sections and chapters referred to in this figure are in NRC 1997a.

Exposure pathway modelling is used to translate the release criterion (0.25 mSv/year) to measurable quantities, the DCGLs. Two types of DCGLs are used in MARSSIM. $DCGL_W$ is derived based on the average concentration over a large area, while $DCGL_{EMC}$ is derived separately for small areas of elevated activity (hot spots). The $DCGL_W$ for residual

concentrations of ^{232}Th in soil, 5.9 Bq/g above background, was obtained from a screening model, using conservative, non-site-specific parameters. The derivation of DCGL_{EMC} is discussed below.

The next step in applying the MARSSIM methodology is to divide the site into Class 1, Class 2 and Class 3 areas. Class 1 areas, prior to remediation, are impacted areas with concentrations of residual radioactivity that exceed the DCGL_w . Class 1 areas have the highest potential for contamination, including the potential for small areas of elevated activity. Class 2 areas are impacted areas with concentrations of residual radioactivity that are not expected to exceed the DCGL_w . Class 2 areas have a potential for contamination, but they have little or no potential for small areas of elevated activity. Class 3 areas are impacted areas that have a low probability of containing areas with residual radioactivity.

Each class area is further divided into survey units. Separate decisions are made about the compliance status of each survey unit. The Class 1 area survey unit selected for this evaluation at the Cushing site is Radioactive Material Area (RMA)-4, which has a land area of approximately 2,300 square meters (m^2). The Class 2 area survey unit selected was also of size 2,300 m^2 . An appropriate background area was identified. No Class 3 area was included in this evaluation of MARSSIM methodology.

For contaminants present in background (or measurements that are not radionuclide-specific), the WRS test is used to test for compliance with compliance criteria. The Sign test is used for contaminants that are not present in background. The Sign test may also be used in circumstances where the contaminant is present at such a small fraction of the DCGL_w as to be considered insignificant such that a background reference area is not needed. These tests are described and illustrated in detail in NRC [I-1]. The application of the WRS test at the Cushing site is described below.

Hypothesis tested

In demonstrating that residual radioactivity levels meet the release criteria, MARSSIM recommends using the null hypothesis (denoted by H_0):

H_0 : Residual contamination *exceeds* the release criterion

The alternative hypothesis (H_a) is that residual contamination does not exceed the release criterion. The null hypothesis is assumed to be true unless the data provide convincing evidence that the residual contamination does not exceed the release criterion.

II.2. Determining numbers of data points for Wilcoxon Rank Sum (WRS) test

The following subsections describe the procedure for determining the number of data points needed for the WRS test. The key parameters affecting sample size include the magnitude of the decision errors (Type I and Type II) and the relative shift (Δ/σ), which are explained below.

II.2.1. Type I and type II decision errors

To determine the data needs for the WRS test it is necessary to specify acceptable probabilities of making Type I and Type II decision errors. A Type I decision error is made when the H_0 is rejected when it is true, which results in incorrectly concluding that the survey

units satisfies the release criterion (regulator's risk). A Type II decision error occurs when the H_0 is accepted when it is false, which results in unnecessary remediation (licensee's risk). The acceptable decision error rates are determined during the DQO process to reflect the magnitude of the consequences (e.g., health risk and costs of additional restoration) of making each type of error. For this demonstration of the MARSSIM approach, the Type I decision error probability (α) was specified to be 0.05 and the Type II decision error probability (β) was set at 0.10. The power of the test to correctly reject H_0 is defined to be $1-\beta$. Hence, for this demonstration of the MARSSIM methodology, the required power was set at $1 - 0.10 = 0.90$.

II.2.2. Calculate the relative shift (Δ/σ) that is important to detect

The contaminant DCGL value, lower bound of the grey region (LBGR), and the standard deviation in the background level of the contaminant were used to calculate the relative shift, Δ/σ , where $\Delta = DCGL_W - LBGR$ and σ is the true standard deviation of the data. LBGR is defined below. When the estimated standard deviation, s , in the reference area and survey units are different, the larger of these values should be used to calculate the relative shift.

The following information was used to determine the relative shift, $(DCGL_W - LBGR)/\sigma$:

- **DCGL_W.** The DCGL_W for ^{232}Th is 5.9 Bq/g in soil.
- **Standard deviation (σ).** An estimate of the standard deviation of the contaminant can be obtained from 1) previous surveys (scoping or characterisation) or remedial action support surveys, 2) limited preliminary measurements (10 to 20 or more) to estimate the distributions, or 3) reasonable estimate based on site knowledge. Note that the estimate of the standard deviation includes both spatial variability of the contaminant and the precision of the measurement system.

Based on characterisation data, the standard deviation of ^{232}Th in the reference area and the survey units was 59 Bq/g in the Class 1 area and also 10 Bq/g in the Class 2 area (it was a coincidence that the standard deviations were equal). It was assumed that the standard deviation in the reference area was not larger than the standard deviation in the Class 1 and 2 areas. That is, the standard deviation for the reference area was assumed to be 10 Bq/g. The MARSSIM recommends using the larger value of the standard deviations for the survey unit and the reference area when the two standard deviations differ.

- **Lower bound of the grey region (LBGR):** The *grey region* is the range of values of the parameter of interest (contaminant concentration in soil) in a survey unit for which the consequences of making a decision error are relatively minor. Because ^{232}Th has a small DCGL_W relative to background, the LBGR was selected as zero. Thus, $\Delta = DCGL_W - LBGR = 0.16 - 0 = 0.16$. The relative shift (Δ/σ) was then calculated directly: $0.16/0.27 = 0.593$, rounded to 0.6.

II.2.3. Determine P_r

Table 5.1 in MARSSIM (NRC 1997a) contains a listing of relative shift values and values for P_r . P_r is the probability that a measurement at a random location in the survey unit exceeds a random measurement in the reference area by less than the DCGL_W when the survey unit median concentration is equal to the LBGR above background. P_r is a function of the relative shift $[(DCGL_W - LBGR)/\sigma]$, and P_r increases as Δ/σ increases.

Using the relative shift value calculated previously, the value of P_r was obtained from Table 5.1 in [I-1]. For a relative shift value of 0.6, the value of P_r was 0.664.

II.2.4. Determine decision error percentiles

The next step in this process was to determine the percentiles $Z_{1-\alpha}$ and $Z_{1-\beta}$ of the standard normal distribution, where α and β are the selected probabilities of making a Type I and Type II decision error, respectively. As stated earlier, α was selected to be 0.05 and β was selected to be 0.10. Therefore, from Table 5.2 [I-1], the percentile $Z_{0.95}$ equals 1.645 and $Z_{0.90}$ equals 1.282.

II.2.5. Calculate number of data points for WRS test

The number of data points, N , to be obtained from each reference area/survey unit pair for the WRS test is calculated below. Note that the N data points are divided between the survey unit (n) and the reference area (m), and that they are split equally ($n = m = N/2$).

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{3(P_r - 0.5)^2}.$$

Substituting in the values determined above, N was calculated as follows:

$$N = \frac{(1.645 + 1.282)^2}{3(0.664 - 0.5)^2} = 106.2$$

Of this total number, 53 samples were designated to be collected from the reference area and 53 from each survey unit.

To assure sufficient data points to attain the desired power level ($1-\beta$) with the statistical tests and allow for possible lost or unusable data, MARSSIM recommends that the number of calculated data be increased by 20% and rounded up for further assurance of sufficient data points. This procedure yielded 64 samples to be collected in both the survey unit and the reference area.

Table 5.3 in MARSSIM [I-1] provides a list of the number of data points to demonstrate compliance using the WRS test for various values of α , β , and Δ/σ . These values were determined using the WRS test sample size equation above and have already been increased by 20%. These numbers represent $N/2$, to be conducted in each survey unit and corresponding reference area.

III. DETERMINING DATA POINTS FOR AREAS OF ELEVATED ACTIVITY

For Class 1 areas, the number of data points required by the WRS test for uniform levels of contamination may need to be supplemented to ensure a reasonable level of assurance that any small areas of elevated residual radioactivity are not missed during the final status survey. Soil sampling on a specified grid size, in conjunction with surface scanning, are used to obtain an adequate assurance level that small areas of residual radioactive contamination will still satisfy DCGLs—applicable to small areas ($DCGL_{EMC}$).

The number of survey data points needed for the WRS test (64 for both reference area and survey units) were positioned, on a scale map of each survey unit, using a random-start triangular pattern. The number of calculated survey locations, 64, was used to determine the grid spacing, L , of the triangular pattern. Specifically, the spacing, L , of the triangular pattern can be calculated as follow:

$$L = \sqrt{\frac{A}{0.866 n}},$$

where A is the area of the Class 1 survey unit ($2,300 \text{ m}^2$) and n is the number of data points in the survey unit (64). The spacing L equals 6.44 m. The grid area bounded by these survey locations was calculated by $A = 0.866 \times L^2$ (equals 36 m^2). This area represented the largest elevated area that could exist and not be sampled by the random-start triangular grid pattern established for the WRS test.

Next, the magnitude (area factor) by which the concentration in this potential elevated area (36 m^2) can exceed the DCGL value while maintaining compliance with the release criterion was determined. The following table provides outdoor area factors for ^{232}Th . These factors were derived using exposure pathway models [I-1], pages 5–36 for details).

Outdoor area dose factors

^{232}Th	Area factor								
	1 m^2	3 m^2	10 m^2	30 m^2	100 m^2	300 m^2	1000 m^2	3000 m^2	$10\,000 \text{ m}^2$
	3610	1200	361	120	36.1	5.54	2.32	1.47	1.00

The minimum detectable concentration (MDC) of the scan procedure that is required to detect an elevated area at the limit determined by the area factor was calculated. That is, the required scan MDC for ^{232}Th was calculated by (area factor logarithmically interpolated for 36 m^2 area equals 100):

$$\text{Scan MDC (required)} = (\text{DCGL}) * (\text{Area Factor}) = 0.16 * 100 = 16 \text{ pCi / g}$$

The actual MDCs of scanning techniques were determined for performing gamma scanning with NaI scintillation detectors. The following scan MDC was determined using current human factors research and modelling of an elevated area and assessing the NaI scintillation detector's response to that radionuclide and radionuclide distribution [I-5]. These values were purposefully determined conservatively for sample size design considerations.

Scan MDC

Radionuclide	Scan MDC (Bq/g)
^{232}Th	141

The actual MDC of the selected scanning technique was compared to the required scan MDC. Because the actual scan MDC (141 Bq/g for ^{232}Th) is less than the required scan MDC (592 Bq/g), no additional sampling points (above the 64 calculated previously) were necessary for assessment of potential elevated areas. That is, the NaI scintillation gamma scan survey exhibited adequate sensitivity to detect any elevated areas of concern.

IV. DATA REDUCTION USING MARSSIM GUIDANCE

The MARSSIM manual [I-1] recommends that a data quality assessment (DQA) be performed to determine if the data are of the right type, quality, and quantity to support their use. The DQA process is the scientific and statistical evaluation of data and includes 1) preliminary data review, 2) selection of statistical tests and verification of assumptions of the tests, and 3) drawing conclusions from the data. The MARSSIM approach to data reduction will be illustrated using the results of the final status survey performed at the thorium-contaminated site.

A 10-meter reference grid system was established in the Class 1, Class 2 and background reference areas to reference sampling locations, as determined from the triangular sampling pattern. Soil surfaces were scanned for gamma radiation using NaI scintillation detectors. Surface scans were performed over 100% of the soil areas within the Class 1 survey unit and 50% of the Class 2 survey unit. Locations of elevated direct radiation, based on increases in the audible signal from the instrument, were marked for further investigation.

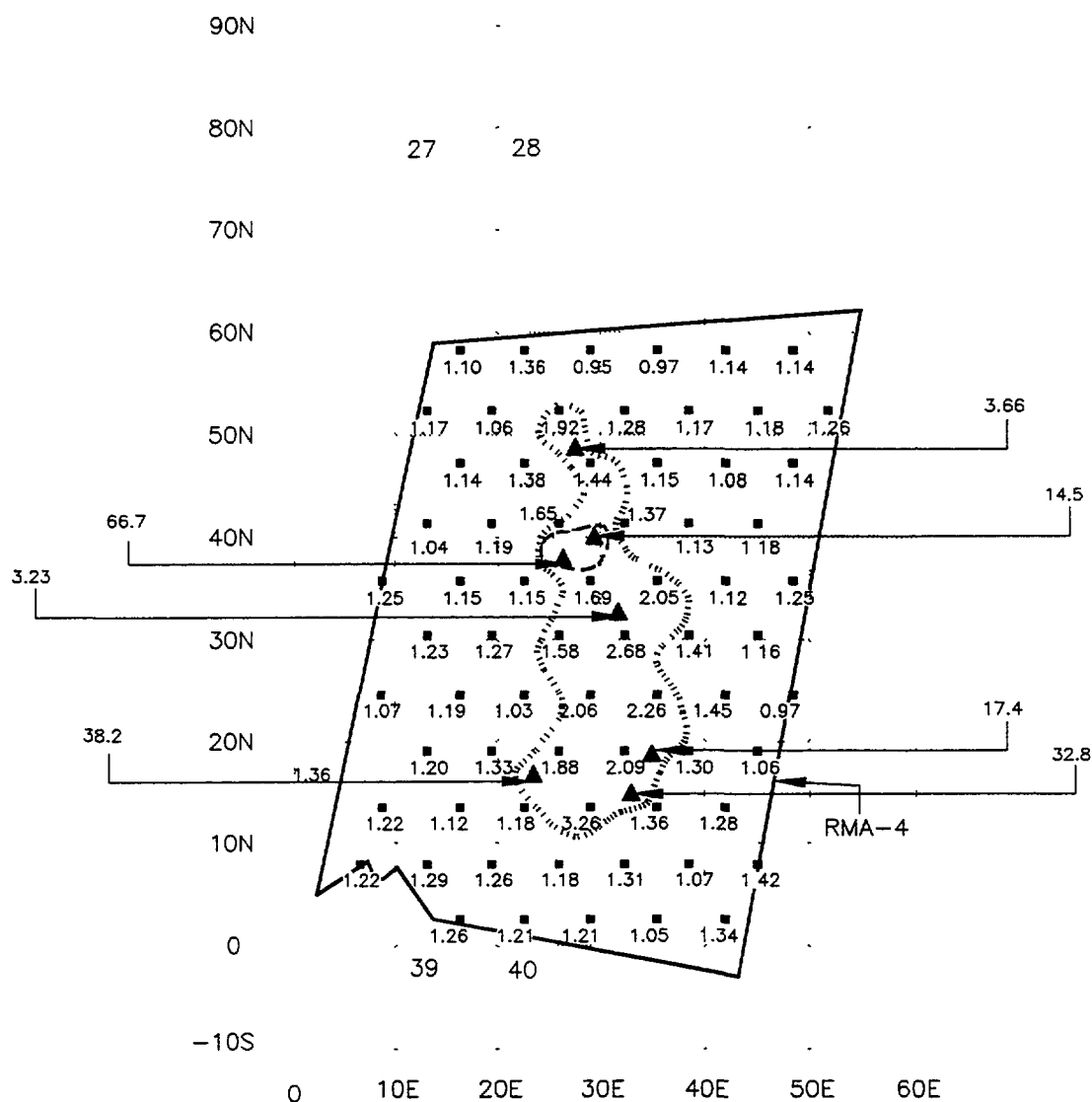
Background soil samples (66) were collected from the selected reference area. Systematic (on a triangular grid pattern) Class 1 and Class 2 surface soil samples (at a depth of 0 to 15 cm) were collected from the locations determined using prepared figures as a guide in locating sampling points. A total of 69 systematic samples were collected from the Class 1 area and 64 samples were collected from the Class 2 area. Soil samples were also collected from seven locations of elevated direct radiation identified by surface scans in the Class 1 survey unit.

IV.1. Preliminary data review

To evaluate the structure of the data (identifying patterns and relationships) graphs of the data were prepared and basic statistical quantities calculated. Inspection of the Class 1 data posting plot clearly indicates several samples with ^{232}Th concentrations in excess of the background in this survey unit — particularly running north to south between east co-ordinates 25 to 35 (Fig. I-2). Posting plots for the Class 2 survey unit and background reference area do not reveal any systematic spatial trends.

The histogram for the Class 1 survey unit (Fig. I-3) indicates there may be two distributions of ^{232}Th : one for concentrations up to about 63 Bq/g, and a second for concentrations greater than 63 Bq/g. Therefore, it may be possible to consider the lower-concentration distribution as a survey unit-specific background reference area for this Class 1 survey unit. As cautioned in MARSSIM, the interpretation of the data for this purpose should only be pursued after consultation with the responsible regulatory agency. In the discussion below, the WRS test compared the distribution of the data in the background reference area with the data for the Class 1 survey unit shown in Fig. I-2.

Basic statistical quantities are provided in the following table for the background reference area, Class 1, and Class 2 survey units.



LOCATIONS MEASUREMENT/SAMPLING



SURFACE SOIL



BIASED SOIL
FROM SCAN RESULTS



GENERAL BOUND OF
AREAS IDENTIFIED
BY SCANS

#

GROSS Th-232
CONCENTRATION
(pCi/g)

N



FEET

0

60

METERS

0

20

FIG. I-2. Kerr-McGee Corporation site, Cushing, Oklahoma, RMA-4 (Class 1) — elevated areas identified by scans and soil sample locations.

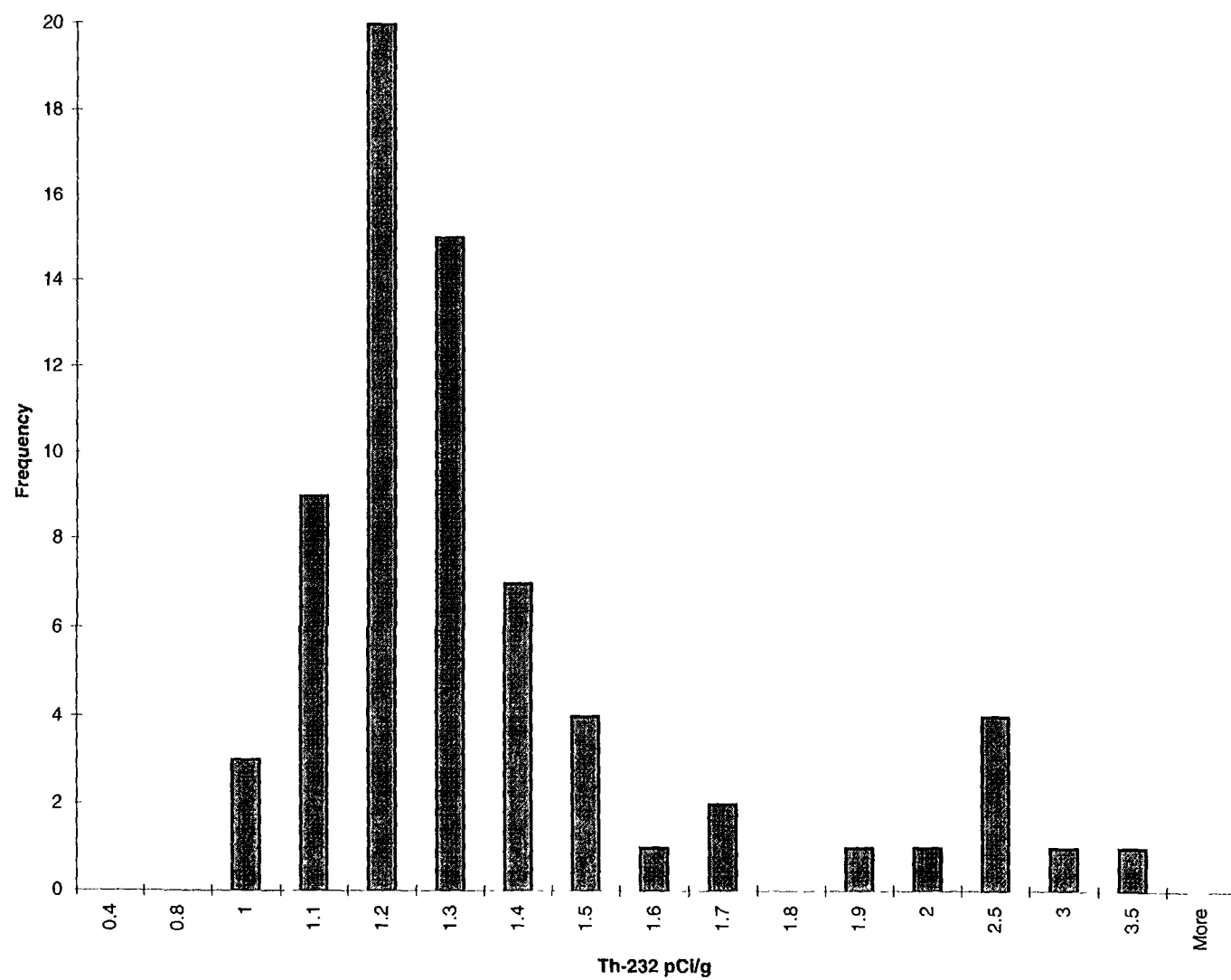


FIG. 1-3. Histogram — Class 1 area.

Basic statistical quantities

Location	²³² Th (Bq/g)		
	Mean	Median	Standard deviation
Background reference area	48	49	5.9
Class 1 area	50	45	14.8
Class 2 area	41	42	8.1

As evidenced in the Class 1 survey unit, large differences between the mean and the median provide an indication of skewness in the data (as discussed previously, the histogram actually shows that two distributions exist in the Class 1 survey unit). Also, the basic statistical parameters (both the mean and the median) show that the Class 2 survey unit data are 6.7 Bq/g less than the background reference area. Therefore, if the two areas were interchanged, it is likely that the background reference area would fail to reject the null hypothesis (not pass the release criterion of 5.9 Bq/g) as compared to the ²³²Th concentration in the Class 2 survey unit.

IV.2. Selection of statistical test and verification of test assumptions

The WRS test is used to evaluate the ²³²Th concentrations in the Class 1 and Class 2 survey units because the contaminant of concern (²³²Th) is present in background. The null hypothesis tested by the WRS test is that “the median concentration in the survey unit exceeds that in the reference area by more than the DCGL_w.” Therefore, rejection of this null-hypothesis results in a decision that the survey unit passes (satisfies the release criterion). Specifically, the result of the WRS hypothesis test determines whether or not the survey unit as a whole is deemed to meet the release criterion.

The assumptions underlying the WRS test are that (1) the samples from the background reference area and the survey unit are independent random samples, and (2) each measurement is independent of every other measurement — regardless of the set of samples from which it came. Each of the samples from the background reference area, Class 1, and Class 2 survey units were collected on a random-start triangular grid pattern — biased (judgement) samples are not included in statistical tests. Thus, the assumption of independent random samples is valid. The posting plot in the Class 1 survey unit (Fig. I-2) suggests that spatial dependencies may exist. This could affect somewhat the performance of the WRS test.

IV.3. Draw conclusions from the data

IV.3.1. WRS test

The specific details for conducting the WRS test for a given survey unit and reference area are as follows:

- (1) Obtain adjusted reference area measurements by adding the DCGL_w (5.9 Bq/g) to each background reference area measurement.
- (2) Rank the pooled adjusted reference area measurements (m) and survey unit measurements (n) from 1 to N , where $N = m+n$.

- (3) If several measurements are tied (have the same value), they are assigned the average rank for that group of tied measurements.
- (4) Sum the ranks of the adjusted measurements from the reference area, W_r .
- (5) Compare W_r with tabulated critical value (MARSSIM Appendix I; based on n , m , and α).

[Note: For m or n greater than 20, the critical value can be calculated as follows:

$$m(n + m + 1) / 2 + z\sqrt{nm(n + m + 1) / 12},$$

where z is the $(1-\alpha)$ percentile of a standard normal distribution ($z = 1.645$ for $\alpha = 0.05$)

Decision rule: Reject H_0 if $W_r > \text{critical value}$

MARSSIM Appendix I provides spreadsheet formulas for ranking the data. The analysis for the WRS test is well suited for calculation on a spreadsheet. To summarise these results, the value of W_r for the Class 1 survey unit was 5,580 and the critical value was 4,862 [I-2]. Because the value of W_r is greater than the critical value, the null hypothesis is rejected and the survey unit passes the WRS test, i.e., the WRS test indicates the survey unit meets the release criteria.

The value of W_r for the Class 2 survey unit was 5,976 and the critical value was 4,676. Because W_r is greater than the critical value, the null hypothesis is rejected and the survey unit easily passes the WRS test. However, the concern in this case is that the background reference area is not representative of the Class 2 survey unit. As discussed previously, ²³²Th concentrations in the Class 2 survey unit are significantly less than the concentrations in the background reference area. Nonetheless, upon review of all the data, the Class 2 survey unit satisfies the release criterion.

IV.3.2. Elevated measurement comparison (EMC)

The elevated measurement comparison (EMC) consists of comparing each measurement from the survey unit with the *investigation level*. Investigation levels are radionuclide-specific levels of radioactivity used to indicate when additional investigations may be necessary. The EMC is intended to flag potential failures in the remediation process. The EMC should be conducted because statistical tests such as the WRS test may reject H_0 when only a very few high measurements are obtained in the survey unit. See page 5-44 in [I-1] for further discussion of investigation levels.

The EMC was performed for each measurement obtained from systematic sampling and those flagged by surface scans. Surface scans identified a relatively large ($\sim 300 \text{ m}^2$) area of elevated radiation that ran through the middle of RM4 (Fig. I-2).

Surface scans, confirmed by biased (judgement) sampling, identified a particularly significant location of elevated direct radiation ($\sim 20 \text{ m}^2$) near co-ordinates 25E, 40N. The derived concentration guideline level (the DCGL_{EMC}) for the EMC is obtained by multiplying the

DCGL_w (5.9 Bq/g) by the area factor that corresponds to the actual area of the elevated concentration. An area of elevated concentrations is deemed acceptable provided that the appropriate DCGL_{EMC} is not exceeded. For example, the area factor for the 300 m² elevated area is 5.54, resulting in a DCGL_{EMC} of 32.2 Bq/g (not including background). Further investigation and sampling would be necessary to determine the average ²³²Th concentration over this 300 m² elevated area in order to make a comparison to the DCGL_{EMC}.

An EMC determination was also made for the smaller area (20 m²). The area factor is 208 (based on interpolation of values in the area factors table), which resulted in a DCGL_{EMC} of 1232 Bq/g. The average of the two biased samples in that 20 m² area is 1502 Bq/g, which exceeds the DCGL_{EMC}. It should be recognised that any combination of area and radionuclide concentration that exceeds the appropriate DCGL_{EMC} should be sufficient for concluding that the survey unit does not satisfy release criteria.

V. SUMMARY

This annex provides an overview discussion and example of an application of the MARSSIM methodology of using the nonparametric WRS test to evaluate whether a Class 1 survey unit and a Class 2 survey unit at the Cushing Site are in compliance with the release criteria. For full details on the MARSSIM methodology the MARSSIM report [I-1] should be studied. Also, we note that the methods in NUREG-1505 [I-6] are very similar to those in MARSSIM. However, the latter report discusses a larger set of potentially useful statistical tests that are included in MARSSIM. Also, Ref. [I-6] shows how to conduct statistical tests for final status surveys when the null and alternative hypotheses used in MARSSIM are interchanged

References to Annex I

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Annex II

UNITED KINGDOM

POST-RESTORATION CHARACTERISATION OF DECOMMISSIONED SITES TO ENSURE COMPLIANCE WITH CLEANUP CRITERIA

Three main types of contaminated land sites have been found to be of concern in the United Kingdom:

(i) Sites or parts of sites, that are currently operated and licensed under the Nuclear Installations Act, but which are no longer required for that purpose. These are invariably part of major nuclear facilities, such as the nuclear power reactors of British Energy and Magnox Electric, the nuclear fuel production, reprocessing and waste management facilities of BNFL, the nuclear research facilities of UKAEA and Ministry of Defence facilities associated with nuclear weapons development and production and nuclear submarine servicing, which have only recently come under the Nuclear Installations Act. Many of these sites are now over 40 years old and as with many other mature industries contamination has occurred to varying degrees on its sites. The contamination has frequently arisen from practices for the handling and storage of unconditioned and particularly liquid wastes which are not consistent with current standards;

(ii) Sites which previously concentrated or processing concentrated levels of naturally occurring radioactive materials, such as radium for luminising, thorium and rare earth's for alloying, catalysts, etc., phosphates for acids, fertilisers, detergents, etc. In many cases the processing and contamination occurred before such materials were regulated as radioactive materials and the organisations responsible for the contamination have long since disappeared. In some cases the existence of the contamination has been known for a long time, but in others it has been rediscovered by potential developers or current owners. The dominant group of sites in this category are those where the contamination results from the use of or disposal of items which include luminising materials. There are a large number of current and past military sites in this group, where the contamination has arisen from the disposal of old aircraft and vehicles with luminous instrument panels, or the operation of luminising workshops.

(iii) Areas contaminated or under threat of contamination as a result of past discharges or disposals at a neighbouring facility. This includes beach contamination at Seascale and Dounreay as a result of pipeline discharges and leaks into coastal waters and contamination spread in dockyard facilities during nuclear submarine servicing and refitting.

There are other types of contaminated site, which are not covered by these descriptions. These are very much less numerous and include those where the contamination was deliberate and part of research to investigate radionuclide migration behaviour and also where it was caused by fallout from the Chernobyl nuclear reactor accident, as in North Wales and Cumbria.

The United Kingdom does not, however, have examples of very large, heavily contaminated areas, such as those associated with major nuclear accidents, poorly controlled nuclear facilities, uranium mining or milling or nuclear weapons testing.

The Windscale Pile fire of 1957, although a major nuclear accident, released predominantly very short-lived fission products, such as ^{131}I , and hence did not result in any long-term

ground contamination. Until very recently all of the major nuclear industry sites have been operational. The policy at these sites has been to undertake only the minimum of decommissioning and site remediation necessary to maintain safe and effective site operations with the bulk of decommissioning delayed until final closure of each site. Uranium mining and milling have never been undertaken commercially in the United Kingdom with only the concentrates being imported for fuel manufacture. Likewise, the sites for the testing of the UK nuclear weapons programme and hence their contamination have all been located overseas, initially in Australia on the Monte Bello Islands and at Emu and Maralinga in South Australia, at Malden and Christmas Islands in the Pacific Ocean and finally at the Nevada test site in the USA.

To date the vast majority of site remediation activities in the United Kingdom have been associated with the cleanup of limited areas of contamination on diverse small sites around the country. These smaller sites are registered under the Radioactive Substances Act (1993) for the storage and possible use of radioactive substances. The latter substances are defined under the Act as materials with a specific radioactivity of greater than 0.4 Bq/g above the local background level. Higher "exemption" limits do exist for limited quantities of certain substances, such as radium, thorium, natural uranium, tritium, etc. These sites are regulated by the Inspectorate of the Environment Agency. For the major nuclear sites, which are licensed under the Nuclear Installations Act, the prime regulator is the Nuclear Installations Inspectorate with the Environment Agency being primarily concerned with releases of radioactivity into the environment, whether by discharge, disposal or potential incident.

The consequence of the emphasis to date on the remediation of small sites has been that, because the risks have been seen to be low, the approach in terms of initial site characterisation, restoration works and indeed post-restoration monitoring has not been prescriptive. Considerable responsibility has been given to the local regulator to assess and deal with sites on a case by case basis within the general risk guidelines of the regulations. The practical result has been that the procedures adopted and required have varied with the site. The emphasis has generally been for the site operator to agree the clean-up targets and the methods for achieving them with the regulator. This is normally achieved by the operator or his representative presenting a written plan of the proposed remedial works to the regulator for approval. This plan would normally detail:

- (i) The characterisation methods to be used with the planar and depth sampling patterns; instrumentation with detection limits and sensitivities for individual radionuclides; quality control procedures; quality accreditation of any laboratories used, etc. Some standard characterisation methods are available from British Standards [II-1, II-2] and recent guidance from the Department of the Environment [II-3, II-4] and these have often been used.
- (ii) Selection and justification of restoration targets. In many cases this has been and continues to be removal of any material with contamination at levels which would cause it to be classified as radioactive material under Schedule 1 of the Radioactive Substances Act of 1993 and the associated Exemption Orders. In some cases for some radionuclides the restoration target has been a residual radiation dose rate.

For the future, however, the UK Government's proposals for both radioactive and chemical contamination are that the restoration targets should be based on residual risk levels [II-5, AII-6, AII-7]. The proposal is that if the land use is to change, as will occur when land is released from a licensed site, then the same standards will apply as for controlled practices, e.g.

discharges into the environment. In this case the residual risks to any individual should not exceed 10^{-5}y^{-1} with the ALARA principle applying. For residual risks below 10^{-6}y^{-1} , it is considered unlikely that any significant expense could be warranted to reduce exposures further. The case would be where no change of land use is proposed. This would apply, if contamination was discovered on the land after development had occurred and hence there is no planned action, which could cause an increase in exposures. This situation would be addressed as an intervention in ICRP terms [II-8]. In this case any dose reduction measures proposed would need to be justified on the grounds of doing more good than harm and optimised to do as much good as possible.

This part of the plan will also detail how the restoration residual risk targets are translated into field measurable quantities, such as surface dose rates, which can be monitored during the restoration works.

(iii) The restoration methods to be applied with a quantitative safety case, including hazard and operability analyses for their application. This will also detail the precautions to be taken to protect the workers undertaking the remedial work and the general public. The restoration methods will include waste management arrangements and procedures for sentencing the wastes and complying with waste licensing conditions. These methods almost invariably include ongoing monitoring as with the contaminated material being removed in layers until the clearance targets are met.

If problems are encountered in achieving cleanup targets, then it is usually at this stage rather than after the post-restoration monitoring that regulatory approval could be sought to relax in the cleanup level in limited areas. Such a variation would only be sought where it can be demonstrated through further assessment that the resulting residual risks will still be acceptable and that the costs and risks involved in fully meeting the original cleanup targets are disproportionate to the extra reduction in risk achievable.

(iv) Post-restoration monitoring. This monitoring frequently implicitly acknowledges that the restoration works involved iterative monitoring until clearance levels were met. Hence, a key objective is to confirm that no significant areas of contamination remain untreated and present significant health risks. It is not usually a requirement that such monitorings should be undertaken independently of the restoration team, provided that adequate assurance can be given of the quality of the methods used. This can involve the analysis of selected duplicate samples by an independent laboratory.

In practice, there is advantage in the use of an independent post-restoration monitoring, particularly where the site in question has a sensitive history or a sensitive use is proposed for its redevelopment, such as housing. In addition, with a growing litigative environment being associated with contaminated sites and past remedial works, contractors are increasingly using such monitoring to demonstrate the professional competence of their work and hence to minimise the risks of future claims.

On completion of the restoration plan and its acceptance by the regulators, the site operator is then responsible for ensuring the implementation of the agreed plan. This may be achieved by using internal staff, who are familiar with the site's history and methods of working or through the use of specialised external contractors. For most of the smaller sites, non-nuclear industry sites, there are not sufficient capable internal resources to pursue the first option and external contractors are invariably used.

On completion of the restoration works and the final site monitoring, a report on the works with all of the associated analyses, waste and quality assurance records, etc., is prepared. Where an application is being made for delicensing of the site, this report is submitted to the regulator as part of the application.

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Annex III

FINLAND

CRITERIA FOR AND POST-RESTORATION MONITORING OF DECOMMISSIONED SITES

INTRODUCTION

In Finland there are few sites where radioactive wastes are stored and special restoration actions have been needed. All of these sites involved industrial activities, where radionuclides of natural or anthropogenic origin, were enriched in the processing wastes. Two mineral mining and milling sites and depositories of fuel peat ash are described as case histories below. Two old uranium mining and milling experimental sites have also been restored in Finland. However, they are outside the scope of this article, although similar radiation protection criteria have been applied.

RESTORATION CRITERIA

Under the Finnish Radiation Act the undertaking or licensee operating any site has the legal responsibility for managing all waste arisings so that they do not cause unnecessary impacts on the environment or to public health. If radioactive substances have been released to the environment, the licensee is also responsible for implementing any necessary remedial measures. The State has the responsibility for restoring any contaminated areas, where the source of contamination is unknown, the licensee will not perform the necessary measures, or no responsible operator exists. The regulatory body, which is responsible for overseeing all issues related to radioactive wastes and to sites contaminated with radioactive substances, is the Radiation and Nuclear Safety Authority (STUK).

STUK issues general instructions, known as Radiation Safety Guides (ST-Guides), concerning the use of radiation and operations involving exposure to natural radiation. These guides do not contain any general dose criterion for restoring old waste areas, decommissioned sites or other contaminated sites. Each site has been treated on a case by case basis. However, case-by-case optimisation has resulted in the same individual effective dose criterion of 0.1 mSv/a above the local natural background radiation being set.

CASE STUDIES

Wastes from lead processing

From 1961 to 1972 lead was mined and processed in the Korsnäs district on the west coast of Finland. High radon concentrations were monitored in the underground parts of the mine during its operation, but no attention was paid on the elevated levels of natural radionuclides in the processing wastes. Some 760 000 tons of waste were produced with average uranium and thorium concentrations of 700 Bq kg⁻¹ and 250 Bq kg⁻¹, respectively. The total area occupied by the main waste depository is about 6 hectares and the nearest buildings are located 200 metres from the site. Some 36 000 tons of lanthanide concentrate, containing 1500–4500 Bq kg⁻¹ of uranium and 1000–1500 Bq kg⁻¹ of thorium, were also produced and are also stored in the mining area. The lanthanide depository is the minor waste site in the mining area, the whole of which is enclosed by a fence.

The restoration of the waste area rose to importance in 1992, when the local municipality began examine new uses for the area. They sought the advice of STUK on the radiation safety of the area. STUK set as the safety objective that the waste should not add more than 0.1 mSv per year to the individual effective dose from natural radiation in the region .

In 1996, before any restoration measures were undertaken, STUK made various base measurements at the site. These included external dose rate, airborne particulate radioactivity and radionuclide concentrations in water from nearby ponds and the sea bay. From these, maximum annual doses to local inhabitants were estimated conservatively to be 0.3 mSv.

The first remediation objective was to isolate the lanthanide waste pile. This was achieved by covering with a moraine layer of thickness 0.5–1 metre and an additional growing layer. This was considered to be sufficient remediation at present. The covered area is also being shaped, so that the rain water will not accumulate on the covered area. Contamination of drinking water sources, either surface or underground, was estimated to be insignificant.

Remediation work was started at the lanthanide depository in 1997 and should be completed by the end of 1998. A final inspection of the restoration will be undertaken on completion, but no programme of post-restoration radiation monitoring is planned.

Restoration of the main waste depository is not considered necessary at present. It will be discussed as soon as the future use of the mining area is known.

Wastes from zinc processing

Zinc mining at Vihanti ended in 1992. The wastes stored at the mine contain elevated levels of uranium with the average uranium concentration being around 400 Bq kg⁻¹. After closure of the mine, the waste pile was covered with a thin layer of soil which, together with the increasing vegetation, will prevent resuspension of radioactive substances to the environment. It also reduces external gamma radiation to normal levels. These measures were performed on the basis of the Mining Act, as part of the normal restoration of mining environments. The measures were also considered to be adequate to meet the radiation safety requirements at this site. No post-remediation monitoring of radiation is required.

Fly ash from burning of peat as fuel

Radionuclide fallout from Chernobyl accident in April 1986 was very unevenly deposited in Finland. Relatively high concentrations of these radionuclides occurred in fuel peat. This was due to a thin surface layer of peat-production bogs was extracted for fuel soon after the fallout occurred. Practically all of the radioactivity then concentrated in the fly ash during peat burning. Concentrations of ¹³⁷Cs in peat ash produced in western and central parts of Finland during the heating season of 1986–1987 varied from few hundreds to 70 000 Bq kg⁻¹. More than four million tons of fuel peat were burned during that period, producing more than 110 000 tons of peat ash.

Special radiation protection measures had to be taken in handling, utilising or depositing this peat ash. Before the Chernobyl accident the ash was widely used in concrete production, as a fertiliser in silviculture and agriculture, or it was used as a landfill material. After the fallout occurred, these uses were halted in many municipalities and power plants had to find new places to deposit the ash. Municipal landfills were suitable for this purpose because protection

of the environment was taken into account in their planning and operation. In addition, radioactive peat ash would quite soon be covered with normal community wastes.

In a few cases peat ash was deposited in specially selected sites. In selecting these sites, special attention was paid to protection of local ground waters and to proper covering of the depositories. The safety requirement of 0.1 mSv per year, as an effective dose of members of the public, was set as the planning basis for the depositories. The plans were examined and tested by conservative impact models to ensure that the safety requirements will be met. Final inspections were performed by STUK after the depositories were covered with moraine and soil layers. Post-restoration monitoring of radioactivity of drinking water from a nearby well was required in one case. The monitoring has not shown any contamination of the well water.

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Annex IV

UNITED STATES OF AMERICA

LONG-TERM ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAMMES AS A BASIS FOR POST-RESTORATION CHARACTERISATION AT TWO US DEPARTMENT OF ENERGY SITES

Introduction

The US Department of Energy (DOE) is currently in the process of cleaning up sites within a weapons complex that is spread across the nation from South Carolina to Washington State [IV-1]. Examples where the cleanup work has been completed and sites or portions of the sites released for other uses are limited. All sites have existing monitoring programs in place that, when integrated with the characterisation efforts implemented under the cleanup process will help to ensure compliance with cleanup criteria. New, particularly in situ analytical techniques will improve the cost effectiveness of these efforts. This Annex provides an overview of the long-term survey programs at two DOE sites and discusses some specific post-restoration survey efforts.

Long-term survey programmes

The Hanford Site and Pantex Plant (Fig. IV-1) are two sites with long-term survey programmes in place and cleanup efforts underway. The Hanford Site was established in south-eastern Washington during the 1940s to produce Pu during World War II. The Pantex Plant in the Texas Panhandle was originally used by the US Army for loading conventional ammunition shells and bombs and was rehabilitated and enhanced in the 1950s to assemble nuclear weapons using the Pu produced at Hanford.

The Hanford Site occupies a land area of about 1450 km² (560 mi²). The Columbia River flows through the Site and forms part of its eastern boundary. The Hanford Reach (about 82 km) is the last unimpounded stretch of the Columbia River in the United States, except for the portion between Bonneville Dam and the river's mouth. Because public access to the Hanford Site has been restricted and the site has been free from agriculture for almost 50 years, it has conserved the habitats of, and now serves as a refuge for, various plants and animals.

Nuclear and non-nuclear industrial and research activities have been conducted at Hanford since 1953. The most significant activities environmentally have involved the production of nuclear materials and associated chemical processing and waste management. By-products have included gamma-, beta- and alpha-emitting radionuclides and various non-radioactive chemicals in gaseous, liquid and solid forms.

The Pantex Plant occupies a land area of about 65 km² (25 mi²). This includes about 24 km² (9 mi²) that are leased from Texas Tech University for use as a safety and security zone. The topography is relatively flat, characterised by rolling grassy plains and numerous natural playa basins (ephemeral lakes). There are over 17 000 playa basins on the Texas High Plains, most less than 1 km (0.6 mi) in diameter, that receive water runoff from the surrounding area. The region is semiarid and the Plant is surrounded by agricultural and range lands.

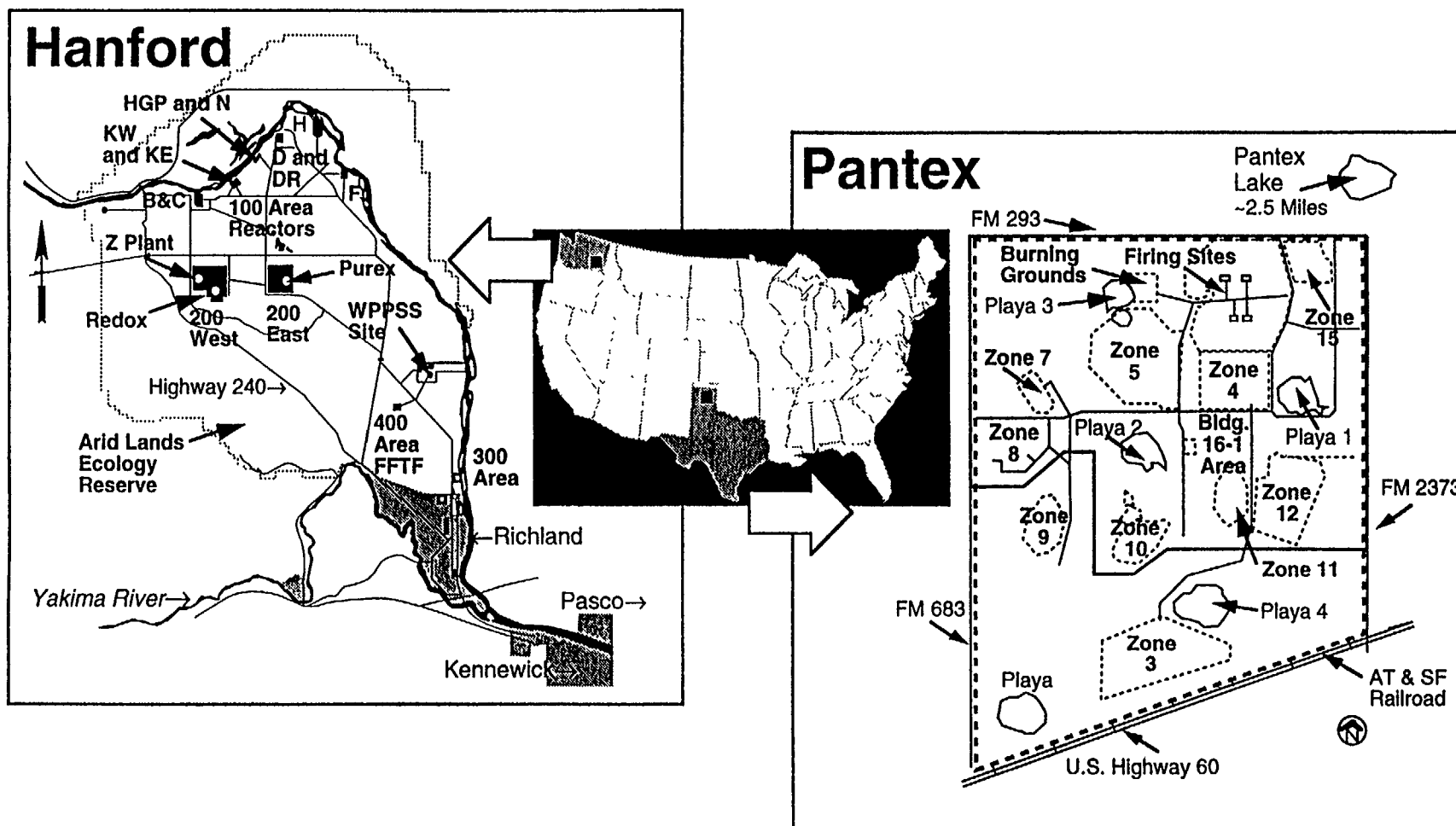


FIG. IV-1. US Department of Energy's Hanford site in south-eastern Washington State and Pantex plant in the Texas Panhandle.

The primary mission of the Pantex Plant is currently the disassembly of nuclear weapons. Pantex is also responsible for assembly of nuclear weapons; surveillance, storage, maintenance, modification, repair, and non-explosive testing of nuclear weapons components; and the manufacture of chemical high explosive (HE) components. Current operations involve short-term handling (but no processing) of encapsulated uranium, plutonium and tritium, as well as a variety of industrial chemicals.

Environmental survey has been conducted for over 50 years at Hanford [IV-2], and for over 25 years at Pantex [IV-3] to assess potential impacts to individuals and populations that may be exposed to radionuclides, ionising radiation and hazardous chemicals. Environmental media sampled have included air, surface and ground waters, foodstuffs (fruits, vegetables, milk, etc.), fish, wildlife, soils, and vegetation. In addition to environmental media, both air and water emissions are sampled and analysed. The population status of key fish and wildlife species are also determined at Hanford. Thus, an environmental survey network was already established at both sites before they were designated for cleanup air. At Hanford and Pantex, air is sampled continuously for airborne particulates and analysed for radionuclides at on site and off site locations [IV-4, IV-5]. At selected locations, gases and vapours are also collected and analysed Surface Water. Columbia River water is used for drinking at cities downstream of Hanford and for crop irrigation and recreational activities (fishing, hunting, boating, water-skiing, swimming). Thus, it constitutes a potential environmental pathway to people for radioactivity in liquid effluents [IV-4]. Pantex Plant does not include or border on any rivers or streams. However, storm-water runoff from the Plant and lands leased from Texas Tech University flows through ditches to on-site playas and off site. Thus, playas are ideal surface locations for assessing Plant releases [IV-5].

Ground water. At Hanford, ground water, primarily from an unconfined aquifer, is currently sampled from about 800 wells and analysed [IV-6]. Tritium, which occurs at relatively high levels in the unconfined aquifer, is one of the most mobile radionuclides, and thus its distribution reflects the extent of ground water contamination from on site operations. Ground water from the unconfined aquifer enters the Columbia River through subsurface flow and springs that emanate from the riverbank. Although concentrations of ^3H and other radionuclides in springs generally reflect those in nearby ground water wells, they are lower in springs due to mixing of ground and surface water.

At Pantex, ground water is sampled from over 65 wells, including both the Ogallala aquifer and perched ground water [IV-5]. One off site location each is sampled for ground water as a control.

Foodstuffs. Samples of alfalfa and several foodstuffs, including milk, vegetables, fruit, beef, chickens, eggs, and wheat, are collected from several locations, primarily downwind (i.e., south and east) of the Hanford site [IV-6]. Samples are also collected from upwind and somewhat distant locations to obtain information on radiation levels attributable to worldwide fallout. Foodstuffs from the Riverview Area (across the river and south-east) are irrigated with Columbia River water withdrawn downstream of the Site. Although human foodstuffs have not been routinely sampled at Pantex, winter wheat and sorghum that are fed to cattle are collected and analysed [IV-5].

Fish and wildlife. Fish are collected at various locations along the Columbia River, and the boneless fillets are analysed for ^{60}Co , ^{90}Sr , and ^{137}Cs . Carcasses are analysed to estimate ^{90}Sr in bone. Short-lived radionuclides, including biologically important ^{32}P and ^{65}Zn , have

essentially disappeared from the river [IV-7] through radioactive decay. Deer, pheasants, ducks and rabbits are collected at Hanford and tissues are analysed for ^{60}Co and ^{137}Cs (muscle), $^{239,240}\text{Pu}$ (liver), and ^{90}Sr (bone) [IV-6]. Routine wildlife sampling (prairie dogs) was initiated at Pantex in 1995 [IV-8].

Soils and Vegetation. At Hanford and Pantex, samples of surface soil and rangeland vegetation are collected at on site and off site locations and analysed [IV-5, IV-9].

Other survey. Survey for chemical contaminants in various environmental media and to determine population status of key species is also conducted [IV-2–IV-4, IV-6, IV-10–IV-13].

Post-restoration survey

Federal agencies in the USA that regulate the use of radioactive materials (Environmental Protection Agency (EPA), Nuclear Regulatory Commission (NRC) and Department of Energy (DOE)) have recently prepared a manual that describes the survey process (procedures and instrumentation) necessary to demonstrate compliance with release criteria. The manual is entitled “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)” [IV-14]. The former NRC policy was to conduct surveys as described in [IV-15].

Hanford/Pantex. The existing survey programmes, when integrated with the characterisation efforts implemented under the cleanup programs will help to ensure compliance with cleanup criteria. New, particularly in situ analytical techniques, will improve the cost effectiveness of these efforts

Enewetak Atoll (part of the Pacific Proving Grounds for nuclear weapons). Following soil removal and disposal into a weapons test generated crater, the islands were surveyed using a germanium detector with wide-angle collimator mounted on an extendible boom. The islands were gridded, and measurements made at each grid intersection. The 60 keV ^{241}Am gamma was measured. Soil sampling and lab analysis were used to develop Pu/Am ratios to allow calculation of total transuranics following cleanup.

Sites containing uranium and thorium. Sites were cleaned up to criteria approved by the US NRC. For uranium mill tailing sites, high-density gamma data were obtained via Global Positioning System-based detectors as a primary verification method. Gamma action levels were established through correlation studies. A limited soil-sampling program provides backup confirmation that the site is clean.

For thorium sites, a composite sample is prepared for each 100-sq m area and analysed. The NRC requires that no hot spots be greater than 3 x the cleanup limit. However, when extrapolating to zero volume, the criterion can't be met. In practice, NRC staff walks the area and if any hot spots likely to exceed the 3 x criterion are found, the contamination is removed.

Savannah River Site, SC. Following soil removal for $^{137}\text{Caesium}$ at a waste site, a surface survey was conducted using a sodium-iodide detector. Soil samples were also collected and analysed. Based on the results, an additional area of soil was removed. Samples were again obtained and analysed. Results confirmed that no soil contained ^{137}Cs exceeding cleanup levels (13 Bq/g). All postings and associated barriers were removed and the unit was declared unrestricted.

Pinellas Plant, Largo, FL. After a 3-year cleanup effort, DOE transferred the first of its major weapons sites to private ownership, September 12, 1997 [IV-16]. Pinellas had no radiological contamination of soil or groundwater. Tritium was the main concern in buildings and on equipment. Buildings were cleaned to unrestricted release levels. When cleanup began, the DOE release level for tritium contamination was 1000 dpm/100 cm sq. Negotiations between DOE and NRC led to that level being raised to 10 000 dpm/cm sq. However, the buildings never exceeded 220 dpm/100 cm sq. Both Pinellas County and , the State of Florida independently verified that cleanup levels had been met. Methods included standard swipes and a gamma meter.

Promising post-restoration survey techniques

Concurrent with the redesign of sample networks and survey efforts, modifications to existing techniques and new analytical tools are been developed. Examples with potential application to post-restoration survey follow.

An in situ radionuclide assay system developed at the Idaho National Engineering and Environmental Laboratory (INEEL) consists of hardware and software designed to record near-surface and sub-surface radionuclide data in boreholes and survey wells. The system utilises a suite of radiation detectors to locate, identify and quantify radionuclide contamination. The system is composed of logging tools (detector(s)and housing, nuclear pulse processing equipment, hydraulic winch, and computer control equipment. The equipment is mounted in a four-wheel drive van. A 120-volt generator operates in place of the engine alternator and provides power for all computer and electronic equipment.

The system is ideal for site characterisation, verification of remedial actions, and post-closure survey. The system detectors are configured and operated to allow for optimal use of field time. Gross counters are used for rapid assessment of the total radionuclide distribution in the subsurface. Zones in the subsurface yielding anomalously high count rates are then counted using techniques to specify and quantify radionuclides contributing to the high count rate(s). Some of the radionuclides that can be identified with the system are ^{40}K , ^{60}Co , ^{90}Sr , ^{125}Sb , ^{137}Cs , ^{152}Eu , ^{154}Eu , ^{208}Tl (^{232}Th daughter), ^{214}Pb , ^{214}Bi , $^{234\text{m}}\text{Pa}$ (^{238}U daughter), ^{235}U , and ^{238}U . Concentrations are reported in pCi/g (soils) and pCi/l (water).

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SITE REMEDIATION IN BELGIUM

Introduction

Radioactive contamination of air, soil, water, vegetation and structures has occurred due to human activities related to the fabrication and use of radioactive sources, the development and application of nuclear energy, the nuclear fuel cycle, mineral processing of ores, industrial and medical applications and waste management practices.

Historic situation in Belgium

Two examples of site remediation cases in Belgium will be discussed in the following pages.

- Site remediation efforts were done already in the 1960s in the environment of a radium refinery, some parts were remediated, others are still waiting for a "final" solution.
- The remediation of waste dumps of Phosphate producing factories.

Former radium refinery

History of the factory and the Olen site

A factory producing copper and cobalt (not radioactive) is located in Olen (Belgium) [V-1]. From 1922 until 1969, this factory also produced radium. The company contributed to a large part of the world production of radium due to the discovery in 1915 in Congo of ore with a uranium oxide content of about 50%. The exact amount of radium produced is not known because the annual radium production was kept secret from 1937 for military reasons [V-1, V-2]. Five dumping grounds in the vicinity of the factory at St Jozef Olen were used for the dumping of radioactive and other waste. Some waste material was also used as a layer on a limited number of roads. Liquid effluents were released in the brook Bankloop since 1922. The Bankloop flows through the village, crosses a canal (Kempisch Kanaal) and flows into the Kleine Nete and finally into the river Nete.

At the end of the 1950s, measurements in the frame of a study to obtain the necessary licences for the start of the Belgian Nuclear Research Centre, made it clear that the water and the sediments of the Kleine Nete and of the Bankloop were contaminated with radioisotopes. The banks of the Bankloop brook were also contaminated because the brook was cleaned regularly and the removed sediments were placed on the banks. The Bankloop regularly flooded the land located just before its confluence with the Kleine Nete as a result of heavy rain, contaminating this boggy soil. Because an agricultural organisation wanted to make this land ready for farming, it had acquired the land and it had taken some measures to change the water management of this piece of land. A road (Roerdompstraat) was constructed to gain access to the area, the part of the Bankloop between this road and the Kleine Nete was moved approximately 100 m to the west, leaving the Old Bankloop as standing water. Drainage of the land between the road and the Kleine Nete was constructed, reversing the normal east to west flow. This was the situation in 1960.

Remediation from 1961 to 1969

A first study on the biological cycle of radium, applied to the Olen site, was undertaken from 1961 to 1967, with a follow up until 1977. This study included aerial radiological survey,

gamma survey at ground level, sampling of water, fish, vegetables, agricultural products, etc. The results were reported by Kirchman [V-3, V-4]. As a result of the study, a number of actions were recommended. Some of these actions were executed, others, e.g. using the place between Old and New Bankloop for forestry, were not. The actions taken included that the Old Bankloop was filled up and that deep ploughing was applied to make pastures for dairy cows.

Post-remediation survey 1969 to 1977

No survey was done to evaluate the immediate effect of the deep ploughing, instead a post-remediation survey programme was developed including periodic measurements of the milk from cows grazing on the remediated pastures (up to 1972) and of samples of vegetation. This programme was stopped in 1977 as it was judged that the results showed no relevancy for public health.

Reappearance of the problem in 1989

In 1989 and 1990, the population of St Jozef Olen became anxious as a result of coverage by the media of observations in some places of high (localised) contamination in the village. There was not sufficient data for evaluation of the situation in the context of a more stringent radiation protection approach because the existing data were mostly about the land near the Kleine Nete. As a result, the federal ministry of public health and environment (DBIS/SPRI) decided to carry out a more detailed assessment of the scattered contamination by a mobile survey (Fig. V-1) and a survey on foot of the most contaminated parts, including the dumping

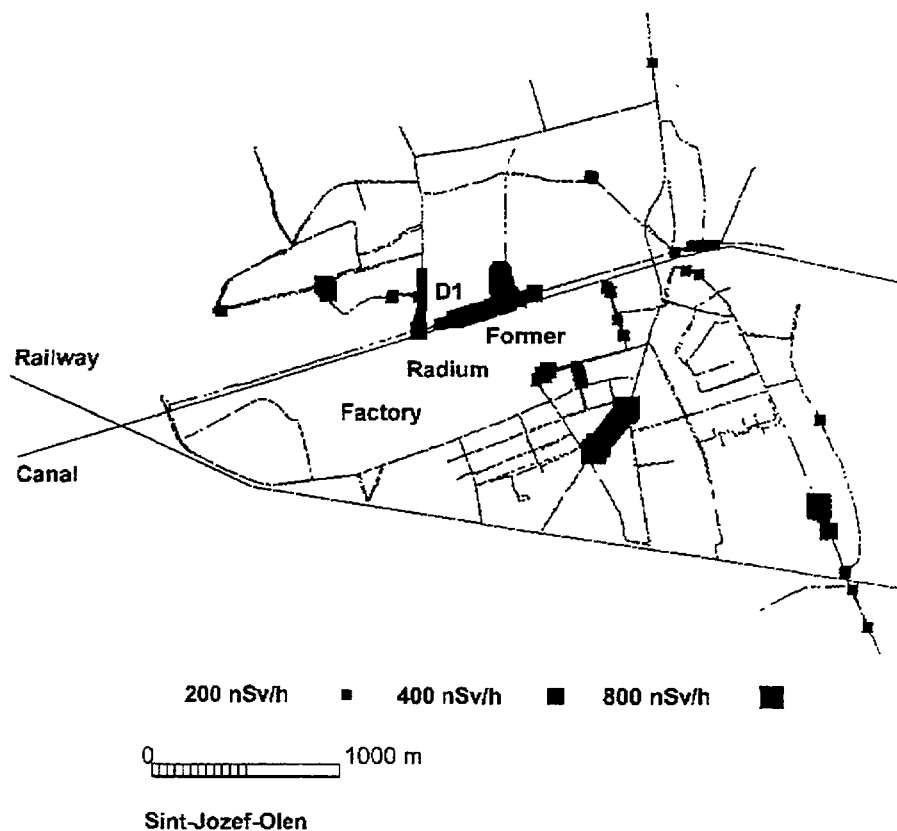


FIG. V-1. Location of the contaminated site.

grounds and the Bankloop. The program also included an evaluation of the radon exposure in the dwellings of St Jozef Olen, the village surrounding the factory, and in open air above the dumping grounds, as well as an evaluation of radium in airborne dust, in surface water, in ground water, in the food chain and in milk teeth of children. In 1991 the research program was assigned to the SCK/CEN and the Institute of Hygiene and Epidemiology (IHE). The final report was approved in March 1993 and was subsequently presented by the federal ministry of public health and environment to the population [V-5].

The highest individual doses are related to the inhalation of radon decay products, on the one hand in a dwelling with contaminated material under the veranda (11 mSv/year) and on the other by the occupants of the dwelling next to the D1 dumping ground in the prevailing wind direction (5 mSv/year). The Radon concentration was monitored in 846 dwellings. The investigation level of 150 Bq/m³ was exceeded in 6 of them. The number of dwellings exceeding the investigation level is in agreement with the radon distribution of the region [V-6]. The exposure of the occupants was calculated assuming a dose conversion factor of 50 Sv/year per Bq/m³ [V-7] and a residence time of 30 % in the bedroom and 50 % in the living room. In the gamma-survey programme, enhanced dose rates were monitored on the D1 dumping ground, in several streets and along the banks of the Bankloop. The dose rate indicates a very inhomogeneous distribution of the contamination, over a distance of one meter differences of more than one order of magnitude are often found. The intake of radium through the food chain is limited, because no crops for direct human consumption were cultivated on contaminated land. Airborne dust contamination was not detected. The analysis of milk teeth of children of Sint-Jozef-Olen confirmed the absence of a significant intake of radium. The principal reason not to classify the issue is the fact that there are several contaminated locations which could result in high doses if the land use is changed. More details about the radiological characterisation are described in Annex B of Ref. [V-8].

A committee has been established consisting of representatives of local and federal government, nuclear and non-nuclear waste management, industry and the nuclear research centre. This committee has to draw up a global restoration plan. In this plan, the D1 dumping ground plays a central role as it is being used as an intermediate storage for soil coming from the restoration of the other contaminated locations.

On the occasion of roadworks, contamination has been removed in three streets under continuous supervision of the radiation control service of the nuclear research centre. The cleanup criterion was a dose rate of less than 200 nSv/h at the surface, but it was possible to remove all contaminated material and to reduce the dose rate at the surface of the (excavated) roads to normal background (70 to 100 nSv/h). This was proved by a post-remediation gamma survey.

Scenarios for the cleanup of the D1 dumping ground have been developed, dose assessments have been made and possible solutions have been proposed. The decision process to obtain a selected solution, including post-remediation survey, is going on.

Phosphate production

Description and remediation

The processing of ores for the production of phosphates results in the concentration of natural nuclides in the waste material. The ²²⁶Ra concentration in the ores is approximately 1.5 Bq/g.

Depending on the production process, this results in 2 to 10 Bq/g in the waste, that is stored in an industrial waste dump.

A characterisation of the site was done to define the necessary parameters for the assessment and optimisation studies. This involved radiological characterisation (geographical dose rate distribution, ^{226}Ra concentration in the sediments) as well as the investigation of migration parameters for the waste dump, water table, soil, well, river, irrigation, and also of the factors determining the transfer of radioactivity in crops, milk, meat and finally to the humans.

In the normal evolution scenario, maximum individual doses for the critical group remain very small ($<10^{-3}$ mSv/year) and require no action, but in an intrusion scenario (building a residential area on top of the waste dump) maximum individual doses for the critical group may be higher than the limit of 1 mSv/year, mainly due to Rn exhalation into the dwellings.

Therefore, on top of the normal finishing of the dump, an additional impermeable layer with sufficient thickness was added, covered by drainage layers (sand and stones).

Post-remediation survey

Remediation survey consisted of making a gamma-survey before and after the installation of the additional layers, completed by a Rn exhalation follow-up programme.

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Annex VI

REPUBLIC OF BELARUS

THE PROCEDURE TO ENSURE COMPLIANCE WITH THE CLEANUP CRITERIA

The Chernobyl accident resulted in extensive contamination of Belarus. Today, 12 years after the accident, ^{137}Cs levels still contribute most to doses received by those living in the contaminated areas. Some 1.6 million people continue to live in the areas where contamination levels are $>37 \text{ kBq/m}^2$. The current Belarus legislation requires that protective measures, including decontamination, be used in these areas.

Full-scale cleanup of these areas is impossible. To aid decision-making on cleanup, some temporary standards have been adopted. Some of these lay down thresholds for external exposure dose rate. The Decontamination Programme for Socially Important Sites has now been started. These sites include kindergartens and schools in areas with contamination levels in the range of $185\text{--}640 \text{ kBq}(^{137}\text{Cs})/\text{m}^2$.

Examples of these standards are given in Table VI-1.

Table VI-1. Extract from the temporary levels for decision-making on cleanup

Contaminated sites	Exposure dose rate, $\mu\text{R/h}$
Kindergarten and school grounds	35
Farmstead	40
Indoors	25

A peculiarity of the contaminated territories is that the radioactivity has concentrated in the top 15-cm soil layer. Cleanup therefore consists of removing this upper soil layer.

To plan the decontamination work a two-stage process is used. An initial assessment of the radiation situation is carried out to determine whether the exposure dose rates are within the Temporary Levels for Decision-Making on Cleanup. This survey is undertaken using dose rate scanning. The standards specify that the measurements should be made with calibrated devices and in compliance with methods approved by national authorities. If the temporary levels are exceeded, the second stage is initiated. The results from the first stage form the basis for making decisions on the priorities among sites for cleanup.

At the second stage supplementary measurements are made to obtain more specific information. These include:

- (i) an exposure rate survey. For this each site is divided into $10 \text{ m} \times 10 \text{ m}$ squares and measurements are taken at each corner;
- (ii) where dose rates significantly exceed the mean values, the extent of the "hot" spot is determined; and
- (iii) soil samples are taken to determine the thickness of the ^{137}Cs -containing layer.

The results from the second stage form the basis for defining the proposed decontamination measures. These measures are only undertaken by specialist companies, in order to assure quality.

There have been problems in finding sufficient adequately clean soil to use as cover. This is because the contaminated regions are very extensive. In addition, transportation from outside considerably increases cleanup costs. To help overcome this problem research was undertaken to define an acceptable level for the soil radiocaesium content. A level of $\leq 400 \text{ Bq}(^{137}\text{Cs})/\text{kg}$ was found to be acceptable, resulting in no marked increase in the exposure dose rate.

A special manual has been prepared, which defines the conditions for accepting when the cleanup may be considered completed. This specifies:

- (i) the exposure rates have been reduced to meet the pre-established criteria;
- (ii) radioactive wastes have been removed from the site; and
- (iii) the necessary restoration work has been completed.

Special commissions have been established to conduct the formal acceptance procedure. These commissions include representatives from local authorities, kindergarten or school administrations, the specialist contractors and environmental health (sanitary) Inspectorate.

The commission undertakes measurements of the residual exposure rates on the site using the same measurement methods as in the initial survey, but sampling at random points. It then reviews the residual exposure rates at the site to confirm that the cleanup criteria have been achieved. It then prepares a final document. This document is to be submitted to the Ministry for Emergencies, which is the relevant regulatory body in Belarus. The administration concerned also receives for each decontaminated site official recommendations on its subsequent use, which are intended to prevent secondary contamination.

The quality of the cleanup is ensured by:

- (i) strict control of activities at each stage;
- (ii) use of specialist and experienced contractors to carry out the decontamination measures;
- (iii) use of consistent methods for assessing the radiological status of each site; and
- (iv) use of formal acceptance procedures.

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Annex VII

CANADA

LLRWMO EXPERIENCE WITH POST-CLEANUP SITE CHARACTERISATION

The Low-Level Radioactive Waste Management Office (LLRWMO) is operated by Atomic Energy of Canada Limited (AECL) through a cost recovery agreement with Natural Resources Canada. The latter is the federal department which provides the funding and establishes national policy for LLRW management. Part of the mandate of the LLRWMO is to resolve historic radioactive waste problems that are a federal responsibility. Historic wastes are LLRW for which the original owner can no longer be held responsible and which are managed in a manner no longer considered acceptable. If they are wastes for which the federal government accepts responsibility, their management comes within the mandate of the LLRWMO. The wastes generally stem from, but are not limited to, the spillage of materials during transport of ores and concentrates from mine sites to extraction and refining facilities during the period when these activities were a federal responsibility, and contaminated materials originating from the use of radium in luminous dials.

The current owners of properties with historic wastes are not licensed by the Atomic Energy Control Board (AECB) to possess these materials. Once the federal government accepts responsibility for the LLRW, the LLRWMO acts as the owner of the materials in dealing with the regulator. The LLRWMO remediates properties by removing the contaminated materials to storage or disposal. Where material concentrations are such that a licence is required, the materials are stored in a facility operated by the LLRWMO and licensed by the AECB. Where material concentrations are not of licensable activity, materials may be disposed of at a local site or held in interim storage until a permanent site is established.

Fort McMurray historic uranium cleanup project

Project background

Beginning in the 1930s, uranium ore and ore concentrates were shipped 2200 km by barge from the Port Radium mine in Canada's Northwest Territories to the barge-to-rail transfer point in Fort McMurray, Alberta [VII-1]. From Fort McMurray, the ore was transported by railcar to its final destination in Port Hope, Ontario for further refining. From the 1930s to the 1960s, approximately 30 hectares of riverside property was used for the unloading of barges and loading of railcars. Incidental spillage and tracking during the transfer of uranium-bearing materials was the cause of the contamination of these properties. In the summer of 1992, during investigations of transfer points along the water route, elevated levels of radioactivity were discovered on these riverside properties at Fort McMurray, Alberta [VII-2]. The management of materials discovered at transfer points along the water transportation route are within the LLRWMO mandate.

Pre-remedial activities

As part of the contaminated site identification project conducted along the water transportation route, the LLRWMO conducted interviews with local long-time residents and workers at the transfer sites, visited local museums, and held discussions with local authorities to understand the history of the sites and the activities conducted there. A public consultation program was implemented and a technical working group was established involving the project participants, including the regulators.

Characterisation surveys were conducted at the sites identified as potentially contaminated. The radiological surveys consisted of surficial radiation measurements taken on a 10 m grid pattern with test pits dug to establish depth profiles at areas targeted from the surficial surveys. Soil samples were taken from areas with elevated gamma radiation and analysed for radionuclides and associated metals.

The nature of contamination at the Fort McMurray sites fell into three categories [VII-3]:

- materials exceeding a uranium concentration of 500 ppm (mainly uranium ore) and therefore requiring a licence from the AECB;
- soil heavily contaminated with fragments of uranium ore with average concentrations greater than 30 ppm and less than 500 ppm uranium; and
- material that does not exceed the cleanup criteria but contains occasional rocks with elevated contaminant concentrations.

A background study was conducted which included soil sampling and radiation measurements in the greater Fort McMurray area. A map of surficial soil types was used to gather representative samples from undisturbed areas around the city. Soil samples were analysed for radionuclides and associated metals.

Data from the background study, site characterisation and an examination of human and environmental toxicity were used to develop cleanup criteria in consultation with the technical working group [VII-4]. The contaminants of concern at the site, associated with the uranium ore, were uranium, arsenic and radium. The arsenic criterion of 30 ppm was adopted from recommendation of the Canadian Council of Ministers of the Environment [VII-5]. A comparison of arsenic and uranium toxicity indicated that uranium represents a hazard less than that of arsenic, so 30 ppm was established as a conservative cleanup criterion for uranium. The most restrictive criterion for the project was the ^{226}Ra criterion of 0.1 Bq/g, which is the upper end of the range of background values found in Fort McMurray. The cleanup criteria were approved by the regulator before remedial activities took place.

Verification strategy

The project manager and a consulting statistician prepared a Verification Plan for the project. The verification project was designed to measure the amounts of residual contaminants, specifically uranium, arsenic and radium, throughout the site and to detect and react to any areas containing contaminant concentrations in excess of the cleanup criteria. Statistical considerations were incorporated into the Verification Plan, so that reported results could be compared directly to project criteria and details provided by the verification document. The Verification Plan contained details of soil sampling frequencies, sample compositing, averaging areas and volumes, and prescribed methods. All project verification activities were conducted on the site at the completion of remedial activities, but prior to restoration work. The Verification Plan was approved by the regulator prior to the commencement of site verification activities.

Verification involved systematic sampling of property areas where remedial work was conducted and no work took place.

In areas where cleanup had taken place, surficial soil samples were collected on a 5 m grid and sets of 6 contiguous samples were composited for analysis. At the sample locations, portable gamma spectrometer measurements were taken. Sample analysis values exceeding the project criteria triggered additional remedial work in the sample area.

In site areas where no cleanup took place, test pits were dug on a 20 m grid and samples collected from the surface down to native, undisturbed soil. Sample results exceeding the project criteria triggered remedial work in the vicinity of the test pit. Trenches were installed in the non-remedial areas by removing 15 cm layers of material and conducting gamma radiation surveys over the exposed surface.

Over the site area, both remedial and non-remedial, gamma radiation surveys were conducted with a computer-assisted radiation survey system developed by the LLRWMO. The system collected gamma radiation readings on a 1 m grid and the data were used to identify the locations of discrete pieces of uranium ore which were subsequently recovered and characterised. Based on analyses and categorisation of the recovered pieces of rock emitting elevated levels of gamma radiation, an estimate of contaminant concentrations could be determined over the survey area and compared to the project criteria.

Implementation of verification programme

The project manager in the LLRWMO was responsible for defining the scope of work, assembling the project team and executing the work plan. The Project Leader acts on behalf of the project manager, in the execution of the work plan including: field operations; health, safety and environmental protection; personnel training; quality assurance; data analysis; and, report preparation. The survey team and contractor services report to the Project Leader. Laboratory analyses may be conducted in-house and by external contractors and are coordinated by the LLRWMO Laboratory Analyst. Contracted staff included earth moving contractors, equipment providers and a consulting geologist.

Field operations progressed in accordance with the Verification Plan. As radiological information was gathered, data analysis was conducted to determine whether criteria failures existed. Where preliminary data based on gamma radiation measurements, in situ gamma spectroscopy or quick turnaround sample analysis, exceeded project criteria, additional remedial work was coordinated concurrent with verification activities at the site. Once the additional remedial work was completed, the area was re-submitted for verification.

On completion of the verification work at the site, a verification report was prepared by the Project Leader for approval by the project manager and subsequently submitted for regulatory acceptance. The report described the verification programme, results collected in both remedial and non-remedial areas, and a determination of criteria compliance.

Closure

To date, approximately 22 hectares of property in Fort McMurray have had remedial works conducted on them and subsequently deemed to meet the project criteria [VII-6]. Approximately 26 500 m³ of contaminated materials were removed to final disposal in a cell constructed at the Fort McMurray landfill site. Approximately 84 m³ of licensable material were removed to licensed storage. One industrial property of 5.3 hectares remains to be cleaned up.

Malvern remedial project

Project background

Low-level radioactive contamination was discovered in 1980 in residential properties in the City of Scarborough, Ontario, Canada. This contamination resulted from a small radium

incineration and processing operation, based on a farm in this area during the 1940s [VII-7]. Development of the farm into a residential area during the early 1970s resulted in the spread of the ^{226}Ra contaminated materials throughout the development. During the 1980s, proposals to remediate the contaminated properties by removal and relocation of the radioactively contaminated soils were deferred because of unavailability of a storage site.

In 1992, the Malvern Remedial Project Steering Committee (MRPSC) was formed to provide overall guidance in the development of a programme for remediation of the contaminated sites. Detailed characterisation studies were conducted in 1992 through 1994. Cleanup of the sites began in the spring of 1995. Contaminated soils were excavated from the properties and segregated with the use of a soil sorting plant. LLRW was segregated, containerised and shipped to a licensed storage facility. Mildly contaminated material was stored in an interim storage mound. Clean excavated soil was used as cover material for the interim storage mound.

The contamination existed in two forms, as bulk volumes of contaminated soils and discrete ^{226}Ra contaminated Artefacts in otherwise clean soil.

Pre-remedial activities

Criteria for the project were developed under the direction of the MRPSC [VII-8]. The cleanup action level for soil contamination corresponded to the 98th percentile of naturally-occurring radium concentrations in the metropolitan Toronto area, i.e. 0.073 Bq/g [VII-9]. Samples collected were to represent areas no greater than 10 m² and 0.50 m in depth. For discrete particles, a risk-based assessment was performed using the most conservative parameters. The goal was to identify and remove any particle with an activity greater than 0.15 MBq (4 μCi). As the contaminated artefacts were known to exist primarily in the topsoil layer, detection instruments were required to detect a source of this activity buried beneath 10 cm of soil.

A computer-assisted, large area gamma radiation survey system was developed by the LLRWMO to perform surveys of properties with data being collected electronically with an on-board computer [VII-10]. Radiation measurements were collected on a frequency of 4 readings per square metre. The intense survey coverage resulted in a greater than 90% probability of detecting a 0.15 MBq source buried at 10 cm.

Prior to the cleanup project and development of the soil sorting conveyor system, a pilot project was conducted to test the technical feasibility of a sorting system. The primary goal of the sorting system was to: detect and segregate bulk soil volumes with a specific activity greater than 3.7 Bq/g; detect and segregate ^{226}Ra contaminated artefacts with an activity greater than 0.15 MBq; and, to determine the average activity of batches of soil for calculation of the radioactive inventory [VII-11].

A detailed investigation of all residences in the effected community was conducted. Gamma radiation surveys were conducted at over 450 residential properties using the computer-assisted radiation survey technology developed by the LLRWMO. The survey programme detected areas of bulk radium contamination on 25 properties not identified during previous survey campaigns. This brought the total number of properties requiring cleanup to 75.

Verification strategy

The Verification Plan [VII-12] for the work was developed by the LLRWMO project manager responsible for the verification activities and his staff. It was reviewed by the internal licensing coordinator and was approved by the LLRWMO Director on behalf of the Technical Advisory Committee established by the MRPSC. The systematic soil sampling and spectral measurements within the excavation area were designed so that composite samples would represent the area a house may be built on, while the individual measurements could be compared to the recommended averaging area of 10 m². The verification programme was also designed to detect contaminated materials in areas on the property outside the excavation area, in the event that they had been overlooked during delineation surveys.

On completion of the removal of contaminated materials from each property, a series of measurements were collected from within the excavation area and outside in the undisturbed soils. All areas of the property were surveyed with the computer-aided survey system. Where radiometric anomalies were identified in the survey data, a series of measurements were collected with hand-held survey meters. Gamma radiation measurements greater than the upper limit of normal for the property were targeted for further remediation as they may be indicative of bulk contamination or discrete artefacts.

Within the excavation area, soil samples were collected on a 3 m grid and composites of 16 contiguous samples were prepared, analysed by gamma spectroscopy and compared to the project criterion for ²²⁶Ra. At each sample location, surficial spectral data were collected in situ with a portable gamma spectrometer. Values exceeding the project criterion for ²²⁶Ra measured either in situ or by laboratory analyses, triggered additional characterisation and remedial work.

Outside the excavation area, a series of boreholes was installed around the excavation perimeter and spectral data gathered in situ on 10 cm increments with a borehole probe. Where values exceeded the project criterion for ²²⁶Ra, excavations were extended during additional remedial work.

A property was deemed by the project manager to meet the project criteria when all tests were passed.

Implementation of the verification programme

The roles, responsibilities and execution of verification programmes conducted by the LLRWMO are as generally described above for the Fort McMurray Historic Uranium Cleanup Project. The verification programme following the remediation of approximately 75 properties under the Malvern Remedial Project required a significant effort by the field teams as post-excavation surveys were conducted on a property by property basis, though excavations may be contiguous across many properties. The goal was to produce individual property reports for each property owner.

At project completion, verification results were reported to each property owner and remain on file at the LLRWMO.

Closure

At project completion, all 75 properties met the ²²⁶Ra cleanup criterion. Approximately 33 m³ of contaminated soils and several hundred radium contaminated artefacts were removed as

LLRW to a licensed storage facility [VII-13]. Material volumes of 9077 m³ exceeding the project cleanup criterion for radium but not considered licensable were stored in an interim storage mound, awaiting future disposal. Materials excavated but found not to be contaminated were used as top cover for the interim storage mound.

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Annex VIII

FRANCE

RADIOLOGICAL SURVEY OF THE ATOLLS OF MURUROA AND FANGATAUFA IN FRENCH POLYNESIA AFTER THE ENDING OF NUCLEAR TESTING

INTRODUCTION

From July 1966 to January 1996, France carried out 193 nuclear tests on the sites of Mururoa and Fangataufa (French Polynesia), firstly in the atmosphere and then underground. During the thirty years of operation of the Pacific Test Centre (CEP), limitation of the radiological impact was an ongoing objective, monitored by an extensive programme of measurements in the environment. This objective has been achieved, as the atolls of Mururoa and Fangataufa are not subject to any radiological restrictions since the final end of testing.

The knowledge acquired about the behaviour of the radionuclides deposited in the geosphere and in the biosphere of the atolls has enabled a suitable radiological survey programme to be established for the post-testing period. Although no present or future scenario predicts significant radiological exposure, it is important to have access to regular measurements so that this can be demonstrated directly. This programme will also collect scientific information of general interest.

GENERAL CONTEXT

The Mururoa and Fangataufa atolls are located in the South Pacific, mid-way between Australia and South America. Like all atolls, they consist of volcanic bedrock overlain by a platform of carbonate formations of coral origin [VIII-1]. The characteristic dimensions of the Mururoa and Fangataufa atolls are respectively 30 km × 10 km and 10 km × 5 km, but only a narrow low coral rim is visible above sea level. This rim is locally discontinuous around a vast lagoon of maximum depth 50 m at Mururoa (40 m at Fangataufa).

The phenomenology of the atmospheric and underground nuclear tests at the CEP and the assessment of the geomechanical and radiological impact of these tests have been the subject of many studies by the French Ministry of Defence, which was responsible for these sites, and by the French Atomic Energy Commission, which executed them [VIII-2], [VIII-3], [VIII-4].

At the request of the French government, an international investigation was organised after the end of testing. This investigation was carried out under the aegis of the International Atomic Energy Agency for the radiological aspects, and by an expert committee under the responsibility of Professor Charles Fairhurst (University of Minnesota) for the issues concerning hydrogeology and geomechanical stability. The results of these studies [VIII-5], [VIII-6] confirm the lack of significant radiological impact of the tests on the present and future potential populations of the two atolls, and *a fortiori* on those of the neighbouring islands. The IAEA study concluded that the radiological situation at Mururoa and Fangataufa does not require any remedial action and nor does it justify the continuation of environmental surveillance.

RADIOLOGICAL IMPACT OF THE ATMOSPHERIC TESTS

Of the 41 atmospheric tests carried out at the CEP between 1966 and 1974, 37 were conducted at sufficient altitude (a few hundred metres, suspended from a balloon or released from an aircraft) for the fireball not to reach the surface of the lagoon. The balloon-suspended approach considerably limited the local fallout of radioactive products and no significant traces of these tests now remain in the environment of the atolls.

The present radioactive labelling of the biosphere of the atolls comes mainly from the fallout from four nuclear tests (three at Mururoa and one at Fangataufa) carried out on barges at the start of operations at the CEP, and from five atmospheric safety experiments that resulted in the dispersion of plutonium in the neighbourhood of a limited sector of the northern coral rim of Mururoa atoll.

The bulk of the radioactive products deposited by these tests are stored in the lagoon-floor sediments, close to where they were generated. Some thirty years of observations now exist on the behaviour of these deposits and their transfers in the physical and biological environment. The plutonium, caesium and strontium from these deposits label the lagoon water at concentrations that are significantly above the background of the ocean surface water, but which remain low and without radiological consequences (present mean concentrations in lagoon water: $^{239+240}\text{Pu} < 1 \text{ Bq/m}^3$, $^{137}\text{Cs} = 3 \text{ Bq/m}^3$, $^{90}\text{Sr} = 2 \text{ Bq/m}^3$).

RADIOLOGICAL IMPACT OF THE UNDERGROUND TESTS

From 1975, all of the nuclear tests and safety experiments were carried out underground, first under the emerged rim, then under the lagoon. The general configuration of these tests considerably limited the transfer of radioactive products from the geosphere to the biosphere, both in the short term and long terms:

- the depth at which the tests were carried out was always substantially greater than the minimum required (a function of the released energy) to ensure containment of the explosion and avoid any instantaneous release of radioactivity into the environment,
- most of the radioactive products are trapped during the solidification of the lava formed by the melting of rock in the immediate vicinity of the test point; only certain elements such as tritium (all), caesium and strontium (part) escape this entrapment,
- the hydrogeological and geochemical characteristics of the volcanic medium (low permeability, presence of clays) limit the mobility of the elements that are not trapped in the lava.

For the vast majority of the underground tests, the deposited radioactive products, including the most mobile ones, are still completely contained in the volcanic formations in the test cavity-chimney. This is the chamber filled with debris that develops with limited vertical extension when the cavity initially formed by the explosion collapses.

Only a few tests resulted in early transfers of mobile products (HTO, and to a lesser extent ^{90}Sr and ^{137}Cs) to the permeable strata of the carbonate formations (karst levels). A small fraction of these products reaches the lagoons and currently gives a measurable tritium activity, i.e. 1000 Bq/m^3 , that has no radiological significance.

In the medium and long terms, assessments both by French organisations [VIII-4] and by the IAEA [VIII-5] indicate that the transfer of radioelements generated by the underground tests will not lead to a significant increase in the activities of artificial radioelements currently detected in the lagoon water.

SURVEY PROGRAMME

The radiological survey of the military sites on Mururoa and Fangataufa is the responsibility of the French Ministry of Defence. It is implemented with the scientific and technical support of the French Atomic Energy Commission. After the ending of nuclear testing, this survey had to meet two objectives:

- provision of data necessary for calculating the impact of the nuclear tests in terms of doses to a real or hypothetical population living on the atolls. These doses are and will remain negligible, but it is important to have regular access to the measurements necessary to confirm this indisputably,
- medium-term follow-up of the behaviour in the geosphere and in the biosphere of the products deposited by the nuclear tests at the CEP, for scientific purposes.

To meet these two objectives, the survey has been based on a limited number of continuous measurements and an annual sampling campaign in the environment, with off-line measurements in France. The detailed technical programme is described in Ref. [VIII-4] (document no. 12 "Guide to the radiological survey of Mururoa and Fangataufa atolls").

The assessment of the dosimetric impact is based on the elements outlined below.

External exposure is recorded continuously on Mururoa by means of a NaI detector installed in the inhabited area and by dosimeters installed at various points on the atoll and read every three months.

Atmospheric aerosols (assessment of exposure by inhalation) are collected continuously in the inhabited area of Mururoa by a filter apparatus with a nominal flow rate of 110 m³/h, with daily filter changes. The analyses are carried out off-line.

The food chain (assessment of exposure by ingestion) is monitored by the annual sampling campaign. In the terrestrial environment, the only significant element is the coconut (copra and coconut milk collected on Mururoa and on Fangataufa). In the marine environment, the various trophic levels of the lagoon are studied: plankton, primary consumers (surgeon fish and trochus) and secondary consumers (groupers). The ocean samples include plankton, shrimps taken at depth on the flanks of Mururoa atoll, and inshore and offshore pelagic fish (fished within the 12 nautical mile limit around Mururoa and Fangataufa atolls).

The effective mobility of the radioelements is observed as described below.

Cavity-chimneys: Two underground tests carried out under the rim on Mururoa were equipped with sampling tubes enabling cavity water to be sampled. The changes in the activity of this water have been monitored for more than 10 years. They have confirmed satisfactory containment of potentially mobile products and the extremely low activity of elements, such as plutonium (< 1 Bq/m³), at the source of the deposits. Continuation of this survey will

provide further knowledge about the mechanisms of retention at the source for the various radionuclides.

Underground water: A network of instrumented boreholes (17 on Mururoa and 5 on Fangataufa) enables of underground water to be sampled by pumping through sampling tubes with intakes at different depths. This network monitors the activity in the permeable strata of the carbonate formations (karst levels) through which mobile radionuclides that were not fully contained in the solidified lava must pass on transit to the biosphere.

Lagoon water: Measurement of artificial radioelements in the lagoon water provides information about changes in transfers from the lagoon-floor sediments and from the carbonate formations.

Ocean water: Water samples from the atoll flanks and from the limit of territorial waters are used to look for any traces (usually undetectable) of transfers of artificial radionuclides from the atolls.

Soils and sediments: Additional soil and sediment sampling campaigns will supplement and update the existing database.

The first annual sampling campaign following ending of testing, was carried out in the first half of 1998. The analyses will be undertaken during the second half of 1998 and the results published in 1999.

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Annex IX

SLOVAKIA

SITE CHARACTERISATION TECHNIQUES FOR REMEDIATION AND POST-REMEDIATION SURVEY PURPOSES

Introduction

Environmental restoration is being undertaken in the Slovak Republic over an area covering 18 km along the banks of the Manivier canal, Dudváh River system. This land was contaminated with ^{137}Cs as a result of two accidents in 1976 and 1977 at the CO_2 -cooled, heavy water moderated A1 reactor at the Bohunice NPP complex. Until 1992, this canal-river system carried the waste water from the Bohunice NPP (A1 and V1) to the Váh River. From that time, the contaminated waste water has flowed through a specially constructed 15 km long pipeline (Fig. IX-1) from Bohunice NPP directly to the Váh River.

In 1990 the regulatory (hygiene) authorities specified an acceptance limit $1 \text{ Bq}(^{137}\text{Cs})/\text{g}$ for residual contamination in soil after remediation [IX-2]. This limit was derived on the basis of preliminary monitoring results. An initial design was prepared for restoration of the upper part of the contaminated banks, based on the removal and disposal of $\sim 5000 \text{ m}^3$ of contaminated soil. Over the period 1991-1994 the contaminated area was extensively characterised [IX-1]. Table IX-1 summarises the resulting contamination characteristics for each section of bank and an affected adjacent field.

TABLE IX-1. CONTAMINATED AREAS AND ^{137}Cs SPECIFIC ACTIVITIES ON THE AFFECTED BANKS NEAR BOHUNICE NPP

Contam. section	S, > 1	As	S, > 8	As	A-resid	Note
	[m^2]	[Bq/g]	[m^2]	[Bq/g]	[Bq/g]	
K1	10000	6.7	2000	9.5	4.9	strip, 1-1.5m strip, 0-2.5m (near village)
K2	5730	16.2	5730	16.2	3.3	
K3	9725	2	0		2	
D1	1200	1.8	0.0	0.0	1.8	(land field)
D2	1500	3.5	0.0	0.0	3.5	
D3	3725	4.7	1400.0	8.4	2.5	
Dpo	1500	2	0.0	0.0	2.0	
DR1	5940	1.9	0.0	0.0	1.9	soil covering
DR2	6050	3.2	0.0	0.0	3.2	
DR3	10500	9.6	9450.0	10.2	0.9	
VPK1	4760	2.1	10.0	8.7	2.1	S< min area S< min area
VK35	2530	2.8	25.0	9.2	2.8	
VK6	4260	1.8	0		1.8	
SUM	67420		18615.0	0.0	2.5	

S, $>1, >8$ - area with activity conc. $>1, >8 \text{ Bq/g}$

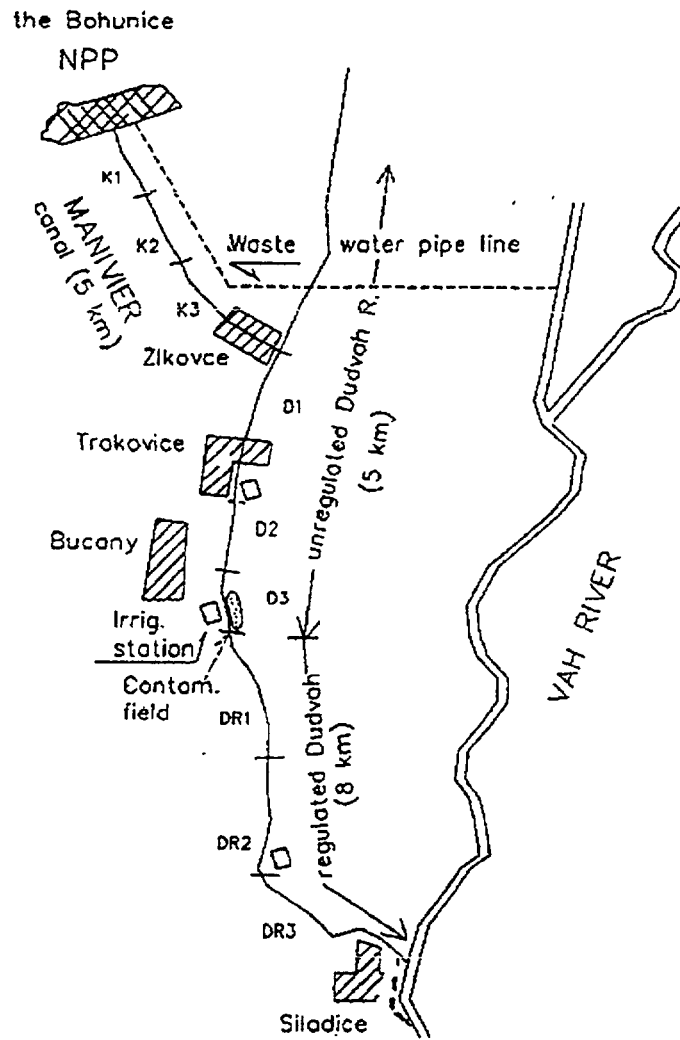


FIG. IX-1a. Scheme of the water system taking out the waste water from the Bohunice NPP to the Vah River.

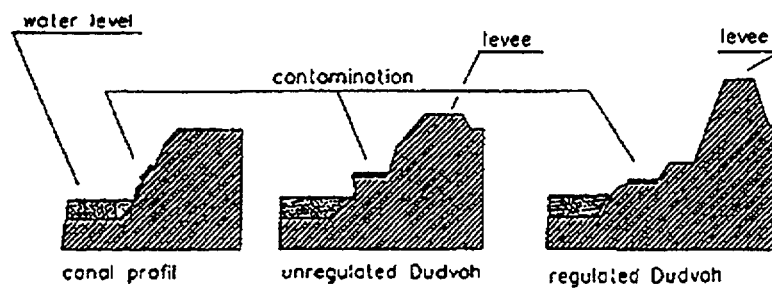


FIG. IX-1b. Width profiles and the location of contamination in typical sections of flow.

The characterisation revealed some 67 000 m² were above the proposed acceptable level, corresponding to a volume ~13 000 m³, if a 20 cm thick soil layer has to be removed. There was insufficient space to dispose safely of such a volume within the Bohunice NPP and no other disposal site was available. The proposed acceptance limits with their underlying assumptions were then re-assessed using the data from the full characterisation. The results were then used to re-plan the remedial works.

This annex describes the approach and principles applied in this re-evaluation together with the resulting acceptance criteria. It also describes the survey techniques applied for the detailed site characterisation.

Principles for evaluating the cleanup criteria for the contaminated banks

There is currently an absence of specific legislation in Slovakia governing the remediation of such land. The derivation of appropriate acceptance limits and the choice of restoration approach depends on whether the cleanup is judged to represent an intervention or practice in radiological terms.

The first step was to develop and then gain regulatory approval for the principles and rules to be used in evaluating the necessary remedial measures, including development of contamination acceptance and cleanup limits. The approved principles were:

- (i) the restoration approach should restrict effective annual doses to members of the public to 1 mSv/a, according to the ICRP 60 recommendations;
- (ii) the main scenario for the risk assessments was to be the removal of contaminated soil and its use in residential gardens [IX-3]. This scenario was to have a small probability of occurrence;
- (iii) in the residential scenario contamination acceptance and cleanup limits were to be derived assuming the partial use of 50 m³ of soil and full use of 200 m³ of contaminated land with no dilution of top soil from the banks;
- (iv) the small probability of the supposed residential scenario was to be derived from likely times before contaminated soil would be removed from the banks. Uncontrolled removal of volumes ~50 m³ was considered improbable before 5 years and before 10 years for volumes ~200 m³;
- (v) decisions on restoration techniques to be used were to be based on a cost analysis considering the different types of the banks;
- (vi) for smaller contaminated areas, the rounded and unrounded values from proposed exemption criteria were to be used, as per Radiation Protection No. 65 [IX-3];
- (vii) if covering was considered, the main protection effect was to be dilution. Such techniques were only to be acceptable for flat areas and a maximum two fold dilution;
- (viii) for the optimisation of less costly remedial measures, such as the use of warning signs, an agreed scenario was to be used with a predetermined factor for collective dose (milk + E_{ext} from banks) of $2 \times 10^{-7} \text{ man Sv.a}^{-1}/(\text{m}^2.\text{Bq}({}^{137}\text{Cs}).\text{g}^{-1})$ applied. Maximum annual effective doses from residence on the banks was to be restricted to 0.25 mSv;
- (ix) Institutional control of the residual contamination of the banks could be considered to remain effective for a period of 50 years.

Site characterisation techniques applied on the banks

Gamma measurements and sliced bulk soil samples for laboratory analysis were taken at the surface of the banks on the inside and outside of the built levees. ¹³⁷Cs was the dominant

contaminant on the site. Other radionuclides, such as ^{60}Co , ^{134}Cs and ^{239}Pu , were present, but at very low levels. ^{90}Sr content in soil was 50 to 100 times lower than that of ^{137}Cs . However, its contribution to effective dose was not insignificant.

Continuous scanning by a vehicle mounted gamma survey system (VMGS) was used for accessible areas on the outside of levees [IX-1]. The VMGS utilised a large, commercially available, shielded scintillation detector (NaI(Tl), 100×100 mm). The NIM module with the electronics, microcomputer and custom software, were developed in the VUJE research institute. This system was used for surveying along the 18 km of affected banks, several hectares of the nearby fields and the flood plain areas. For the areas, where access was difficult, such as the steep banks of the Manivier canal, the VMGS was mounted on the hydraulic arm of a tractor.

Inside the levees discrete point measurements were made on a 20 m line-grid system using hand held, slightly shielded, gamma-survey meters with large plastic scintillators ($75 \text{ mm} \times 75 \text{ mm}$). For the hot spots along the canal sections, the grid survey was supplemented with continuous scanning.

The comprehensive survey undertaken between 1991 and 1994 revealed that the top soil contamination on the banks varied widely from background level to 20 Bq/g along the Dudváh River with hot spots up to $250 \text{ Bq}(^{137}\text{Cs})/\text{g}$ on the canal banks. The contamination was spread in a strip 0.5 to 3 m (average 2.2 m) on the lower part of the banks. The average level of ^{137}Cs in the top 10 cm soil layer was 6.3 Bq/g . Using the depth distribution of contamination for typical parts of the banks, this equates to a total surface contamination of $\sim 1.0 \text{ MBq}(^{137}\text{Cs})/\text{m}^2$.

Acceptance criteria and their impact on the proposed site restoration extent

Two scenarios were selected for evaluating the risks from occupancy of the banks and contaminated fields. Another two were selected for evaluating potential risk from the use of contaminated soil in residential gardens. One of these latter assumed $\sim 200 \text{ m}^3$ of contaminated soil spread fully over the garden, whilst the second assumed $\sim 50 \text{ m}^3$ partially spread. Critical individuals were selected, based on an analysis and authorisation which considered estimated typical annual durations of stay or rates of contaminated food consumption. The most critical residential scenario was the use of 200 m^3 of contaminated soil in a garden. This could lead potentially to an individual, annual effective dose $\sim 0.21 \text{ mSv}$ per $1 \text{ Bq}(^{137}\text{Cs})/\text{g}$ of soil.

Acceptance criteria (AL) were derived, based on the residential risk assessments. Assuming a strip of contaminated top soil on the banks, 2.5 m wide and 0.25 m thick, ALs for ^{137}Cs in soil were derived to be 6 or $8 \text{ Bq}(^{137}\text{Cs})/\text{g}$ of average activity of soil, depending on the size of contaminated area. These ALs were approved by the regulatory authorities.

Along the Dudváh River, where the surface distribution of the contamination is highly non-uniform, the cleanup criterion of AL_{50} of 8 Bq/g was averaged over 100 m bank sections. (Table IX-1). The actual residual activities automatically complied with the more severe AL_{200} limit for larger areas (Table IX-1). This cleanup criterion was also beneficial in terms of the volumes of soil to be removed, as shown in Fig. IX-2. The volume distribution of ^{137}Cs specific activities on the partial bank sections is shown in Fig. IX-3.

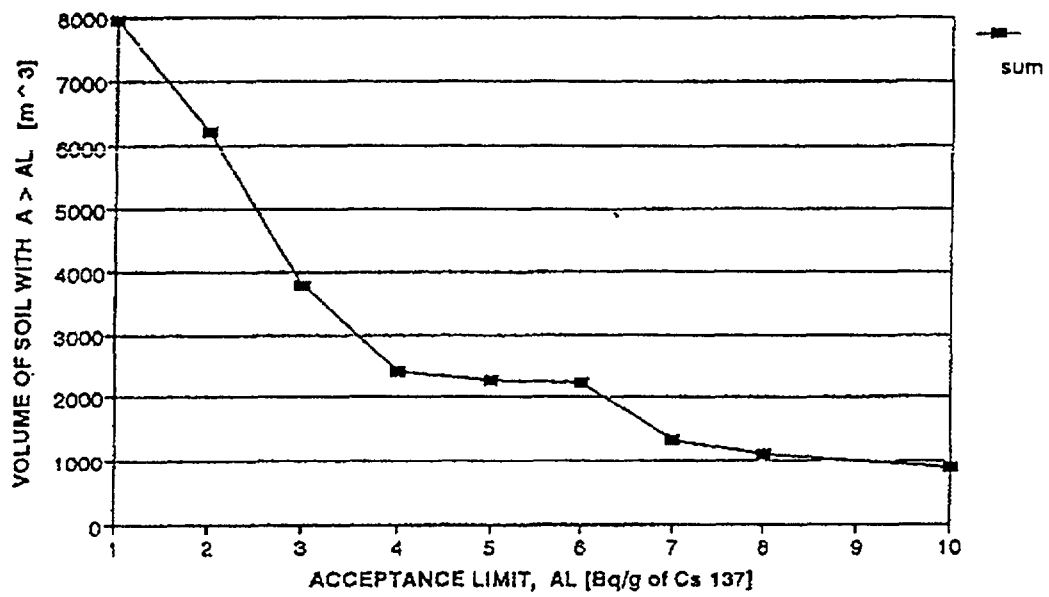


FIG. IX-2. Soil to be removed from overall contaminated banks depending on AL.

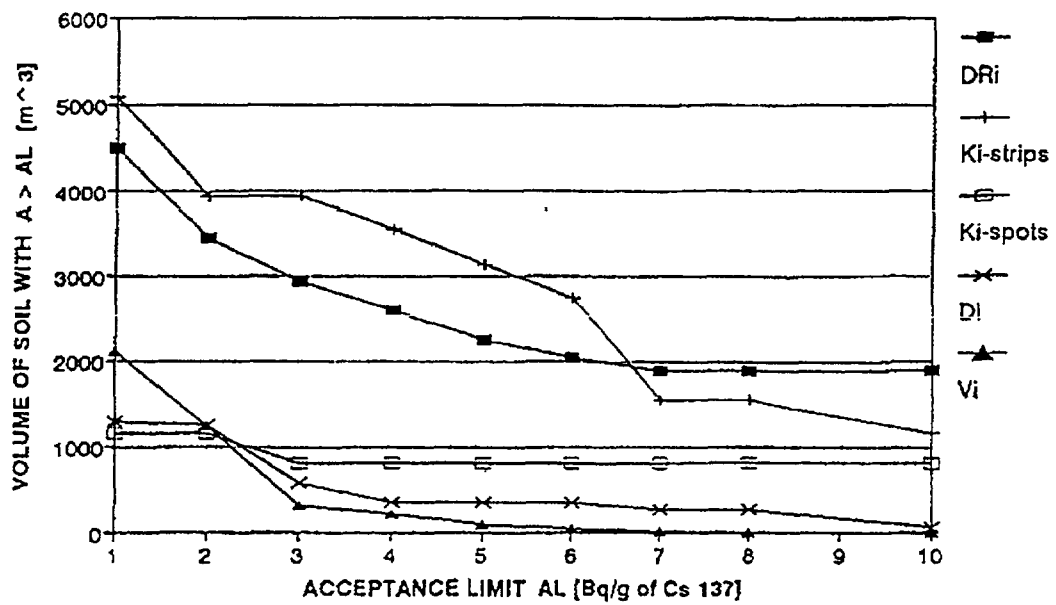


FIG. IX-3. Soil to be removed from partial sections of banks depending on AL.

The proposed restoration project now involves the removal and safe burial of 1100 m³ of contaminated soil from steep area and covering a flat area ~1 ha of the contaminated banks with a 15 cm thick layer of clean soil [IX-4]. The removed contaminated soil is to be buried in a subsurface disposal facility within the Bohunice NPP area, as this was the only site acceptable to the local population.

A post-remediation survey scheme is planned to ensure compliance with the derived acceptance criteria. This was planned as a part of prepared site restoration design. The same techniques will be used as for the earlier site characterisation, but with an even more emphasis on the automated survey systems.

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Annex X

RUSSIAN FEDERATION

ECOLOGICAL SURVEY OF TERRITORIES CONTAMINATED WITH RADIONUCLIDES

In Russia the key annual radiation dose limits for individuals when taking decisions on whether to rehabilitate and with what priority for contaminated sites are 1 mSv for members of the general public and 5 mSv for certain members of critical groups. The factors by which these limits are exceeded are key criteria in deciding rehabilitation priorities. Other key criteria in this respect are:

- the psychological impact on the population of apparent high dose levels;
- the need to prevent further increases in collective doses;
- the need to reduce environmental risks by removing or reducing the number of nuclear facilities in areas with high populations, such as large cities and resort areas; and
- the need to return contaminated areas economic use.

In view of the high cost of some of these restoration works, detailed studies with economic justification and technical planning are required to ensure their effectiveness.

To aid ecological monitoring of contaminated areas during restoration, local information and administration centres are proposed within the Federal system for ecological monitoring and response to emergency situations. In setting up these centres the following steps are to be used:

- cost minimisation through the maximum use of existing information, structures, systems, tools and experienced staff;
- full implementation of the system prior to the rehabilitation stage;
- provision of adequate funding to meet technical and administrative requirements;
- development of clear system input procedures;
- clear system for ordering priorities. This should take into account for each specific case the level of risk of specific contamination of human beings and environment, the scale of real or possible contamination, the scientific and technical scope for detailed assessment and impact on situation and the social-political aspects of the situation.

Before any decisions are made on the need for rehabilitating any area, a radiation survey must be undertaken. This includes both a gamma survey and discrete sampling for the laboratory analysis. Once the analyses are complete a contamination map of the area is prepared. This is overlain with information on doses to the population, critical groups, economic activity, etc. Using these data and the basic radiation dose limits, derived criteria are prepared for the purpose of taking decisions on rehabilitation work. These latter criteria may be expressed as concentration of individual radionuclides on surfaces, in soil, water, foodstuffs, etc.

A second set of criteria are also considered in the decision-making. These are not based on irradiation effects, but on the psychological impacts that radioactive contamination can have. Their impact may be that the public are unwilling to live or work in some contaminated areas. The impact of these effects may extend over larger areas and populations than are affected by significant radiation risks.

The main and final goal behind creating a comprehensive system of monitoring is to provide administrators with a sound basis for making decisions on whether to restore particular contaminated areas and, if so, the extent of rehabilitation to be undertaken. In addition, the monitoring results are available to better inform the public and influence their opinions.

To reach this last goal, the following are required:

- (1) the real ecological and human health situation in each affected region should be understood, including the impacts of radioactive and chemical substances;
- (2) estimates are needed on how these situations will develop with time.

To fulfill these requirements, the system must be able to:

- give a common picture of radiation situation in each area of the region;
- reveal and evaluate how radionuclides are entering into environment;
- evaluate the radiological situation on the local scale where radioactive materials are entering into the environment;
- enable permanent control to be exercised over the radioactive content of different media and substances in the environment. e.g. water, suspensions, bottom deposits, atmospheric aerosols, fallout, precipitation, soil, plants, biota, agricultural products, foodstuffs;
- forecast changes in the radiation situation under the normal conditions at the local and regional scales;
- forecast how the radiological situation will change under hypothetical abnormal conditions in the region;
- forecast how environmental conditions will develop;
- permanently control of the environmental situation during the rehabilitation works;
- provide expert assessments of the impacts of abnormal situations and variants of administrative decisions;
- evaluate doses load to the population and ecosystems during restoration works and after;
- provide project expertise and support for the development of new and reconstruction of existing businesses and other forms of economic activity in the restored areas.

The main components of the survey system are:

- base analytical laboratory;
- network of observation stations and posts;
- automated network of remote data gathering stations;
- mobile teams for surveying and control.

The base analytical laboratory analyses environmental samples taken from various media, in accordance with developed regulations of control. It also undertakes specific planned investigations of samples of particular materials, etc., on the regional scale. Finally, it undertakes any necessary development and improvement of analytical methods used.

Observation stations and posts are situated within the territory of the affected regions. They carry out permanent sampling of environment objects and undertake direct measurements of environment parameters at their locations. They then transfer these data directly to the information and analytical centre (IAC).

The environmental monitoring network uses widely distributed sensors to maintain permanent control of environment contamination. It also collects additional information needed for the

effective operation of the IAC. This information is transferred to the IAC in accordance with established regulations. When the defined contamination levels, etc., are exceeded, the information is transferred immediately.

The monitoring systems in rehabilitated areas can be incorporated into the main automated system as a subsystem. Mobile field teams maintain effective control of the environment in the affected territories by a combination of sampling from environmental objects and direct measurements.

Ecological surveys of the rehabilitated areas is undertaken according to defined procedures, e.g. standards, principles for conducting surveys, sampling strategies for determining radioactive and chemical substances.

Annex XI

DENMARK

THE PROJECT CRESTED ICE [XI-1]

On January 21, 1968, a B-52 bomber carrying four nuclear weapons crashed on the sea ice off the shore of Thule, Greenland. Both the aircraft and the weapons disintegrated on impact. There was, of course, no nuclear explosion since the design of the weapons precluded any nuclear reaction. Nevertheless, limited contamination resulting from the dispersed radioactive material from the weapons had to be controlled and removed, as did the aircraft debris.

This major disaster was turned into a classic example of international cooperation at governmental, scientific, and local levels. During the following months, the Danes and Americans at Thule provided a striking example of international teamwork. The seemingly insurmountable task of recovering and removing all traces of the accident proved again that truth may be stranger than fiction -and fully as exciting. This issue has been chosen to provide a condensed but complete summary of details of this true modern saga of international cooperation by the people who were there.

Technical and laboratory support

A contamination incident such as the one described in other articles invariably creates a real or perceived need for specific technical information not readily available or easily obtained under field conditions. The type of supplemental information required is usually determined by the specific needs of the field commander and various special committees and policy-setting groups as an adjunct to their making decisions as to the extent of contamination, the magnitude and nature of the potential hazards to operational personnel and the inhabitants of the region (whether direct or through ecological modes), and the extent of decontamination that is acceptable and technically feasible.

Within 5 days after the incident an American technical advisory group was assembling at Thule, and discussions were initiated with a similar group of Danish and Greenland scientists. In the next few weeks various agencies (Atomic Energy Commission [AEC], Department of Defense [DOD], etc.) assembled expert committees to advise them. In addition, joint US-Danish policy-setting groups met in Copenhagen and Washington to consider the technical aspects of the incident. The final decisions as to cleanup levels, methods of disposal and many other issues were made by these high-level groups and committees. Since these authoritative committees and groups needed all the information possible within the time frame of the negotiations, the demands placed upon the field operations became one of the field commander's biggest problems. Often these demands could not be met without additional technical and laboratory support beyond that available at the scene. To comply with these demands, data and samples were sent to the Los Alamos Scientific Laboratory and other laboratories in the USA for analysis and interpretation. This article summarizes the early work done at the Los Alamos Scientific Laboratory and elsewhere in an effort to provide some of the information requested.

Partitioning of the contamination

In an incident of this type the most important information to have as soon as possible is the absolute quantities of material partitioned among the various vectors, modes or regions of dispersal, and deposition. At Thule the important considerations in this regard were:

- The amount of contamination carried aloft in the cloud from the detonation of the high-explosive and fire and dispersed over the general area by the prevailing meteorological conditions.
- The amount deposited on the surface locally.
- The amount deposited on aircraft and weapon debris.
- And the amount in and beneath the ice at the impact point.

Contamination associated with debris would be expected to be distributed beneath, in, and on the surface. Determination of the absolute quantities of contamination associated with each of these vectors or modes of dispersal and deposition was essentially impossible. However, from the practical viewpoint, the most important considerations at Thule were the amount, form, and fixation of plutonium and tritium on the surface in the immediate vicinity of the crash site and in the refrozen ice at the impact point where decontamination operations were technically feasible.

The speed of the plane at impact was in excess of 500 knots. Its gross weight was about 1.86×10^5 kg, this included about 1.02×10^5 kg of JP-4 fuel. The shallow impact angle and mass and speed of the aircraft resulted in a great forward vector of momentum. When the high-explosive components of all four weapons detonated, the contamination was blown out in all directions and impinged into the materials of the weapons and the aircraft and blown into the splashing, burning fuel. The fuel and much of the debris from the aircraft were catapulted forward on the surface of the ice. When the burning fuel fell back to the surface the fire was soon extinguished, leaving the blackened refrozen crust on top of the snow pack (Fig. XI-1). The ice was completely shattered and disoriented at the impact point and sustained circular cracking out to a distance of about 100 m in all directions. The peculiar markings on the ice showed the drag and destruction of the left wing, from this the crash attitude of the plane was deduced. From momentum considerations and the pattern on the snow pack, one would expect to find a large fraction of the surface contamination confined to the blackened crust where it was fixed by refreezing of the melted surface. This was indeed found to be the case.

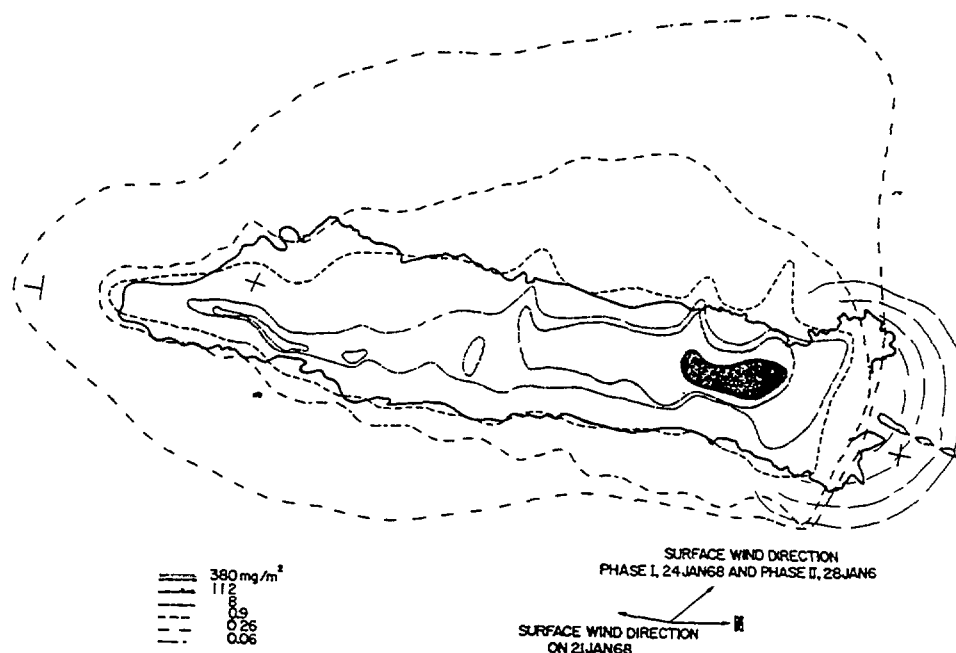


FIG. XI-1. Plutonium contamination levels observed

The remainder of the contamination was dispersed in the smoke plume, impinged on the debris of the bombs and the aircraft, and blown into the ice at the site of impact.

Contamination of the surface

Plutonium distribution and amount. Simple autoradiographic studies, as well as instrument measurements, established unequivocally that the depth-distribution of plutonium in the snow pack was strictly a function of the depth of blackening and melting of the surface. Over a large part of the blackened area, this depth was no more than about 1.25 cm. More plutonium contamination was found and its distribution was to a greater depth in those areas where more fuel collected and burned, resulting in more melting of the snow pack. In the most highly contaminated area, the snow pack had melted down to the surface of the ice. Surface distribution of plutonium (other than that adhering to large pieces of aircraft debris which were picked up) is shown in Fig. XI-1. The contours were established by the survey teams using the Lawrence Radiation Laboratory Field Instrument for Detection of Low Energy Radiation (LRL FIDLER instrument). Because of the variable thickness of the overburden of ice and snow (complicated further by the two phases of 25 and 28 January), it was necessary to apply different calibration factors to the instrument readings for the areas within each contamination control. As an example, where the contamination level was highest ($\sim 380 \text{ mg/m}^2$) more fuel had burned and the snow pack had melted down to and even into the ice. Upon refreezing, the absorption characteristics for the soft X rays from plutonium and americium were quite different than where little depth of melting and refreezing had occurred. Absolute contamination levels were obtained by taking representative samples in each contour area subsequent to a careful instrument reading and returning them to Los Alamos for plutonium and americium analysis. Total amounts of plutonium were obtained by integrating the surface concentration as a function of area (Table XI-1).

TABLE XI-1. DISTRIBUTION OF PLUTONIUM ON THE SURFACE IN THE VICINITY OF THE CRASH (EXCLUDING THAT PICKED UP ON AIRCRAFT DEBRIS)

Contamination boundary mg/m^2	Enclosed area (m^2)	Plutonium (g)	Deposition* (%)
380	1.97×10^3	845	27
112	1.10×10^4	2816	89
8	2.49×10^4	3014	96
2.4	3.90×10^4	3079	98
0.9**	5.97×10^4	3109	99
0.26	1.10×10^5	3135	99+
0.19	1.34×10^5	3140	99+
0.06	2.23×10^5	3151	100

* Total out to the specified boundary.

** Edge of the blackened area.

The plutonium values are probably good to ± 20 per cent out to the edge of the blackened crust area, which corresponded roughly with the 0.9 mg/m^2 contamination contour. This information indicated $3150 \pm 630 \text{ g}$ of plutonium on the surface (excluding that picked up on aircraft debris), of which about 99 per cent was in the blackened pattern and would be removed by removing the snow pack over this area. Assuming removal of the crust and packed snow to an average depth of 10 cm, the volume removed would be 6000 m^3 . Assuming further that the volume ratio of packed snow to water is approximately 2.5, this would constitute about 2270 m^3 of water, which would contain between 2500 and 3800 g of plutonium.

Plutonium — Form, particle size and fixation. It was felt that the ultimate distribution of the plutonium in the event large amounts of the blackened crust were allowed to break up with the ice and go into North Star Bay might be influenced by its form, particle size, and fixation. Detailed nuclear track autoradiographic and microscopic studies of melted crust samples were conducted to obtain pertinent information. These studies showed the plutonium to be in the form of oxide particles with a very wide size distribution. The count median diameter was $2 \mu\text{m}$, with a standard deviation of about 1.7. The calculated mass median diameter was about $4 \mu\text{m}$. The particles were associated with or adhering to particles and pieces of inert debris of all kinds (metal, glass and nylon fibers, plastic, rubber flecks of paint, etc.) of all sizes. The mass median diameter of the inert particles with which the plutonium was frequently associated appeared to be at least 4 to 5 times larger than the plutonium particles themselves. Many of the melted crust samples showed the presence of unburned jet fuel. A very crude estimate suggested that as much as 18 per cent (18 140 kg) of the fuel may have remained unburned in the blackened crust. Sedimentation studies showed that up to 80 per cent of the plutonium was associated with low specific gravity debris that remained suspended in the jet fuel. The general feeling was that this fact increased the probability of contamination of the shoreline should the blackened crust be allowed to melt and enter the bay.

Tritium — Form, distribution and amount. Laboratory examination of samples of the snow pack from the blackened area showed the presence of tritium oxide confined largely to the depth of the blackened crust. As water, a major fraction of the tritium contamination would have been expected to be carried away and dissipate with the smoke plume. Only that would remain which condensed on surfaces and nuclei that were rapidly cooled to the ambient temperature (-25°C to -35°C). The tritium fixed in and on surfaces in this manner would be expected to dissipate at rates that would fluctuate with temperature and wind conditions.

It is not possible to establish tritium surface deposition levels with field survey instruments because of the extremely low energy (17.9 keV maximum) of the beta radiation it emits. To determine the amount of surface tritium contamination present with any degree of certainty would have required an extensive and intensive sampling program which hardly seemed justified under the circumstances. It was considered adequate, therefore, to determine tritium in a relatively few samples of the blackened crust to confirm its presence and to establish the magnitude of contamination as assurance that no personnel exposure problems would occur during the operations. Analyses of these samples were considered representative of the areas within the plutonium contamination boundaries (Fig. XI-1) from which they were taken.

Integration of the tritium levels within these boundaries gave a very crude estimate of the distribution and total amount of tritium within the blackened pattern. The results are shown in Table XI-2 and suggest a total of approximately 1350 curies of tritium confined to the area in the form of tritium oxide. The estimates are probably accurate to ± 50 per cent.

TABLE XI-2. DISTRIBUTION OF TRITIUM ON THE SURFACE IN THE VICINITY OF THE CRASH (EXCLUDING THAT PICKED UP ON AIRCRAFT DEBRIS)

Plutonium contamination boundary (mg/m ²)	Enclosed area (m ²)	Tritium (10 ¹² Bq)	Deposition*(%)
380	1.97×10^3	13.5	27.2
112	1.10×10^4	24.3	49.1
8	2.49×10^4	36.5	73.7
2.4	3.90×10^4	49.5	100

*Total out to the specified boundary.

Contamination in the ice at impact point

The ice at the point of impact was approximately 1 m thick. Impact of the plane and detonation of the high explosive components of the four weapons on board completely fractured and displaced the ice over an area of about 2100 m² (46 m × 46 m). The ice sustained circular cracking without displacement out to about 100 m from the impact point. Isotropic propagation of the shock wave from the high-explosive detonation accelerated a fraction of the contamination and debris from the disintegrating aircraft in the downward direction, impinging it into the fracture area. When fractured, the pieces of ice were displaced downward into the water, randomly oriented, and returned to the surface where they refroze in position. The attitude of the plane at impact was such that essentially all of the fuel was forward and above the weapons. This would be expected to result in the majority of the fuel and contamination entrained by a large solid angle being accelerated up and forward on the surface of the ice by the dominant forward momentum. The general feeling, however, was that additional information regarding amount, distribution, form, fixation, etc., of the contamination of the fractured area was desirable before making decisions as to its ultimate disposition.

Plutonium — Distribution and amount. A closely spaced core sampling grid was laid out over and around the fracture area (Fig. XI-2), and 49 full-thickness core samples were taken and examined. These cores were studied visually and microscopically and were scanned cm by cm

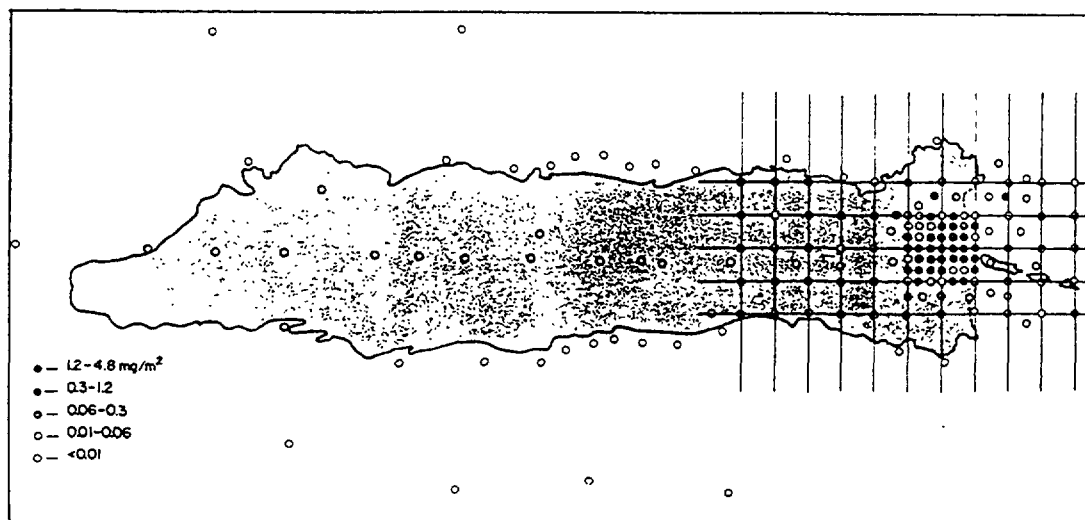


FIG. XI-2. Ice core sample locations.

with survey instruments. Representative cores were transported to Los Alamos for further study and chemical analyses for plutonium as a means of standardizing the scanning measurements made at Thule. Results showed that the plutonium contamination was usually confined to a narrow band which often could be detected visually because of the associated debris from the disintegrated aircraft and bomb casings. The band of debris with the associated contamination was sometimes on the bottom of the core, sometimes on the top, and sometimes displaced from either end. Some cores showed diagonal bands and others no bands at all. These observations reflected the fact that the fractured ice was displaced downward, returned to the surface, and refrozen in a more or less random pattern with respect to the reconstituted surface.

The fact that cores were scanned cm by cm permitted a crude statistical estimate of the depth-distribution of the plutonium in the ice. It appeared that about 13 per cent of the total plutonium in the crushed and refrozen area was in the top 5 cm, 36 per cent was in the top 10 cm, and 45 per cent was in the top 15 cm. About 15 per cent was in the bottom 25 cm. The remaining 40 per cent was distributed between 15 cm from the top and 25 cm from the bottom.

The plutonium distribution pattern, in terms of contamination per m² of surface area, was highly erratic, and it was not possible to represent the results by any simple contour pattern (Fig. XI-2). There was a tendency for the most highly contaminated cores to extend to the back and sides of the center of impact, which might be expected from the relative position of the bombs with respect to the main body of fuel and the crash attitude of the plane. However, cores of comparatively low radioactivity were interspersed among the most radioactive cores, suggesting a highly segregated pattern probably related to reorientation of blocks of ice by the force of the impact and explosion. The random orientation of the rectangular grid with respect to the crushed ice pattern supports the assumption that the cores were statistically representative of the primary impact area in terms of total plutonium and range of local concentrations. Results from the 49 cores showed that 16 per cent contained 65 per cent of the contamination and 52 per cent contained 97 per cent. An estimate of the total amount of plutonium in the fractured ice area (~ 2100 m²) showed about 350 g. The accuracy of estimate was probably ± 25 per cent. The amount of plutonium in the ice would have to be dispersed in about 5×10^4 m³ of water to be at the maximum permissible concentration. This is about 60 times the water volume produced by the melting of the porous ice itself.

Plutonium – Form and fixation. It was felt generally that information on form and fixation of the plutonium in the fractured area might have bearing on questions regarding its ultimate availability to local ecological chains. Microscopic and autoradiographic observations of the residues filtered from melted ice core samples showed fine particles of plutonium oxide impinging into or adhering to pieces of aircraft and bomb casing debris of all sizes. The blackened bands in the ice cores consisted of small pieces of metal, rubber, fiberglass, paint, plastic, etc., up to 1 mm in size to which the plutonium oxide particles were fixed. Sedimentation studies of melted ice cores showed that 85 to 95 per cent of the debris and associated plutonium oxide sank immediately. No JP-4 fuel floated on the surface; only a thin film of fine carbonized material. The remainder of the plutonium was retained on the surface associated with this carbonized film. Only about 1 per cent was suspended through the water phase as very fine particles. This rapid settling of most of the plutonium greatly decreased the possibility of shoreline contamination from floating debris subsequent to melting of the ice.

Tritium – Form and amount. Only a few cores from the crushed ice area at point of impact were examined for tritium contamination. The contamination was in the form of oxide, and

the amount appeared to be of the order of 6.3×10^8 Bq/m³ assuming the ice averaged 1 m in thickness. This value, multiplied by the area (2100 m²), suggested a total of only about 1.3×10^{12} Bq of tritium activity in the ice at the point of impact.

Contamination beneath the surface

A very difficult question involved the possibility that contamination might have been dispersed beneath the ice in a form that could reach the shoreline or be concentrated by some biological process in the local food web. Two possible modes of contamination and dispersal beneath the ice were proposed for examination.

One possibility was that a pool, or pools, of highly contaminated jet fuel might have been trapped beneath the surface near the impact point. To examine this possibility the field teams took an additional 133 core samples, 85 on a grid pattern around the fractured area and over the blackened surface pattern and another 48 outside the periphery of the pattern (Fig. XI-2). None of these cores showed any contamination on the bottom end, and no jet fuel or other floating debris was forced up through the core holes by the hydrostatic pressure beneath the ice.

The second possibility considered for plutonium to have gone beneath the ice was in connection with contaminated aircraft debris that might have been blown through the ice and sunk to the bottom. Pieces of the aircraft found on the surface were transported to Los Alamos to observe the amount, form, and fixation of the associated plutonium contamination. No tritium observations were attempted. Debris consisted of pieces of steel, aluminum, and other materials. Some pieces were highly contaminated on both sides, others on only one side, and still others showed hardly any contamination at all. Due to the numerous unknown quantities and inherent inaccuracies, no attempt was made to determine from the contamination observed on the debris the amount of plutonium that might have gone through the ice. However, later underwater observations during the summer season established that the aircraft debris which penetrated the ice was stabilized on the ocean floor.

Microscopic and autoradiographic observations showed that the contamination on the pieces of debris consisted of particles of plutonium oxide impinged into or adhering to the surface. Lavation tests in sea water were conducted on contaminated pieces of steel and aluminum to determine removal as a function of time. Different rates were observed for different materials, as well as for different pieces of the same material. The observations supported what might be expected, i.e., that removal rate would depend on the nature and hardness of the surface and velocity of the impinging particles, which would be dependent on the distance of the surface from the detonation. In any event, these observations suggest that, if indeed a large amount of plutonium was carried to the bottom associated with aircraft wreckage, it would not all be released rapidly or at the same time. This would make the possibility of high concentrations at any given time very unlikely.

Atmospheric dispersal and general area contamination

The amount of plutonium and tritium taken up in the cloud from the explosion and fire and its distribution as long-range or general-area contamination were virtually impossible to predict with the available information. All available data, including cloud height, regional meteorological conditions at the time of the crash and for 10 days after, pyrotechnic information, etc., were sent to the Sandia Laboratory for consideration in view of that

organisation's experience with non-nuclear detonation experiments. These field tests have resulted in the development of detailed data and calculation models for estimating deposition patterns and contamination levels from non-nuclear detonation of plutonium-bearing weapons. The principal parameters needed are source strength, aerosol characteristics, high explosive yield, and detailed local and long-range meteorology. Unfortunately, conditions at Thule were such that several of these parameters were either obscured, unknown, or unpredictable. Based on the inadequate information and several assumptions, the Sandia Laboratory was able to draw three general conclusions which are summarized as follows:

- Deposition of the aerosol produced initially would have been expected in a west-south-westerly direction on open ice and Wolstenholme Island. No deposition levels could be estimated, since the source term was obscured by the crash conditions and aerosol characteristics were unknown. However, the original long-range deposition pattern would be expected to be changed under the prevailing phase conditions during the first few weeks after the crash
- Wind-resuspended contamination probably travelled around and possibly over Saunderson Island. However, the condition responsible for the transport made redeposition of much activity on the island unlikely
- The levels of long-range contamination expected would be radiological insignificant but, because of the inherent sensitivity of chemical methods, plutonium should be detectable in surface samples taken south and west of the crash site.

Plutonium analyses of surface samples from the principal land masses in the general area are presented and discussed elsewhere.

Summary and conclusions

Immediately following the Thule incident a technical and laboratory support effort was mobilized to comply with requests by the field commander, expert committees, and policy-setting groups for additional technical information and consultation. This effort contributed, in part, to the following factors thought pertinent to the Thule situation:

- Laboratory calibration of field instrument readings and integration of deposition contours at the crash site suggested that the amount of plutonium on the surface was 3150 ± 630 g, approximately 99 per cent of which was confined to the blackened pattern on the snow pack. The plutonium in the crust was in the form of oxide particles, often associated with larger particles of low density inert material which tended to remain suspended in unburned JP-4 fuel. Tritium contamination in the form of tritium oxide was found on the surface largely confined to the blackened crust. The amount present was estimated at about 5×10^{13} Bq \pm 50 per cent. These observations suggested that removal of the blackened crust and its associated plutonium contamination was desirable.
- Laboratory analysis of representative ice cores taken from the fracture pattern at the impact point, which were related to field instrument scans of other cores from the area, gave an estimate of 350 g of plutonium trapped in the ice. Reorientation and refreezing of the broken ice resulted in a segregated contamination pattern both with respect to depth and area. In this area also, the plutonium was in the form of oxide particles associated with inert debris from the bombs and aircraft. There was little or no unburned jet fuel, however, and upon melting of the ice the contamination did not float or remain suspended. This fact was further assured by covering the entire fracture area with black carbonized sand, which

in addition to accelerating melting of this area, absorbed and sank a jet fuel film that might have remained afloat to suspend contamination. The estimated amount of tritium (as the oxide) trapped in the ice at the impact point was about 1.3×10^{12} Bq. These and other factors, such as distance of the impact point from shore and depth of the bay, suggested that it was unnecessary to remove the approximately 2×10^3 kg of ice involved,

- Projection of contamination through and beneath the ice at impact point was considered also. Additional core drillings made throughout the general area of the crash failed to reveal any floating pools of jet fuel trapped beneath the surface.
- All contaminated large pieces of aircraft wreckage on the surface were picked up and confined. Laboratory studies were carried out to determine the form, fixation, and lavation rates of plutonium from the surfaces of wreckage. These studies suggested that, if indeed large pieces of contaminated wreckage had broken through the ice and sunk to the bottom, there was little likelihood that high concentrations of plutonium could enter some aquatic factor of the local food web.
- Attempts to calculate meteorological transport and deposition of long-range contamination, although quantitatively unsuccessful, did suggest that contamination levels on land masses south and west of the crash site would be radiologically insignificant but probably measurable by chemical analysis of surface samples.

Radio-ecological investigations

Introduction

During the first week after the accident, environmental samples of sea water, bottom sediments, and zooplankton were collected from holes drilled through the ice in Bylot Sound. Most of these samples showed no or only a small ^{239}Pu content; however, a few samples showed levels significantly above background. As it was extremely difficult to ensure that the marine samples collected in the early period had not been contaminated by surface snow (which contained ^{239}Pu in most cases), it was decided to make a more detailed radio-ecological study of the environment in August, when the ice had broken up in Bylot Sound.

The purpose of such a study was to examine whether plutonium was present in the environment in concentrations that might be harmful to man and animals, and to collect information on the radio-ecology of plutonium, which is only imperfectly known.

Fallout levels

Since the beginning of nuclear weapon testing, plutonium has been present in nature. The global inventory of ^{239}Pu in worldwide fallout is at present approximately 0.3 megacuries, or approximately 5×10^3 kg. In the temperate zone of the northern hemisphere the accumulated ^{239}Pu fallout is approximately $3.7\text{--}7.4 \times 10^7$ Bq $^{239}\text{Pu}/\text{km}^2$, and in the Arctic environment the level is estimated at $7.4\text{--}14.8 \times 10^3$ Bq/ km^2 . Hence in Bylot Sound (approximately 300 km^2), before the B-52 accident we had approximately 3.7×10^9 Bq ^{239}Pu or 1-2 g plutonium from fallout.

Earlier measurement of plutonium in marine environments

The measurements of plutonium from fallout in marine environments have been few. A 1964 American report [XI-2] found extremely low concentrations in sea water, of the order of 3.7×10^{-5} Bq/L. Pillai found that especially zooplankton and bivalves concentrated plutonium from the sea water. The activity ratio between 1 kg fresh weight of zooplankton and 1 kg sea water was approximately 2500, and for bivalves a ratio of approximately 250 was found.

Food chain

The ultimate goal was to evaluate whether the radioactive substance under study reaches man in harmful quantities. Figure XI-3 shows a simplified model of the food chain in an Arctic marine environment like the Thule area. The Greenlanders are hunters, not fishermen. The animal most important for their nutrition is the seal; they eat the meat, heart, liver, and kidneys. The Greenlanders also eat walrus, although this animal is normally used for the dogs; from the stomach contents of the walrus they get bivalves. Birds are hunted during the summertime and eggs are collected in appreciable quantities.

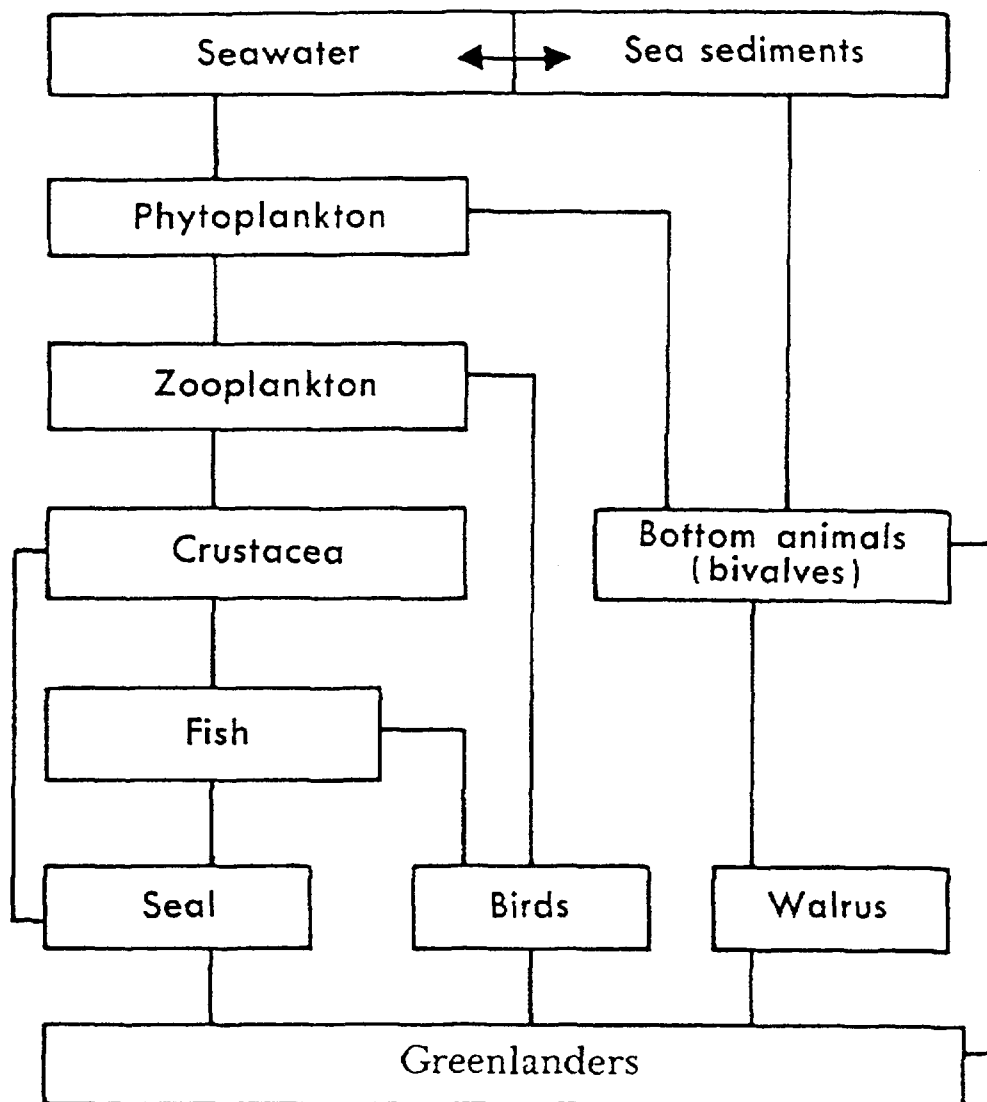


FIG. XI-3. Food chains in an Arctic, marine environment.

Primary samples

As will appear from Fig. XI-3, sea water and sea sediments are the first links of the food chain. The levels in these media, determine the levels in the remaining part of the food chain. Samples of sea water and sea sediments were hence considered primary samples, and were as far as possible to be collected at all locations. The collection of these samples was carried out with special equipment constructed by the Danish Atomic Energy Commission. The water sampler had a collection capacity of 100 L of water from any depth from the surface down to the bottom, and the sediment sampler scraped the upper most layer of the sea bottom to a depth of 1 cm over an area of 0.1 m².

Secondary samples

With the aid of the ship AGLANTLIA, bivalves, zooplankton, crustacea, and fish, were collected by using triangle dredge, plankton net and shrimp trawls.

Ternary samples

Seal, birds and walrus, were mostly obtained by the Greenlanders, but a few were killed by members of the expedition.

Urine samples

Finally, urine samples were collected from the Greenlanders for the purpose of checking any human body burden of plutonium.

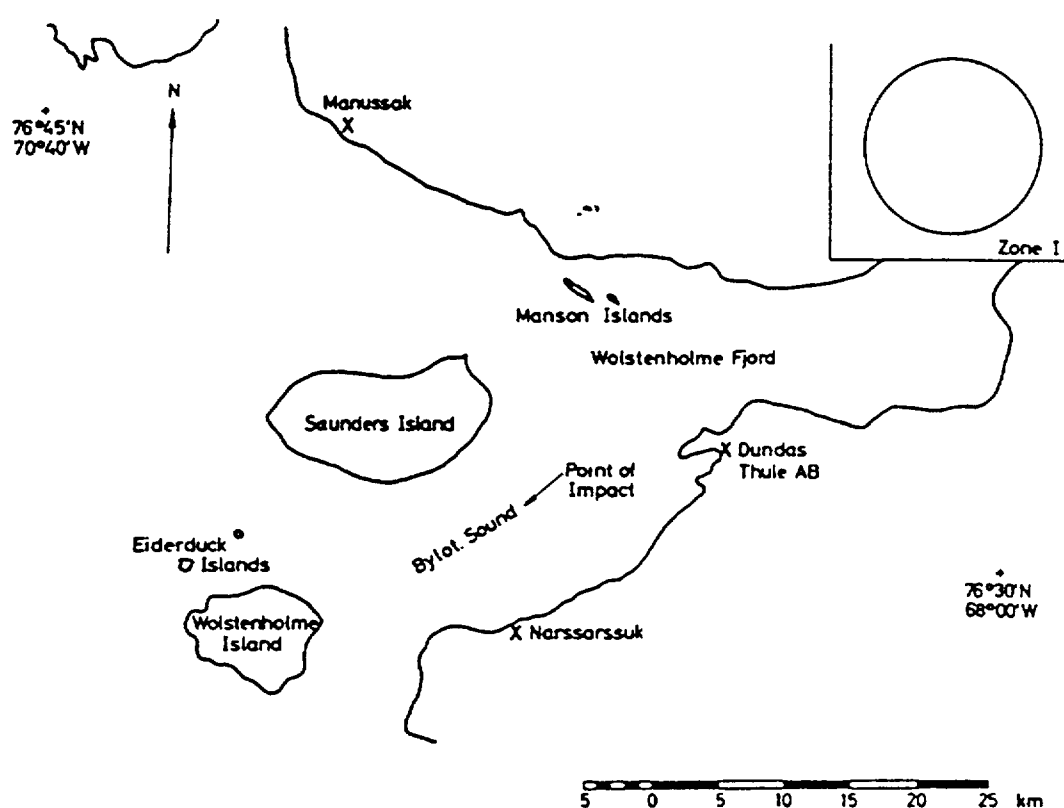


FIG. XI-4. The sampling area at Thule AB, Greenland. Zone I has its centre at the point of impact.

The sampling area

The sampling area (Figure XI-4) was divided into two zones, I and II. Zone I was a circular area with its center at the point of impact and with a radius of 1 km, and Zone II was the remaining part of the surrounding area in Bylot Sound and Wolstenholme Fjord.

The sampling team

The scientific expedition consisted of one zoologist, one marine biologist, one hydrographer, two physicists, two assistants for the sampling, and an American lichenologist. The sampling began in the last week of July and was finished by the end of August. By then more than 150 samples had been collected for plutonium analysis.

Sample treatment

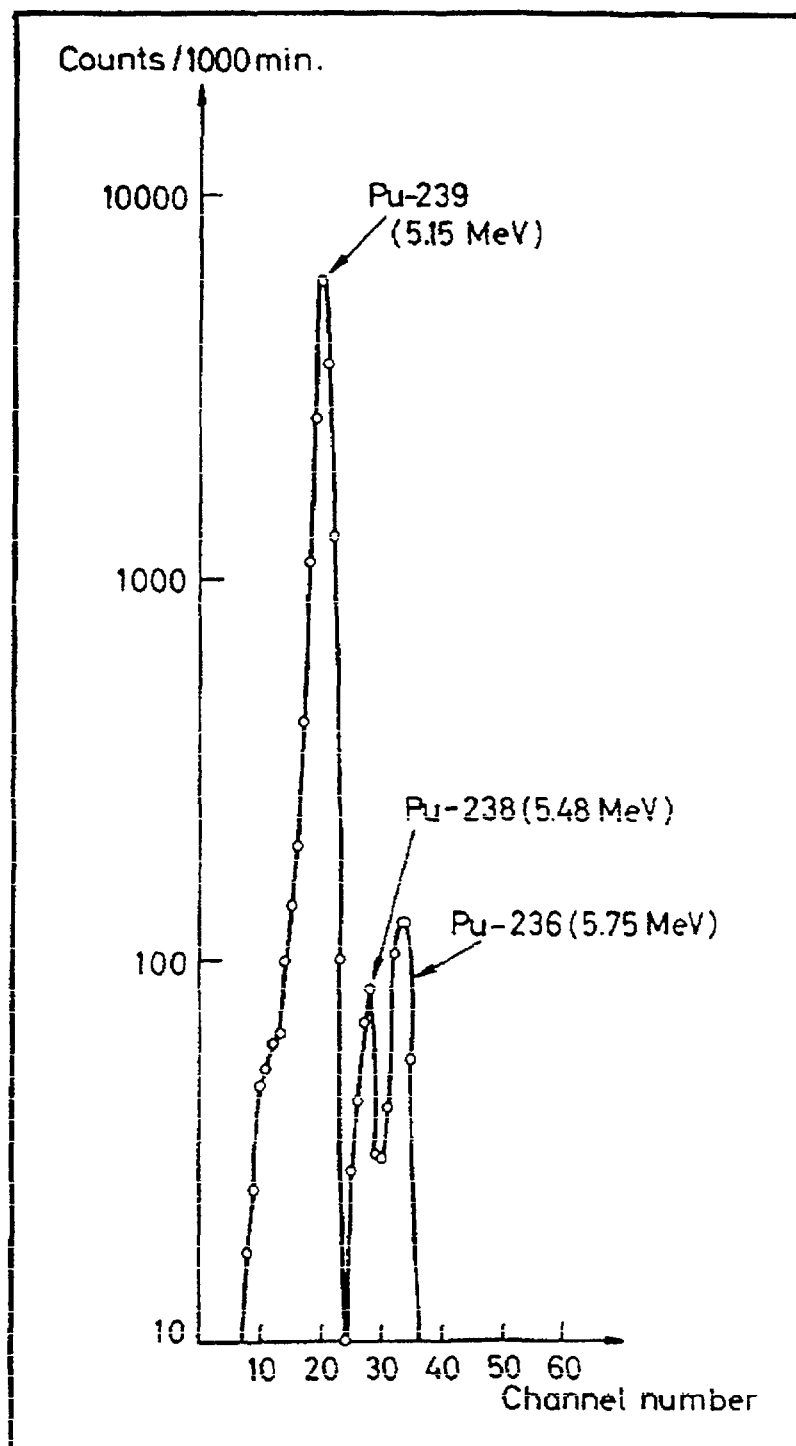
The samples were kept at -10°C until they could be processed in the laboratory. The solid samples were ashed at 600°C and after the addition of carriers and spikes, the ash was melted with potassium pyrosulphate to ensure that all plutonium was in a soluble form before the radiochemical analysis, developed especially for this purpose by a combination of an American ion-exchange procedure and a Danish extraction method. After the radiochemical analysis, which could be accomplished within a day for most types of samples, the samples were counted for 3-4000 minutes on silicon-surface-barrier alpha counters in connection with a multichannel analyser. Figure XI-5 shows a typical spectrum from one of the stronger samples. Sea water samples were processed by a similar method; iron hydroxides were in this case precipitated directly from a 50-litre sample.

RESULTS

Sea water. In Fig. XI-6 the results of the sea water analysis are shown. The maximum for water samples was $2.81 \times 10^{-3} \text{ Bq } ^{239}\text{Pu/litre}$ found in a sample collected approximately 5 km west of Dundas Mountain. The median fallout background in sea water from five Greenland locations far away from Thule (Danmarkshavn, Anginagssalik, Prins Christians Sund, Godthab, and Godhavn) was $1.48 \times 10^{-4} \text{ Bq } ^{239}\text{Pu/litre}$ as compared with the median level found at Thule: $1.85 \times 10^{-4} \text{ Bq } ^{239}\text{Pu/litre}$. At Qanaq, approximately 100 km north of Thule, the level was $1.11 \times 10^{-4} \text{ Bq } ^{239}\text{Pu/litre}$. In Zone I the sea water samples were collected both at the surface and at the bottom.

From most other locations at Thule they were collected only at the bottom. The samples from Zone I showed that the bottom samples normally had a slightly higher activity than the surface samples. A number of samples were filtered through a 1μ Millipore filter before the analysis, and filtrate and filters were analyzed separately. These analyses gave no indications of significant amounts of particulate ($>1 \mu$) activity in the water samples. It is concluded that sea plants showed levels of Pu. However, we do believe that the few samples that showed relatively high levels ($3.7 \times 10^{-4} \text{ Bq } ^{239}\text{Pu/L}$) contained particulate activity, probably particles stirred up from the bottom during the sampling. It is concluded that the accident caused only a slight increase in the ^{239}Pu concentration of the sea water in Bylot Sound.

Bottom sediments. The median level of bottom-sediment samples collected in Zone II was $1.48 \times 10^8 \text{ Bq } ^{239}\text{Pu/km}^2$, whereas it was $4.44 \times 10^9 \text{ Bq } ^{239}\text{Pu/km}^2$ in Zone I (Fig. XI-7). The highest level was found 1 km northwest of the point of impact; at that location $4.81 \times 10^{10} \text{ Bq } ^{239}\text{Pu/km}^2$ was found. From the median level the total deposition of ^{239}Pu in Zone I (3.14 km^2) was estimated at $1.48 \times 10^{10} \text{ Bq}$. In the remaining part of Bylot Sound (300 km^2) the ^{239}Pu level in the bottom sediments was estimated to approximately $3.7 \times 10^{10} \text{ Bq}$. These estimates do not include ^{239}Pu on pieces of debris, which might remain on the sea bottom.



The α -spectrum of a bivalve sample from zone 1. The activity ratio $\text{Pu } 238/\text{Pu } 239 = 0.02$. This ratio was nearly the same in all samples from Thule in which Pu 238 was detectable. (Pu 236 is the spike used for the yield determination.)

FIG. XI-5.

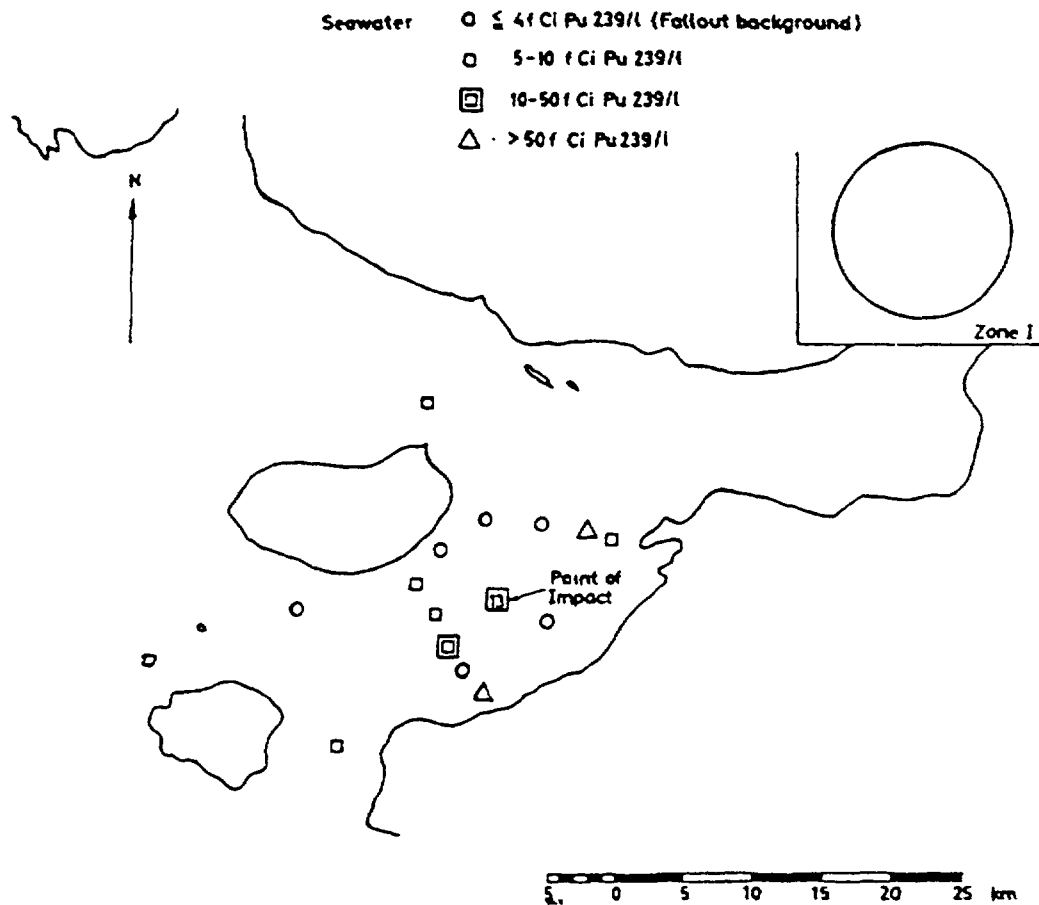


FIG. XI-6. Pu-239 levels in sea water. Thirteen samples were collected in zone I.

It is concluded that the ^{239}Pu level in the top layer of bottom sediments in Bylot Sound is approximately 10 times the expected fallout background. In the inner zone around the point of impact the level was more than 100 times as high as the background. This inner zone of high activity might extend as far as a couple of kilometers from the center.

Seaweed. The plutonium level in sea plants (*Fucus* and *Laminaria*) was measured in seven samples collected along the shores of Bylot Sound. The median level was $14.8 \text{ Bq } ^{239}\text{Pu/g ash}$ ($555 \text{ Bq } ^{239}\text{Pu/kg wet weight}$) as compared with $7.4 \text{ Bq } ^{239}\text{Pu/g ash}$ in samples collected in other parts of Greenland (Godthab, Prins Christians Sund, Danmarkshavn). A sample from Qanaq contained $11.1 \text{ Bq } ^{239}\text{Pu/g ash}$.

It is concluded that sea plants showed levels of ^{239}Pu hardly significantly above fallout background.

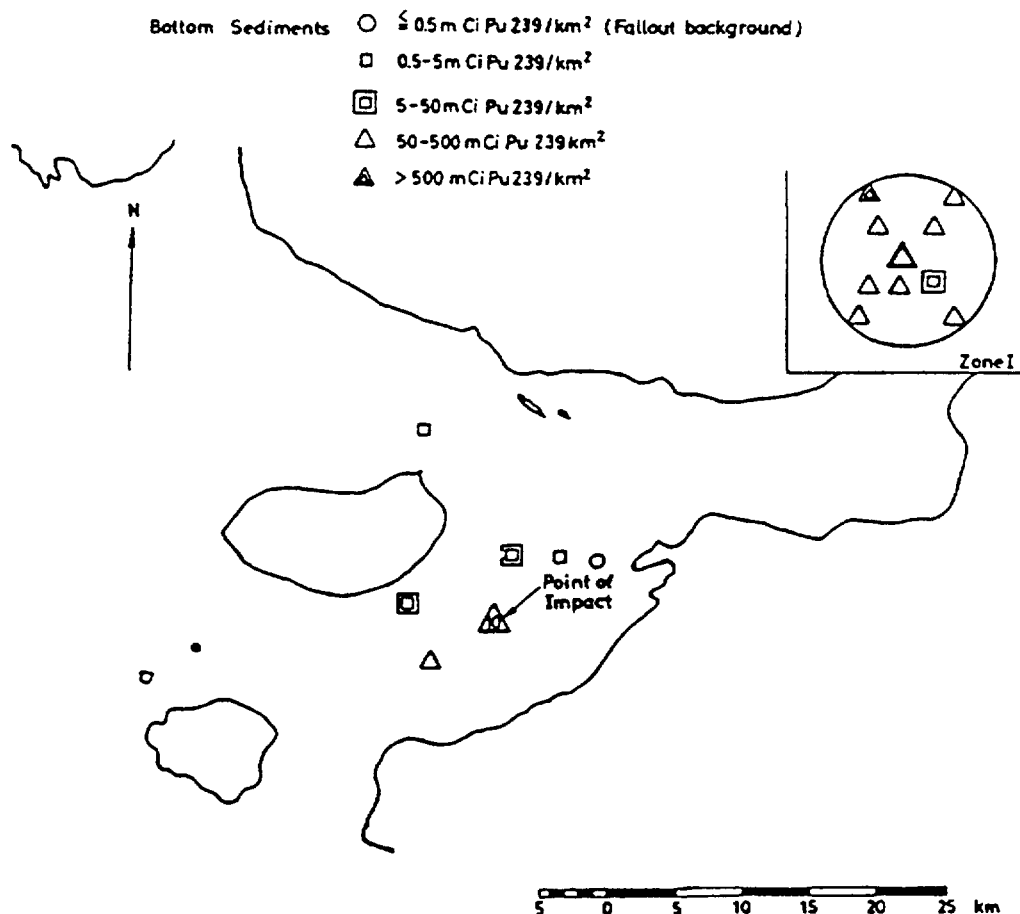


FIG. XI-7. Plutonium-239 levels in bottom sediments. Ten samples were collected in Zone I.

Plankton. Mixed samples of zooplankton were collected in the surface water layers southwest, northeast, and southeast of Zone I. Furthermore *Gammarus* were collected along the shore at Manussak and north of Dundas Mountain. The median level of the zooplankton was 111 Bq ^{239}Pu /kg fresh weight. In *Gammarus* the mean level was 4.1×10^4 Bq ^{239}Pu /kg. If the ratio between the plutonium levels in zooplankton and sea water is 2500 (cf. above), the estimated plutonium level in zooplankton (incl. *Gammarus*) is ~370 Bq/kg.

It is concluded that the plutonium level in zooplankton (incl. *Gammarus*) was hardly significantly different from the fallout background.

Crustacea. Eight samples of crustacea caught during trawling on the outskirts of Zone I were analyzed. Some samples were divided into flesh and shell. The median level of the total animal samples was 7.03×10^4 Bq ^{239}Pu /kg fresh weight. The median levels of the flesh and the shell samples were 3515 and 1.22×10^4 Bq ^{239}Pu /kg respectively. The maximum level for

crustacea samples was 4.44×10^5 Bq ^{239}Pu /kg total animal. Shells normally contained more ^{239}Pu than did flesh tissue. As these crustacea are bottom animals, it is believed that most of their plutonium content was particles incorporated from the bottom sediments. Samples of crustacea from southwest Greenland contained 111 Bq ^{239}Pu /kg, and samples from Danish inner waters contained 74 Bq ^{239}Pu /kg. It is concluded that crustacea from Thule contained certain amounts of ^{239}Pu from the accident, the median level being nearly 1000 times the fallout background.

Bivalves. Figure XI-8 shows the level of ^{239}Pu in bivalves. The median level of all samples from Zone II was 2368 Bq ^{239}Pu /kg. In Zone I it was 2.96×10^5 Bq ^{239}Pu /kg. The maximum level was 2.81×10^6 Bq ^{239}Pu /kg; the sample concerned was collected in Zone I, a few hundred meters north of the point of impact. The fallout background in bivalves was estimated to be approximately 185 Bq ^{239}Pu /kg on the basis of measurements of bivalves from Danish waters. Figure XI-8 shows that nearly all samples from Thule were above this fallout background. Bivalves thus seem to be very sensitive organisms for the detection of plutonium in marine environments. Five different species of bivalves were investigated; it was, however, not possible to see any significant difference between the plutonium levels in the different species. From replicate analysis it was evident that the plutonium activity was very inhomogeneously distributed within a sample. This was undoubtedly due to the fact that most of the plutonium in the mussels was in particulate form. It is concluded that bivalves contained plutonium levels significantly higher than background and that the highest concentrations (more than 1000 times the fallout background) were to be found near the point of impact. Plutonium could, however, be detected in levels significantly above background even as far away as 20 km northwest of the crash area.

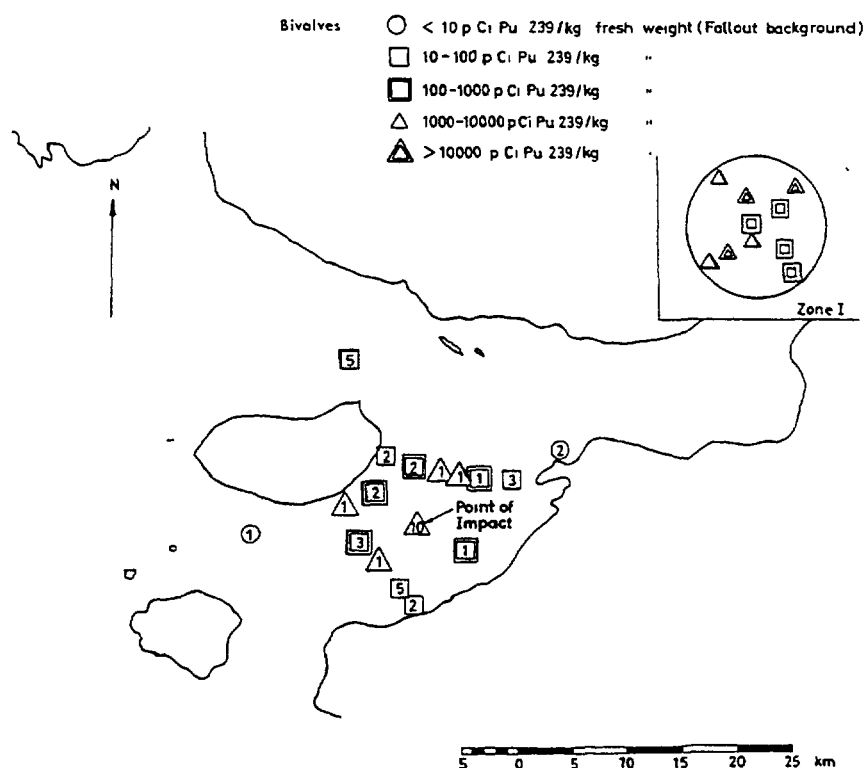


FIG. XI-8. Plutonium-239 levels in bivalves. The numbers refer to the number of samples analysed from each location.

Bottom animals. From Zone I a few samples of worms, starfish and sunstars were analyzed. A mixed sample of worms from nine stations in Zone I contained 1.11×10^6 Bq $^{239}\text{Pu/kg}$, and starfish and sunstars contained between 7030 Bq and 40 700 Bq $^{239}\text{Pu/kg}$ fresh weight. It is concluded that not only bivalves, but also other bottom animals, concentrate ^{239}Pu from the environment and that significant amounts were present especially in the samples collected near the point of impact. Fish. Sea scorpions were found at the low waters along the southeast coast of Saunders Island. Two samples were analyzed. The plutonium content of the first sample was hardly significantly above the background, the other sample contained 518 Bq $^{239}\text{Pu/kg}$. The polar cod is the most common fish in the district. Three samples of this species were analyzed and showed levels from 703 to 8510 Bq $^{239}\text{Pu/kg}$. A Greenland halibut caught just north of Zone I contained 1.74×10^4 Bq $^{239}\text{Pu/kg}$. This was the maximum level found in any fish sample. The medium level of all fish samples (10) was 1369 Bq $^{239}\text{Pu/kg}$.

It is concluded that especially fish living near the sea bottom, as the Greenland halibut, contained Pu levels significantly above fallout background. However, the concentrations were lower in fish than in bivalves and crustacea.

- *Sea birds.* Five samples of intestinal contents of eider, black guillemots and Brunnicks guillemots were analyzed. The median level was 130 Bq $^{239}\text{Pu/kg}$. Eiderdown collected on the Manson Islands and the Eiderduck Islands contained 4810 Bq $^{239}\text{Pu/ kg down and dust}$ (adhering to the down).

It was concluded that the sea birds contained plutonium levels which were hardly above the fallout background. The plutonium levels in their intestinal contents were nearly the same as in zooplankton, which is a main constituent of their diet. The down, or rather the dust in the down, from the Eiderduck, however, contained significant levels of plutonium.

- *Seals.* Five samples of intestinal contents of seals killed in Bylot Sound and Wolstenholme Fjord were analyzed. The medium level was 37 Bq/kg fresh weight. The maximum level was 148 Bq/kg found in the stomach contents of a ringed seal shot by the expedition just north of Narssarsuk.

It was concluded that seals contained very low levels of plutonium, and that the levels were hardly significantly different from the fallout background.

- *Walrus.* Intestinal and stomach contents of five walrus killed in late spring west of Saunders Island were analyzed. The median level was 48 Bq $^{239}\text{Pu/kg}$ and the maximum was 66.6 Bq $^{239}\text{Pu/kg}$. It was concluded that walrus did not contain ^{239}Pu levels significantly above background. On the other hand, this was not unexpected, as the walrus were killed before the ice melted in Bylot Sound.
- *Human urine.* Samples of urine from the Greenlanders at Narssarsuk were collected three times: just after the accident, in September 1968, and in February 1969. A few of the samples from the first two collections showed traces of ^{239}Pu ; however, the possibility that these samples had been contaminated during the sampling could not be excluded. Hence a new set of samples was collected in February 1969, and none of these samples showed any traces of ^{239}Pu .

It was concluded that it was unlikely that any Greenlander in the Thule district had been exposed to significant levels of plutonium as a result of the accident.

- *Hazard evaluation.* The International Commission on Radiological Protection (ICRP) have not given maximum permissible concentrations (MPC) for marine samples. If food habits and concentration factors in the food chains are known, it is, however, possible to estimate

an equivalent to the permissible levels in such samples. In this case, probably the bivalves were the critical sampling object. From the ICRP's recommendations for drinking water it is calculated that the maximum permissible daily intake of ^{239}Pu with the diet is 3700 Bq. If, for instance, a Greenlander eats 100 g bivalves daily, which undoubtedly is an upper estimate of his consumption, the MPC in bivalves becomes 37000 Bq Pu/kg. Even the strongest sample of bivalves contained only one tenth of this pessimistically estimated MPC value.

- *Eiderdown*. Eiderdown collected in the summer is cleaned of dust by the Greenlanders. This cleaning might be a matter for concern as an inhalation hazard if the down and dust contained appreciable amounts of plutonium. From the ICRP's recommendations, the daily permissible intake of insoluble ^{239}Pu into the lungs is calculated at 7400 Bq, i.e., the permissible annual intake would be 2.7×10^6 Bq. The concentration of ^{239}Pu in eiderdown was 4810 Bq $^{239}\text{Pu}/\text{kg}$; it is thus extremely unlikely that any Greenlander occupied with the cleaning of down might reach the permissible intake of ^{239}Pu into the lungs.

Conclusions

The radio-ecological investigation showed that the plutonium levels in the collected samples in no instances were such that they can be considered harmful to man or to higher animals in the Thule district or in any other part of Greenland. Nonetheless, the B-52 accident in Bylot Sound at Thule in January 1968 measurably raised the plutonium level in the marine environment as far out as approximately 90 kilometres from the point of impact. The highest concentrations were found in bottom sediment, bivalves and crustacea. The higher animals such as birds, seals, and walrus showed plutonium levels hardly significantly different from the fallout background. Plutonium was not, with certainty, detected in urine from Greenlanders.

References to Annex XI

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